HUNTING Technical Services

H T S

REPUBLIC OF YEMEN
MINISTRY OF AGRICULTURE AND WATER RESOURCES
TIHAMA DEVELOPMENT AUTHORITY

TIHAMA ENVIRONMENT PROTECTION PROJECT
SAND DUNE STABILISATION PROGRAMME

AEOLIAN SAND FORMATIONS OF THE TIHAMA - GEOMORPHOLOGY AND ASSESSMENT OF SAND STABILISATION PROGRAMMES

FINAL REPORT

January 1999

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SUMMARY

S.1 Background

This report covers investigations on the Yemen Tihama of aeolian sand formations and reviews current programmes for sand dune stabilisation being undertaken by the Tihama Development Authority (TDA) on the International Fund For Agricultural Development (IFAD) funded Tihama Environmental Protection Project (TEPP). The TDA requested Hunting Technical Services Limited (HTS) to carry out field studies, using recently acquired SPOT satellite imagery, and report on the dynamics of the sand dunes, their interaction with land use and assess the sand dune stabilisation programmes. The geomorphological studies would be supported by laboratory analysis of dune sediments.

S.2 Work Programme.

Five SPOT PAN scenes, imaged in November and December 1997 and February 1998, were procured for the project and processed into 1:50,000 image maps at HTS. The HTS consultant arrived in Yemen on 7 June and returned to the UK on 30 July. The field study comprised reconnaissance tours throughout most of the Tihama with detailed examinations at selected sites and along transects; and visits to all locations of the sand stabilisation programme of TEPP. Measurements were made of dune sizes, present and indicative seasonal wind directions.

S.3 Laboratory Analysis.

Sand samples were dry sieved in Hodeidah. The main laboratory work was undertaken at the Postgraduate Research Institute for Sedimentology at the University of Reading, during August 1998, and included: particle size analysis of sediments by Laser Granulometry; X-Ray Diffraction to assess bulk mineralogy of sand sources; examination of sand grains using a Scanning Electron Microscope to assess grain surface textures, and qualitative elemental composition of grains and surface coatings using energy dispersive X-ray analysis; geochemical analyses to assess carbonate loss in sands, and total chemistry to assess levels of elements in the sands; and thin section preparation and microscope examination of concretion, topsoil, and cemented coastal aeolian sands, to assess the type and degree of cementation.

S.4 Map Production.

At the end of the field season field interpretations for each of the 1:50,000 image sheets were digitised to provide area measurements and incorporated into final image map sheet overlain by the thematic information of aeolian landforms / underlying landforms / land use / assessment of drifting sand hazard / and wind directions.

S.5 Previous Studies.

In the past there have been only limited studies concerning the aeolian geomorphology of the Tihama. Geomorphological and soil studies on the multidisciplinary studies in each wadi basin, and also a nationwide soil survey conducted by FAO / USAID, have provided useful background materials. Concerning sand stabilisation however, extensive proposals to assess and implement an action plan for mitigating drifting sands, were made for Wadi Rima' during the 1970s' by the Land Resources Division (LRD) team. Unfortunately, little of this was implemented except for shelter belts in the irrigated lands. More recently, plans for sand dune stabilisation in the Wadi Mawr, Wadi Siham and Wadi Zabid were drawn up in the preparation phase for the present project by the FAO's Investment Centre (1990 and 1991). The IFAD Appraisal Report (1992) amended the design features for the dune stabilisation programme and form the basis of the present sand stabilisation programme. It was concluded that stabilisation of the sands in coastal areas was unnecessary.

S.6 Analysis of Wind Directions.

Incomplete collections of data on wind speed and wind directions have been given in many earlier studies. The principal study on winds was an agro-climatic study conducted by the Land Resources Division (LRD) as part of the Wadi Rima' Project, reported in considerable detail by the LRD team (1979). That study remains the most comprehensive investigation of winds in the Tihama that has been published. The TDA currently carries out meteorological readings at a number of stations throughout the Tihama but has had software problems in processing data from several stations where there are automatic recordings of a range of parameters including wind speed and direction.

All wind speed and wind direction data given in reports however, has been collated for the present study. Data from Kamaran Island shows that wind directions were from the south and south west for 55% of the year (October to May), and from the north and north west for 19% of the year (June through September). Inland at Ad Dahi prevailing wind directions are from the north west and south west with daily mean wind speeds of 1.5 to 1.9 m/s, considerably less than at Kamaran. Data from Hodeidah again shows that wind speeds are higher along the coast: monthly mean is 4 m/s, with range from 2 to 6 m/s. The significance of these higher speeds near the coast is that coarser grains will be moved by the higher threshold velocities. Inland only smaller sized particles can be moved by normal winds. In the Wadi Rima there are strong diurnal changes in wind directions that persist for much of the year with westerly sea breezes forming every day as the land heats up, being replaced by easterly land breezes during the night as cool air descends off the mountains. The data for Al Madaniyah shows that the strongest winds are from southerly to south-westerly directions which occur during the winter, whilst in summer north-westerly and west-north-westerly winds are dominant.

S.7 Classification of Active Aeolian Landforms.

The classification of aeolian sands used in this report follows that given in 'Aeolian Sand and Sand Dunes' (K. Pye and H. Tsoar, 1990). The study has used their four groups of dune landforms :

a). *Sand Accumulation related To Topographic Obstacles.* Includes echo dunes, climbing dunes, cliff-top dunes, lee dunes and falling dunes. These are minor features on the Tihama, generally related to buildings at the present time.

b). *Accumulations of Fine Sand Related to Bed Roughness Change/ Aerodynamic Fluctuations:.* Includes barchans, transverse ridges, unvegetated linear dunes (seifs), dome dunes and star dunes. All but the last two are present and common in the Tihama.

c). *Accumulations of Poorly Sorted & Bimodal Sand Related to Bed Roughness Change or Aerodynamic Fluctuations.* Includes sand sheets and undulating zibar sand plains. Sand sheets are ubiquitous, and zibar occur in the central area of sand seas that lie between the main wadis.

d). *Sand Accumulation Related to Vegetation.* This type includes parabolic dunes, hummock dunes (nebkha) vegetated linear dunes. Parabolics occur only in the coastal areas, whereas hummock dunes are present throughout the Tihama. Vegetated linear dunes may be forming over a series of ancient sand ridges.

S.8 Formation of Modern and Ancient Sand Dunes

Recycling of sediments, eroded from the mountains of Yemen into the Red Sea, and then blown back to the mountains and interior by winds is a controlling process in the region, which whilst complex spatially and temporally, contains several characteristic components. The detailed field and laboratory analytical studies carried out during the present study have concluded that the coastal and inland dunes are intimately connected, and that coastal dunes supply the interior sand seas.

In the wadi beds the winds separate out the coarser fractions of flood bed loads, and limited supply of sand, and quantities of silt sized dust, are blown out onto adjacent lands from the wadis. The majority of the flood's transported load, comprising silty and clayey alluvium, is deposited on fields and canal banks within the spate irrigation systems. At intervals, floods with sandy and silty sediments reach the coast to deposit their bedload in coastal waters. These sediments are transported by currents either into deeper waters, onto offshore sand spits and bars, or onshore onto the beaches where the coarser fractions, generally composed of shell fragments, are progressively reduced in size. Wind then separates out the finer fractions, transporting them inland, first as fairly coarser textured aeolian sands of coastal hummocks, coastal foredunes, parabolic dunes and barchans, and then into the interior plains, where sands become finer and the amount of shell material is reduced.

Modern sand movement in the interior is north-easterly, the resultant of the dominant wind directions from the north to north-west (summer) and the south-south-west (winter). The interior aeolian landforms include hummocks, sand sheets, barchans, transverse dunes, complex networks of transverse dunes, and seif dunes. These form extensive sand seas in the inter-wadi areas that are transgressing over other landforms. The aeolian sands also become progressively finer towards the mountains.

The north-easterly movement of sand sheets and sand dunes is modified by the variability of seasonal and diurnal winds. Although the annual movement of the slip face of a sand dune in the area is at least 10 m / year, individual sand grains are likely to move far greater distances, and in the unvegetated sand seas of the Tihama, with closely spaced transverse dunes, saltating sand grains may well move hundreds of meters during single periods of strong winds, being transported from one dune ridge onto the next by saltation, or by short-term suspension of the finer particles when there are strong gusts. By contrast, the slip face of the dune is advancing at a more steady rate, up to few tens of centimeters a day and often much less than this. Thus, sands originating on the coast can be blown rapidly inland to augment dunes threatening farmlands, and the coastal areas should be regarded as intimately connected with the inland dunes. Research is needed in the Tihama to measure and quantify the local situation.

In general, the development of sand sheets and sand dunes reflects local supply of sands from the sea and coastal areas. On high energy coasts the sand supply coming onshore is substantial and forms coastal dunes that feed the interior sand seas. The role of natural vegetation in coastal dune formation is critical, and acts as natural stabiliser, reducing rapid movement inland. Where coastal barriers exist, such as mangrove and coral reefs, the sand supply is reduced but thin sand sheets often still form, and over time can accumulate inland into significant mobile dunes. On the coast modern dune formations are often saline and are progressively cemented by calcium carbonate into aeolianites. These present harsh environments for plants to colonize, and wind erosion of aeolianites probably supplies a considerable volume of sand from coastal areas to feed the interior dunes.

The modern sands overlie an older set of aeolian formations, termed the ancient sand plains and sand ridges. The ancient sand dunes form a series of regularly spaced and approximately east to west aligned linear dunes. These dunes have been stabilised in the past by soil formation processes, and can be 20m or more high, 250 to 500m broad, and many kilometers long. Sandy inter-dune corridors are 1 to 2 km wide. These palaeo-dunes formerly reached the escarpment. Fluvial erosion of the soils that have developed on the ancient sand formations is now the dominant process and locally contributes to sand dune formation. The ancient dune formations also include aeolianites along the coasts that are often being eroded by sand laden winds.

S.9 Analysis Of Sand Dune Stabilisation Programmes.

Movement of aeolian sands is taking place over much of the Tihama. This affects main roads and access tracks to many population centers, necessitating costly operations to clear sand drifts. Until recently, the general absence of sand stabilisation measures and on-farm shelterbelts in many areas has led to sand movement into the irrigated lands and deflation of dust from alluvial soils. The loss of farmland from encroaching sand dunes is particularly serious and unrelenting.

The present study has concluded that site conditions play a central role in the origins, presence and stability of aeolian features. There are no simple rules for sand control that can be applied right across the Tihama. A complete investigation of the local conditions (winds, aspect, sediment sources, nature of the coast, topography, land cover and land use etc) should be undertaken at each site prior to establishing stabilisation measures.

The study assessed the TEPP Sand Dune Stabilisation Programme under implementation by the TDA. Components of the programme include: the Hodeidah Green Belt, a protective shelterbelt being afforested on the north east side of Hodeidah; sand dune stabilisation along the Sana'a road and in adjacent villages; and farm shelterbelts and dune stabilisation efforts in the Wadi Siham and Wadi Zabid. The TEPP has drilled numerous water wells in these areas which will be used for irrigating shelterbelt species. The present study has concluded that a number of improvements can be made to the present methods being adopted, summarized as follows:

i). Use of Checkerboards Design for Fencing.

The checkerboard system of fencing, using dried plant residues, is recommended for reducing wind speeds on mobile sands prior to planting, and ideally should be extended onto all drifting sand landforms in the affected areas and not just on the dune forms. Shallow sand sheets can rapidly develop into dunes and bury young plants. Fences should be regarded as standard procedure in all areas of the TEPP. Though locally they may have a significance, parallel fences, or fences with L-shaped design, are unlikely to work as efficiently in most areas of the Tihama where multi-directional winds blow throughout the year. In addition, winds from unusual directions do occur and can cause considerable damage on unprotected planting zones. Fences will also need replacing at intervals as they deteriorate, for without fences dune formation will be initiated again.

ii). Flattening of Dunes.

Attempts to stabilize routes through large areas of mobile dunes, by flattening and then carrying out afforestation should be avoided, as changing wind directions, dry conditions of sands and general access, will compromise efforts to stabilize a narrow pathway. Where possible the margins of dunefields should be tackled first, and this now appears to be the method to be adopted in the Hodeidah "Green Belt".

iii). **Establishment of Automatic Stations for Determining Wind Velocity.**

There is a need to install automatic stations with anemometers to record wind speed and wind directions on a continuous basis using data loggers. Data can then be analyzed to show wind directions and resultant sand drift wind velocities throughout the year. Existing TDA stations require maintenance and / or upgrading to fulfill this requirement, and to carry out analysis of existing databases at TDA and the Civil Aviation and Meteorology Authority.

iv). **Use of Mesquite for Sand Stabilisation.**

The use of Mesquite (*Prosopis juliflora)* in areas remote from farms should be considered for sand dune stabilisation work. It has a proven usefulness in semi-arid and arid zones as a very rapid stabilizer of mobile sands, and locally has stabilised dune fronts to the east of Hodeidah, and dunes within the city. It is a vigorous colonizer of soils however, and will become a very serious weed on agricultural land if allowed to become established. It is thus not recommended for use on dunes adjacent to farmlands, nor on coastal foredunes where sands, and thus seeds, can move rapidly inland.

v). **Proposed Construction of Foredunes in the Interior Dune Lands.**

The building of foredunes in the interior areas requires testing before this high cost operation is initiated. A pilot area should be initiated, prior to large scale construction work. Sand accumulation will occur where obstacles are placed and assist in the growth of foredunes. Dunes flattened by bulldozer will have a natural tendency to rapidly re-assert themselves back into dune shapes, if checkerboard fences are not constructed. Foredunes can be considered however, for rapid construction in certain areas where there is a critical and timely need to stop sand. Elsewhere natural dune accumulation, following fence and checkerboard establishment, is desirable.

vi). **Coastal Foredunes.**

Any establishment of foredunes in coastal areas is considered best left to natural processes of sand accumulation, aided by checkerboard palisades / fences and plant establishment. The natural vegetation however must be allowed to survive, on the beaches and coastal dunes, as it plays a vital role in stabilizing sands.

vii). **Soil Improvement.**

The use of mulches and green manuring is to be encouraged as these will lead to formation of stable soil aggregates and release of plant nutrients from the various minerals that comprise sand grains. Composting of surplus green vegetable matter (e.g. from Mesquite) and its incorporation into sandy soils will enormously aid in stabilisation of aeolian sands. Mixing of silty and sandy soils should to be investigated as an additional method of helping to form a wind-stable soil. Stabilisation and soil formation of the ancient aeolian sands however, was probably accomplished under a climatic regime considerably different than the present.

viii). **Farm Shelterbelts.**

Farmers should be strongly encouraged to establish shelterbelts over farmlands, and in the pastoral lands that exist upwind of dune belts. Tree-free zones designed to stop birds roosting adjacent to crops, and advocated by some landowners, are leading to an increase in sand movement of a number of the dunefields that lie adjacent to villages. The villages by contrast are often well vegetated with similar shade trees. It is considered that the benefits from reduced sand and dust movement on the health of people and crops, will well outweigh any effect of increased bird populations on crop loss.

ix). Protection of the Natural Vegetation Cover to Assist in Stabilizing Drifting Sands.

Human disruption of the vegetation cover of sand hummocks along the margins of the cultivated lands and in the coastal areas, appears to lead to extensive development of more mobile sand sheets, which in turn, form sand dunes. A major effort is required to educate land users on the effects of vegetation loss on sand dune mobility, and to show that stabilisation of dunes is a function of the land cover.

x). Rejuvenation of Shelterbelts.

Established shelterbelts, left to develop without further management (e.g. Zabid to Tuhaytah), will often require rejuvenation as plants die from effects of drought and sands re-mobilize. Irrigation, repeated every year or two would be costly to implement, but would have long-term benefits in saving a shelterbelt and reducing the impact of drifting sands. Checkerboard fences also need to be replaced in these areas if dunes are to be controlled with the long-term view in mind.

xi). Periodic Use of Spate Irrigation to Rejuvenate Alluvial Lands on Margins of Sand Seas.

Some alluvial lands on the margins of the sand seas, that were formerly spate irrigated in most years but which now lie completely outside the zone of the managed irrigation systems, have suffered increased encroachment by dunes. Periodic inundation of these lands in the past appears to have confined sands to valley margins, but now dunes and sand sheets threaten agricultural lands increasingly further away from the original dune front on the valley side. Over-pumping of aquifers is desertifying some agricultural areas where pump irrigation had been developed. Where groundwater is limited consideration should be given by TDA to carrying out periodic controlled floods of such areas so as to recharge groundwaters, allow establishment of shelter belt trees, and rejuvenate agriculture.

xii). **Protection of TDA Tubewells.**

The TDA should check all recent drilled wells to ensure that the well head caps are tightly sealed. If they are not there is a high risk that sand will fill in wells when drifting sand dunes bury well structures.

S.10 Proposed Interventions For Future Programmes.

The study has also made a number of conclusions concerning additional interventions that will assist in the stabilisation of sands throughout the Tihama, in a future programme adjustment. These include:

a). Reducing Sand Movement In Coastal Areas.

Coastal areas have been denied an input into the present programme because they have been said to play an insignificant role in the problems of movement sand dune onto agricultural land, and that the links with the inland dunes were distant enough to be unimportant. The present consultancy has concluded that this view is largely unfounded. Coastal areas should be included in the overall scheme as some have severe problems with drifting sands. Although dunes move slowly, sand supply from coastal to inland areas can be very rapid. The report discusses the ecological requirements necessary for successful sand stabilisation along the coast using indigenous and exotic plant species. By allowing nature to build up dunes and abandoning the concept of constructing a coastal foredune costs would be considerably reduced. The TDA is thus urged to reinvestigate the proposals for work in coastal areas, and specifically in those farmlands where dunes are burying date plantations.

b). Establishment of Additional Protection Areas.

A number of proposed protection areas, coastal and inland, are shown on the 1:50,000 image maps that accompany this report. These are areas which have very considerable problems with sand movement at the present time, but are not included in the IFAD funded programme. From field studies conducted throughout the Tihama during this consultancy it was concluded that these areas will need protection in the future if they are to survive. In some areas the situation is deteriorating and fields and rural communities could be overwhelmed by sand dunes sand lost. These include:

Qutay to Munayli Area:	Margins of ancient sand sheets, and stabilisation of gullies cut into sand ridges.
Kulzum Area, W. Siham:	A relatively small area of date palms that are threatened with engulfment by dunes.
At Ta'if area:	Coastal parabolics and hummocks protected from land use pressure.
Sawlah to Al Lawiyah:	Stabilisation of dune front that is engulfing villages in Wadi Rumman.
Wadi Kuway Area:	Protection of date palm plantations that are threatened by parabolic dunes.
Madaniyah to Wadi Ajji:	Protection of irrigated lands from transverse and parabolic dunes.
Mutayna Area:	Investigate local success in maintaining vegetation cover in coastal parabolic dunes.
Wadi Urfan Area:	Protection of main road south of Hays from dunes and sand sheets.

c). **Monitoring wind velocities and the movement of sand.**

No detailed study has yet been made of the actual threshold velocities to lift sand and dust particles in the Tihama, and they are beyond the scope of the present reconnaissance study. It is important to quantify local thresholds where detailed sand stabilisation efforts are being undertaken, by measuring the movement of the different types of (Tihama) sands under different wind velocity regimes. Such a study would require the establishment of several sand movement stations where the process could be investigated over the course of a year. Use should be made of existing weather stations where sand velocity is measured, though not yet analyzed, such as automatic station operated by TDA on the shelter belt between Zabid and Tufaytah. Sand traps would need to be emplaced to measure volumes of annual sand drift past fixed points. A future programme to assess sand movement and threshold velocities however, should firstly carry out a full analysis of the existing TDA wind data. This investigations could form the core of a higher degree study for a Yemen national at an appropriate university.

d). General Investigations.

The present study has made a number of conclusions on the origins of the sand formations and their distribution. Many other questions remain unanswered where there are dunes moving inland and into irrigated lands. Future studies should attempt to determine, for example:

- Are dunes advancing any faster in recent years, and how much of this is due to the cutting of vegetation growing on dunes?
- Or has there been drought and drying up of the shallow water tables causing the vegetation to desiccate ?
- If there is a lowering of watertables is it due to overpumping in the valley or is it due to reduced recharge ?
- Has the development of controlled irrigation systems led to a reduced 'flushing' of the dunes by occasional large floods, or is it due to climate changes?
- How will any changes in sea level in the future affect sand supply along the Tihama coast ?
- What are the effects of biological stabilisation of sands by faecal pellets, and how can this be improved and sustained?

S.11 Conclusions from Sedimentological Analysis for Sand Stabilisation.

Particle Size Distributions.

Dry sieving and microscope study of sand samples carried out at TDA has provided important data on the particle size distributions of the sands. It has also showed that soluble salts derived from coastal winds, and faecal pellets from soil animals have an important role in forming soil aggregates and form part of the process of stabilisation in sand hummocks. This is an important lesson for sustaining a programme of biological based stabilisation of mobile sands in the Tihama.

The more advanced technique of laser granulometry, carried out at Reading University in the UK, has provided a more quantitative analysis of the sands. This information is vital in studying the movement of sand particles under different wind velocities. In the Tihama these preliminary studies, carried out along several transects, suggest that the diameters of sand grains decreases with distance inland from the sea. Since wind velocities are shown to be stronger on the coast than inland, the finer sands of the interior, with their reduced threshold velocities, will be moved easily by interior winds. There is scope for more detailed investigations comprising sand traps to measure movement and climate stations to measure wind directions and strength as well as ambient conditions. The data also indicates the precise amounts of silt and clay present in samples, essential knowledge for planning the establishment of plants, the moisture and nutrient requirements of vegetation and, in the case of the ancient sands, their structural stability and susceptibility to wind erosion under different types of land use.

X-Ray Diffraction and Scanning Electron Microscope Studies.

The x-ray diffraction was conducted on ground up sands from a range of sites throughout the Tihama. The results show that there is a similar range of minerals in the sandy sediments. Whereas aeolian sediments, in for example central Saudi Arabia, are composed mainly of quartz grains with prominent iron oxide coatings, the Tihama sands are different with fragments of minerals and rocks and limited iron staining. These will provide colonising plants with an abundant supply of nutrients. Micropores in the rock fragments and mineral grains will trap soil moisture and raise the water holding capacity of the sands.

A range of sand grains were studied under the scanning electron microscope with a view towards characterising surface features and establishing their elemental and mineral composition. Surface features on sand grains, particularly quartz, can provide a clear indication of the origin and environmental history of the grain. X-ray bombardment of grain surfaces and individual crystals additionally provides an analysis of major elements present. Results from this work have shown that surface textures of fresh grains from river sediments and beach deposits have similar angular fractures. Inland these grains become more rounded and show fractures and cavities characteristic of aeolian abrasion. Secondary accumulations of salts (halite and gypsum) in coastal areas. Inland, clay minerals and various oxides occur on grains of older dunes. In contrast the modern active sands of the interior plains have almost no secondary coatings of clay minerals and soluble salts. The present study provides an introduction to this method of investigation. There is very considerable potential to enlarge the scope of the studies which will provide benefits to sand stabilisation.

Thin Section Studies.

The thin section investigations show that cementation of sand formations is largely by microcrystalline calcium carbonate though the degree of hardness of cementation varies. These have variable consequences for stabilising sand formations. In the coastal areas where the aeolianites occur on older sand dunes and also on apparently recent hummocks there is a strong cement of CaC03, for example at Mujaylis. Loose sand is moving inland over such dunes as a thin veneer and wind abrasion has exposed the aeolianites in many areas. Thus there is no stabilising of the sands such as occurs in coastal parabolic dunes.

The presence of aeolianites on recent sand hummocks (as evidenced by plastic detritus in the layers) suggests that there is a widespread process occurring on the coast. This is probably taking place in the subsoil of the hummocks as carbonate minerals in the sea spray crystallize out. Loss of vegetation, whether by human interference or natural processes is not clear, leads to exposure of these hard layers at the surface.

Under such conditions, and with the additional factor of high levels of soluble salts in the coastal zone, these are now very difficult substrates for colonising plants to take root in. The challenge for a future sand stabilisation programme in such an environment will be to create a rooting zone for suitable plants to develop and permit re-development of an overlying foredune and a permanent vegetation cover.

Geochemical Analyses.

Sand samples were taken from a range of coastal and interior dunes along transects. Acid soluble analyses provide a total analysis of the elemental composition of sand sediments. These can be compared with the results of the x-ray diffraction work and show similar differences between the coastal and interior dunes. The analyses indicate the total levels of elements and nutrient availability that exist in the samples, and suggest that there are no major deficiencies which may need correcting to benefit plant growth. High levels of calcium in some of the coastal sands may reduce uptake of magnesium. The water soluble determinations indicate the nutrients that can be readily available to plants, including those salts which may be toxic, in these sands. Soluble salts, such as sodium chloride, have elevated levels in coastal areas but would be reduced if the sand stabilisation programme includes irrigation. Since there is a continuous supply of salts in spray laden winds being driven onshore the reclamation process has to be maintained.

The results of the determinations of CaCO3 equivalents suggest that in the majority of cases looked at the CaCO3 equivalent decreases inland with distance from the sea. The particle size analysis shows significantly higher amounts of non-sandy fine materials, that is silt and clay, existing in the older sands compared to the active sands. A certain amount of this will be as fine particles of calcium carbonate deposited as dust on sandy surfaces and these may explain the high anomalies in some of the geochemical analyses. The low $CaCO_3$ values such as on some active dunes near the coast and inland on older dunes suggest that the modern dunes in these location are derived from sands that are depleted in calcium carbonate, such as the older dune sediments.

The presence of fine carbonate, whether fairly close to the coast or far inland, will generally have beneficial effects on sand stabilisation. The carbonates will provide storage for soil water and a medium for plants to root in, all aiding in soil formation, aggregate stability and reduction of sand movement. The microcrystalline development of calcium carbonate around grains to form hard aeolianites in coastal areas however poses a management problem if these layers become exposed at the surface since they act as barrier to plant establishment. Inland, there is a development of isolated calcium carbonate concretions along former plant roots in the ancient sand dunes, but these are not thought to be forming at present.

1 INTRODUCTION

1.1 BACKGROUND TO PRESENT STUDY

Detailed proposals for a sand dune stabilisation programme were originally given in the First Phase Preparation Mission report (FAO-Investment Centre, 1990), and the subsequent Project Preparation Report (FAO-IC, 1991). An amended programme of investigations was presented by the IFAD Appraisal Mission report for the Tihama Environmental Protection Project (IFAD, November 1992) which recommended that a ten month, three visit, consultancy in Arid Zone Geomorphology be undertaken of the dune systems during the first phase of the Tihama Environmental Protection Project (TEPP). The consultancy would be supported by placing a UN Volunteer Physical Geographer in the TEPP for three years. In July 1993 a proposal for environmental assessment of dune stabilisation and farmland protection was presented to the Tihama Development Authority (TDA) by Hunting Technical Services Limited (HTS).

The TDA requested HTS on October 12, 1997, to prepare a new costed technical proposal for the following: acquisition of new satellite imagery; a seven week field study of the origins and dynamics of the dunes, their interaction with land use, and an assessment of the ongoing sand dune stabilisation programme; and within the TEPP, mapping of the sand dunes in the Tihama at 1:50,000 scale. Subsequently, a contract between the TDA and HTS was signed on 13 March 1998. Following delivery of new 1997/98 SPOT imagery, and its processing into 1:50,000 scale image maps at the HTS laboratories, a programme of field work was carried out by an HTS consultant, experienced in arid zone geomorphology, land use planning and Yemen, during June and July 1998.

1.2 TERMS OF REFERENCE

The Terms of Reference (ToR) are reproduced in full in Appendix A. Summarising, the ToR call for a study of the dune dynamics to cover the whole of the Tihama area, indicating the nature and origins of the dunes for both the coastal and inland areas; the relations between the various the dune systems throughout the Tihama; and the nature of the wind directions in the Tihama. The geomorphological studies would be supported by laboratory analysis of dune sediments. The study would also assess the effect of dune movement on farming and pastoral communities; evaluate the effect of sand dunes on land use patterns; evaluate previous sand dune stabilisation activities with suggestions for improvement measures; and provide recommendations for siting of the sand dune stabilisation and farm protection measures. Using SPOT imagery a programme of mapping would be undertaken in the TEPP area to show the extent of sand dunes and associated farm areas in the TEPP sites, the line of stabilisation works, and other relevant features.

1.3 ACQUISITION OF SPOT IMAGERY AND IMAGE MAP PREPARATION

Recent acquired remotely-sensed SPOT satellite panchromatic (PAN) imagery was obtained for this consultancy and processed by the Remote Sensing Department of Hunting Technical Services, from the original digital data into a series of 1:50,000 scale image maps. The SPOT PAN, with a spatial resolution of 10 m, has scene sizes that are 60 x 60 km, and a single broad spectral band of 0.51 to 0.73 microns which imitates the conventional black and white tones of aerial photography. Five SPOT PAN scenes were procured which cover the TEPP area. The location of the images and of the map sheets that have been produced are given in Figures 1.1 and 1.2. Details of the path, row and acquisition dates of the imagery are given in Table 1.1.

The raw data from the five scenes were computer processed to provide enhanced and geometrically correct imagery suitable for visual analysis and interpretation in the field. The first stage involved geometric correction of the imagery, the purpose of which was to register the imagery to existing map series so that images can be referenced according to Longitude and Latitude and also Grid Co-ordinates. For the Tihama area the 1:50,000 scale map series (Y.A.R. 5C, Edition 1- D.O.S. 1980), with a grid based on Universal Transverse Mercator (UTM) Zone 38P, was used for this purpose. Since Hunting Technical Services had previously prepared image maps of the region for the TDA, and by using archived coordinate data and control point information for the region, it was a relatively straightforward matter to prepare a new series of image maps.

The next stage was to carry out a geometric correction in a block adjustment of the five scenes together. In the block adjustment, where the boundaries of scenes cover two or more topographic sheets it was necessary to mosaic together the individual scenes so that any obvious changes in contrast between juxtaposed scenes became less obvious.

The block-adjusted mosaic was then ready for the next stage of image rectification. In rectification the pixels of the image were rearranged, by processes known as warping and resampling, so that they fitted into the correct position on the Yemen cartographic base. In preparing the map sheets a degree of overlap between sheets was also allowed for, so as to aid in the later transferring of mapping boundaries to adjacent sheets.

A final stage of processing was image enhancement, whereby the contrast and brightness of the image was optimised according to the particular requirements of the project. In this case the available scenes on path K144 appear to have been acquired at a period of considerable haze present over the sea, and there may have been atmospheric dust also. There were very strongly contrasting differences between bright high reflectance values of sand dunes, very dark areas of moist soils on agricultural lands and low reflectance of dense vegetation in certain areas (for example the *Salvadora persica* forest in Wadi Rimah'). This resulted in a very wide range of reflectance values over the whole region but relatively low contrast within each land cover type, which could not be completely compensated despite careful image enhancement.

The processed data was then inserted into twelve 1:50,000 scale sheets and cartographic information added concerning the scale, co-ordinates and the locations of the SPOT PAN scenes and maps. The finished map sheets in digital form were then transferred, using a film writer, onto black and white photographic film. Printed copies of the twelve image map sheets were then prepared by enlargement from a 200 mm by 200 mm negative.

TABLE 1.1 SPOT PAN IMAGES.

Path	Row	Acquisition Date	Topographic Sheet Coverage (1:50,000 scale)
K144	J320	09 November 1997	1442-B2, 1443-A1, 1442-B4, 1443-A3
K145	J320	31 December 1997	1443-A2, 1443-A4
K144	J321	05 February 1998	1442-B4, 1443-A3, 1442-D2, 1443-C1
K145	J321	31 December 1997	1442-D2, 1443-C1, 1443-D1, 1443-C2, 1443-C4, 1443-D3, 1443-A4
K145	J322	31 December 1997	1443-C3, 1443-C4, 1443-D3, 1343-B1, 1343-A1, 1343-A2

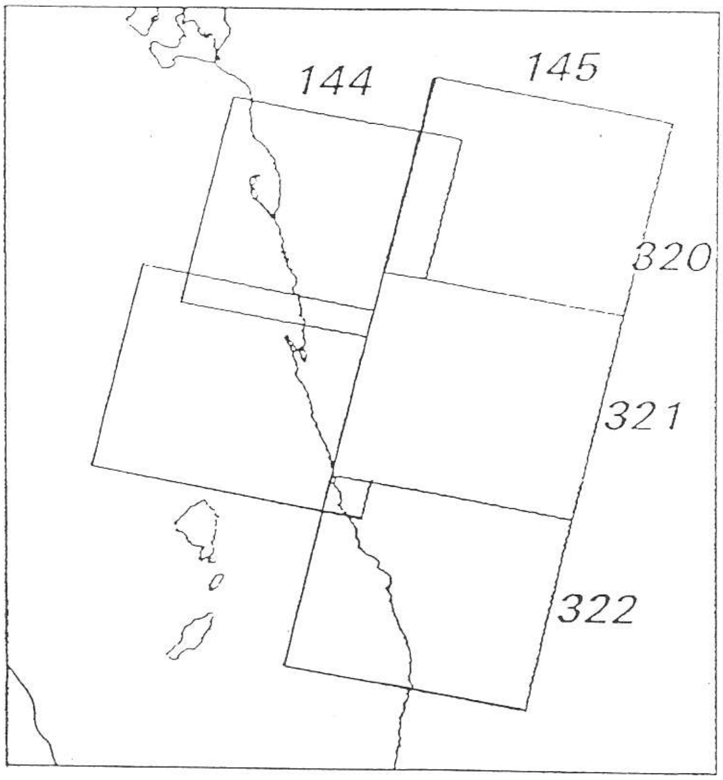
1.4 CONSULTANT'S WORK PROGRAMME IN YEMEN

The HTS consultant (Mr R. Neil Munro) arrived in Yemen on the 7 June and returned to the UK on the 30 July. A daily record of his work programme is given in Appendix B. Whilst in Yemen the consultant reported to and was supervised by Dr. Babiker Ahmed El-Hassan, the Chief Technical Adviser (CTA) to the TDA. The CTA was responsible for ensuring that logistical support was well organised and uninterrupted during a field programme conducted during the middle of the Tihama summer. In this respect the consultant wishes to gratefully acknowledge the services of TDA staff driver Omar Saed who was provided for the duration of his stay in Yemen.

During the field work period the consultant was also accompanied by counterpart staff from TDA Headquarters and each of the regional areas and extensive thanks are to be given to the following for their co-operation and assistance:

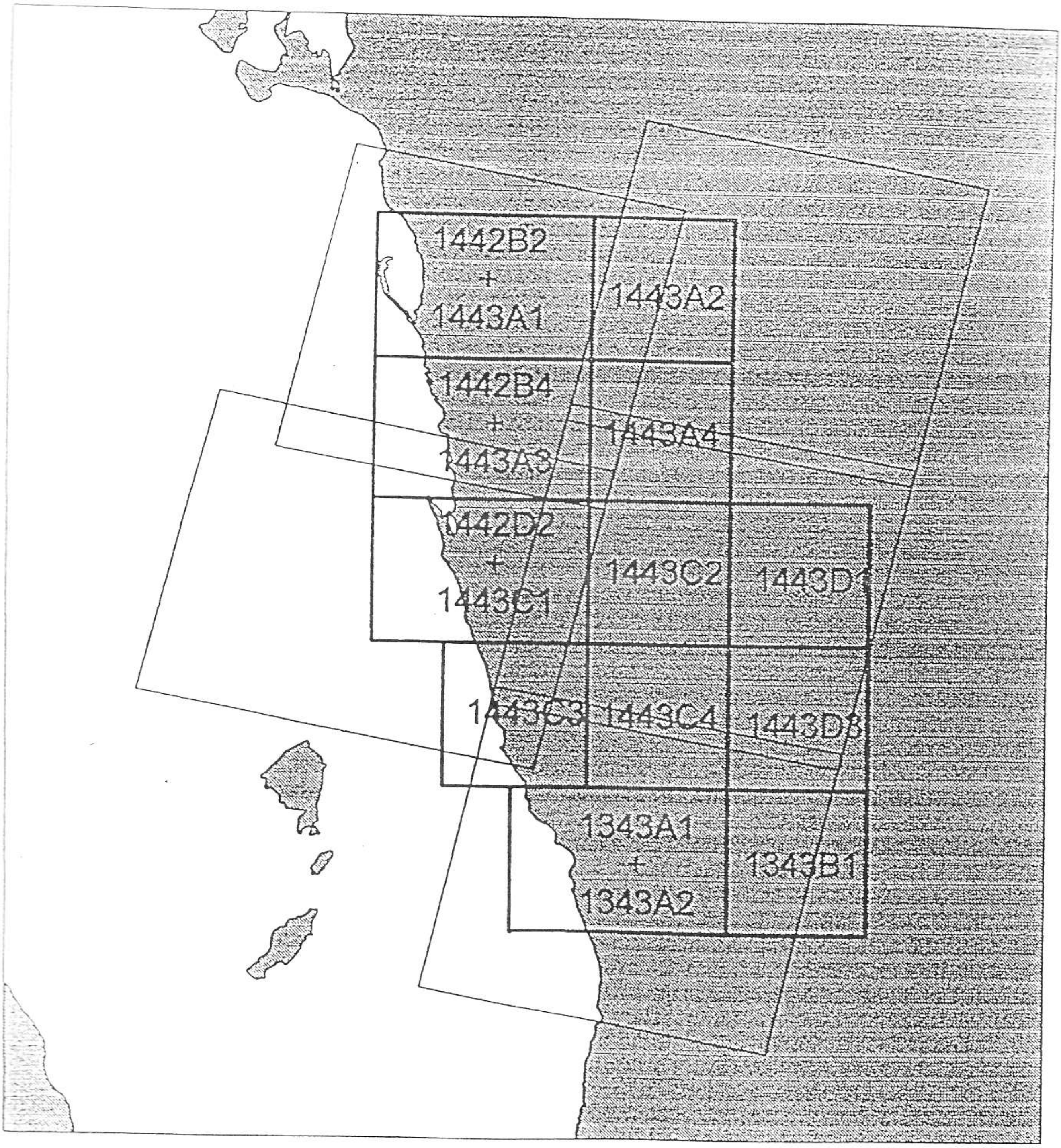
Central Area and TDA HQ (Hodeidahh):

Mr Ibrahim A. Al-Domi (Chairman, TDA)
Dr Babiker Ahmed El-Hassan (CTA)
Mr. Zein M.H. Haig (Director, TEPP)
Mr. Adnan Abdulrahman Mohd. Saleh (Forestry Sp.)
Mr Abdullah Abdul Magid (Extension)
Mr Ahmed Al-Bakiri (Extension)
Mr Mohd Qasim Sultan (Forestry & Engineering)
Mr Abdullah Hassan Abdul Karim (Sand stabilisation)
Mr Mohd Abdul Rahman (Meteorology)
Mr Saleh Hisam (Director, Laboratory)
Mr Amin Mohammed Tohlan (Technician, Laboratory)



Path	Row	Acquisition Date
K144	J320	09 November 1997
K145	J320	31 December 1997
K144	J321	05 February 1998
K145	J321	31 December 1997
K145	J322	31 December 1997

FIGURE 1.2 LOCATION OF 1:50,000 SCALE IMAGE MAPS PRODUCED FROM 1997/98 SPOT PAN



Southern Area (Zabid):

Mr Abdul-Wali Haider (Director, Zabid Station)

Mr Abdul Aziz Abdul Saleh (Forestry, Sand Dune Stabilisation)

Mr Mohd. Mohd. Al Asar (Forestry)

Mr Abdul Hussein Wassel (Forestry, Sand Dune Stabilisation)

Mr Nawaf Salim Ahmed (Hydrology)

Northern Area (Zuhran):

Mr Mohamed Hadi Haig (Director, Northern Region)

Mr Abdul Hakim Sulwe (Sand stabilisation)

Mr Gasher Mohd. Halib (Extension)

Mr Ahmed Shuay Ali (Extension)

Thanks are also due to Dr Ahmed Kotba and Dr Abdul Karim Al-Subbary of the Department of Geology, Sana'a University for technical information and assistance with air freight samples to the UK; and to Dr Ismail Al-Ganad, General Manager of Yemen Mineral Resources and the Geological Survey for access to the library reference collections.

At the end of the mission to Yemen the consultant participated in a half-day seminar at TDA headquarters. The seminar was chaired by Mr Ibrahim Domi, Chairman of the TDA, and was attended by over 25 technical staff of the TDA from all branches and field locations. A short end-of-mission report was prepared by the consultant prior to departure from Yemen.

1.5 FIELD METHODS

The field study period was in the nature of reconnaissance tours throughout most of the Tihama with more detailed examinations at sites randomly selected as tours progressed. The fieldwork included visits to all locations of the sand stabilisation programme within the TEPP, and studies along transects where features in aeolian landforms were studied. Measurements of dune sizes, present and indicative seasonal wind directions, and other features were made throughout the Tihama. A hand-held Garmin G-75 Global Positioning System (GPS) was used to determine the UTM Easting and Northing coordinates at each site. Samples for analysis were collected from different types of sand landforms and some associated soils in the project areas.

A short description of the location and characteristics at each sampled site is given in Table C.1 of Appendix C. The site reference, e.g. M 71, refers to the consultant's numbering system for observations in the field. Only sites with analytical data are listed in the table. The locations that occur within the TEPP are also indicated on the 1: 50,000 scale image map sheets accompanying this report. Other sampled sites, that is those to the north of latitude 15° 00′ north, and south of latitude

13° 45' N can be located with reference to their coordinates. Interviews were also made with a number of farmers and pastoralists throughout the study area.

1.6 LABORATORY METHODS OF ANALYSIS IN YEMEN AND UK.

In Yemen some 80 sand samples were dry sieved at the TDA technical laboratories, using British Standard test sieves, at a range of mesh sizes from gravel to coarse silt. Some samples, because of salt aggregates proved to be inappropriate for this method but valuable data was generated from most. In the UK this data was then processed on a computer using an Excel statistical package to provide a graphical output of the particle size data. Data for this is shown in Table D.1 of Appendix D. The main laboratory work was undertaken at the Postgraduate Research Institute for Sedimentology (PRIS) at the University of Reading, in the UK, under the supervision of Professor Kenneth Pye, a research scientist specialising in aeolian processes and their analysis by laboratory techniques. A substantial programme of analysis was carried out at PRIS during August 1997 and results are summarised in Appendix E. Thanks must be given to the laboratory technical staff at PRIS for their considerable support and instruction. The work at PRIS has included:

a). Particle size analysis of 46 samples of sand and soil by Laser Granulometry (Lozeau et al, 1994), which augmented the work carried out in Yemen.

b). X-Ray Diffraction of eight samples to assess bulk mineralogy of different sand sources;

c). Examination of carbon-coated samples from ten sites using a JEOL JSM5300 Scanning Electron Microscope (SEM) to assess grain surface textures, and qualitative elemental composition of grains and surface coatings using energy dispersive X-ray analysis provided by an Oxford Instruments Link AN10000 Analyser coupled to the SEM.

d). Geochemical analyses of 17 samples for carbonate loss in sands, and total chemistry for 23 samples to assess levels of acid soluble and water soluble elements;

e) Thin section preparation and microscope examination of 6 samples of concretion, topsoil, and cemented coastal aeolian sands, to assess the type and degree of cementation.

The laboratory work in the Yemen and at PRIS in the UK has provided an initial assessment of the nature of the Tihama sands. From this examination various preliminary conclusions and trends have been noted and these are reported in this report. The reader is advised to refer to the data appendices when site samples are given in the text. A full assessment of the sands would require a longer study, a carefully planned sampling programme and a considerably longer analytical phase accompanied by a broadened range of analytical techniques. It is considered that there is scope for several higher degrees, to MSc and PhD levels, perhaps within the framework of existing academic cooperation agreements that the University of Sana'a has with universities in the UK and elsewhere.

1.7 FINAL MAP PRODUCTION.

At the end of the field season the consultant prepared fair copies of his field interpretations. These thematic overlays covered each of the twelve 1:50,000 scale image sheets. The mapping units comprised a combination of aeolian landforms with the underlying older landforms, the predominant land use on those landforms and an assessment of drifting sand hazard. Information on wind directions and sampled sites was also added. The worksheets were given to the Remote Sensing Section of HTS for digitisation, area measurement and production of the final version of combined image map sheet overlain by the thematic information.

After checking the boundaries between each map sheet the interpreted worksheets were manually digitised with interpreted lines, areas and mapping unit codes converted to digital form. Each digitised polygon was labelled with the appropriate code, and area measurements prepared for each sheet and for the region as a whole. Test plots of the thematic overlays were then given a final check prior to being overlain onto the image maps. A legend was then added to the sheet series and the finished maps then transferred onto the film writer for negative production and printing.

1.8 AEOLIAN CLASSIFICATION AND SAND STABILISATION REFERENCES.

A considerable number of texts are now available for consultation when studying arid zone geomorphology and aeolian landforms. An important general work is 'Desert Geomorphology' by Cooke, Warren and Goudie (1993) which replaces the earlier text by Cooke and Warren (1973), 'Geomorphology in Deserts'. This covers all aspects of geomorphology in arid areas including aeolian sediments and landforms. 'Arid Zone Geomorphology' (Thomas, 1989 and also recently updated) is a complementary text. An older general texts is 'Desert Landforms' by Mabbutt (1977). Most texts on aeolian landforms rightly pay considerable credit to the pioneering work by R.A. Bagnold, 'The Physics of Wind Blown Sands and Desert Dunes' the result of research in the Libyan and Arabian deserts (Bagnold, 1941, 1951).

Modern texts include 'Geomorphology of Desert Dunes' by Lancaster (1995) which is largely based on experience in Southern Africa. The most comprehensive recent review of aeolian sediments, landforms and their management however is 'Aeolian Sand and Sand Dunes' by Pye and Tsoar (1990). The role of dust in aeolian landforms is reviewed by Pye (1987).

Other works consulted include: Binda (1983), Carter et al (1992), Folk and Ward (1957), Fryberger et al (1983, 1984), Goudie (1981), Greeley and Iverson (1985), Holm (1960), Kocurek (1996), Pye (1993, 1995); Pye and Lancaster (1993), Reineck and Singh (1975); Scharpensel and Ayoub (1993), Tsoar and Pye (1987), Tucker (1988), Whitney et al (1983), Khalaf (1989), McKee (1978), Forbes (1985).

Works on sand dune stabilisation outside of Europe are largely available as reports by agencies of the United Nations and Governments (e.g. FAO, 1985, GTZ 1977). The present study has also carried out a literature search of sand dune stabilisation programmes throughout the world. Of particular relevance to this study are investigations carried out in Arabia and the Near East by Kerr and Nigra (1951, 1952), Stevens (1974), Watson (1985, 1990), Jones et al (1986), Alios (1994), Bristow (1996), Cooke et al (1982), El-Baz and Hassan (1986), FAO, (1997), FAO – Investment Centre (1995), Hartley (1976), Hudson (1987, 1991), Jensen (1997), Leblond and Guerin (1983), Phillips and Willets (1978), Stifho (1992), Trossel (1981), UNCSD (1996), Al Jamie et al (1995), FAO, (1974).

Aspects of the natural vegetation occurring on the aeolian landforms are contained in the following references: El-Demerdash and Zilay (1994), Mullington (1988), HTS (1992, 1993), Stone (1985), Van der Maarel (1997), Vesey Fitzgerald (1955), Wood (1983), Zahran and Al Kap (1996), Al Hulaishi and Muller Hohenstein (1984), Batanouny (1987), DHV Consultants (1988, 1990), Scholte et al (1991).

Copies of a number of these papers have been made for the office of the CTA at TDA in Hodeidah. These, and other references consulted for this study, are listed in the Bibliography.

1.9 SCOPE OF THE REPORT

This introductory **Chapter One** is followed in **Chapter Two** by a review of previous investigations on sand dunes, stabilisation programmes, a classification of the dune types used, and related studies in the Tihama. In **Chapter Three** a detailed outline is given of the major aeolian landforms in the Tihama, and how they interact with the coastal area, the wadi systems and Tihama escarpment. The ancient and modern dunes are classified and analytical data generated during the present study is incorporated into the descriptions and discussion. **Chapter Four** provides regional assessments of aeolian sand movement and their impacts on land use, and in **Chapter Five** an analysis is given of the TEPP Sand Dune Stabilisation Programme. **Chapter Six** discusses commendations for improvements in protection areas, and suggests possible future interventions to soil improvement and dune stabilisation and additional protection areas. Finally, **Chapter Seven** reports on the mapping programme carried out using 1998 SPOT imagery and describes the mapping units, and their aerial extent. These are followed by a **Bibliography** of references that have been consulted, and supporting **Appendices** including: Terms of Reference (**A**), Work Programme (**B**), Records of Sampled Sites (**C**), and Analytical Data (**D** and **E**).

2 RESULTS FROM PREVIOUS STUDIES ON AEOLIAN LANDFORMS AND SAND STABILISATION

2.1 AEOLIAN GEOMORPHOLOGY

In the past there have been limited studies concerning the aeolian geomorphology of the Tihama. An investigation by Guilcher (1952) on the Tihama north of Midi, where there are extensive plains with dunes, noted that the finer sands had been deposited in the east farthest from the coast and up to the edge of the mountains. Brown et al (1989) re-examining this area on the Saudi Arabian side, reported that they are seif dunes aligned perpendicular to the trend of the coastline and formed due to effects of NW and SW winds. Quoting Guilcher, they note that sand grains of interdune 'para-ripples' (mega ripples) are 3-4 mm diameter, much greater than the sands of the Great Nafud in Saudi Arabia. It should be noted however that these diameters are for sand grains in ripples rather than the dune building sediments, and the present survey has noted some mega ripples in coastal areas which included granules (2-4 mm) and very coarse sand (1-2 mm).

Geological maps of the area (Grolier and Overstreet, 1976) which were largely based photo-interpretation of Landsat imagery suggested that linear ridges on the Tihama were formed on alluvial gravels and sands. These features were also shown on the topographic maps, but an aeolian origin for the linear ridges (which do in places overlie older gravels) was not considered by these authors. A description of the geology of Yemen by Geukens (1966) attributes all the Tihama sediments to alluvial formations.

The more recent geological mapping by Kruck (1983) at 1:250,000 scale did not differentiate the aeolian landforms on the Tihama. The location of active aeolian dunes in the Tihama was indicated on a sketch map in the Preparation Mission Report (FAO-IC, 1990) but this does not show dunes north of Wadi Mawr and south of Wadi Rasyan, nor does it illustrate the disposition of the older sand formations.

The Soil Survey of Yemen carried out by Cornel University / USAID (King et al, 1983), and summarised by Forbes (1985), showed that modern and ancient dunes are common over large area of the Tihama. A sketch map from this survey is given in the FAO-IC 1991 report on the TEPP. This is based on interpretation of Landsat imagery without field checking, and shows active barchan and transverse dunes migrating eastwards where they merge with longitudinal dunes. The latter often have active crests. Unfortunately the writer was unable to see all relevant parts of this important report which is reported to contain additional detailed correlative information on the soils and geomorphology of the Tihama.

The preparation report for the TEPP (FAO-IC, 1991) provided an estimation of desertification by analysing multi-temporal aerial photography. The study compared 1976 (1:20,000 and 1:60,000 scales) and 1987 (1:10,000 scale) photography to allow the measurement of sand dune movements over an 11 year period. In the Wadi Zabid it was shown that dunes had moved over irregular fronts to cover farmlands, and it was estimated that dune movement in the Suwayq and Masabilah areas amounted to some 27 m/year. Along the Red Sea, to the north of Fazzah, coastal dunes (parabolics) were measured to have moved at a rate equivalent to 41 m / year.

A slight element of caution needs to be introduced here, since according to Hunting (1992) the older 1:60,000 scale aerial photography was that flown by the Royal Air Force in 1973, rather than 1976. It is also known that 1:20,000 photography was flown for the Wadi Rimah project in 1972 (DOS Contract 128-1972) as noted by Anderson (1979). The consultant did not locate any 1976 photography other than that at 1:80,000 (DOS Contract 158 – 1976). Thus, it is possible these estimates may require revising downwards if a longer (14 year) interval has been the case. This would give reduced rates of 21 and 32 m/year respectively. Rates have also been measured by the consultant and are given in Chapter Three.

Along the coast of the Tihama some important conclusions on the composition and sediment size on the sand dunes were given by Robertson Research (1993a, 1993b) as part of beach mineral surveys carried out south of Salif and at various locations between Hodeidah and Mokha. The heavy mineral content from black sand locations at Salif, Al Urj (Wadi Surdud mouth), At Ti'faf (Wadi Rimah mouth) and the mouth of the Wadi Rasyan, showed moderate quantities of magnetite and ilmenite, with a low presence of rutile, zircon and leucoxene. The reports noted that active north-easterly migrating barchan and seif dunes overlie vegetated and now static older 'fossil' dunes. Relevant results from these beach surveys are summarised below:

a). Yachtul: dunes up to 25 m high; the dune sands consist of quartz and pyroxenes with slight mineralisation of heavy mineral opaques.

b). Wadi Rasyan, 2 km north of wadi mouth: dunes consist of dark grey quartz sands with 5-10% heavy minerals comprising pyroxenes (probably augite), amphiboles, garnet, ilmenite and hematite.

c). Ghuwarraq: Seif dunes, 10 –25 m high, with quartz sands and 5-10% heavy minerals including, pyroxene, amphibole, garnet and epidote.

d) Wadi Zabid: Quartz dunes with heavy minerals of pyroxene, amphibole and epidote.

e). Wadi Siham: Quartz-rich dunes with 10-15% heavy minerals comprising pyroxene and other ferrosilicates.

f). At Ti'faf: Quartz-rich dunes with up to 45% concentrations of heavy minerals comprising pyroxene, ilmenite, epidote, garnet, hematite and some zircon.

g). At Ta'if: Quartz and carbonate rich dune sands with 5% heavy minerals of pyroxene, amphibole, epidote and garnet.

h). Al Urj', Salif Bay: One of the few naturally-formed collecting points for detrital sediments suspended in northerly tidal currents along the Red Sea. At Al Urj' the active sands are backed by a scarp of brown sand s and silts, thought to be of fluvial origin. The beach sands contain high proportions (up to 40%) of pyroxene, amphibole, and epidote with lesser amounts of garnet, ilmenite, olivine and zircon.

i). As Salif Dunes: Older dunes are well vegetated dark grey sands, and younger more mobile barchans with up to 50% heavy minerals. The younger dunes are considered to be derived from the older. The younger dunes, up to 20 m high and on average 5-6 m, are banded and comprise quartz –rich bands and darker layers with pyroxene (clinopyroxene), amphibole, ilmenite, olivine and garnet. Further west are quartz- and carbonate-rich white sands.

Particle size analysis of sands from the Salif area gave the following results:

As Salif dunes	112 to 355 microns size (Medium to Very Fine Sand, 3.2 to 1.5 phi)
Al Urj' beach sands	200 to 630 microns size (Coarse to Fine Sand, 2.3 to 0.7 phi)

They noted that winds have separated out different fractions of minerals within different sieve fractions. In the salif dunes the heavy minerals are concentrated in the finer fractions of 200 - 63 microns (3.2 to 4.0 Phi), whilst in the Al Urj' beach sands heavy minerals are distributed erratically through all fractions. It was concluded that sorting by wind is a function of the relative specific gravity of the light and heavy minerals.

In the Wadi Mawr area the presence of extensive silt and sand plains was reported during the groundwater and engineering surveys conducted by Sir M. MacDonald and Partners (1982, 1983). Windblown silts and sands were shown to be present as a sheet overlying the older fluvial sands and gravels. Although it was recognised that windblown silts and sands had accumulated almost up to the mountain front, their present distribution was considered to have been largely reworked by water and agricultural development. Sand dunes were shown to be moving from coastal areas in a north-easterly direction

2.2 SAND STABILISATION COMPONENTS IN THE TIHAMA REGIONAL STUDIES.

The Tihama has been the subject of a number of multidisciplinary studies conducted since the 1970s in each of the major drainage basins, for the purpose of agricultural development, especially irrigation planning and the construction of dams and canals. These have included studies in the Wadi Mawr, the Wadi Surdud, the Wadi Siham, Wadi Rimah, The Wadi Zabid and the Wadi Rasyan. These include studies by: DHV Consultants (1979), Sir W Halcrow and Partners (1978), Sir M MacDonald & Partners (1982, 1983), Tesco (1971), Tipton and Kalmbach (1974, 1979), TNO-DGV (1988), World Bank (1979). A regional water resources study was carried out by DHV (1983, with a follow-up survey in 1988). The monitoring, operation and maintenance of water resources planning continues to the responsibility of the TDA.

Despite the presence of sandy landforms and drifting sand over much of the Tihama, investigations on sand stabilisation problems have been rather limited within these major basin studies. In the Wadi Zabid, for example, despite the presence of sand dunes encroaching onto farmland and lands that were seasonally flood-irrigated, no plans for sand stabilisation were drawn up as part of the irrigation development planning (TESCO, 1971).

A major effort, however, to assess the problems of drifting sands, was made on the Montane Plains and Wadi Rimah Project during the 1970's by the Land Resources Division (LRD) team (Makin, 1977, Pratt, 1975, 1976, 1977). It was recognised that the dune problem in the Tihama was one of 'major proportions' and that a pilot study was needed. The threats to certain areas of the Wadi Rimah by mobile dunes was detailed, and the more insidious threat from sands drifting onto farmlands and changing the character of the silty alluvial soils was also described. The costs to road maintenance were substantial from sands drifting over and partly closing main roads. A four year pilot study, testing a range of methods and plant species, would provide a model for replication to cover the tens of thousands of hectares of sand affected lands throughout the Tihama (Pratt, 1977, p. 123.).

Following a field assessment by a consultant (Le Houérou, 1977), and drawing on the successful sand stabilisation programmes initiated by FAO in the Abyan and Wadi Tuban deltas of southern Yemen (Costin et al, 1974), a sand dune stabilisation pilot programme was drawn up for inclusion in the World Bank funding of the project (World Bank, 1979). This called for stabilisation of 1,500 hectares over an 18 km long area of sand dunes along the southern edge of the Wadi Rimah, from a point some 8 km east of the main road, westwards to the Ourshiya area near Al Madaniyah. Additional stabilisation belts were to extend southwards bordering some 10 km of the main road towards Wadi Zabid.

The proposed work also included 7.75 km of sand stabilisation over 230 hectares on mobile dunes threatening dates at four localities in the Mujaylis oasis, Wadi Zabid. These would be as strips, between 0.5 and 1 km wide on the coast, and to the south / south-east of Mujaylis village.

Proposals were also made to stabilise sands along the line of a newly constructed (1970s) road from the Zabid to Tuhaytah. The stabilisation of the sands was also to be accompanied by encouraging the establishment of shelterbelts throughout the farmlands. An arid zone forester / sand dune stabilisation specialist was to be appointed to initiate the proposed pilot studies.

Based on the work of Costin et al (1974) in southern Yemen, also reported by Girgirah et al (1975), the LRD team concluded that the following species should be planted on different dune types:

a). On top of medium dunes: *Tamerix aphylla, Acacia tortilis, Calligonum commosum.*

b). On slopes of dunes: *Tamerix aphylla, Prosopis juliflora, Acacia cyanophylla, A. cyclops, Parkinsonia aculeata.*

c). Depressions/lower slopes: *Parkinsonia aculeata, Tamerix aphylla, Azadirachta indica, Acacia arabica, Salvadora persica.*

On the sand dunes a network of palisades were to be established prior to tree and shrub planting. These would be based on a 10 x 30 m pattern on the low dunes and sand sheets bordering the highways, and 5 x 10 m on the higher and more mobile dunes at Mujaylis. Palisades would be made of palm fronds but other materials, such as grasses and herbs should be set out in trials as the supply of fronds could be limited. Potential species identified included:

a). Shrubs: *Haloxlon persicum, Leptadenia pyrotechnica, Salvadora persica, Calligonum commosum.*

b). Grasses: *Panicum antidotale, Lasiurus scindicus, Cenchrus ciliaris.*

It was also suggested that bituminous emulsions should be tried.

Plans for sand dune stabilisation in the Wadi Mawr, Wadi Siham and Wadi Zabid were drawn up in the preparation phase for the present project (FAO-IC, 1990 and 1991). Annex Five of the 1990 Preparation Report contains a detailed programme for stabilisation in the wadis and also on the coast where the importance of sand moving onshore and inland was recognised. This report provides an excellent introduction to the problems of growing plants on mobile dunes. In the programme it was proposed to implement some 70 km of sand dune stabilisation along the southern margin of the wadis with a 200 m wide protective strip, comprising a 6 m high artificially constructed foredune with shelter belts on either side of the foredune and with suitable shrub and tree species planted on the foredune. In addition shelterbelts acting as windbreaks would be planted along the banks of wadis, streams and along farm and field boundaries.

On the coast it was proposed to construct some 60 km of artificial foredunes with supporting forested shelterbelts along the shores where sands are moving inland. However, plans to stabilise dunes along the coast were later dropped from the proposed programme in the Appraisal report (IFAD, 1992) as the coastal areas were not considered to warrant protection.

The 1991 FAO-IC report modified the construction of the foredune to 3 m height, base length (width) of 18m and a total volume of 27,000 m^3 / km, with a 20% slope on the windward side, and 70-100% on the leeward side. Permeable palisades made up of vegetation and of checkerboard (10 – 15 m and 15 – 20 m), or of parallel (20 –25 m apart) design would be established on dunes prior to afforestation. Shelter belts would also be planted on the leeward side of coastal foredunes.

The Appraisal Report (IFAD, 1992) finalised the design features for the dune stabilisation programme. Foredune design was unaffected, and revised costs were presented. These form the basis of the present sand stabilisation programme. It was concluded that stabilisation of the sands in coastal areas was unnecessary. This was considered due to the long distance from the sea to threatened areas, since sand movement from coast to interior was relatively slow, and the volume being transported was low. The coastal origin of the sand dunes as opposed to an alluvial origin was also considered unproven. However, as is presented shown later in the present report these findings are disputed.

It should be pointed out, for correction, that the IFAD report provides an illustration of some of the types of sand dune found in the study area, but this figure (taken from Cooke and Warren, 1973) misleadingly shows the wrong wind directions in relation to slip faces and dune movement.

2.3 COASTAL STUDIES IN MARINE ECOLOGY.

A major investigation of the marine ecology of the whole Tihama coastline in Yemen was undertaken in the last quarter of 1985 (Barratt et al, 1987) for the International Union for the Conservation of Nature (IUCN). The study mapped the principal habitats and species that occur in the coastal zone and discussed currents, wind directions, sediment supply in the seas and onto beaches, and the selection of proposed conservation areas. It provides a useful baseline study of conditions along the coast.

The Department of Oceanography, at the University of Sana'a, is currently carrying out ecological studies along the Red Sea coast (Dr Mohd. Mahdi). The Faculty of Oceanography is due to open in Hodeidah during the current year and will be involved in similar studies.

2.4 LAND USE AND LAND COVER CHANGE.

The vegetation of the Tihama, and adjacent mountainous areas, is covered in the mapping at 1:500,000 scale carried out by DHV Consultants (Scholte et al, 1991). Their accompanying report provides a useful outline of the flora that occurs on the coastal and inland dunes.

Land use over the whole of the Tihama basin was described and mapped for both the Yemen Woodland Resources Mapping and subsequently the Land Cover Change Study both conducted by Hunting Technical Services (HTS, 1992 and 1993). These studies utilised up to date Landsat satellite imagery and aerial photography with extensive fieldwork to produce land cover maps.

The land use cover classification established by HTS for the Tihama Land Cover Change Project has largely been adopted for the present study. Their classification has been modified to allow for a systematic description of the sand dune formations that cover large parts of the Tihama.

2.5 CLIMATE AND WIND DIRECTIONS.

2.5.1 Introduction.

Reviews of the regional hydrology of the Tihama have been conducted during each of the basin studies, and an overall assessment was carried out by DHV Consultants (1988). An agro-climatological assessment was carried out on the FAO/UNDP soil survey and land classification project (Rhebergen et al, 1990). Irregular collections of data on wind speed and wind directions have been given in many studies. The principal study on winds was a three agro-climatic study conducted by the Land Resources Division as part of the Wadi Rimah' Project, reported in considerable detail by Williams (1979). The TDA currently carries out meteorological readings at a number of stations throughout the Tihama but has had software problems in processing data from several stations where there is automatic recording of a range of parameters including wind speed and direction. Many years of windspeed and direction data exist from TDA and from Civil Aviation Authority operated stations in the Tihama and could be could be similarly treated.

The existing sources have been collated to provide the following assessment of regional wind directions and related effects. All data has been converted to metres per second.

2.5.2 General Circution of Winds and Currents in the Tihama and Red Sea littoral.

Important sources are Williams (1979), the Red Sea Pilot and the coastal study by Barratt et al (1987a, 1987b). These provide authoritative accounts of the processes along the Red Sea.

Between latitude 20° North and the Bab-al-Mandab the winds are subject to seasonal change. The winds are also canalised by the trough-like topography of the Red Sea and adjacent mountainous lands. The prevailing wind directions that are blowing in the Tihama area are generally considered to be from two main directions. In summer the winds are from the 'north' as the North West winter winds blow towards and merge with the South West monsoon of the Arabian Sea. In winter the North East monsoon takes over resulting in winds from the south in the Tihama area. Along the coast there are also the effects of diurnal change with onshore, westerly, winds during the day, and offshore, easterly, winds during the night. These local effects are driven by differential cooling of the land and the sea.

Surface water currents along the Red Sea coast are related to the prevailing wind directions, which in the Tihama reflect the seasonal movement of major air masses in the Afro-Arabian area.

In **winter** (January) Yemen lies on the southern edge of the high level polar westerly winds but at the surface strong subsidence associated with high pressure results in easterly winds blowing towards areas of low pressure over Egypt and Arabia. The canalising effect of the Red Sea trough causes these winds to become south-westerly.

In winter the surface waters, entering the Gulf of Aden from the east and north-east direction, move north into the Red Sea increasing in temperature and salinity. These denser waters sink to deeper layers in the Red Sea and produce a slow moving southwards submarine counter current that returns water back into the Indian Ocean. The northerly surface flow is responsible for a northerly longshore drift of sediments lying on the coastal shelf. Winds also are blowing from the south-west to south and these move sandy and shelly carbonate sediments onshore. These are generally stated to be the strongest winds, affecting fishing operations by high sea conditions, and farmers by blowing sand.

By **spring** (April) the subtropical anticyclone of the Inter Tropical Convergence Zone (ICTZ) is moving north with high level westerly and north-westerly winds. At the surface south-easterly and south-westerly winds blow along the Red Sea trough.

During **summer** (July) northerly to north-westerly (*shamal*) surface winds are blowing towards the low pressure area of the ICTZ. In July the ICTZ lies some distance north of Yemen, but as it moves south again during August the period of highest rainfall is encountered.

In summer also the currents in the Red Sea are reversed. The north to north-westerly winds induce a southerly surface flow that moves out of the Bab-el-Mandab and then north-eastwards into the Indian Ocean.

By **autumn** (October & November) the ICTZ is moving south of Yemen. An area of strong high pressure re-develops over Arabia. At the surface the north-easterly trades are re-established over Yemen, but in the Tihama these veer round to the south west.

An important aspect of local modification of the trade winds in the Tihama is the diurnal cycle of winds caused by the land-sea-breeze system (Williams, 1979). During the day the Tihama heats up faster than the Red Sea resulting in an easterly flow of wind, as the trade winds are inverted. This flow reaches its maximum in the early afternoon, with rising warm humid air forming convection cells and storms over the escarpment. This is also the period of maximum sand movement. During the night the differential cooling is reduced and cool air from the highlands flows down into the Tihama and over the Red Sea. Thus, as shown in the data for Al Madaniyiah by Williams (1979), for much of the year in the early hours there is usually an easterly surface flow. This abruptly changes at around 06.00 hours becoming by 10.00 hours either a south-westerly flow in winter and spring, or a west to north-westerly flow in summer. At 18.00 hours it turns around again, through either north or south, to the east again.

In terms of sand movement it is important to understand the strength and direction of these diurnal changes throughout the year in order to calculate the sand drift potential (section 2.5.7 below).

2.5.3 Agro-climatology.

The Tihama coastal plains fall into three agro-climatic growing period zones (Rhebergen et al, 1990) that lie subparallel to the Red Sea coast. The coastal belt is some ten kilometres wide, and has a rainfall regime that is insufficient for rainfed agriculture. At Hodeidah and Mokha rainfall is generally less than 100 mm/year. Evapotranspiration, relative humidity and annual temperatures however are high, and these permit a growing period of only some ten days. This area is also subject to the accumulation of salts caused by onshore winds lifting beach spray inland.

The second agro-climatic belt is up to thirty kilometres wide and includes the population centres of Zabid, Beit al Faqih, Ad Dahi, and Zuhra, which lie on the easterly edge of this zone. There is a growing period that varies from ten to thirty days, increasing inland and with altitude. This belt is marginal for rainfed agriculture.

The third Tihama zone is some fifteen to twenty five kilometres wide, and includes the slopes nearest to the foothills and valleys that extend deep into the Tihama escarpment. The towns of Bajil and Abs, and the TDA meteorological stations at Zabid and Al Barh, lie in this zone. The potential growing period ranges from thirty to fifty days and annual temperatures and relative humidity are less harsh than along the coast.

Selected meteorological data from stations in the Tihama are given in Tables 2.1 and 2.2.

TABLE 2.1 CLIMATIC DATA FOR SELECTED STATIONS IN THE TIHAMA.

Station	Eto mm/ year	Rainfall mm/ year	Max. Temp.	Min Temp.	Mean, Temp.	Mean % Relative Humidity	Max. % Relative Humidity	Min. % Relative Humidity	Average Sunshine Hours
Ad Dahi	2229	142	36	25	30	63	73	54	7.0
Zuhra	2253	158	39	22	31	66	73	61	7.4
Zabid-Jurbah	2447	348	36	23	29	64	71	55	7.3
Zabid- town	2447	166	36	23	29	-	-	-	-
Hodeidah	2274	61	34	25	29	80	88	69	8.4
Mokha	2432	45	32	25	29	75	86	65	8.4

Source: Rhebergen et al. 1990. Eto = potential evapotranspiration.

TABLE 2.2 RAINFALL DATA FOR SELECTED STATIONS.

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Al Zuhrah,, 43° 01' E 15° 42' N 70 m.a.s.l.	4.2	2.4	4.2	16.4	19.4	1.2	6.7	18.8	23.7	27.1	3.8	13.1	141.0 (1979-96)
Hodeidah 42° 50' E 14° 45' N 11 m.a.s.l.	22.8	7.4	14.9	40.5	0.6	0	6.3	14.3	3.7	2.9	0	1.7	115.1 (1941-70)
Al Khalifa 43° 19' E 14° 53' N 139 m.a.s.l	5.2	21.5	7.2	40.0	53.8	37.0	48.1	107.5	101.5	61.9	6.8	3.5	438.4 (1987-95)
Zabid 43° 19' E 14° 11' N 105 m asl	4.0	8.7	5.7	11.0	14.3	5.4	25.6	30.0	53.5	22.0	3.9	0.7	184.8 (1969-90)
Zabid (Al Jerbah) 43° 26' E 14° 09' N 240 m.a.s.l.	9.9	11.7	9.9	19.3	47.5	6.4	38.4	77.8	93.9	48.4	4.0	1.6	368.4 (1970-96)
Al Kudeyha 43° 26' E 13° 30' N 111.2 m.a.s.l	9.5	17.9	8.1	20.6	20.8	8.8	5.1	8.8	30.4	17.6	3.2	2.9	152.9 (1983-96)
Al-Barh 43° 42' E 13° 27' N 600 m.a.s.l.	12.1	2.8	16.8	33.4	53.5	19.6	16.7	24.6	68.9	36.0	0.5	2.7	287.6 (1980-95)

Sources: TDA, 1998.; FAO-IC, 1990; Red Sea and Gulf of Aden Pilot. Based on available data. Heights of stations given in metres above sea level. Data in mm

2.5.4 Winds in the Wadi Mawr area.

In the Wadi Mawr area detailed wind run data was collected by Sir M. MacDonald & Partners during the early part of the summer of 1982. The data shows that maximum velocities occur during the afternoon when onshore winds reach their peak (Table 2.3 and 2.4).

TABLE 2.3 WIND SPEED DATA FOR AL ZUHRAH (43° 01' E, 15° 42' N).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Mean
Mean max wind speed m/s 1979-88	3.3	3.3	3.5	3.2	3.2	3.2	4.1	3.5	3.4	2.4	2.7	3.2	3.0
Mean wind speed U24 M/s 1972-82	2.1	2.4	2.5	2.4	2.3	2.4	2.8	2.6	2.0	1.8	1.8	2.1	2.3
Mean wind speed m/s 1980-96	2.1	1.8	1.9	1.8	1.8	1.7	2.1	2.0	1.9	1.4	1.3	1.5	1.8

Source: TDA, 1998; FAO-IC, 1990; Sir M. MacDonald & Partners, 1982 (U24, data, taken at 6 m above ground). Data runs often incomplete.

TABLE 2.4 DETAILED WIND SPEED DATA FOR AL ZUHRAH (43° 01' E, 15° 44' N).

Month	March 1982	April 1982	May 1982	June 1982	July 1982
Mean wind speed m/s 0600-1200	2.7	3.1	2.4	2.5	2.3
Mean wind speed m/s 1200-1800	3.9	4.4	4.0	4.2	4.4
Mean wind speed m/s 1800-0600 (UN)	1.4	1.5	1.4	1.2	1.9
Mean wind speed (U24). M/s 24 hours	2.4	2.6	2.3	2.3	2.6

Source: Sir M. MacDonald & Partners, 1982. All data was measured at 6 m above ground. UN= night-time wind run; U24 = 24 hour total wind run originally measured in km.

2.5.5 Winds in the Wadi Surdoud area

At the mouth of the Wafi Surdud there is data from the station at Kamaran at 09:00 hours for the period 1941-1970 (Red Sea & Gulf of Aden Pilot). This showed that wind directions were from the south and south-west for 55% of the year mostly from October to May, and from the north and north-west for 19% of the year, mainly during June through September. Westerly winds were also quite common from April to November. Mean directions and wind speeds are given in Table 2.5.

TABLE 2.5 WIND DIRECTION & SPEED DATA FOR KAMARAN (42°37'E, 15°20N).

Direction	N	NE	E	SE	S	SW	W	NW	Calm
Mean % in year	4	rare	rare	5	44	10	21	15	1

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Mean wind speed m/s	5.5	6.0	5.0	5.0	2.5	2.5	3.0	2.5	2.5	4.0	6.0	6.0	4.0

Source: Red Sea & Gulf of Aden Pilot.

Inland, data is available from the town of Ad Dahi on the banks of the Wadi Surdud, where DHV Consultants (1988) summarised wind data for 1987. This shows that the prevailing wind directions are from the north-west and south-west (Table 2.6) The wind speed data shows daily means of 1.5 to 1.9 m/s. The detailed records show that about 10% of days in the year have windspeeds over 3 m/s. A wind rose diagram was prepared by DHV (1988) and is reproduced in Figure 2.1.

TABLE 2.6 WIND DIRECTION AND WINDSPEED DATA FOR AD-DAHI (UTM 38P: 290825E. 1682335N).

Wind Direction	0-30 N to NNE	30-60 NNE to ENE	60-90 ENE to E	90-120 E to ESE	120-150 ESE to SE	150-180 SE to S	180-210 S to SSW	210-240 SSW to WSW	240-270 WSW to W	270-300 W to WNW	300-330 WNW - NNW	330-360 NNW -N
Number of days	14	6	10	5	8	21	23	26	20	20	42	37
Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Mean daily windspeed m/s 1986	2.21	2.09	1.93	2.07	1.81	2.21	2.54	2.18	1.48	1.34	1.59	1.58
Mean daily windspeed m/s 1987	1.54	1.94	no data	1.56	1.46	1.54	1.63	1.55	1.17	1.12	1.16	no data
Mean daily windspeed m/s 1988	1.10	1.37	1.20	1.31	0.75	0.96	1.67	1.23	0.82	0.87	1.25	1.14

Source: DHV Consultants, 1988 (1986-87data); Rhebergen et al, 1990 (1988 data). Elevation of station is 70 m asl.

Data for Gumeisha in the Wadi Surdud (Halcrow, 1978) showed NW to NNW winds during May to September, and SW to SSW from October to April. Wind run data, originally in km/day is given in Table 2.7.

TABLE 2. 7 WIND DIRECTION AND SPEED DATA FOR GUMEISHA (43° 04'E, 14° 43' N).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Mean wind speed m/s	2.8	3.1	2.9	2.8	2.7	3.5	3.8	3.7	2.6	2.3	2.8	2.8	2.9
Dominant wind direction	SW-SSW	SW-SSW	SW-SSW	SW-SSW	NW-NNW	NW-NNW	NW-NNW	NW-NNW	NW-NNW	SW-SSW	SW-SSW	SW-SSW	-

Source: Halcrow. 1978. Years 1973-75.

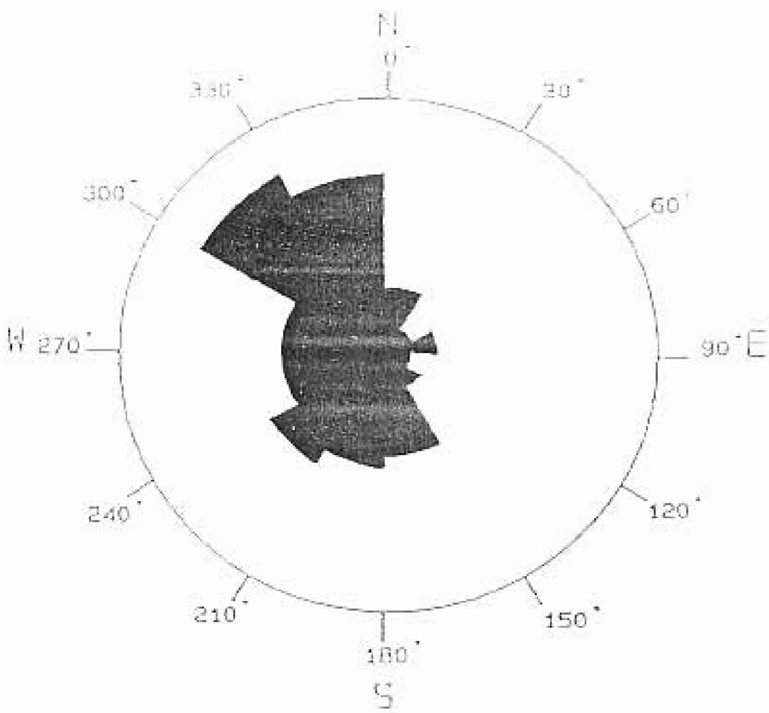
2.5.6 Winds in the Hodeidah area.

Wind speed and direction for Hodeidah are available for various years. The data (Table 2.8) shows that wind speeds appear to be considerably higher along the coast than inland, that dusty days (as opposed to haze) occur on significant occasions, and that the wind directions are southerly in winter and spring, becoming westerly to south-westerly in summer to autumn with additional gusts from northerly winds during July and August. The significance of these higher speeds near the coast is that coarser grains will be moved by the higher threshold velocities.

2.5.7 Winds in the Wadi Rimah and Wadi Zabid areas.

The winds of the Wadi Rimah and Wadi Zabid area were the subject of a detailed study by Williams (1979). In general there is a strong diurnal change in wind directions that persist for much of the year. During the night winds are easterly with cool air descending off the mountains and plateaux of Yemen.

FIGURE 2.1 WIND ROSE FOR AD DAHI (1987). SOURCE: DHV CONSULTANTS, 1988.



NOTE: This figure uses data from Table 2.6 to show the number of days during 1987 that wind blew in 12 compass directions.

The data from these stations provides a clear picture of the wind strength and directions during the year. This is shown for Jarubah in Table 2.9, Medaniyah in Tables 2.10 and 2.11, and Mishrafah, on the escarpment, in Table 2.12

TABLE 2.8 WIND DIRECTION AND SPEED DATA FOR HODEIDAH (42° 50'E, 14° 45'N).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Mean max wind speed m/s	11.6	11.5	11.8	10.1	11.8	8.3	10.8	9.9	9.4	10.6	10.8	11.1	1983 & 1984
Max wind speed m/s 1400 hrs	9.0	9.4	10.0	8.9	8.3	8.2	9.0	8.9	9.0	9.3	9.7	9.4	1963 to 1966
Mean daily wind speed m/s	4.7	5.2	5.3	3.3	5.1	2.7	4.7	4.0	4.4	4.3	5.3	4.6	1983 & 1984
Mean wind speed m/s 0800 hrs	4.2	4.8	5.6	5.5	4.7	3.8	4.9	4.6	2.9	4.2	5.0	4.7	1963 to 1966
Mean wind speed m/s 1400 hrs	8.3	8.0	8.6	6.9	7.7	7.5	8.5	8.1	6.5	9.0	9.0	8.8	1963 to 1966
Predom Wind Direction	S	S	S	S	S	W	W	W	SW-W	SW-W	S	S	1963 to 1984
Max Daily Wind Direction	S-SW	S	S-SW	S	S	W-SW	W-NW	NW-N	W	S	S	S	1963 to 1984
Dust (days)	4 11	- 11	13 19	3 -	6 10	0 -	3 2	5 2	1 4	5 13	10 7	13 9	1983 1984

Source: 1983-84 data from Meteorological Dept. Hodeidah Airport, In. FAO-IC, 1990; 1963-66 data from Beskök, 1971

The wind data from Al-Jirbah (Jarubah) (Table 2.9) is from a TDA automatic weather station. Unfortunately wind direction data has not yet been processed due to software problems at TDA. In terms of windspeed, the months of July and August appear to have the highest mean speeds. This particular station lies on the irrigated plains close to the edge of the mountain front, and is well to the east of the main areas of sand movement, though there is some drifting sand in the adjacent Wadi Zabid floor.

TABLE 2. 9 WIND SPEED DATA FOR AL JARUBAH, WADI ZABID (43°26' E. 14°09' N).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Mean
Mean wind speed m/s 1970-1986	1.2	1.3	1.5	1.6	1.5	1.7	2.0	2.0	1.4	1.1	1.1	1.1	1.4
Mean wind speed m/s 1979-1996	1.5	1.4	1.8	1.7	1.8	1.7	1.9	2.0	1.4	1.1	1.1	1.3	1.6
Max wind speed m/s 1979-1990	2.6	3.1	3.1	3.2	3.6	3.2	4.0	4.0	3.2	2.0	1.8	1.9	3.0

Sources: TDA, 1998 (1979-1996 data). DHV Consultants, 1988 (1970-1986 data).

This station is very close to that of the former FAO Camp, where TESCO (1971) recorded wind data from 1970, and datasets may have been combined by previous reporters to provide long-term means.

Data for wind direction at Madaniyah shows that the strongest winds are from southerly to south-westerly directions which occur during the winter. In summer north-westerly and west-north-westerly winds are dominant.

TABLE 2.10 WIND DIRECTION AND WINDSPEED DATA FOR AL MADANIYAH (APPROX: 43° 10'E, 14° 16' N).

Wind Direction	N to NNE	NNE to NE	NE to ENE	ENE to E	E to ESE	ESE to SE	SE to SSE	SSE to S	S to SSW	SSW to SW	SW to WSW	WSW to W	W to WNW	WNW to NW	NW to NNW	NNW to N
Degree Classes	0 - 22.5	22.5-45	45 - 67.5	67.5 - 90	90-112.5	112.5 -135	135-157.5	157.5 -180	180-202.5	202.5 - 225	225-247.5	247.5 - 270	270-292.5	292.5 -315	315 - 337.5	337.5-360°
% Year Based on 98% record	4.5	3.4	4.0	6.5	5.6	5.2	3.4	6.1	12.9	7.4	3.6	6.5	6.7	9.5	8.4	4.2

Source: Williams, 1979. Based on automatic weather station data

These wind directions can be shown on a wind rose, which illustrates the principal directions from which wind is blowing (Figure 2.2). The example given is based on the percentage of the year that wind blows in a given location.

In terms of the movement of aeolian sands and the direction at which they travel it is necessary to calculate the wind velocity for each station. The wind velocity, Table 2.11, is the vectored mean of each wind speed and direction combined, obtained from the mean of the diurnal variation. It has a direction (argument) in compass degrees, and a strength (modulus) given in the wind speed (m/s). The % year data is based on a dataset from wind directions measured at 22.5 degree sectors at hourly intervals. The dataset covered 98% of the year.

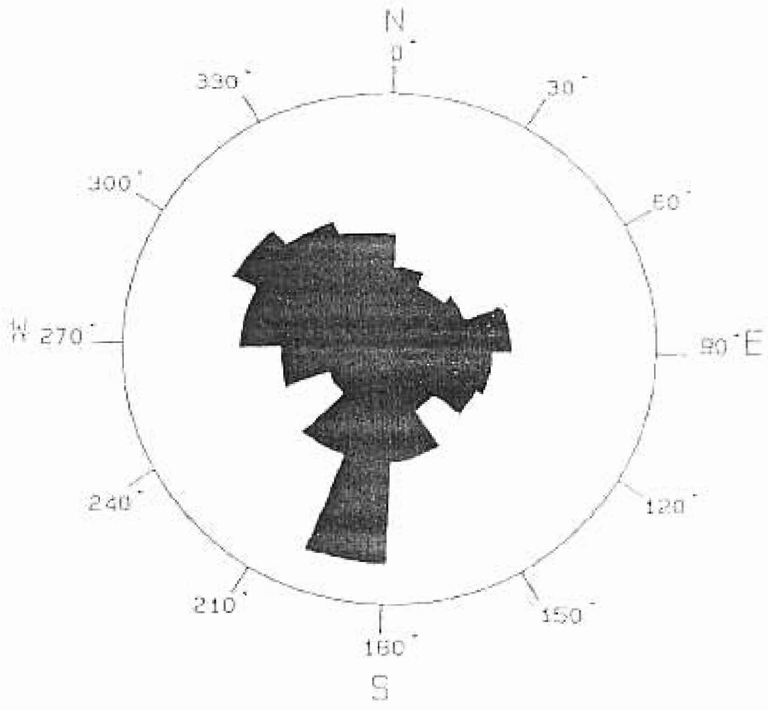
TABLE 2. 11 WIND VELOCITY DATA FOR AL MADANIYAH (APPROX: 43°10 'E, 14° 16'N)

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Mean hourly wind speed m/s	3.0	2.5	3.1	3.1	2.8	2.7	3.7	3.1	2.5	2.5	2.4	2.9	1979
Wind vector strength (modulus) m/s	2.17	1.28	1.93	1.61	1.13	1.98	3.13	2.06	1.33	1.57	1.19	2.22	1976
Wind vector direction (argument) compass degrees	190	227	197	212	237	296	310	304	294	202	199	179	1976
Equivalent direction (compass class)	S	SW	SSW	SSW	SW	WNW	NW	NW	WNW	SSW	SSW	S	1976

Source: Williams, 1979.

These wind directions can be shown on a wind rose, which illustrates the principal directions from which wind is blowing (Figure 2.2). The example given is based on the percentage of the year that wind blows in a given location.

FIGURE 2.2 WIND ROSE FOR AL MADANIYAH (BASED ON DATA GIVEN IN WILLIAMS 1979).



NOTE. This figure, using the data given in Table 2.10, shows the percentage of the year that winds blow within 16 compass directions. Contrast this with Figure 2.1 where the southerly component is less well developed.

With sand velocity information it is possible to show the sand drift potential for an area, the sand drift potential, shown as a rose diagram, illustrates the resultant direction for sand (and transported dust) movement at any one time. Using the more detailed data on wind speed and direction from TDA automatic stations it should be possible to calculate sand velocities and sand drift potential roses, using the methods outlined by Fryberger and Dean (1979). It was hoped to do this but it has not been possible at present due to analytical problems with the raw data supplied by TDA. However it is hoped to resolve this at a later stage.

Another station in the Wadi Rimah catchment was located at Mishrafah. Data given in Table 2.12 shows quite low average wind speeds for much of the year.

TABLE 2. 12 WIND DIRECTION AND SPEED DATA FOR MISHRAFAH (APPROX: 43° 34 'E, 14°17 ' N).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Year
Mean hourly wind speed m/s	2.1	2.1	2.1	2.1	2.1	2.3	2.6	2.0	1.8	1.6	1.6	1.7	1977

2.5.8 Winds in the Wadi Rasyan and Mokha areas.

There are several stations recording wind speeds in the southern part of the Tihama, and data is given in Tables 2.13, 2.14, 2.15 and 2.16. Available wind direction data is limited, though a complete dataset for Mokha should be available from the Civil Aviation and Meteorological Authority, and indicates north-westerly winds in summer changing to 'southerly' in winter. Mean wind speeds for Mokha on the coast, and like that of Hodeidah, appear to be higher than the interior stations.

TABLE 2.13 WIND DIRECTION AND SPEED DATA FOR AL KUDEYHA, WADI. RASYAN (43°26' 33" E, 13°30' N).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Mean
Dominant wind direction >30% (1989)	SE	SE, NW	SE, NW	SE	NW	NW	NW	NW	NE, SW	NE	NE, SW	SW	-
Max wind speed m/s (1989-90)	4.0	5.2	5.4	5.2	4.7	4.3	4.5	4.6	3.5	4.2	5.1	4.9	4.6
Mean wind speed m/s (1983-89 & 1992-96)	3.0	2.9	3.1	3.2	2.5	2.5	2.9	2.9	2.1	2.3	3.0	3.1	2.8

Source: TDA, 1998; FAO-IC, 1990 No wind data collected from April 1989 to January 1992.

TABLE 2. 14 WIND SPEED DATA FOR AL-KHALIFA (43° 19' E, 14° 53' N; 139M ASL).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Mean
Mean wind speed m/s 1987-96	1.1	1.2	1.2	1.1	1.1	1.1	1.6	1.3	1.0	0.9	1.0	2.1	2.1
Mean max wind speed m/s 1988-90	2.6	2.1	1.8	1.4	1.3	1.7	2.1	1.7	1.4	1.4	1.8	1.3 ?	-

Source: TDA, 1998 (1987-1996 data); FAO-IC, 1990 (1988-1990 data). No data from June 1995 to August 1996.

TABLE 2. 15 WIND SPEED DATA FOR AL- BARH (43°42'E, 13°27' N; 600M ASL).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Mean
Mean wind speed m/s	1.4	1.5	1.8	1.8	1.6	1.9	2.1	2.1	1.6	1.5	2.0	1.7	1.8

Source: TDA, 1998.

TABLE 2.16 WIND SPEED DATA FOR AL- MOKHA (43°17'E, 13°15' N; 3 M ASL).

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Mean
Mean wind speed m/s	5.6	4.3	5.2	4.0	no data	0.7	0.9	1.2	4.0	7.4	5.1	6.7	4.0

Source: Rhebergen et al, 1990. Data for 1988 only. Station operated by Civil Aviation & Meteorological Authority

3 GEOMORPHOLOGY OF AEOLIAN AND OTHER LANDFORMS OF THE TIHAMA.

3.1 GENERAL DESCRIPTION OF THE TIHAMA.

3.1.1 The Tihama Escarpment.

The history of the sand formations on the coastal plains in Yemen is considered to be intimately linked to the erosional development of the Tihama escarpment and the piedmont fan systems that lie between these mountains and the Red Sea. The escarpment, rising in elevation from between 200 m and 400 m to about 2,000 m above sea level, is today an erosional feature, up to 70 kilometres wide, developed along the faulted margin of the Red Sea rift. During the Tertiary period, uplift of the Afro-Arabian dome led to volcanism and later graben formation as the East African and Red Sea rifts opened along sea floor spreading axes. During the late-Tertiary, and for much of the Pleistocene, hundreds of metres of alluvial formations were laid down along the margins of the Red Sea graben, the products of erosion of metamorphic, sedimentary and igneous rocks and soil from the Highlands of Yemen (Kruck, 1983).

The distribution of the parent material rock types in the escarpment one is indicated on the most recent geological maps (Kruck, 1983, Davison et al, 1994) and has been related to each drainage basin. These are shown in Table 3.1.

TABLE 3.1 DISTRIBUTION OF PARENT MATERIALS BY DRAINAGE BASIN.

Drainage Basin	Acid Gneiss	Basic Gneiss	Other Meta-morphic	Ultra-mafic	Amran Lst	Tawilah / Kholan Sst	Granitic / Grano-diorite	Tertiary Basalt	Tertiary Rhyolite
Bawhal	X	X	X	-	-	-	X	X	-
Mawr	X	X	X	X	X	X	X	X	-
Surdud	X	X	X	-	-	X	X	X	X
Siham	-	-	-	-	X	X	X	X	X
Rimah'	-	-	-	-	X	X	X	X	X
Zabid	X	X	X	-	X	X	X	X	X
Nakhlah	X	X	X	-	X	X	X	X	X
Rasyan	-	-	-	-	X	X	-	X	X

Note: Lst = Limestone; Sst = Sandstone. X = rocks present - = no major presence.

Erosion of these rocks has produced a wide range of mineralogically and chemically distinct rocks (Overstreet and Ibrahim, 1997; Tag et al, 1990), that are likely to be the source materials for the quartz, opaque iron and titanium minerals, feldspars, pyroxenes and amphiboles that are commonly found in the aeolian sands as fragments of rock or minerals. These erosion products have been deposited on alluvial fans of the coastal plain and in the sea, and later extensively re-worked into aeolian sand formations.

Table E.2 provides an explanation of the minerals of 9 sand samples by X-Ray analysis. These show that the mineral content of the river sands, modern and ancient interior dunes and coastal dunes appear to have a common origin. The dark dunes of the Salif area show sorting of heavy minerals that likewise are believed to have originated from the Tihama escarpment as river sediments.

3.1.2 Alluvial Fans of the Tihama.

Field investigations carried out for the present study have indicated the surface of the Tihama coastal plain today consists of a series of coalesced alluvial fans of different ages. The terraces represent alluvial fans that have been dissected and abandoned by their streams probably as sea level dropped in the past. No aeolian sequences were seen in these terraces close to the escarpment, but along the coast old alluvial sequences contain aeolian layers at intervals. The composition and chronology of these terraces has not yet been fully described, yet their history is related to the development of the sand landforms.

The oldest fans form high level terraces and comprise layers of gravel, sands, loams and buried soils. On an old terrace level bordering the Wadi Urfan silty sediments were found which had shells of *Melanoides tuberculata*, a freshwater loving species indicative of perennial streams and lakes. In arid areas of the south, specifically east and north east of Mokha, the surfaces of the fans have "desert varnish" on cobbles. Based on studies conducted elsewhere, these coatings probably originated from deposition of aeolian dust comprising clay minerals, iron oxides, other elements, and characteristically form thin crusts in very arid areas (Pye, 1987). The process is likely to be continuing at the present.

On the old terraces further north, for example to the east of Mansuriyah at Suknah, there are deep loamy and silty soils developed on the terraces, and these support rainfed and irrigated agriculture. Other terraces, within the escarpment zone, are apparently barren and dissected.

Contemporary alluvial fans have cut down through terraces of older alluvium and older sand formations, and occur as broad piedmont fans with deep loamy and silty soils. The main flood channel is incised into the plain with cliffs up to ten metres high and there is often a narrow flood plain either side of a sinuous channel bed. The natural fan surfaces, which have a low slope down to the west of less than 2%, have been much modified by human use with artificial terracing, which is important to distinguish from natural river terracing. These lands are intensively cultivated; by irrigation from wadi floodwaters, spate irrigation from mountain torrents and catchment zones, pump irrigation or by rainfall alone. Local circumstances reflecting the availability of surface and ground waters, and the annual increments from rainfall, all combine to produce a varied agrarian landscape.

In some areas of these fans, notably east and south-east of Al Hussaniyah, there are eroded lands with rilling and shallow gullies, and where the drainage is peculiarly reversed, with stream lines flowing eastwards for short distances. In these areas an upper mantle of silts appears to have been stripped off to expose older sediments and some rock outcrops. Remnants of older aeolian sand formations are also present in these higher zones and there is a slight drifting sand hazard. The features may reflect uplift along a north-south alignment such as a buried fault. The silty plains in these areas are also sources of aeolian dust that is deflated during periods of high windspeeds to be dispersed into the atmosphere. The range of terraces and alluvial fans that have been distinguished are differentiated in Chapter Seven which describes mapping units in more detail.

3.1.3 Classification of Aeolian Landforms.

The dune classification used in this report follows that as defined by Pye and Tsoar (1990). This has three basic groups that are subdivided into dune forms as shown in Table 3.2. As investigated in the field, the aeolian landforms have been grouped into older and recent sand formations.

TABLE 3.2 CLASSIFICATION OF MAJOR DUNE TYPES (AFTER PYE AND TSOAR, 1990).

1	**Sand Accumulation Related to Topographic Obstacles.**		
	A. Windward Accumulations:		
		Echo Dunes.	Ramp of sand ending in a steep slope that faces, and echoes shape of an obstacle such as cliff face.
		Climbing Dunes.	Dunes with continuous ramp to top of an obstacle.
	B. Cliff-top Accumulations:		
		Cliff-top Dunes,	Irregular sand accumulations and dunes on cliff tops.
	C. Leeward Accumulations:		
		Lee Dunes.	Sand drifts and dune forms in lee of an obstacle.
		Falling Dunes.	Sand drifts / linear dunes descending off an obstacle.
2	**Sand Accumulation Related to Bed Roughness Changes or Aerodynamic Fluctuations.**		
	A. Dunes Composed of Fine Sand:		
		Barchans.	Crescentic dune. Slip face & horn pointing downwind.
		Transverse Ridges.	Series of alternatively barchanoid and linguiod-facing ridges (also known as network, aklé)
		Unvegetated Linear Dunes	Linear ridges, slip faces on opposing sides to winds (also known as seif dune).
		Dome Dunes.	Flat crested dune without slip faces.
		Star Dunes.	Large, pyramidal dunes with radiating arms.
	B. Forms Composed of Poorly Sorted and Bimodal Sand:		
		Sand Sheets.	Areas of sand without dune slip faces.
		Zibars.	Long-wavelength, low amplitude areas of sand sheet, often with megaripples on low slip faces.
3.	**Sand Accumulation Related to Vegetation.**		
		Parabolic Dunes	U- or V-shaped, with trailing arms, which point upwind either side of blow-out feature. Includes foredune ridges at coast. Linear features extend inland.
		Hummock Dunes.	Mounds (nebkha) of sand with surface wholly or partially vegetated by stabilising grass, herbs or trees.
		Vegetated Linear Dunes.	Rounded ridges formed from opposing wind directions, similar to seif but with plant growth.

During the present study in the Tihama many of these dune forms have been identified. Dunes in the first category are common around man-made obstacles in settlements and factories, and have also been noticed elsewhere in the field as small scale features. Dome Dunes and Star Dunes have not been observed so far in the Tihama and may be absent. Vegetated linear dunes may be re-forming on the ancient sand ridges. The dunes formations have been grouped into recent aeolian landforms and older aeolian landforms. A summary of the major aeolian and adjacent landforms of the Tihama is shown in Figure 3.1. This updates the map shown by FAO-IC (1990) which illustrated the position of many of the active sand dunes in the Tihama. The present map shows additional areas of active sand deposition over the whole length of the Tihama, between the border with Saudi Arabia and Al Mokha.

3.2 GEOMORPHOLOGICAL PROCESSES.

3.2.1 Recycling of Sediments.

The recycling of sediments, from the mountains of Yemen to the Red Sea with aeolian movement then back towards the mountains and the interior, is thought to be the key to understanding the dynamics of the aeolian geomorphology of the Tihama. This recycling process, whilst complex spatially and temporally, contains several characteristic components.

Sediments and soils are eroded in the Yemen highlands during rainstorms and transported to the plains, to be deposited on piedmont fans. The sediments reaching the Tihama plains, as noted above, are derived from a wide range of rocks, and consist of clay to gravel sized particles. The sand fractions of escarpment derived sediments contain common rock forming minerals such as quartz, feldspars, micas, pyroxenes, amphiboles, and heavy minerals rich in iron, sphene, zircon and many other minerals (See Appendix E).

In the dry wadi beds, winds commence to separate out coarser fractions of the bed load and a limited supply of sand is blown out onto adjacent lands from the wadis. Locally, these have been observed to form sand sheets and dunes of limited extent. The majority of the flood's transported load, comprising silty and clayey alluvium, is deposited on fields and canal banks within the spate irrigation systems. Some deflation by wind will occur where these sediments are deposited on open plains, or fallow areas, but generally they are incorporated into the agricultural soil, resulting in a steady building up of the surface. This anthropogenic alluviation amounts to at least five metres in places. In the past, before these human depositional systems were initiated, the floods deposited their loads on piedmont alluvial fans that coalesced into the broad plains that characterise the Tihama today.

At odd intervals, exceptional floods with sandy and silty sediments reached, and still reach, the coast to deposit their bedload in the sea. At Al Jilah, to the south of Wadi Zabid, the Wadi Marir was said to have last reached the sea over 30 years ago. Elsewhere floods are said to reach the sea every ten years or so. In the past, deposition of sandy material was probably on a much greater scale than the present, since substantial deposits of sandy sediments are known to exist on the shallow shelf of the Red Sea.

Whilst these flood processes have not been observed at the present it is simple to observe the movement back onto land of the shell enriched fluvial sediments. These sands are transported by currents, either onto offshore sand spits and bars, or onshore onto the beaches where the coarser fractions, generally composed of shell fragments, are progressively broken down. Wind then separates out the finer fractions, transporting them inland, first as fairly coarser textured aeolian sands of coastal hummocks, foredunes and parabolic dunes, and then into the interior plains, where sands become finer and the amount of shell material is reduced.

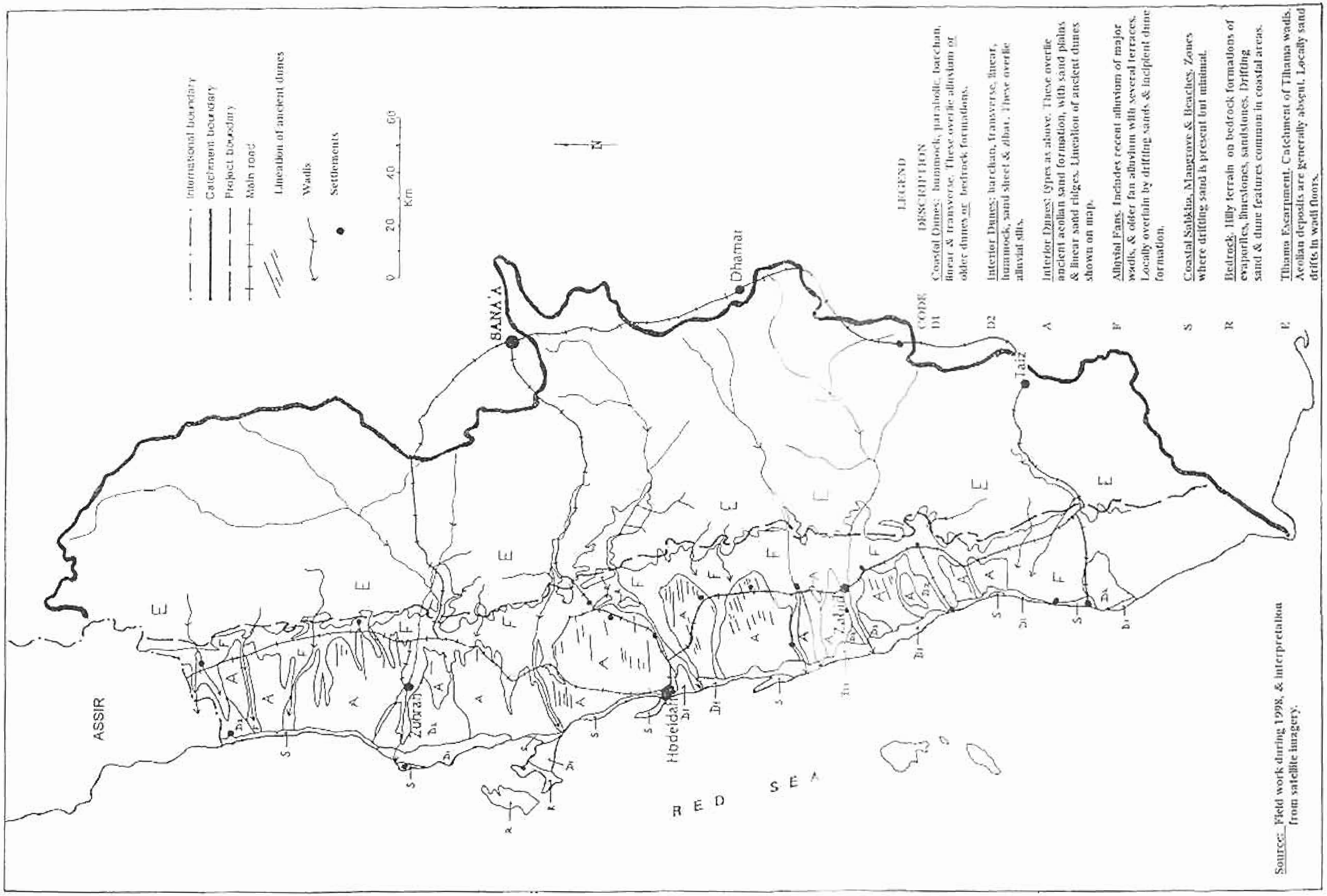
The interior aeolian landforms include hummocks, sand sheets, barchans, transverse dunes, complex networks of transverse dunes and seif dunes. These form quite extensive sand seas in the inter-wadi areas, and are progressively moving north-eastwards covering all other landforms, including the wadi floors and alluvial plains. The aeolian sands become progressively finer towards the mountains. The modern sands overlie an older set of sand plains and convex ridges, former linear dunes. A certain amount of sand appears to be generated from fluvial erosion of the older sands, but most mobile sand originated from the coast.

Modern sand movement is north-easterly the resultant of the dominant wind directions from the north / north-west (summer) and the south-south-west (winter). The ancient sand dunes appeared to have reached the escarpment but modern dunes still remain considerably to the west of the mountain front in most areas.

Deflation of the alluvial silts and aeolian sands, the mechanisms of which are discussed below, results in the eastwards transportation of silt sized dust into the valleys and ridges of the escarpment. Deposited as loess on the highland plains there is evidence that the dust is reworked by erosion into alluvial deposits (Nettleton and Chadwick, 1996).

FIGURE 3.1 THE LOCATION OF AEOLIAN LANDFORMS ON THE TIHAMA

Source: Field work during 1998



3.2.2 Aeolian Processes.

The hazards from deposition of wind blown sands and erosion of dust from alluvial silts in the Tihama are directly related to the location of alluvium, active sand dunes and the ancient sand plains. Parts of the ancient sand plains have either a well defined soil surface (albeit often truncated) and can expect to be wind stable due to presence of soil moisture during the rainy season. The problem of sand movement, however, generally increases towards the coast as rainfall decreases and as modern dunes overlie the ancient sand plains. Throughout the area that contains sandy landforms loose modern sands are burying fields, obscuring tracks in rural areas and blocking the principal tracks. Where these sands are cut by the channels and fans of the recent alluvium there are transition zones where sands are moving onto the alluvium. In almost all areas where this is occurring the lands being buried are of agricultural importance even if at present they do not have a guaranteed supply of water for irrigation.

Wind erosion of the silty alluvial soils is also a serious problem affecting large parts of the Tihama agricultural lands. During summer westerlies, blowing inland as the land heats up, generate very substantial amounts of dust that often cause very low visibility conditions on the roads and in villages.

Entrainment of particles into the air is a function of the grain-size distribution, sorting of the grains, and the cohesion and roughness of the source material (Pye, 1987). For the finer silt and clay particles higher values of fluid threshold velocity are required in order to overcome resistance (drag). Experimentally derived fluid threshold velocities of undisturbed silts on desert surfaces range from 1.5 to >3.0 m/s, whilst for disturbed surfaces they generally range from 0.2 to 0.6 m/s (Pye, 1987). The actual windspeeds, as measured between 2 and 10m above the ground, will be higher than the threshold velocities. In a study of desert dusts, it was found that the minimum wind speed required to generate blowing dust was 6 m/s on sand dunes and > 16 m/s on alluvial fan surfaces (Pye and Tsoar, 1990).

Comparing this to Tihama wind speeds (Chapter 2) it can be shown that generation of dust into the atmosphere and movement of sand sheets in the Tihama fall within similar ranges. Higher velocities have been recorded along the coast, but the location of stations in relation to actual sand pathways could provide more appropriate data. Sand movement will be confined to periods of high winds, generally common at certain times of the day with directions and strengths according to seasonal and diurnal wind patterns, and it may attain stronger velocities according to local topography.

However, as pointed out by Williams (1979), and still valid, no study has yet been undertaken which relates threshold velocities of Tihama aeolian sands and silts materials to actual wind conditions. There is thus a fairly urgent scope here for a research project to address this requirement.

Where sand is present, such as on the borders of fields with sandy areas and on the sand sheets and dunes moving across the interdune valleys of the sand plains, there is movement of both sand and dust. This will take place at lower threshold velocities due to the effects of aerodynamic lift and ballistic impact of sand grains (> 100 microns) on finer silt particles.

On the spate irrigated lands (Land Cover Unit A 2) where rainfall is generally insufficient for agriculture there are large areas of bare silty soil where lands are fallow. Towards the coast extensive areas of silty deposits, deposited from former massive floods, are permanently fallow and often partly or wholly covered by drifting sands. Such areas were observed to be important source areas for deflation of silty dust.

In the arable fields also, deflation of silty material appears to occur where wind speeds are increased in certain locations. This does not necessarily appear to involve any coarser sandy particles which are normally considered to assist in the detachment of the finer particles. Deflation of the alluvial silts from bare unploughed lands, bunds, furrows, tracks, foot paths, livestock-trampled grounds and wadi lines is common and appears to be caused by rapidly moving gusts of the *shamal* wind or dust devils generated by surface heating. Ploughed fields with blocky structures of the same silty soils generally appear unaffected by gusts, though the concentrated effects of dust devils will entrain particles.

On the older sand formations, as suggested by the particle size determinations, there is a certain amount of wind erosion taking place. Sand sheets that overlie ancient dunes may have almost identical particle size distributions. Blasting by sand-laden winds erodes and scours loose and weakly cemented sands, leaving linear features known as yardangs. Yardangs are seen in many parts of the study area where seasonal winds have eroded the recent and older sand formations. Along the coastal zone winds are rapidly eroding the cemented aeolianites leaving an irregular topography. Inland, where there are quarries or erosion gullies in the older sands, winds are channelled into such features and deflation of sands is common. Elsewhere the stabilised soil on the older sands appears to protect surfaces.

It should be stressed that these observations were made during a rapid reconnaissance of the Tihama. More precise observations, with the use of appropriate instrumentation at key sites within the TEPP, could provide a clearer understanding of the causes for the severe problems of sand and dust deflation in the alluvial and sandy lands, and thus assist in deciding how they can be mitigated.

3.2.3 Sand Movement and Accumulation in Coastal Areas.

As the study by Barratt et al (1987a, 1987b) has shown there are considerable amounts of sandy sediment lying on the coastal shelf. In shallow areas, in response to currents and the rare floods from the main wadis which reach the sea, these form long bars and spits. The spits protect the shoreline from rough seas, erosion of the coast and from sand accumulation. Sabkhas, shallow lagoons and mangrove swamps lie in their lee.

Sands accumulate on offshore bars and shallows and coral reefs. Meigs (1966) stated that the sand spits of the Red Sea are generally attached at their northern ends and open out to the south, due to the prevailing north-westerly winds driving the currents. However, along the Yemen coast it is apparent that the opposite is the case, with most spits attached at their southern end. This confirms that the dominant longitudinal drift is northwards. The coastline in the lee of the sand bars is largely described as low energy, with mangrove and seagrass marine communities, and only moderate sand accumulation on beaches.

Where the bars and reefs are absent there is onshore accumulation of sands on high energy beaches and these sands move inland to form sand dunes. The quantity of sand coming onshore is related to the current direction, the available fetch, and local supply of sandy sediments. High energy coastlines with sand accumulating onshore and building up aeolian dunes occur especially on the Salif peninsula, in the sweeping curve of the Al Urj' bay, and at intervals south of Hodeidah to Mokha and beyond. Major dune forming areas occur south of At Taif towards the Wadi Rimah, at Mujaylis in Wadi Zabid, and from Mutaynah southwards to Al Khawkhah. An additional area of sand accumulation lies south of Mokha.

Along large parts of the coast north of Hodeidah there are groves of mangrove woodland which occupy the seaward side of the sabkha on protected shorelines. Rather than the mangrove being seen as a barrier to sediment movement, it is apparent that tidal channels and currents allow the transfer of a certain amount of sandy sediments through this zone onto the sabkha plain, where it is then comes under the influence of aeolian transporting systems. If there is too much sand coming ashore then the mangrove is threatened, as is happening south of Mokha (Barratt et al, 1987). A balance is being struck east of Salif where the black sand seif dunes move into the shallow waters directly down wind of mangrove. In the area south of Hodeidah, where there are massive offshore bars and spits, there is only a small quantity of sand moving onshore and the mangrove community passes landwards into date palms, grassy plains and old stabilised dunes

3.2.4 Recent Coastal Change.

By comparing the 1987 aerial photography with the 1997/1998 SPOT imagery it is apparent that there have been changes to the coastline. It is noted for example that the shape of spits has changed in recent years, with for example a southerly movement of the Ras Al Hisy cuspate foreland. This lies at the mouth of the Wadi Zabid. The shape of the foreland appears similar but there has been an overall displacement southwards. This suggests that the net movement of sediment at present is to the south. Interestingly, the general movement of longitudinal drift is generally northerly.

In the Al Fazzah area the coastline appears to be receding quite rapidly. A comparison with 1987 aerial photography showed that the coastline has receded some 8 m since then. The historic early mosque of Ahmed al Fazzah is in grave danger of being eroded by the sea within a decade, and possibly considerably less, unless there is coastal protection. In 1987 the edge of the mosque was 10 m from the cliff edge. It is now only 4 m. Some attempts at coastal protection have recently been made by placing groins across the beach so as to induce nourishment of sand onto the beach, but this appears to be having little beneficial effect.

The coastal erosion at this and other points can be fairly easily documented by comparing the aerial photography with the recent imagery. It appears to be a widespread phenomena in the Tihama in response to seasonal changes in current. It is likely that the local fishermen are able to document change quite accurately, as these changes will also effect fish populations and the depth for boats.

It is necessary also that planners are aware that any rise in sea level could also lead to an increase in beach erosion and the onshore supply of sand, augmenting the coastal dunes and their spread towards or into agricultural lands.

3.2.5 Effects of Past Changes in Sea Level.

In the past, where the bars may have been absent or sea level lower, it is likely that the movement of sand to the coast was different from the present. During the long hyper-arid period of the last glacial maximum (LGM), ca. 12,000 - 20,000 years BP, sea level in the Red Sea is thought to have dropped to some -120 m below the present level (Jado and Zotl, 1984). This would have exposed an undulating plain at least 35 km wide comprised of unconsolidated alluvial sands, probably with a mixture of shelly marine carbonate deposits. It is considered that these loose deposits would have formed the source for coastal sand dunes blown far inland by westerly winds during the late Pleistocene.

It has also been suggested that there was a local rise in sea level to some 2 m above the present level at about 4,000 to 6,000 years ago (Jado & Zotl, 1984). This is held to explain the broad strands of sabkha that border the coast and the high salinity of sediments in this area (Barratt et al, 1987a). The present study agrees that this is feasible. Traces of what may be slightly higher shoreline occur along the coast on the landward side of the sabkha and lagoons. Low cliffs, cut into the Pleistocene sand sheets, occur near to Luhayyah for example and may have been formed by wave action.

This hypothetical slightly higher Holocene sea level would probably have resulted in an enhanced supply of sands to beaches along the coast as stable sandy features were eroded by wave action. Later as sea level dropped to its present level and bars formed offshore, these dunes stabilised.

This could explain the distribution of recent stabilised dunes and hummocks in several areas:

a) The mouth of Wadi Siham northwards to the port of Hodeidah. Large fossil foredunes occur along the coast to the south of Hodeidah where the sand supply is now largely cut off from the sea by mangrove and sabkhas.

b) The coastal lands north of Al Jah' in the Wadi Kuway, towards At Taif.

c) Lands north of Fazzah, where cliffs are covered by stabilised hummocks.

More local research is needed to assess the effects of past sea level changes on dune sediment supply as this will lead to a better understanding of how any future sea level change will, perhaps similarly, modify the sediment supply available for dune building. It is thought at a slight rise of sea level will result in erosion of beach hummocks. Eroded materials will accumulate on beach strands and then deflate at low tide to supply dunes.

3.2.6 Water Erosion.

In the upper parts of the wadis, in the steeply sloping lands of the highlands, there is loss of land from water erosion. In terraced lands of the high plateaux erosion has been reduced due to the efforts of terrace production over many centuries. Despite periods of neglect in the past, programmes to rehabilitate the terrace systems are being undertaken. On the very steep range lands of the escarpment, where terracing may never have been initiated, there is high soil loss from storms during the rainy season. Materials being transported into the drainage network include topsoil, dust layers of very fine silt that have been deposited as loess, and sand to gravel and boulder sized rock particles. Floods entering the Tihama plains, for example in the Wadi Mawr, Wadi Surdud, and Wadi Zabid all have bedloads with a high sand fraction.

Recently many unregulated concrete dam structures have been built in the upper parts of the main wadis (eg Wadi Zabid) and these effect a narrowing of the channel width. During flood events though these structures may be washed away, as they were in the past before the main offtakes were constructed, and there is considerable lateral erosion to the banks of the alluvial silt plain.

In addition, run-off from the adjacent plains, either from leakage from canals, poor distribution of flood waters, or from intense local rain storms, has caused piping and gullying of arable lands and the banks along the rivers.

On the alluvial fans occupied by Parkland Agriculture of land cover unit A1 (see Chapter 7) water erosion of the silty soils is present where channels are unprotected by grass and herb cover. Close to the mountain front rainfall is sufficient to sustain grasses on field bunds; consequently wind erosion of the silts is low. Deposition of sand is a problem on the margins of this unit where the alluvial lands abut against the higher ground of the ancient sand sheet (land cover unit Ap).

In the lower parts of the wadi systems flood waters only rarely reach the sea and sands occupy the wadi floors, cascading off the ancient sand plains that flank the valleys. These wadis originally would have carved broad channels through the sand plains to the coast, probably at a period of lower sea level, but the age of these events is not yet known. Recently, within the last century or so, as concluded from features observed on the aerial photography and by field examination, it is apparent that substantial floods have reached the coast and cut meandering channels into the existing silt cover. These floods have also cleared pathways through sand dunes that had choked the wadi floors but may occur only about once every ten to thirty years or even less frequently. Despite the presence of modern irrigation control along the edge of the escarpment, it is debatable whether this has led to reduced flooding in the lower parts of the wadis. It is likely that when large floods occur in the future they will easily cut through to the sea again.

In the intermediate areas of some wadis, for example on the southern margins of the Wadi Zabid where there is no new network of canals and sand dunes lie to the south, some farmers have reported that irrigation control has led to less flooding and, in contrast, a greater invasion by encroaching sands. Fortunately, some of these areas lie within the TEPP and should benefit from sand stabilisation measures.

3.3 OLDER AEOLIAN SAND FORMATIONS.

3.3.1 General Description.

In the field it is seen that the recent alluvial plains of the Tihama have dissected an older, sandy formation comprising aeolian sand plains and linear dune ridges that are found at the coast and inland as far as the mountain front. The linear dunes are many kilometres long with regular spacing between ridges, and their upper surfaces have been stabilised by soils, at some stage in the past. These older sand formations now occupy much of the terrain between the principal alluvial systems on the Tihama northwards of the Wadi Rasyan. They are distinguished in the field as older aeolian formations on the basis of:

a) They retain typical features of linear dunes, with narrow ridges, Y-shaped junctions, and 1 to 2 km wide inter-dune corridors;

b) They are generally lacking in any originally gravelly material greater than 2,000 microns except for root concretions of calcium carbonate (also known as rhizoconcretions or dikaka), and have a well sorted unimodal distribution of medium to fine sands characteristic of aeolian sands,

c). They have a moderate content of silt and clay considered to be indicative of dust formation during a long period of soil formation; aeolian depositional features are uncommon, except on the coast; in coastal areas older dunes do show original stratification that has been preserved by carbonate cementation of the dunes into aeolianites;

d). They are overlain, never underlain, by modern active sands and sand dunes, and generally, a sharp truncated boundary exists between the two types of sand formation.

In the laboratory at TDA and in the UK, studies were conducted on a wide range of sediments. Analytical data is given in Appendices D and E. It is considered that the older sand formations are distinctive from recent aeolian sands, recent wadi sands, and recent beach sands, in that the sand grains show clay and oxide coatings that are visible under the scanning electron microscope and can be identified mineralogically by the energy dispersive X-ray analyser. These coatings show that clay minerals have formed in pockets and on the surfaces of quartz and feldspar grains. Clay coatings are absent on more recent sands. Microcrystalline carbonate, calcite crystals and salt (halite) crystals however are present in the older and recent sands. On the beaches and sabkhas, gypsum is also present, and cements of calcium carbonate on rims of grains form aeolianites (Gardner, 1988). Thus, it is tentatively concluded that the older sands show a different suite of secondary features and can be distinguished from the recent sands.

The older sand formations in turn overlie earlier alluvial formations, including loams and gravels, that have been noted throughout the Tihama.

Significantly, almost all the major settlements on the ancient sand plains of the Tihama sand plains are located on the convex summits of the old sand ridges, for example, Qutay, Beit al Faqih, Hussaniyah and Mansuriyah. Materials from older settlements, midden material of shells and pottery, are also common in many areas, often forming a wind-stable cover or mulch on the surface.

Given that it is unlikely that these settlements would have been deliberately sited on active dunes in the past, it can perhaps be safely concluded that the dune ridges were already well stabilised by soils (and vegetation) at the time of the first settlements, which was at least three thousand years ago. The inter-dune valleys, lying parallel to the ridges may well have been swampy and subject to floods originating on the escarpment.

These environmental considerations for the Tihama however are somewhat speculative at the present stage of investigations, and are based on dune characteristics seen elsewhere.

The older aeolian formations also occur along the coast, where modern mobile sands overly the older sand formations. These include large foredune ridges parallel to the coast, aeolianites where the sand are cemented by carbonates, and eroded and bevelled remnants of sand landforms.

The older sand formations were described in the Appraisal Report (IFAD, 1992) as longitudinal draa dunes. The use of this term is not carried on in this report, since it is genetic implying that the dunes were formed parallel to the wind direction. We do not actually know that the winds were unidirectional at that time. It is thus safer to suggest that the ridges originated as linear dunes (Pye and Tsoar classification of 1990) with narrow ridges formed from various wind directions. Active dune formations now partly or wholly overlie these ridges and it is has been suggested in the previous reports that the dunes are now re-forming locally.

It is concluded that although there is a degree of water erosion on the stabilised soils and wind deflation in some ploughed up or exposed areas of the older dunes, they remain largely stable features, with the active dunes traversing over the older dunes surfaces.

3.3.2 Characteristics of Sand Ridges (Unit Ar).

The sand ridges are from 250 to 500 m across and heights of up to 20 m. Exact measurements were not made during the present study. Between the ridges are concave dune corridors that are typically 1 to 2 km across and often at least 15 km long. The ridges show a number of Y-shaped junctions, characteristic of linear dunes (Cooke and Warren, 1973) and these tend to open out to the east. The slope on the ridges, in the Mansuriyah area, varies from 4 to 9%, though the original dune slope is unknown. These measured values were on stabilised surfaces dissected by gullies cut into the soil of the old ridge, so it is likely they approximate the slope of the ancient dune when it was stabilised. Near Qutay slopes were measured at 14 - 19%.

The sand ridges vary slightly in their direction around an overall easterly travel, and include the following:

TDA nursery on south side of Wadi Siham:	060 °
track to Suknah:	060 °
Mansuriyah:	090 °
Beit al Faqih:	060 °

The soils of the sand ridges have been given a preliminary examination during this study, by carrying out laser granulometry analysis of the particle sizes. These (samples R41, R42, R11, R112 at a section at Beit al Faqih) show that soil formation is largely confined to an upper layer where there is considerable silt and clay fraction. It is suspected that much of this would have been added to the soil from airborne dust during a long period of soil stabilisation.

Active sand sheets and transverse dunes are also common on parts of the ridges. Both of these often appear to have migrated in from adjacent sand seas, but local origins may be possible. Samples R38, R39 and R40, from recent and active sands at the same section at Beit al Faqih have very similar characteristics to the older sands. Much more detailed research is needed, however, to fully understand the relationships of the recent and old sands, but it is significant for understanding whether local re-mobilisation or long distance of sand dunes is the key process.

3.3.3 Characteristics of Sand Plains (Unit Ap).

The ancient sand plains are gently undulating terrains that extend inland from the coast towards the escarpment, where they merge into the sand ridge topography (Unit Ar). Although traces of linear ridges are often seen on the ground along tracks and roads in the west of the Tihama, these features are not as clear on the photography and imagery as they are further to the east. This is probably due to the blanket of recent sand sheets and transverse dunes which covers much of the sand plains and has obscured the outlines of the ridges. It is suspected, however, that they are all part of one geomorphic unit deposited and then modified together.

The sand plains at the coast are well exposed on the track to Salif where a section was investigated. This shows a massive soil layer (sample R85) that has formed in the sands and which has elevated silt and clay levels, similar to those at Beit al Faqih. The subsoil, with loose sands and concretions, is also similar to the inland sands on the dune ridge. Inland, ancient sand plain sediments that have been analysed include R70, east of Qutay, and R62 north of Hodeidah.

The surface soil of the old sand plains forms a wind stable layer over much of the Tihama. This is thought largely due to the soil structure present, and the higher silt and clay levels. Coarse materials from human settlement occupation are also very common, and include pottery, gravels that were probably associated with former buildings and walls, and marine shells that have been brought from the coast and then dumped in middens. This accumulation of coarse waste products is also very important in maintaining the stability of the ancient sands, by protecting the surface from deflation.

3.3.4 Characteristics of Ancient Coastal Dunes.

Ancient coastal dune landform have been observed in several localities. Over much of the area though the older sand formation comprises a weakly undulating plain that is truncated at the coast. South of Hodeidah there is an ancient foredune, some 15 m high distinguished by its ridge form parallel to the coast, a stabilised soil on top with midden materials (R 56) and a subsoil packed with rhizoconcretions of calcium carbonate.

Near Luhayyah, in the north, undulating sand sheets have with soil layers and concretions (R 92, R93, R94). This may be a remnant of a coastal barchan.

Between Fazzah and Mujaylis recent sand sheets and aeolianites overlie an older sequence of aeolianites. These dip northwards at some 10 %, suggesting that they were deposited from southerly winds. Inland of the Wadi Zabid there is a chaotic terrain comprising eroded ridges and valleys that represents aeolianites that have been exposed and subject to scouring and deflation by wind.

3.3.5 Period of Formation, Sand Dune Stabilisation and Soil Formation.

Very little is known at present about the methods of formation and stabilisation or the exact age of the ancient sand formations on the Tihama. As noted elsewhere (Section 3.3.1), the stabilisation of the dunes, would in all probability, have preceded settlement location on the dune ridges. The stabilisation was accompanied by soil formation at the surface, probably aided by accumulation of clay and silts from deposition of airborne dust, and formation of calcium carbonate concretions around roots (rhizconcretions) in lower parts of the profile. In the eastern parts of the Tihama the soil formation process has been such that the dune ridges have dendritic drainage gully systems. The massive nature of the sands with an absence of bedding in deep sections suggests that biogenic activity was taking place during the formation of the dunes, such that they may have accumulated as a Vegetated Linear Dune type.

Alternatively, they could have accumulated as bare seif dunes in a hyper-arid environment and subsequently been modified by soil formation in more humid times. Evidence from dune formation and stabilisation in Saudi Arabia can support either theory, and depends on the evidence for past climate change in the area (McClure, 1978).

The present study has provided the opportunity to carry out a preliminary examination of these ancient dunes. Only a detailed study of the morphology and micromorphology of the dune sediments may be able to reveal their history of formation. A programme of dating the sands using modern techniques such as optically stimulated luminescence (OSL) dating (Aitken, 1994; Munro et al, 1997) would also aid establishing the chronology of dune formation.

It is recommended that research projects of the ancient dunes be undertaken as soon as possible. Firstly, to carry out a comprehensive understanding of their initiation and development. Secondly, and of direct application to the programmes of sand dune stabilisation in the Tihama, to answer the questions on the stability of the these ancient dunes, and their susceptibility to wind and water erosion under present climatic conditions and different types of land use.

3.4 RECENT AEOLIAN SAND FORMATIONS.

3.4.1 General Description.

The recent sand dunes on the Tihama include both coastal and inland types of dune. They are distinguished on the basis of their morphology and from the particle size features of grains.

Sand dune formation is enhanced on high energy beaches where there is greater supply of sand available offshore. On such coasts, blowing inland off sandy beaches, and sometimes moving across saline crusted sabkha, are saline sand hummocks, sand sheets, non-saline sand hummocks and larger foredune ridges. These aeolian landforms progressively accumulate away from the coast. On the coast there are recently cemented sand sheets and dunes (aeolianites) with weak cementation by calcium carbonate. In these the original layering of sand grains is clear. These sub-recent dune remnants are also being eroded by sand bearing winds.

Slightly further inland there are extensive belts of barchans and parabolic dunes. The latter are often extended in a linear fashion with vegetation playing a significant role in formation and stabilisation. Inland of the parabolics the dunes may reform as barchan dunes or areas of sand hummock. Combinations of these are common, and in all produce a complex picture.

In the interior areas, emerging somewhat nebulously from the coastal areas, are extensive sand seas (defined as areas > 125 km^2 in area by Pye and Tsoar, 1990), in which sand hummocks merge into barchans and, finally, extensive chaotic terrain of transverse ridges. In places, seif ridges occur at the downwind edge of expanding dunefields. Elsewhere, where sand may be of more limited supply, barchans are seen to be performing a similar process. Lying between all these types of dunes are mobile sand sheets with coarse and fine grained ripples.

3.4.2 Examples of Initiation of Coastal Sand Deposition and Dune Movement.

The initiation of sand accretion was observed at several locations along the coast of the Tihama during periods of high wind speed. Descriptions of processes at these are instructive in understanding the pattern and complexity of dune formation. Sample numbers refer to analysed dune sediments (Appendix D and E).

a). Beaches of the Salif Peninsula.

The sweeping curve of the Salif beaches on the southern side of the peninsula show that pale, shell-rich sands are accumulating on the western and more northerly part of the beach, and dark sands rich in heavy minerals accumulating on the southern edge. These high energy beaches, apart from appearing to confirm a northerly longshore drift of sediments, show that the sands that move inland are also of different character.

The white sands have high shell and quartz components. Immediately inland of the beach (sample R81) the sands accrete into intensely undulating terrain, with sand hummocks one to two metres high stabilised by *shawkam* grass (samples R79 and R80). Some three hundred metres inland these are piled up in broad foredunes parallel to the shore, which merge into parabolic shaped dunes immediately inland where there is a sabkha surface. Large barchan dunes (samples R77 and R78) then break out across the sabkha and, after crossing the main road, have accumulated over the northern part of the peninsula as a complex megabarchan, probably a composed of recent and older barchans, before they re-entering the sea to the north.

On the black sands the beach material (R83) forms low drifts (R84) stabilised by the grass *Halopyrum mucronatum*. These hummocks merge into parabolic ridges (unsampled) which break out across the sabkha as narrow seif dunes (Samples R76 and R82). The latter frequently cut the main route to Salif.

b). Sabkha Lands South of the Wadi Siham.

In this area there are low lying sabkha that merge with beach ridges along the coast. Sediment supply is moderate here and mangroves occur nearby. However, an appreciable amount of sand is moving onshore and inland.

The sabkha surface has a saline crust made up of aeolian sands and salt crystals (sample R58). Sands move over this when threshold velocities are sufficiently high to overcome the resistance offered by the rough surface of the salt crust. Sand drifts then accumulate in low drifts (R55) which in turn pass into deeper drifts stabilised by *Halopyrum mucronatum (Qasabo)* grass (sample R54). Slightly further inland and still on the sabkha surface larger hummocks accumulate. These dunes are some 3 m high, stabilised by *Tamerix* trees, have a soft saline crust on the surface and are permanently moist (R61). On higher ground, now above the level of the sabkha, there are large hummocks that do not have salts (R60) and, where these have been eroded, they are being replaced inland by transverse ridges (R59) that show the influence of NW winds in summer. These dunes are of limited extent and are unusual along the coast. They appear to reflect destruction of the vegetation cover by cutting.

In general it appears that sands normally accumulate further inland as hummocks (R57) stabilised by *Odyssea mucronata (Shawkam)* grass. These are piled up within a few hundred metres of the sabkha edge into foredunes that are parallel to the coast and some two hundred metres deep. Further inland they merge into hummocky terrain. Some of the foredunes are also clearly ancient features with soil surfaces and human settlement materials stabilising them (sample R 56).

c). Mujaylis Area.

The Mujaylis area at the eastern end of the Wadi Zabid shows how sands move off the beaches into parabolic dunes. This appears to have occurred in recent and ancient times. At the coast the beach material includes gravelly and sandy alluvial and shelly marine sediments, derived from coastal sediments washing up on the beach (R 26) and from low cliffs of older alluvial materials (R20). These form an undulating strand that may be occasionally flooded but is generally above high tide mark (R 23). On this strand are hummocks with *Halopyrum mucronatum* grass (R21). The hummock stabilising vegetation in the Mujaylis area appears to have been largely removed and few hummocks are forming. Older hummocks, weakly cemented by calcium carbonate also appear to have been stripped of vegetation (R29). The ground then rises into a broadly convex foredune some 20 m high, with coarse and fine grained ripples (R25 and R28 respectively). These ripples are migrating over a very hard older surface, in effect a fossil foredune. The latter (R30) is shown to be an aeolanite comprised of calcium carbonate cemented sands. At the crest of this foredune there is no stabilising vegetation at Mujaylis and a series of parabolic dunes extend northwards over the alluvial deposits where in the recent past they have buried houses, date palms and also dom palms. Sample R22 is on the crest of the parabolic, whilst R24 is on the slip face immediately above the floor of the alluvium.

The front of the parabolic dune is just over one kilometre north of the foredune, and has a northwards moving slip face some 5 metres high. Average annual movements were measured by comparing the aerial photography (1973 and 1987) with detailed field observations. Preliminary estimates suggest that from 1973 to 1987 the rate was between 15.4 to 16 m/year, whilst from 1987 to 1998 it was from 9.1 to 10.9 m/year. This is considerable less than that measured by FAO (1990).

3.4.3 Characteristics of Coastal Hummocks (Unit D1n).

The coastal hummocks (nebkha) are substantially larger than those of the interior. South of the Wadi Siham hummocks some 3 m high are accreting along the edge of the sabkha and are stabilised by the grass *Halopyrum mucronatum* and also *Tamerix aphylla* trees. These dunes have a saline crust on the surface and are permanently moist from salts. They show bedding in several directions indicating seasonal wind directions.

The material of these aeolian landforms is generally fine sand when analysed by laser granulometry. Dry sieving however suggests a coarser grain size distribution, and examination under the microscope showed that grains are commonly coalesced by salt particles. These were identified in the scanning electron microscope (SEM) to include both common salt (halite) and gypsum.

3.4.4 Characteristics of Coastal Foredunes.

Coastal foredunes consist of rounded ridges up to 20 metres high, 200 m broad and one or two kilometres long which have formed along the edge of the sabkhas and beach strands. Their long axes are at right angles to the wind direction blowing onshore. Active foredunes are prominent at the mouth of the Wadi Siham south of Hodeidah where they are fed by sand hummocks on the coastal side and pass inland into a series of similar hummocks. The vegetation on the dunes generally includes *Odyssea mucronata*. Some fossil foredunes are also noticed along the coast in the same area; active sands continue to blow over them.

3.4.5 Characteristics of Coastal Parabolic Dunes (Unit D1p).

These dunes that form along the coast generally have broad parabolic rounded fronts that advance inland, a largely sand free corridor behind the front and long trailing lateral arms that reach back to the beach zone. Sands, rich in shell, quartz and other rock fragments are blown off the beach and initially form a beach ridge or foredune, but under conditions of enhanced sand supply these evolve into parabolic shaped dunes. Sands are blown along the linear corridor in the centre of the dune, to form a blow-out, with sands accumulating on the higher ground of the trailing arms and crest.

The front of the dune has a characteristic rounded crest with a slip face along a broad convexo-concave front. The crest and arms are generally vegetated forming groups of sand hummocks, in the Tihama this is usually the spiky grass *Odyssea mucronata*, with slightly coarser sands on the bare crests (R17, R22) compared to the vegetated hummocks (R18) and the slip faces (R24).

In the Mujaylis area the blow-out area marks an area of date palms and houses that have been buried and are now being exhumed as the dune front continues to advance over the plantation. The arms of the dunes at Mujaylis have been denuded of vegetation, whether by natural or human causes is not clear, and coarse sand blows off the beach onto the dune (R28, R25). By contrast, in the Mutayna area the broad corridors and arms are both well vegetated with *Odyssea mucronata*, and the dune front is less prominent with no clear features that show an advancing front.

Thus, vegetation appears to control the stability of the dunes and whether they function as a holding ground for sand to build up and be transferred inland slowly, as at Mutayna and other dune areas to the south, or advance more rapidly inland as a whole, as at Mujaylis.

In terms of dimensions, the parabolic dunes, in the area between At Ta'if and the Wadi Zabid, have trailing arms that range from 250 to 800 metres or more long, and the width of the parabolic is about 250 metres at the front and 400 metres at the coastal end. They show that the onshore wind directions strong enough to build these dunes are from the south-south-west to south-west.

South of At Ta'if and about one kilometre further inland these parabolic dunes are replaced by a secondary line of parabolic dunes that are densely covered by hummocks. Further south at the mouth of Wadi Rimah the coastal parabolic dunes are replaced immediately inland by unvegetated transverse ridges. It is not yet known why there is such a startling change in vegetative cover on different coastal dune fields. Near Mutayna for example the vegetated parabolic dunes extend to the coast, but at Mujaylis they are barren at the coast but underlain by hard aeolianites. A contributing factor could be the removal of stabilising vegetation on coastal dunes leading to deflation and exposure of sub surface aeolianites.

Linear types of parabolic dune are also observed advancing into the trough of the Wadi Rimah. These have originated several kilometres to the south-west on the coast, have fronts that are 60 to 250 metres broad, and blow-out zones that are occupied by advancing chains of transverse dunes. East of the dune front, sand sheets move through the valley floor, associated with large hummocks densely forested with *Salvadora persica*, and emerge on the north side of the Wadi Rimah to form transverse dunes.

Further south, in part of the Mujaylis area, there are densely packed areas of transverse dunes advancing to the north-east. Overall these occupy a mega-parabolic shaped feature that is developing in advance of normal shaped parabolic dunes.

Thus, the parabolic dunes can adopt a range of features that reflect sand supply, the type of sand, wind direction, local topography and natural vegetation.

3.4.6 Characteristics of Coastal Barchans (Unit D1b) and Transverse Dunes (Unit D1t).

Coastal barchans and transverse dunes generally form inland of the parabolic dunes. One example was seen on the aerial photography where a small barchan was attached to the front of the parabolic dune. The coastal barchans and transverse dunes are usually formed of fairly coarse sands and shelly material and are often closely related.

At Salif the coastal barchans transform into transverse dunes and then back into barchans (samples R77 from a slip face, and R 78 from the crest of same dune). They are much larger features than the dunes which develop in the interior lands. Coastal barchans and transverse dunes in the Mutayna - Fazza area have widths of 70 to 100 m and wavelengths of 50 to 150 m, with gaps of bare ground up to 100 m wide between the slip face and the dune in front.

3.4.7 Contemporary Aeolianite Formation.

From the presence of refuse layers within some coastal aeolianites, at Mujaylis, it is concluded that aeolianite formation is a process that is happening today. Cementation of sand grains is a result of calcium carbonate precipitation from salt sprays blowing inland (Pye & Tsoar, 1990). The Tihama aeolianites appear to have formed under sand hummocks that were colonised by *Sueada*, *Tamerix*, and other plants. The vegetation has been destroyed, whether by natural or human means is not clear, and the cemented layers become exposed at the surface. Once in this state plant colonisation is extremely difficult.

More research is needed on the aeolianites of the Tihama to determine their origins and how they can be re-vegetated. It is apparent that once they are exposed at the surface their hard layers make them very difficult to be penetrated by plant roots in the absence of moisture. The cementation however becomes weakened with addition of fresh water, such as may occur with irrigation during afforestation. Elsewhere, vegetated and non-vegetated aeolianites exist side by side.

3.5 AEOLIAN LANDFORMS OF THE INTERIOR PLAINS.

3.5.1 Characteristics of Sand Hummocks (Unit D2n).

The sand hummocks (nebkhas) on the interior plains are generally up to one metre high, spaced between one and five metres apart and mostly stabilised by perennials, especially the grasses *Panicum turgidum* and *Odyssea mucronata*, either in association or as large zones of one species. Other hummocks are stabilised by *Lasiurus scindicus*, *Leptadenia pyrotechnica*, *Acacia ehrenbergiana*, *Salvadora persica*, *Cadaba rotundifolia*, *Tamerix aphylla* (and several other plants) and also the invasive *Prosopis juliflora*. The roughness of sand hummocks causes sand and dust particles moving close to the ground to be deposited. The vegetation, and its ability to grow under conditions of low rainfall, plays a vital role in the formation of the hummocks. Find sand and dust is entrapped in the hummock, especially where the plant canopy is dense. The ground between the hummocks is bare in summer and autumn, when sand will move freely through the landscape according to the seasonal wind direction. In spring when the sands are carpeted with annual flowers and herbs, sand movement is reduced. The role of soil-living animals in forming wind stable features is believed to be of major significance. As sand is trapped in the hummock it is affected by soil animals and flora. Faecal pellets from undetermined soil-living animals were found to be very common in sand hummocks, and sometimes in dunes derived from them. This biological stabilisation is worthy of a detailed study on its own.

However, destruction of the vegetation cover, often for fuelwood, destroys the equilibrium of this landscape and leads to renewed mobilisation of sands as natural processes work on the degraded hummocks: rainfall will wash sands off the hummocks and break down soil aggregates; wind erosion breaks up the hummock by scouring and formation of yardang structures; browsing animals will break up more of the surface as they hunt for pasture; and sand movement will be increased as windspeeds rise in a less rough terrain.

Sand hummocks that have been sampled in the interior lands include: R65 at Dayr al Issa to the north-east of Hodeidah; R34 to the west of Tuhaytah (beside R33); R8 on gravel plains on the track to Yachtul; R35 in the lower Wadi Rimah'; and R38 on the top of an ancient dune ridge at Beit al Faqih.

3.5.2 Characteristics of Sand Sheets (Unit D2s).

The sand sheets of the interior occur in a range of situations where dune types are changing: for example, from barchan to transverse dune; where sand hummocks are being swamped by mobile sands and forming transverse forms; where rolling zibar plains with low-amplitude occupy poorly defined areas in the centre of sand seas; and where sands are moving through cultivated lands or rangelands as low drifts of transient appearance.

The zibar plains, which were noted on the aerial photography, occur in fairly remote areas of the sand seas and it was not possible to study them in the Tihama summer, but other sand sheets were sampled and these were analysed in Hodeidah and the UK. Active sand sheets forming on rangeland areas include: samples R87, R97 and R99 in the Wadi Mawr areas, R72 east of Qutay; R33 near Tuhaytah; and R5 on the track to Al Khawknah.

3.5.3 Characteristics of Barchan Dunes (Unit D2b).

Barchan dunes occur where there is a moderate supply of sand. In the Tihama barchans are usually seen as individual dunes moving through farmland or on the plains. They vary in size from one to four metres high and five to twenty or so metres across. The barchans are generally not vegetated. They are often forming down-wind of transverse dunes and in turn may supply new chains of transverse dunes further downwind. Given the differing wind directions it is not certain, but likely, that they also seasonally change directions.

It was noticed that the large dunes that occur on the margins of the cultivated lands, such as at Qaza, will be largely static and immobile for parts of the year when winds are blowing southwards and out of the plantations in this locality. At al Qaza, in the Wadi Rumman, a series of large barchans occur on the edge of the transverse dune sand sea. Some 15 m high with slip faces of 62-65%, these dunes were said to have moved 100 m in 20 years and buried houses and date palms.

On the track to Buhays, north of Zuhra, barchans are moving eastwards. Derived from coastal areas these dunes are less than 2 m high and showed slip faces that indicated a westerly wind direction in summer.

Sampled barchan dunes include: R95 on the track to Buhays north of the Wadi Mawr; R47 at Sawlah; R31 at Beit al Mashareh; and R3 north of Mokha where barchans are crossing the main road.

3.5.4 Characteristics of Transverse Dunes (Unit D2t).

The transverse dunes of the interior are probably the most common type of dune seen on the Tihama. They are composed of loose sands, and are generally devoid of vegetation.

They consist of slip faces that face downwind of the prevailing seasonal wind direction. Transverse dunes measured in the Wadi Zabid area from the aerial photographs had wavelengths of 50 to 70m, and the dunes were some 50 m across and with gaps of 25 to 70 m between dunes. The rates of movement of these dunes was unknown.

Near Maghras the transverse dunes were measured to be advancing into farmland at 10 m over an 11 year period. The rate of movement of the transverse dunes moving into the Wadi Rimah was estimated by comparing 1973 and 1987 aerial photography and the 1997/98 SPOT imagery.

In addition farmers were asked for their opinion on the rate of burial of houses at a village south of Al Madaniyah. The measurements showed that since 1987 there has been an average north-easterly movement of some 7.2 m/year, and in total the dunes have advanced some 80 m across the channel of the Wadi Rimah onto the edge of the farmlands.

More complex areas of transverse dunes were noticed where several slip faces are present and form a network. These will always be seen at the start of the changing season as a new wind direction asserts itself on the old dune pattern. On the ground at this time the dune pattern appears very complex. In time, however, the pattern reflecting the new wind direction becomes dominant. Thus, most of the aerial photography taken in winter shows slip faces facing the north-east, in response to the southerly winds. Permanent areas of dune networks occur in some sand sea areas where the seasonal winds have produced two strongly opposing sets of slip faces.

Analysis of transverse dunes has been carried out for: samples R64 and R67 located to the north-east of Hodeidah; R44 at Qaza; R46 at Al Qaria; R32 in the Sharqiyah area, Wadi Zabid; R36 in the lower Wadi Rimah' valley; and for R10 south of Hays on the main road.

3.5.5 Characteristics of Linear Dunes.

Linear dunes in the form of seif like ridges are present in many parts of the Tihama. Generally they are too small to be mapped out separately, and occur as either the downwind trailing edge of a transverse ridge or the extended arm of a barchan that is changing into a linear dune, or as a single winding ridges. The seif has a narrow crest with a slightly concave steep slip face on the downwind side. The upwind side is less steep and more convex. The slip faces change according to the dominant wind direction.

There are several coastal seif dunes migrating across the main road on the route to Salif. These require constant clearing during much of the year. They are formed of black sands, rich in heavy minerals. Seasonal wind changes include NW and SW directions. These produce a NE drift resultant. These dunes are up to five metres high, though often less, and appear to form where the winds have channelled sand movement into a few distinct pathways. They have narrow crests and steep slip faces.

Seif dunes also occur on the eastward edge of some transverse dunes that are advancing into farmlands south of the Wadi Zabid. These are several metres high and show that there is an overall easterly movement of sands.

3.6 ORIGINS OF THE SEDIMENT SOURCES FOR THE TIHAMA AEOLIAN SANDS.

Previously, the origins of the coastal and interior dunes were suggested to have been separate and that there was little or no connection between the two types of dune (HTS, 1993). The Appraisal Report (IFAD, 1992) was undecided on either a coastal or inland origin, and noted that whilst remobilisation of the ancient dune ridges (termed "longitudinal draa") was an important process in the eastern part of the Tihama, the supply of sand in the west from the sea was a minor component. For this reason the plans for stabilisation of coastal areas were dropped from the TEPP.

The more detailed field and analytical studies carried out during the present study have concluded that the coastal and inland dunes are in fact intimately connected, with the former feeding the latter, be it over a long period with small annual increments. Although the wadi beds and alluvial fans of the Tihama may locally supply sand for dune building they are not believed to be, as considered by HTS (1993), the principal sources. The coastal shelf with abundant sand supplies is considered to have always been the main source for aeolian sand formation.

The sources of the aeolian sand formations in the Tihama are now considered to have originated almost entirely from alluvial sediments derived from erosion on the Yemen highlands, later deposited in the coastal waters of the Red Sea during large flood events in the past.

Laboratory analysis by X-Ray diffraction of alluvial sediments from the Wadi Surdud, active dunes on the sand plains, older dune sediments and recent beach deposits all suggest a common origin, and support the view that sediments are being recycled from the sea back towards the escarpment (see Table E.2).

In another investigation carried out for this consultancy, laboratory analysis of a transect of hummock and dune samples from modern mobile sands between the coast at Al Ta'if and inland at Sawlah in the Wadi Kidiyah / Wadi Naba strongly suggests that both grain size and calcium carbonate content decrease with distance from the sea. This would support the view that shell fragments and rock particles are progressively crushed within a short distance of the sea. (See analyses for samples R 44, R47, R49, R50, R 51 and R52 in Table E.5).

It is also important to remember that, although the annual movement of the slip face of a sand dune in the area is probably at least 10 m/year (as measured in the field during 1998, and also reported by FAO-IC, 1990), individual sand grains are likely to move far greater distances. For example, sand particles are known to move several hundred kilometres a year in parts of the Namib desert (information from K. Pye). In the unvegetated sand seas of the Tihama, with closely spaced transverse dunes, saltating sand grains may well move hundreds of metres during single periods of strong winds, being transported from one dune ridge onto the next by saltation, or by short-term suspension of the finer particles when there are strong gusts. By contrast, the slip face of the dune is advancing at a more steady rate, up to few tens of centimetres a day and often much less than this. Thus, sands originating on the coast can be blown rapidly inland to augment dunes threatening farmlands, and the coastal areas should be regarded as intimately connected with the inland dunes. Research is needed in the Tihama to measure and quantify the local situation.

Remobilisation of the older sand sheets and dunes is also considered to be of minimal significance in many areas since these older sand formations have, in all locations visited, a protective surface soil or a lag gravel of anthropogenic derived shells and pottery fragments. However, there is some local gullying of the older sands where there is higher rainfall and disturbance from farming. Fluvial outwash from these gullied areas, which occur on the old sand plains and sand ridges that lie east of a line from Qutay to Mansuriyah, will nourish the development of small sand sheets and limited dune development. Analysis of sands from active and ancient sand sheets in the Qutay area showed almost identical particle size distributions. Thus, it cannot be ruled out that local remobilisation of the ancient dunes from rainwash is contributing to modern problems of drifting sand though it is suspected it is on a small scale.

Disturbance of the surfaces of the older aeolian dunes during farming operations for rainfed millet production was regarded as an important process in the Appraisal Report (IFAD, 1992). It is clear that where millet is grown on moist, loose sands there will be erosion problems when this surface dries out, and in the field it was noted that from the position of millet roots, some 20 cm of sand could be lost in a season. But this occurs on active loose dunes, temporary stabilised by rainfall, and is to be expected. On the older dune formations, there is often a loose cover of fine sand in which the millet is placed. Moisture extends down into the older sands, which will not deflate as the soil water is used as they have a stable structure. Where the surface of the older dunes is broken however, by ploughing and during seeding, then deflation is more likely to occur as the dry season progresses.

3.7 RESULTS FROM SEDIMENTOLOGICAL ANALYSIS

3.7.1 Grain Size Analysis by Dry Sieving of Samples

Summary of Results.

A large number of sand samples were dry sieved at TDA in Hodeidah (Table D.1). Each sample was examined under a microscope to determine the nature of the sand grains and type of aggregates. The particle size distributions from several samples were rejected because of salts (identified in the laboratory at PRIS in the UK as Halite and Gypsum) which were weakly cementing small sand grains to group together into larger grains.

The particle size analysis shows that all the sampled sands have over 90% sand content. Most sands have a unimodal distribution with one dominant peak, in the Very Fine Sand to Coarse Sand range. Bimodal sands include certain types of hummocks and sand sheets near the coast and inland, and also older sand sheets where there appears to have been secondary accumulation of finer particles.

The mean grain size of sands is seen to decrease away from the coast as particles become finer. Using Phi units to measure grain size, coastal sands generally range from 0.6 to about 2.0 phi, and rarely up to 3.2 phi; interior dunes and sand sheets from 1.9 to 2.7 phi, and ancient dunes from 2.6 to 2.9 phi. The Mode shows the grain size at the peak or top of the distribution curve. The mode often correlates to the Mean grain sizes of unimodal distributions, but will show several peaks for more complex bimodal or multimodal distributions of certain sandy sediments. The dry sieving method underestimates the amount of silt plus clay in the sediment. This is because a certain amount of fines is either held electrostatically onto the mesh of the sieves, or is bound together by salt crystals and also as faecal pellets excreted by soil fauna, or is lost as fine dust during sieving, or is held in pores and cavities on larger grains.

The skewness of the samples is a statistical measure which characterizes the asymmetry of the distribution curve. It has negative or positive values according to whether more coarse or more fine materials are present than in a normal distribution. In the dry sieved Tihama sands there is a wide range of skewness values that appears to reflect the complex mixing of grain sizes derived from coastal areas, with additions of finer materials from dust and alluvial silts.

Implications for Sand Stabilisation.

The dry sieving of sands has provided quantitative data for a large range of aeolian sediment types in the Tihama, although the amount of silt and clay fines may be underestimated. A notable effect is the presence of larger aggregates based on salts and soil faunal pellets.

In most coastal areas the sand grain particles are bound together by halite and gypsum salts as they move across the sabkhas along the coast. This makes these particles larger and as a result they are more wind stable, leading to the formation of large hummocks close to the coast. These hummocks are quite saline and hard salt crusts and soft saline mulches occur on both on the surface and as buried layers. Examination of aggregates under the microscope shows that very fine grains of sand and silt are held together by salts. Where vegetation types are colonising the saline hummocks there are also soil fauna present and these produce faecal pellets mixed with the saline aggregates.

Further inland on most interior hummocks, where saline crusts and mulches are absent, the coarser fractions (0.5 to 2 mm) typically have many aggregates comprising finer sand particles bound together in faecal pellets. It should be noted that with prolonged dry sieving these aggregates are gradually diminished. With the laser granulometry technique many of the aggregates will be destroyed. The influence of soil microfauna in coastal and interior sand hummocks is probably related to the presence of vegetation growing on the hummock. The aggregates appear to illustrate that stabilisation of sands around vegetation is likely to be a function of the soil fauna, which are feeding on decaying organic matter of plant materials, leading to the creation of larger grains that are wind stable. This is an important lesson for sustaining a programme of biological based stabilisation of mobile sands in the Tihama.

3.7.2 Grain Size Analysis by Laser Granulometer

Analytical Results.

The laser granulometry technique provides a far more precise and rapid method of determining the particle size distribution of a sediment than by the traditional dry sieving methods. The samples show the detailed breakdown of the sand, silt and clay components of the sands from 0.1 to 900 microns (respectively 13. 3 to 0.3 Phi). The results are shown in Table E.1.

The majority of the sand dunes samples show over 90 percent of sand (63 to 900 microns) with low contents of silt (2 to 63 microns) and clay (0.1 to 2 microns). In some sands on active hummocks near the sea there is over 5 % clay which suggests fine materials blowing off the sabkha. The alluvial origin of other sediments is characterised by high silt contents, often over 30%. The ancient sand sheets have variable silt contents probably due to additions of airborne dust in the past.

The statistical analyses show broadly comparable results with the dry sieved sediments. Many of the sediments show positive skewness reflecting the presence of very fine materials, and only some active dunes and sand sheets are negatively skewed. Distribution curves have been calculated from the laser granulometry data and presented for a series of transects in Appendix E, Figures E.1 to E.7

Beit al Faqih Section (Figure E.1-A and -B).

The Beit al Faqih section was described in a quarry cut into a stabilised ancient sand ridge with active sands on the crest. The sequence is at least 9 meters thick. An active sand drift overlies weakly stabilised recent hummock sands and an older sequence of sands with eroded coarse and fine particles. The analysis shows that the modern sands are coarser and better sorted than the layers below, whilst the layer with eroded materials has appreciable silt and clay accumulation and has a mode which matches that of the underlying layers. In the lower layers the sediments represent the ancient sand ridge dune surface with a stabilised soil overlying softer sand. The analysis shows that silt and clay content decreases with depth.

Mujaylis Transect (Figure E.2)

The particle size distribution curve of four aeolian sand samples studied from the Mujaylis area of Wadi Zabid. Sample R24 and R22 lie on the slip face and crest respectively of a parabolic dune that is burying date palms. The slip face is composed of finer sand than the crest. Other samples are from recent and ancient carbonate cemented aeolianites that occur close to the sea, 1 km from the parabolic dune, and suggest that coarser and comparatively poorer sorted sands of the aeolian sediments occur closer to the sea and sand source.

Ta'if - Duraywimi Transect (Figure E.3).

This describes the particle size distribution curves of four aeolian sand samples, collected along a transect from the beach at At Ta'if inland towards Duraywimi. They comprise an active sand hummock located 100m inland of the beach; a transverse dune overlying ancient sand plain, a two kilometers inland, a barchan dune advancing onto dates at Qaza village, about 5 kms from the sea, and a barchan closing on agricultural lands at Sawlah, 16 km from the sea. The results suggest that the modal diameter of sand grains rapidly decreases inland, from 316 microns (1. 9 Phi) at the coast to 127 microns (3. 0 Phi) at Sawlah.

Salif Dunes (Figures E.4- A and -B).

The sand dunes in the bay south of Salif peninsula include shelly beach sand sands forming parabolic and barchan dunes with darker sands, largely comprising heavy minerals, forming linear seif dunes. The barchans are slightly coarser grained than the seif dunes. Further south, poorly sorted beach sands pass into sand hummocks stabilised by *Halopyrum mucronatum*. These move inland past eroding sand hummocks that in turn abruptly overlie a soil developed on the ancient aeolian sand plain formation. The modern sands are similar to the barchan and seif dunes to the north with strongly unimodal fine to medium sands, whereas the older sands show almost 20 % silt and clay accumulation and significantly, a much finer modal sand size of around 200 microns. This suggests that the sand fractions of the older aeolian formation accumulated at some distance inland from the source area, assuming they were derived from beaches.

Luhayyah - Wadi Mawr-Ad Dawmah Transect (Figure E.5).

This compares three samples collected in the northern part of the Tihama. They include: a unimodal sand from a sand hummock on the coastal plain due east of Luhayyah with almost 44% of silt and clay, whose origin at present is not exactly determined, but it may be that fine sediments encased in salts are being deflated from the mangrove mudflats to the west; an active sand sheet that appears to be developed from cultivation of an ancient sand ridge in the Ad Dawmah area, and shows a broad unimodal peak of coarse to very fine sand; and a sand sheet encroaching onto rainfed farmland on the south side of Wadi Mawr. The latter shows a bimodal distribution, which is unusual in the Tihama aeolian sands, but characteristic of sand sheets described elsewhere (Pye and Tsoar, 1990).

Luhayyah Dunes (Figure E.6).

The analysis shows the particle size distribution curves for three samples from a section in a stabilised ancient sand dune on the coast at Luhayyah. The surface samples (0-30 and 30-90 cm) show unimodal distribution at around 200 microns, with significant silt and clay. The lower horizon (90-150) shows a peak with coarser sand and a secondary peak with accumulation of silt, and may represent a buried soil.

Mutaynah Dunes (Figure E.7).

The sample is located on the crest of a parabolic coastal dune at Mutaynah, Wadi Zabid. The analysed sand has a distinctive unimodal distribution mainly of medium sand with a modal peak at 1. 5 phi (0. 35 mm). The sample has 99. 44 % sand (4.0 to -1.0 phi). Analysis of the data in the long 'tail' of the curve shows that minute increments of silt and clay occur down to 9.0 phi (2 microns). From 9.0 to 13. 2 phi there is almost no clay present and the trace is flat. The finer materials on coastal dunes suggest that fine sorting is accomplished further inland than on the coast. The dunes are partly covered by stabilising vegetation, mostly *Odyssea mucronata.*

Implications for Sand Stabilisation.

The laser granulometry provides precise data on the particle size distributions for each type of sand dune and this information greatly assists in determining the optimum techniques for sand stabilisation. Each of the areas described above will require a slightly different management technique for sand stabilisation, according to grain sizes and the amount of fine materials present..

Where sand grains are aggregated into larger particles by faecal pellets on hummocks there is considerable potential for soil improvement in the down-wind areas as dunes forming from deflated hummocks will still contain much of this aggregated material. With adoption of checkerboard techniques and use of appropriate drought resistant plants the organic matter can be put to use to ameliorate the sands.

In coastal areas which have water resources and scope for irrigation it is recommended that salt tolerant colonising grasses (*Halopyrum mucronatum, Odyssea macronata*), trees *(Tamerix aphylla)*, and shrubs (*Sueada spp)* are planted on the coarse sands of accreting foredunes, resulting in hummock formation and deposition of nutrient bearing silt and clay.

In transects from the coast into interior, such as shown in the Taif - Durawimi transect, the precise particle size distributions of the laser granulometry show that dunes decrease in grain size from the coast. Where these are threatening agricultural lands inland the dunes will be moved by lighter winds than on the coast since the smaller sized grains will have lower threshold velocities for movement. This is borne out by wind speed records and recorded movements of sand in the Tihama.

In some area the analytical data from laser granulometry indicates that certain modern sands have very similar particle size determinations when compared with adjacent older dunes. This suggests that erosion and deflation is taking place on a local scale. The reasons for this may be due to ploughing up of the fine sands of the old dunes for rainfed cropping resulting in loss of soil structure and susceptibility to wind erosion. In these areas it will be necessary to create a checkerboard system to create windbreaks along the dunes. In general much of the lands under rainfed agriculture lack vegetative barriers that would reduce wind speeds and their ability to move sands.

The laser granulometry shows that the underlying sands of the ancient dunes (below the paleosol that occurs at the boundary of ancient and modern sands) have a high percentage of sand and few fine materials. Where quarrying of older sands is being conducted a process of destabilisation of the older sands is under way, and their remobilisation by wind. In such locations measures should be taken to afforest or fence off quarry areas so as to reduce re-mobilisation of unstabilised sands that occur below the surface paleosol. Care should be taken to protect the paleosol layer as it acts as a protective mulch.

3.7.3 Results from X-Ray Diffraction Analysis of Sand Samples

Analytical Results.

The analyses has provided an explanation of the mineral content of nine sand samples. The samples include fresh sediments from rivers entering the Tihama (Sample No. R2), those of the coastal dunes (R17, R29), those from sand dunes in the interior areas (R44, R50) and from ancient aeolian sand dunes (R41, R43). These all show very similar x-ray diffraction analyses and suggest that they have a common sediment source of alluvial materials being brought down by wadis into the Tihama. The common minerals include quartz, feldspars, calcite and pyroxenes, with traces of chlorite, micas, and amphiboles. These are present as fragments of individual minerals and rocks comprising several minerals.

The dark dunes of the Salif area (R76) are particularly rich in amphiboles and pyroxenes, probably derived from fresh unweathered sediments, and are similar to those seen in the Wadi Surdud river bed. These sediments have been sorted by coastal processes, in the vicinity of the mouth of the Wadi Surdud, to produce concentrations of the heavier minerals.

Implications for Sand Stabilisation.

The x-ray diffraction results show that throughout the Tihama there is a similar range of minerals in the sandy sediments. Whereas aeolian sediments, in for example central Saudi Arabia, are composed mainly of iron stained quartz grains, the Tihama sands are quite different with fragments of minerals and rocks. These will provide colonising plants with an abundant supply of nutrients. Micropores in the rock fragments and mineral grains will trap soil moisture and raise the water holding capacity of the sands.

3.7.4 Results from Scanning Electron Microscope (SEM) Study of Sand Grains

Analytical Results.

A range of sand grains were studied under the scanning electron microscope with a view towards characterising surface features and establishing their elemental and mineral composition. Surface features on sand grains, particularly quartz, can provide a clear indication of the origin and environmental history of the grain. X-ray bombardment of grain surfaces and individual crystals provided an analysis of major elements present. These were then related to grain characteristics and features to provide an identification of types of minerals and any surface coatings present. The two examples below illustrate the difference between ancient and active aeolian sands.

Ad Dawmah Area Ancient Sand Dunes (Figure E.8).

The sand particle (sample R 98) was a sub-rounded grain of quartz with yellow staining, from a stabilised ancient aeolian sand ridge. The SEM showed secondary crystal growth and coatings on the surface. Dispersive X-Ray elemental qualitative analysis on the SEM shows the high peaks of Si and O for the quartz grain, and suggests that clay mineral and oxides dust coatings are present. The latter are given by peaks in Al, K, Fe, Mg and Ti. In addition, there is secondary carbonate on the surface (Ca, C, O) and some accumulation of airborne salts (Na Cl).

Ta'if, Wadi Rumman Active Sand Hummock (Figure E.9).

This is a subrounded grain of clear quartz, from a sand hummock 100 m from the sea at At Ta'if (sample R52, site M179. The S.E.M. shows that there are no obvious coatings, and an absence of late-grain breakages indicative of aeolian abrasion. The dispersive X-ray elemental analysis shows high peaks of Si and O, for the quartz. Secondary small peaks of Ca, Al, Mg, Cl, and Na are most likely due to small quantities on the surface of biogenic shell fragments and salts acquired from wind-borne spray off the sea.

Summary of Results from Transects from the Coast to the Interior.

Sands on an active sand hummock on the sabkha fringe terrain south of Hodeidah show large gypsum and halite crystals, that are also present as infillings of cavities in quartz grains. These are thought typical of a coastal environment high in soluble salts.

On an active sand hummock on the beach in the At Ta'if area there are rounded grains with carbonate coatings. These may be oolitic grains formed in shallow marine waters, with later secondary growth on surface. The quartz grains have salt coatings showed absence of late-grain breakages from aeolian collisions.

Parabolic dune crests on the coast at Mutaynah however have sands with rounded to angular grains showing the effects of aeolian abrasion. There are no obvious secondary coatings on grains, which are generally fresh looking and similar in appearance to those of the river sediments of Wadi Surdud. This suggests that there is rapid transportation from the sea onto the dunes without accretion of salts on a sabkha.

On an active barchan dune at Sawlah some 15 kms further inland, the sand grains have sub-rounded features typical aeolian abrasion, and show presence of clay mineral and oxide coatings, with iron, aluminium, potassium. It is thought that the grains may include older sands being re-worked. Surprisingly there are fresh grains of mica, suggesting that transportation from coastal sources does not necessarily break down this fragile mineral. Salts are also present as NaCL in cavities of mineral grains.

By comparison the sediments from the ancient aeolian dunes near Qutay, which have been stabilised by soil formation in the past, show rounded grains of quartz with thick clay mineral and iron oxide coatings, indicated by high Fe, Al, K, Mg and Ti. On a similar ancient linear dune ridge north east of Mansuriyah subrounded grains of quartz and feldspars have thick coatings of clay minerals and iron oxides. Crystals of NaCL (halite) suggest that airborne salts have been moved down the profile by moisture and crystallized out.

An alluvial sediment on a sand bar in the Wadi Surdud shows fresh grains with angular fractures caused by recent transportation in a river bed. There are no secondary crystals or coatings.

Implications for Sand Stabilisation.

The scanning electron microscopy examinations are useful in determining the shape of sand grains and the nature of the pores, cracks and coatings on grains. The elemental analyser is then able to carry out, as in this case, qualitative determinations of the types of the chemical composition of these grains and the coatings. These show that there are secondary accumulations of soluble salts, often halite and or gypsum, as well as clay minerals and various oxides. A knowledge of the presence of these minerals is important in planning a programme for future plant growth on the sands, and the results show that there are substantial reserves of plant nutrients available as coatings or within mineral and rock fragments that are making up the various sand fractions.

The soils developed on the ancient dune sands are particularly well endowed with a range of nutrients (considered to be the result of long periods of accumulation from airborne dust) and establishment by plants will be comparatively easy on these sands. In contrast the modern active sands of the interior plains have almost no secondary coatings of clay minerals and soluble salts. Because these sand grains comprise a mixture of quartz and rock fragments there is potential for providing nutrients to plants if sand stabilisation measures include techniques for improving moisture availability, structure and organic matter in sandy soils.

The present study provides an introduction to this method of investigation. There is very considerable potential to enlarge the scope of the studies further which will provide benefits to sand stabilisation. These may include, for example: the effects of salt weathering on the disintegration of rock fragment sand grains along the coast and their subsequent movement inland; the nature of micropores in mineral grains and their role in storing moisture in modern and ancient sands; the quantitative analysis of secondary coatings and their role as nutrients for plant growth; the rate at which secondary coatings are accumulating in stabilised sands and hummocks.

3.7.5 Geochemical Analysis: Results from Acid Soluble Analysis.

Analytical Results

Concentrations were measured by inductively-coupled plasma spectrometry (ICP) on filtered solutions derived from heating a sand sample with hydrochloric acid. The results show the range of elemental compositions for different groups of sand samples. No statistical work has been carried out on these analysis but the following observations can be made which support observations made in the field and in other determinations.

Low values of silicon and high calcium near the coast generally appear to reflect the presence of coarser shell materials in coastal areas. Inland, calcium declines as calcium carbonate decreases and silicon becomes the more dominant constituent of the sands, either as quartz or as components of silicate minerals. Values for magnesium, manganese, iron, zinc and aluminium have similar concentrations throughout the area as they reflect the ubiquity of alumino-silicate minerals and rock fragments in the Tihama sands. Values for sodium, a constituent of soluble salts and feldspar minerals show higher values near the coast.

Implications for Sand Stabilisation.

The acid soluble analyses provide a total analysis of the elemental composition of sand sediments. These can be compared with the results of the x-ray diffraction work and show similar differences between the coastal and interior dunes. The analyses indicate the total levels of elements and nutrient availability that exist in the samples, and suggest that there are no major deficiencies which may need correcting to benefit plant growth. High levels of calcium in some of the coastal sands may reduce uptake of magnesium.

3.7.6 Geochemical Analysis: Results from Water Soluble Analysis.

Analytical Results.

The water soluble concentrations were measured by inductively-coupled plasma spectrometry (ICP) on centrifuged and filtered solutions derived from sand sample mixed with de-ionised water. The results show the range of elemental compositions for different groups of sand samples. No statistical analysis has been carried out on these analysis but the following observations can be made which support observations made in the field and in other determinations.

Levels of soluble Sodium and Chloride reflect higher concentrations of soluble salts (halite) near the coast, but it is apparent that salts are also blown inland. Sodium is also a constituent of clay minerals that are present as airborne dust. High levels of SO4 in some coastal areas reflect deposition of gypsum in these areas, and a general low level of incidence inland. Levels of soluble Zinc Manganese and Iron are all low and have a slight variation through the area. Aluminium reflecting clay minerals in fines, has moderate levels in most coastal and inland areas, but is notably very low in some coastal zones in beach deposits. Levels of Bromine, a constituent of sea water, are predictably higher at the coast but decline inland. Levels for Nitrate NO3 are generally low.

Implications for Sand Stabilisation.

The water soluble determinations provide an indication of the nutrients that can be readily available to plants in these sands. Soluble salts, such as sodium chloride, have elevated levels in coastal areas but would be reduced if the sand stabilisation programme includes irrigation. Since there is a continuous supply of salts in spray laden winds being driven onshore the reclamation process has to be maintained.

3.7.7 Results from Determination of CaCO3 in Sands.

Analytical Results.

The results of the determinations of CaCO3 equivalents suggest that in the majority of cases looked at the CaCO3 equivalent decreases inland with distance from the sea. The samples taken between At Taif and Sawlah show a decrease from 15.84 to 0.69% in the active dunes. This may be attributed to the crushing effects that take place as sand grains are saltated, rolled and wind abraded by other particles as they move inland from the coast. It is thought that much of this abrasion and loss of calcium carbonate as fine dust occurs close to the coast. Very low values occurring on a paleosol developed on ancient dunes inland at Beit al Faqih (sample R41) suggest that carbonate has been leached during soil formation on these dunes. Low values also occur such as on active dunes at Luhayyah near the coast and inland at Ad Dawmah area.

Implications for Sand Stabilisation.

The particle size analysis shows significantly higher amounts of non-sandy fine materials, that is silt and clay, existing in the older sands compared to the active sands. A certain amount of this will be as fine particles of calcium carbonate deposited as dust on sandy surfaces and these may explain the high anomalies in some of the geochemical analyses. The low CaCO3 values such as on some active dunes near the coast and inland on older dunes suggest that the modern dunes in these location are derived from sands that are depleted in calcium carbonate, such as the older dune sediments.

The presence of fine carbonate, whether fairly close to the coast or far inland, will generally have beneficial effects on sand stabilisation. The carbonates will provide storage for soil water and a medium for plants to root in, all aiding in soil formation, aggregate stability and reduction of sand movement.

The microcrystalline development of calcium carbonate around grains to form hard aeolianites in coastal areas poses a management problem if these layers become exposed at the surface since they act as barrier to plant establishment. Inland, there is a development of isolated calcium carbonate concretions along former plant roots in the ancient sand dunes. These are not thought to be forming at present. There does appear to be any laminar crusts (calcrete) which would reduce root penetration.

3.7.8 Results from Thin Section Analysis of Intact Sand Samples.

Analytical Results.

The thin section results are given in Table E.7. Six samples were impregnated in resin and ground down to a thickness suitable for examination under a polarizing microscope.

Aeolinaite samples on the coast were examined from the Fazzah, Mujaylis and Salif areas. The Fazzah sample shows a finely stratified sandy deposit with subangular to well rounded grains of Quartz, Opaques & Carbonate. $CaCO_3$ on rims of grains lightly cementing sediment. In the Mujaylis area recent and ancient aeolianites show similar features with subangular to rounded grains of Quartz, Pyroxene, Opaques, FeOxide, Carbonate fragments and rock fragments with $CaCO_3$ on grain rims cementing sands. The Salif sections are similar but have weaker caCO3 cements on rims.

Concretions in soil formed in ancient aeolian sand, from Luhayyah at the coast, showed rounded grains of Quartz, Opaques and Fe-oxides with large clasts of microcrystalline carbonate. $CaCO_3$ on grain rims appear to be from an earlier phase of development.

Inland, to the NE of Mansuriyah, concretions from ancient aeolian sands were sampled 5m below the surface in a gully cut into the aeolian sands. This showed subangular to rounded grains of Quartz, Pyroxene, and Opaques with $CaCO_3$ rims around grains and irregular patches of calcrete. There are also root channel features.

Implications for Sand Stabilisation.

The thin section investigations show that cementation of sand formations is largely by microcystalline calcium carbonate though the degree of hardness of cementation varies. These have variable consequences for stabilising sand formations.

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Implications for Sand Stabilisation.

The thin section investigations show that cementation of sand formations is largely by microcystalline calcium carbonate though the degree of hardness of cementation varies. These have variable consequences for stabilising sand formations.

In the coastal areas where the aeolianites occur on older sand dunes and also on apparently recent hummocks there is a strong cement of CaC03, for example at Mujaylis. Loose sand is moving inland over such dunes as a thin veneer and wind abrasion has exposed the aeolianites in many areas. Thus there is no stabilising of the sands such as occurs in coastal parabolics.

The presence of aeolianites on recent sand hummocks (as evidenced by plastic detritus in the layers) suggests that there is a widespread process occurring on the coast. This is probably taking place in the subsoil of the hummocks as carbonate minerals in the sea spray crystallize out. Loss of vegetation, whether by human interference or natural processes is not clear, leads to exposure of these hard layers at the surface.

Under such conditions, and with the additional factor of high levels of soluble salts in the coastal zone, these are now very difficult substrates for colonising plants to take root in. The challenge for a future sand stabilisation programme in such an environment will be to create a rooting zone for suitable plants to develop and permit re-development of an overlying foredune and a permanent vegetation cover.

In the interior areas the soil concretions appear to represent earlier periods of soil stabilisation on aeolian sands and occur in a range of sizes. The thin section studies assist in determining the history of these ancient dunes. The upper part of the soil on the ancient dunes has a degree of crusting from carbonates and this has led to a stable surface. The lower parts of the sands, in which the concretions occur, lack this cementation. A characteristic dendritic drainage pattern has been formed on the convex ridges of the old dunes, and rilling and gullying (for reasons that are not clear) have cut through the surface crusting into the unstable sands below. Deep gullies are now common and sand is washed out onto adjacent fields.

3.7.9 Grain Size and Wind Speed

Analytical Results.

Preliminary work on the wind speeds and directions shows that wind directions are multiple, with winds possible from most parts of the compass. This is especially the case inland. On the coast the wind directions are usually related to the two main monsoon directions, with winds from the south west and north west. As a general observation wind speeds are greater on the coast and decrease inland.

Implications for Sand Stabilisation.

The significance of these higher wind speeds near the coast is that they facilitate transport of the coarse and fine grained sand grains. The coarse grains require higher threshold velocities for movement to be initiated and these higher wind velocities appear to be limited to the coastal strip.

Inland however, coarse grains are not transported since the threshold velocities that are normally reached will only move finer grained sands. Under exceptionally strong winds coarser grains will be moved.

Because of the multi-directional nature of winds over much of the interior lands of the Tihama, the establishment of physical windbreaks to create roughness and reduce wind velocities must be designed so as to cope with these conditions. It will be of little use to construct fences that only protect against one wind direction. For this reason the checkerboard system of fencing is recommended for adoption throughout the Tihama.

A complete investigation of the local conditions, particularly for wind speeds and direction is important in the preparing a management plan for any one area. Other elements such as aspect, the nature of the sediment source, the energy level along local coastlines in relation to supplying sands onshore, the topography of active and ancient dunes and other physiographic features and their effect of wind speeds, the land cover and the land use should also be assessed at each site prior to establishing stabilisation measures.

The present study has concluded that these site conditions play a central role in the origins, presence and stability of aeolian features. There are no simple rules for sand control that can be applied right across the Tihama. The TDA has considerable raw data on wind speeds and directions which has not yet been analysed. It is hoped to provide a suitable software programme to study this archive. At the same time climatic stations need to be established to provide a network of wind data in the major parts of the Tihama.

4 REGIONAL ASSESSMENTS OF AEOLIAN SAND MOVEMENT AND IMPACTS ON LAND USE.

4.1 AREA NORTH OF WADI SURDUD TO THE SAUDI ARABIAN BORDER.

The present survey was conducted to the latitude of Buhays and Shafar (approximately 16°00' North). North of this, as far as the Saudi border, it is understood that there are old sand plains and active sand sheets similar to those that lie between Buhays and the Wadi Mawr.

Over much of the area ancient sand plains occupy the coastal plain, to within a few kilometres of the Red Sea, and form flat to gently undulating lands between the main wadi channels, with *Acacia tortilis, Acacia ehrenbergiana* and *Cadaba rotundifolia*. A number of prominent sand ridges, former dunes in the ancient aeolian land system, extend eastwards towards the escarpment, and in several cases these ridges cross the road and reach the mountain front. In the western parts of the sand plains these ridges appear to be stable features. As is common close to the coast they support halophytic vegetation, and also *Panicum turgidum* grasses, and have a loose cover of mobile sand sheets. On the sand plains slightly saline groundwater occurs at depths of some 16 metres and supports a largely pastoral population that grows millet and other crops in response to rainfall events.

Closer to the mountain front, and with increasing rainfall, the sand ridges are annually cultivated for millet, and this is leading to disruption of the soils developed on the old sandplains. The surface of the ancient dune ridges has a smooth surface with a polygonal cracking network in the sands. A loose layer of active sands overlie this but may be absent where winds and water have stripped off the loose materials. The underlying soils have moderate silt and clay content (see analyses R 96 and R 98 Table E. 1) and when disturbed by ploughing are susceptible to wind erosion. The loss of silt and clay from these soils will be reflected in lower crop yields as essential nutrients are deflated and blown further inland.

In terms of the modern aeolian sand cover, almost all of the northern coastline in this zone has low energy beaches with mangrove forest formations as extensive fringes to the coast. These limit the landward movement of sandy sediments. Where there are breaks in the mangrove fringe, there is a greater source of sand and dunes are moving inland as low sand sheets which are largely stabilised by halophytic vegetation. Some sands may originate from blow-outs from the wadi channels but it was not possible to investigate this.

North of the Wadi Abbas at least one major belt of 2 m high barchans and transverse dunes is moving, in summer, towards the east and south and is overwhelming agricultural fields. The winter direction of these dunes, as seen from slip faces, is towards the NNW. (See analyses R 95, Table E.1; and R97, Table D.1 for these active sands).

It should be noted however that although fields are seen within ten kilometres of the coast, between Buhays and Wadi Abbas, there is only a low chance of rainfall in these areas and the fields reflect periodic high rainfall years.

Further east, along the course of the Wadi Al Qawr and towards Ad Dawmah there is irrigated agriculture from groundwaters. This area is important for mangoes and other field crops. Drifting sand from the same active sand sheets is steadily moving north-eastwards from the coastal areas and threatens fields. Where the active sands overlie the old sand ridges the clay and silt content is low (see analysis R99 , Table E.1) and, if these have originated from the older dunes, there has been considerable loss of finer materials during deflation.

There is reported to be an increasing problem of drifting sands in this area, and in terms of the means being taken to stabilise sands there is a demonstrable lack of shelter belts or other techniques to limit rapid movement of sands. Locally there are fences, made of crop residues, which have been placed along field boundaries to entrap sands. Annual cropping is unlikely where these occur in the marginal areas of erratic and low rainfall, and fences may have been placed in the hope of limiting sand cover over fields until the rains return. In the higher rainfall areas however, and along the margins of the irrigated lands, it is felt that far more effort could be made to plant shelter belts which would reduce wind speeds and halt sand movement

Between the Wadi Surdud and Wadi Mawr is a large area where the ancient sand plains in this area do not have such extensive belts of mobile sand dunes as occur further south, but significant problems exist locally around villages where sands are blowing inland. In addition, transverse dunes blow over the main road at several locations. The ancient sand ridges form low features and actively moving sands appear to be concentrated along these features.

4.2 SALIF AREA.

The Salif peninsula provides an excellent study area for a variety of sand dunes that are forming immediately inland of the beaches. The aeolian processes and landforms in this area have been described in Chapter 2. This area has a high energy coastline and a long fetch uninterrupted by offshore bars and reefs. Both shelly and heavier black sands form sand hummock, foredunes, barchans and seifs. These move across the peninsula and re-enter the sea to the north. They do not affect any agriculture, as there is none in this area, but they cause serious disruption to the main road to the port and oil installations necessitating a year round clearing programme, as described below.

On average the contractor, using a grader with blade to clear drifting sand and dunes, spends about one day per week during summer (May to December) when north-westerly winds are blowing. During winter (December to May) however, clearance is carried out every day, when strong winds are blowing from a south-westerly direction

4.3 NORTH AND EAST OF HODEIDAH, BAJIL AND SOUTHERN MARGINS OF W. SAHIM.

This region lies within the Tihama Environment Protection Project (TEPP), and includes a vast extent of ancient sand plains and undulating sand ridges which are largely covered by mobile sand sheets and sand dunes. The dunes include barchans and seifs, but are principally extensive complex chains of transverse dunes that alternately move to the south-east or north-east depending on the seasonal wind direction. The resultant sand drift direction appears to be slightly north of east.

Sand movement in this area poses major problems to agricultural land use, factories, residential complexes and villages, and along the road and track communication routes.

Major efforts have been made by numerous private companies to protect their factories, often with successful results. Others, in the absence of shelterbelts, have been overwhelmed by dunes. Along the main roads there is daily monitoring and control of drifting sands by the highway authorities but, at present, removal of sand is given more attention than trying to halt dune movement across highways. In remote rural areas however the tracks are frequently blocked by sand sheets and dunes, necessitating lengthy detours. At the same time, fields are buried by drifting sands.

The TDA is carrying out sand stabilisation programmes in many parts of this area and these are reported in the following chapter. This work includes stabilisation plans on the sand plains of the interior, the margins of the sand plains with the silty alluvial plains of the Wadi Siham, along the main road, and along the fringes of Hodeidah as a continuous shelter belt.

Some of these rural areas, lying to the north of the main road and where rainfall is marginal for rainfed agriculture, are to be targeted by the TEPP. Others, outside the present programme will hopefully learn from the experience of their neighbours, but will largely have to carry out their own stabilisation works, with assistance from the TDA extension service.

4.4 COASTAL AREAS FROM HODEIDAH TO WADI ZABID.

South of Hodeidah the coastal zone is dominated, at present, by a series of coastal sabkha with mangrove patches. Up to ten kilometres offshore there are sandy bars with recurved spits with northward and southwards accumulation of sands. Onshore movement of sands is generally slight in this area, but is locally significant where there are gaps in the mangrove belts and where sandy beaches occur on the seaward edge of the sabkha. In these areas sand hummocks and foredunes form and merge into dune fields inland.

Immediately south of the airport, sand hummocks pass into a broad foredune ridge that lies parallel to the shore with *Odyssea mucronatum* grass as the principal stabilising plant. Survey beacons concreted on the top of the dune in the early 1970s have been locally damaged by deflation, but the dunes do appear to have grown any higher, and local people also said they were the same shape.

Significantly, there is greater protection of the hummocks around the airport where the land is fenced and entry prohibited for livestock and fuelwood collection. Inside the perimeter fence the hummocky terrain has been stabilised by *Suaeda spp* on mounds that are 2 to 3 m high and often 4 m across. Outside, in the common lands, almost all of the vegetation has been stripped off, and the hummocks are bare, subject to sand blasting by winds with increased deflation of sand and the underlying silts.

Along the mouth of the Wadi Siham, where floods rarely reach the sea, the hummocks and coastal foredune areas are also poorly vegetated and sand movement in this area causes additional deflation of silt.

Between the Wadi Siham and Wadi Rumman active and ancient foredunes occur along the shore. Sands are blowing inland from the sabkha plain and initiate the dune fields that stretch north-eastwards to threaten the Kulzam and Shalamah areas and also drift into Durayhimi town during the summer months. The sequence of aeolian landforms developed on the coast here has been described in Chapter 2.

As to why there is a considerable quantity of sand coming ashore at this rather narrow (3 km broad) strip, the answer may be partly explained by the presence of a sandy fan on the sabkha plain. This occurs on the seaward margin of the Wadi Rumman, where alluvial fans appear to have been washed into lagoonal areas during floods. If so, then sands are being rapidly re-cycled from sandy alluvium (probably themselves mostly of aeolian origin) back into dunes. Detailed studies would be required in this area to fully document processes at work.

South of the Wadi Rumman, an extensive belt of coastal dunes occupies 30 km along the coast from At Tai'if to the Wadi Zabid valley. At Al Ta'if sand hummocks merge inland into transverse dunes and overlie an older sequence of the ancient sand sheets (see Chapter 2 for details of the sequence). Further south, the dune forms include linear coastal parabolic and barchan dunes that merge 1 - 5 km inland into either dome-shaped landforms overlain by transverse dunes and hummocks, or transverse dune fields. There is an abrupt change from the coastal features into the regular pattern of transverse ridges. Extensive sand bars lie parallel to the coast in this zone and appear to supply sands to nourish the coastal barchans after the sands traverse a sabkha plain.

4.5 MANSURIYAH, BEIT AL FAQIH AND HUSSANIYAH AREAS.

This extensive region forms the eastern margin of the ancient sand sheets from Wadi Zabid to the Sana'a road. Aeolian landform features noticed in this area are similar to those all along the edge of the old sand plains. The topography comprises rounded linear ridges of old dunes, now stabilised by soils. Erosion on the stabilised dune ridges has formed a dendritic drainage system and sandy fans accumulate in the 1 - 2 km wide inter-dune valleys, where they become active as sand sheets.

Rainfed agriculture on the dunes and valleys is widely practised, up to the limit of available moisture which lies towards the west. Disruption of the stabilised soils of the ancient sand plain by farming practices causes a certain amount of deflation, but most sand movement is thought to be due to the eastwards movement of more recent sand sheets and transverse dunes.

The active dunes and sand sheets now threaten large areas of the stabilised dune landforms. Sands also drift through and around the villages, which lie on the sand ridges. There are a few shelterbelts of *Acacia ehrenbergiana* woodland on the sand ridges, often around villages, but much of this landscape is very poor in natural windbreaks. Similarly, there are few attempts to grow new windbreaks as trees are thought to bring increased attack of crops by birds. Farmers also will almost never conserve the millet stalks in the ground to help stabilise the dunes. Perennial grasses and herbs have little opportunity to mature. Thus, there is increased movement of sands in this large area and, increasingly, this will not just encroach onto the remaining sandy lands that are at present free of mobile sands but move further eastwards onto the alluvial silts; locally this is occurring. This therefore is a key area to carry out sand stabilisation works in the future and successful implementation in the lands to the north of Mansuriyah (see Section 4.3 above) will provide models for copying elsewhere. In the meantime, TDA extension workers should advise land users in this area on suitable methods for windbreaks and stabilising sands.

4.6 WADI RIMAH AND WADI ZABID.

Both Wadi Rimah and the Wadi Zabid valleys are bounded on their northern and southern edges by sand seas with extensive belts of mobile sand dunes and sand sheets. These active dunes are considered to have originated along the coast at several foredune and parabolic dune accumulation areas, and have steadily moved in an overall eastwards and north-eastwards direction, towards the escarpment. Based on present annual rates of 10 metres per year for dune movement, this encroachment has taken a long time, probably well over two thousand years, for those dunes which have moved the farthest distance from the sea.

It has also been long recognised that the dunes and sand sheets are increasingly threatening the farmlands on the alluvial soils of these valleys. Transverse dunes composed of unimodal fine sand steadily move into the valleys. On the north side of the valleys the main period of dune movement is during summer when dunes move to the south-east. This results in sand dune threatening the farmlands on the northern flanks, whilst on the southern flanks of the valley there is a beneficial trend of sands being blown out of the valleys. In winter this situation is reversed, when the strong south-south-westerly winds move sands onto the southern borders of the valleys, whilst removing them from the north. This simplified pattern is upset by other modifying wind directions, such as diurnal changes with sea and land breezes (Williams, 1979).

A degree of equilibrium has been reached between these sand movements and the occurrence of seasonal floods along the wadis, that clear channels blocked by sand dunes and sand sheets, which has led to the preservation of irrigated agriculture in the valleys. If flooding and irrigation decreases in any major way then sand encroachment will increase and bury many fields in both valleys. At present this is the danger on the southern flanks of the Wadi Rimah and Wadi Zabid.

In the Wadi Rimah the southern flanks in particular are threatened by transverse dune ridges and parabolics that are moving over the irrigated farmlands and thickets of *Salvadora persica*. As reported earlier in Chapter 2, proposals for sand dune stabilisation were implemented as part of the World Bank funded Wadi Rimah Project in the late 1970s. However, it appears that only farm shelterbelts were initiated in parts of the Wadi Rimah and nothing was done to halt dune migration into the oasis. A comparison of aerial photography shows that the *Salvadora* natural vegetation along the margin of Wadi Rimah has greatly decreased since the 1970s, but the exact reasons for this, drought or clear felling, are not clear. This is a key area for urgent works.

Detailed proposals for coastal stabilisation, put forward in the 1979 study, were only partly implemented in the Mujaylis oasis, where the village is now largely protected. The problem of drifting sand actually on the coast at Wadi Zabid was not tackled. Further east, in the Wadi Zabid, a sand stabilisation belt was later planted along the line of the road from Tuhaytah to Zabid, and although these have partly halted dune movement south into Wadi Zabid the road was abandoned for general use.

Along the western edge of the Wadi Zabid sand movement onshore is also significant, and barchan dunes (R12) are generated from coastal sand sheets (R14, R16) coming ashore at Ras al Hisy, a prominent cuspate foreland that shows southerly accretion of sands along ridges. These dunes threaten the date palms to the east of Mutayna and the Suwayq areas, and successful efforts have been made by farmers here to reduce sand movement into the date palms by creating foredunes with brushwood fences, and limiting the cutting of *Sueada* bushes that form on the sand hummocks. However, even in such areas where the value of the vegetative cover appears to have been recognised, examples were observed of large areas of *Sueada* being clear cut close to active dunes.

Almost the whole southern flank of the Wadi Zabid valley is threatened by dunes. A large area of silty soils is largely buried by barchans and transverse dunes up to 3 m high, and traces of old field boundaries, villages and mosques are common. The dune front now threatens villages such as Maghras where a war is waged against the steady north-eastwards movement of sand. The efforts of villagers have created foredunes around this and other villages. More assistance is now being given to this whole zone, as part of the IFAD-funded TEPP (see Chapter Five), with the aim of creating a shelterbelt along the southern margin of the Wadi Zabid: it will be a massive task however to show progress.

4.7 FROM WADI ZABID TO MOKHA.

This large area lying for the most outside the TEPP was investigated during several traverses made along the main roads and on tracks to Al Khawkah, to Al Mutayna, and to Yachtul and Mokha. South of Wadi Zabid there is an extensive ancient sand plain that is largely covered by a modern sand sea. The ancient sand plains appear to be truncated by the Wadi Rasyan and were not seen to extend further south, being replaced by gravelly alluvial plains that extend south of the Mokha - Taiz road.

The modern sands, with seasonal movement towards the north-east in winter and south-east in summer have extended their cover up to the whole length of the Wadi Zabid west of the main road, and cross the main road 15 km south of Hays. They also extend southwards over the wadi on the track to Al Khawkhah.

Along the coast there are coastal dune belts from Mutayna southwards to Qatabah, due west of Hays. These form along a high energy coast, with sandy beaches, coastal sand hummocks and parabolic dunes that that have long linear arms extending inland about one kilometre. From Al Khawkhah to Qatabah there are mangroves and lagoons along the coast, with well stabilised sand hummocks and only a few dunes. To the north of Qatabah the coastal parabolic dunes are well vegetated with *Odyssea mucronata* (site R11) and inland merge into hummocky terrain, suggesting that the supply of sand is limited.

North of the mouth of the Wadi Marir at Ras al Haymah the parabolic dune belt grows in width to three kilometres and is the principal feeder of sands to the Wadi Zabid. These parabolic dunes extend along some 16 km of coastline to Mutayna (samples R17, R18, R19). Inland, the sand hummocks (sample R4) merge into sand sheets and closer to the Wadi Zabid form extensive belts of transverse dunes (R 15). These active dunes overly plains formed on the ancient sand sheets.

Further south, in the middle parts of the Wadi Rasyan there is irrigated agriculture from groundwater and spate floods. Aeolian sands are of minor occurrence in this area, since only small quantities of aeolian sand are present, being derived from north-easterly movement from sand dunes along the coast north of Yachtul and from deflation out of the Wadi Rasyan.

The dunes north of Yachtul are isolated large coastal barchans, but inland these are replaced by hummock and shallow sand sheets. Sands from these areas eventually merge into the dunes that feed the sand sea south of the Wadi Zabid. Most of these lands are under rangeland with characteristic tussock grasses *Laiurus scindicus* and scattered *Acacia sp / Commiphora sp* woodland.

Along the Mokha to Taiz road there are sand sheets and low transverse dunes which in summer are crossing the road in an easterly direction. The sand source for these dunes (See analysis R 3, Table D.1) however is thought to be further south, along the coast to the south of Mokha, where dunes are blown inland by south-westerly winter winds. This appears to be a relatively recent aeolian advance, inland from the coast, for in this area the fringing reef offers limited protection to the shoreline and allows mangrove formation. Despite this, sand dunes are moving onshore on this high energy coast and obscuring the mangroves (Barratt et al, 1987). The precarious balance seen to exist here, between stabilised coast with mangrove formation and accreting dunes moving inland, demonstrates that many areas of the coastline are at risk if ecosystems are damaged or modified. Movement of these sands across the highway near Mokha presents a minor hazard to road conditions, but the occasionally a dune feature will advance up to the road, from either direction, and will need to be flattened by bulldozer.

5 ANALYSIS OF TDA SAND DUNE STABILISATION PROGRAMMES.

5.1 THE HODEIDAH "GREEN BELT".

5.1.1 The Proposed Route.

The Hodeidah "Green Belt" is part of an ambitious plan to stabilise sand and plant a shelterbelt to the east of the city. The project has been initiated at the northern and southern ends of its proposed route. The route of the "Green Belt" was originally planned to go straight through a large area of transverse dunes, in effect a sand sea, in a north-westerly direction, to the sewage works on the road north of Hodeidah. This would have entailed flattening sand dunes, putting up fences in a checkerboard system and then planting them with approved grasses, shrubs and trees with water supplied from the wells. The consultant after hearing of this proposal reported that a route straight through the dunes would lead to very severe problems in managing the stabilisation works. The loose sands would dry out over large areas and be difficult to moisten accept at a few points at any one time. In addition, changes in wind direction, perhaps from unusual directions could overwhelm the sand fences and the afforested areas struggling to grow. The cost of subsequent re-flattening sand dunes and possible re-planting would be very high. Keeping access tracks open in the deep sands would be a difficult task.

This proposal has subsequently been abandoned and a more practical and cheaper option initiated. This will involve the "Green Belt" route following approximately the southern and western limits of the transverse dune sand sea that lies to the east of Hodeidah. The belt will lie along the margin of the dunes and the underlying silts and stabilised soils developed on the old aeolian sand plain. Plants will root through the sands into the silt and sand deposits, where they will more securely anchored than if they were on deep mobile dunes. This is a common natural process in parts of semi-arid Arabia and Africa, whereby plants root through moistened drifting sand sheets onto a finer textured substrate. Access will be simple, along a trackway bordering the dunes, and the belt will have the purpose of providing a shelterbelt to protect the Hodeidah urban area to the west.

In this area, and also throughout the TEPP, it is being proposed (TDA, 1988) that the standard checkerboard system of palisading dunes prior to planting trees on dunes should be replaced by a system of L-shaped or even parallel fences. However, such methods are designed only for where there is a unidirectional wind (Kaul, 1985). In the Tihama, as discussed in Section 2.6, there are at least two wind directions, roughly from the north-west in summer and south-west in winter, as well as a host of minor wind directions. There can also be no doubt that the wind systems in the Tihama veer about with sudden frequency, and in the process of veering may well produce gusts in unexpected directions and result in stress on unprotected sands and planted areas.

Thus it is recommended that the standard checkerboard systems, as advocated by Kaul (1985), is the principal method to be employed by the TDA. In the long run this proven method with fences facing in four directions, will provide protection from the changing wind directions in the Tihama.

In certain areas where winds may be believed to be more unidirectional the parallel or L-shaped fence system could be adopted but it is suggested that this is only in areas where the failure of the system to slow down winds would lead to sand movement and burial of the plantations.

5.1.2 Existing Work on the "Green Belt" along the Sana'a Road.

The "Green Belt" to the east of Hodeidah has reached a length of 1.9 km and at present lies up against the transverse dunes that form an extensive sand sea northwards. Numerous trees and shrubs have been planted on this belt and there is good growth of species, which are irrigated from a tubewell drilled by the project. Planted species include: *Acacia themeda, Conocarpus lancifolia, Parkinsonia sp, Zizyphus spina-christi, Azadirachta indica*. A number of ornamental plants have also been planted. Various indigenous colonisers, such as *Dipterygium glaucum, Panicum turgidum, Indogofera indica, Aerva sp., Odyssea mucronata* , and *Propospis juliflora* have also started to invade and stabilise the generally shallow sand sheets that form the ground surface.

Despite the density of plants and the ground cover they protect, it is noticeable however that low barchan dunes, less than one metre high, are advancing over parts of the area (during summer from a westerly direction) and these are commencing to overwhelm the afforested plants. The reason for this is that no checkerboard system of fences was employed in this area, as it is considered only important when there are mobile dunes.

The field evidence shows however that even sand sheets will change in their level and bury plants where there is no protection from the wind. Since the "Green Belt" was established in this location sand sheets have evolved into low barchans and these may well grow in size.

In the south of Yemen, Costin et al (1974) observed that unprotected sand sheets can raise a 2 metre high dune within one year, but on protected sand sheets the level only varied by some 10 cm. The project is therefore recommended to establish simple checkerboard system across the whole area to reduce movement of the sand sheets to a minimum.

5.1.3 Existing "Green Belt" Work at the Sewage Ponds.

The Hodeidah sewage farm lies at the northern end of the "Green Belt" where afforestation has been underway for two years. This area has the advantage over the other end of the belt in that there is only a little drifting sand in the vicinity of the sewage ponds. Many of the planted species are growing well with the sewage effluent wastewater that is used for irrigation. This is not surprising as the effluent will provide benefits to the generally nutrient poor sandy substrate, and replace soluble salts present in these plains that lie close to the coast and sabkha conditions with a fertile growth medium.

Apart from the numerous tree species planted by TDA along the line of the belt, there are invasions from the multipurpose tree *Prosopis juliflora* which form extensive forests to the east and south. No attempt is made to pull out the roots of the seedlings of this plant and it could invade the whole belt, thus diminishing the results of the trials being conducted.

Although *Prosopis juliflora* (mesquite) is, and quite rightly so, regarded more as a weed in many areas adjacent to farmland, it is a fact that it is a most successful coloniser of sand dunes being able to exist in a wide range of soil conditions and quickly put out a broad canopy over the sands, in conditions of low moisture availability. The rapid spread of plant on sands causes wind speeds to drop dramatically and halt sand movement as threshold velocities are no longer achieved.

In the Preparation Reports for the TEPP the use of mesquite was included in the list of species for multipurpose uses. Since then its unregulated control into farmland in many areas has resulted in it being avoided for afforestation work, since windbreaks along farm boundaries would almost certainly result in it invading the fields. Elsewhere in Yemen, for example in the Wadi Hadhramaut, *Prosopis juliflora* has infested many farmlands after spreading out of afforestation areas. In other countries it is officially banned.

At present however *Prosopis juliflora* occupies very large swaths of land to the east of Hodeidah and has successfully stabilised areas of transverse dunes on the margin of the city. Whether this is by design or chance the mission was not able to discover but it is recommended that in areas remote from farmlands, such as the northern parts of the "Green Belt", the TDA study the practicalities and hazards of utilising *Prosopis juliflora* to stabilise sand dunes. Since the plant is so well established in the area already it may be prudent to include it in these lands.

5.1.4 The Next Phase of the "Green Belt".

On the "Green Belt" the next phase will be to initiate the joining up of the two nodes that have so far been planted. If the programme is seen more as the growth of a live shelterbelt along the margin of the dunes, designed to protect 'Greater Hodeidah' from drifting sands, rather than the earlier concept of a massive attempt at dune stabilisation through a sand sea, then it is believed it will be successful. The lessons learnt from this programme will help the TDA prepare a model that can be repeated elsewhere by Government or by other private operators planning schemes around factories, etc.

5.2 WADI SIHAM PROGRAMME

5.2.1 Qutay to Kilometre Sixteen.

This programme lies along and north of the main road to Sana'a. This entire area lies on undulating sand plains and sand ridges of the ancient sand formation. Active dunes and sand sheets are moving in an overall north-eastwards direction, the resultant of north-west and south-west winds. Sand dunes move across the main road at certain localities. Eight wells have been drilled by the TDA and this component is now ready to start in fourteen villages that have drifting sand problems. The project will provide irrigation water for shelterbelts around villages. These will be up to 150 m deep and be placed on sand sheets and sand dunes. At Damania village, where there is a new TDA well, the local people said that wind directions were from the west and north depending on the season. It is suspected that these are generalisations since observed sand movement indicators showed different and more precise compass directions. To avoid confusion and placing of fences in the wrong positions, by using an L-shaped fence for example, it is recommended that the project ensures that palisades are placed in checkerboard fashion, in these areas where there are problems with drifting sand.

To extract actual wind directions from the qualitative opinions of villagers is often difficult. It would be very desirable to have a record of wind directions and speeds in a few sample villages like Damania, but in practical terms however this will be difficult to achieve without installing an automatic recorder with a data logger.

Existing shelterbelts and sand stabilisation around a number of factories in this area have shown the value of careful planning with zones of protection. The outer layer are sand sheets with rainfed millet. The millet roots and 10 to 15 cm of stalk are left in the soil to produce roughness and break up winds. Elsewhere these stalks are often pulled out. The next layer is a strip of *Acacia ehrenbergiana*, a local plant with thick bushy growth if coppiced. The next zone are tall trees of *Prosopis juliflora*, and this is followed by open fields used for rainfed crops. The last zone outside the factory wall are tall trees of *Conocarpus lancifolia*.

One of the problems of carrying out a water well drilling programme in areas of mobile sands, well in advance of the stabilisation and planting programme, is that the well heads may become buried by the dunes that are intended to be stabilised. As long as the position is known and the top of the casing tightly sealed there should be no problem. Several wells are located on mobile dunes or close to dunes in this area. Since some casing caps did not always provide a complete seal, sand could infill the casing. The TDA should check all wellheads to ensure this does not happen.

5.2.2 Zubayri to Shera and Al Marawi'ah.

This area lies on the northern edge of the Wadi Siham alluvial plain where stabilised sand plains form higher ground. There are significant development of dunes along the edges of the sand plains here and these threaten the farmlands and villages, such as Ash Shera, Dier Alhiba and Al Zubayri. The project is providing wells and shelterbelts along this sand front so as to protect the alluvial lands from further encroachment.

As seen elsewhere along the margin of the sand plains, there is often stabilisation of these sands in villages where shelterbelts of *Acacia ehrenbergiana* and other *Acacia* species are indigenous, but in the lands between the villages movement of sand is rapid and dunes are moving in from the west.

Locally there is some mobilisation of the ancient sand plains where the surface has been disturbed or gullied by rainfall. Much of the sand however is blowing into these areas from the sand sea that lies to the west and north of the Sana'a road and dunes cross the main road along the lineation of the ancient sand ridges.

The project should encourage the planting of shelterbelts along the edge of the sand sheets, especially between settlements, and include stabilisation measures along the main road where it crosses the sand ridges. The system of checkerboard fences or palisades should be used on sand sheets and dunes wherever possible. Proposals to stabilise gullies on the ancient sand ridges are given in Chapter Six.

5.2.3 Southern Flanks of Wadi Siham.

This programme lies along the margin of the arable lands where they abut onto the higher ground of the ancient sand sheets. Active sand sheets and transverse dunes are moving north-eastwards into the farmlands. Locally there are wind deviations. For example, where a channel of the Wadi Siham is crossed by the main road east of Al Mukayminiyah, there are westerly winds during the day in summer. Along the dunes to the south however, the more usual north-westerly winds are present. When asked where the sands came from, one old farmer answered that all the sands came from the sea and that the winter winds from the south-west were the main sand moving winds.

The TDA has a nursery for afforestation species located on the first sand ridge south of the Wadi Siham. The species grown there include those listed for the "Green Belt" in Section 5.1.2, and also *Tamerix aphylla, Acacia seyal, Acacia nubica, Capparis somaliensis, Cassia italica, Lucaena spp, Albizzia labada* and *Acacia mellifera.*

On the adjacent dunes many of these species have been planted for several years and show good growth. The plants are watered using a water tanker filled from the project well, but distant areas in the deeper sands away from the road receive infrequent watering. There also appears to be an absence of checkerboard fencing in this area, and this may be the reason for sands continuing to drift through the area despite the vegetative cover.

Further west at the TDA well near Mohayrian a shelterbelt has been planted on dunes for over a year. These contain many of the species listed above. A checkerboard system is in place here on a 10 m by 10 m grid using data palm fronds. The fences appear to have been successful, but thought should be given to repair and renewal where dunes have grown upwards.

5.2.4 Shalamah Area.

The Shalamah area is centred on the western part of the Wadi Siham alluvial plain. To the south the land rises abruptly onto the old sand ridge. Transverse and barchan dunes are moving form the south-west onto the alluvial plains, and locally these are moving eastwards and east-north-eastwards along the Wadi Siham as seif ridges. The TDA has sited a new well in one of the interdune corridors in this area. In the adjacent farmlands around Shalamah Dom and Date Palms are being buried under transverse dunes which showed westerly and west-south-westerly wind directions. Despite local attempts to halt the movement of sands here, with brushwood palisades on the windward slopes of the transverse dunes, there is a progressive movement of sands over the Dom *(Hyhaere thebaica)* and Date Palms.

It is likely that the lack of ground cover and checkerboard fencing on the dune surfaces results in continued sand movement. The project, which so far has not started work in this area, should initiate standard procedures for stabilising the sands with suitable grass and shrub species that will entrap sand.

5.3 WADI ZABID PROGRAMME.

5.3.1 Zabid to Tufaytah Shelterbelt.

This ten kilometre long shelterbelt was initiated in 1983 when the sand plain track from Zabid to Tufaytah was blocked by advancing dunes that were moving out of the sand sea to the north-west of Zabid. A number of trees, including *Balanites aegyptiaca, Eucalyptus sp, Acacia arabica, A. themeda, Tamerix aphylla, Salvadora persica* and *Prosopis juliflora* were included in the shelterbelt and these have grown to considerable heights. Metal fencing protected the shelterbelt at an early stage but is now often broken to allow access for livestock. It is believed that a checkerboard system of fencing was adopted to stabilise the sands prior to planting, but the materials used have now disintegrated. The shelterbelt has been considered a success, halting the massive movement of dunes into the outskirts of Zabid town. The track through to Tufaytah however is not generally used any more because of loose sand. Irrigation of the shelterbelt ceased some years ago. An automatic weather station exists within this shelter belt (located at UTM 38P. 0314700E, 1571800 N) but data collection is apparently no longer taking place due to instrumentation problems.

At present, sand hummocks with *Odyssea mucronata* and *Leptadenia pyrotechnica* are common in the area and have invaded since the tree planting. Over large parts of the shelterbelt, however, sand sheets and low dunes are moving back into the area and again threaten the settlement and farm lands to the south. It is thought that this is due to degeneration of the groundcover on the sand hummocks on the plains to the north and west and lack of irrigation water within the shelterbelt causing introduced trees to wilt and die.

It is concluded that this important shelterbelt requires rejuvenating. It has been successful and then largely left to its own devices to survive. Unfortunately, introduced species which require irrigation will decline if groundwater and soil moisture levels decrease, which is what appears to have happened here, and their effectiveness in trapping loose sands is diminished. The simplest technique to achieve this would be to carry out an irrigation of this shelterbelt, and repeat the process every year or so, depending on the occurrence of local rainfall. Though quite costly, the long-term benefits in saving this shelterbelt will be important to Zabid. Important lessons will also be learnt for the long term management of shelterbelts.

5.3.2 Wadi Birah and Rawiyah Area.

The situation for farmers due to movement of aeolian sand in this large area is drastic. Transverse dunes and sand sheets are progressing north-eastwards into farmlands and there is a steady loss of fields to sand. The sand dune stabilisation programme in this area plans to stabilise the dunes along the southern edge of the Wadi Zabid alluvial plain. A number of tubewells have already been completed and TDA staff have initiated several shelterbelts at well sites. It is planned in the next year to commence work at all the well sites, with the eventual aim of linking up these core areas into a continuous shelterbelt strip. The work at each site includes stabilisation of dunes with checkerboard palisades and planted grass, shrub and tree species. On the sand sheets a linear belt of tree species will also be irrigated from a network of pipes.

At those sites where work has commenced there has been a good start to the planting operations. The effect of planting on the 2 m high barchan dunes was observed at one site in the Wadi Birah area during a period of sand movement:

- on unprotected dunes the sands were advancing rapidly over the surface of the dune and also saltating through the air, finally cascading down slip faces, and thus advancing the dune front.

- on dunes with *Tamerix aphylla* seedlings there was a noticeable drop in wind speed at the surface, with only slight movement of sands. Above the dune there was a slight increase in wind speed.

- on dunes planted with *Tamerix* and *Panicum turgidum* grass there was no movement of sand on the dune, and wind speed only was noticed at about 1 metre above the ground. Thus, the dune was stabilised.

This clearly showed the remarkable effect of creating roughness on the surface of a dune to slow down and halt sand movement. However, it was apparent that on the windward edge of the planted dunes the winds were drying out the sands and starting to scour the surface around the plants.

Some plants had already died. There was deflation of sand around these dead plants, and further desiccation would likely proceed further up the surface of the dune. The reason for this desiccation is thought to be that no checkerboard system of fences had been put down on these dunes prior to planting.

If checkerboard fencing is not made mandatory on dunes and sand sheets then this sort of reversal of the initial stabilisation will be common. If, at the time of planting and establishment of plants on dunes without fences, there are only weak winds the operation will appear a success. But if the same work were to be attempted during a strong sand-moving wind the results would in all probability a failure. By contrast, planting on dunes with a well constructed permeable checkerboard fence system should be possible during periods of even moderate winds.

Several wells are located on mobile dunes or close to dunes in this area and at least one well was buried by sands, with others threatened. Since some casing caps did not always provide a complete seal, sand could infill the casing. As elsewhere, the TDA should check all wellheads to ensure this does not happen.

There is a modest presence of on-farm shelter belts in this area at present, though groves of shade and multi-purpose trees are common in villages. The TEPP programme will provide a vegetated linear strip along the southern dune edge and numerous farms are also participating in schemes to build up windbreaks. Many more are needed throughout the farmlands so as to reduce windspeeds and protect lands from dust deflation and sand encroachment. The resultant changes to microclimate will also reduce evapotranspiration loss. The topic is discussed further in the next section.

5.3.3 Maghras Area

In the Maghras area immediately to the west there are very severe problems with sand dunes endeavouring to bury the villages. In the past, dunes have covered houses and mosques and it is likely the village was originally a single settlement rather than split as at present. A series of ramparts, up to 15 m high, have been built up by the winds, and these are stabilised to some degree by layers of plant residues. These naturally constructed foredunes go some way towards halting the north-easterly movement of the dunes.

The landowner in this area is stated to refuse permission to any of the landusers for any shelterbelts to be grown in the areas upwind of the dunes and in general on the farms. The reason is said to be that the resultant bird populations will eat all the crops. Yet the villages here have numerous trees and there are large bushes of *Cadaba rotundifolia*. The absence of shelterbelts in the Maghras area is leading to increasing desertification by a range of processes, for example:

- loss of topsoil soil from dust deflation;
- movement of sands over fields and into villages;
- higher exposure of soil surfaces from winds and increased evaporation loss.

The TEPP appears to have no regulatory controls to insist on landowners adopting shelterbelts in this area and the effort must therefore be extended to the educational approach. In adjacent villages there is satisfactory adoption of sand stabilisation policies and the answer must be to initiate an understanding in the Maghras area, otherwise many farms, and probably the villages, will be covered by dunes. A simple set of shelter belts one kilometre to the south west of Mahgras would probably start the process of starving the dunes of further development.

The problem of birds is not a new one. It is true that in certain years there may well be high bird populations living in the trees and eating crops, but these populations will have great mobility and affect all areas within the Wadi Zabid, unaffected by the presence or absence of a shelterbelts. It is not an excuse to deny the benefit of shelterbelts and sand dune stabilisation to a large rural population because of the irregular risk from swarms of birds. It is just as likely that the onset of environmental conditions that can result in the large populations of birds appearing will also be producing large populations of crop pests, to which the birds are attracted.

5.4 ARTIFICIAL FOREDUNES

It is proposed to construct artificial foredunes along the southern dune front of the Wadi Zabid. As noted in Chapter Two, these are scheduled to be 3 metres high and have an 18 metre broad base. The Work Programme for the second half of 1998 (TDA, 1998) concludes that foredunes should be initiated during 1999 at first on a trial basis so as to judge their success prior to any wider application. The consultant agrees with this decision and hedges caution on their widespread construction until the method is proven. Several aspects of the interior foredune construction cause concern.

The construction of foredune is likely to cause an increase in wind erosion. Since the average height of dunes is often less than 3 metres the construction of a linear foredune ridge, up to 3 metres high and 18 metres wide, will involve bringing in sand from a broad lateral strip of land on the windward side of the proposed shelterbelt. This will cause disruption to a large area of the desert surface.

The wind-stable soil and surface crust of the underlying parent material will be broken up by the pulverising effect of the bulldozer. This will then be far more susceptible to deflation by wind erosion than in the past. Disruption of silty soils will likely lead to an increased mobilisation of dust during and after construction. Disruption of the old sand plain soils may also cause re-mobilisation of these long-stable sands. In areas where dunes have been disturbed for supplying this movement it is probable that there will be a greater movement of sand than before.

Is it necessary to physically construct a massive dune-shaped feature that will only grow higher with time, as sand is added to it naturally from upwind sources? Dunes will form where obstacles occur, and an area of checkerboard fences established on a sand sheet, or flattened dune, will act as such an obstacle and commence to accumulate sand as a dune. By planting suitable tree and shrub species inside the fences, the plant cover will grow up as the dune accumulates.

Flattened dunes will also have a natural tendency for them to re-assert themselves back into dune shapes. It is thus essential to install a system of checkerboard fences as soon as possible on the flattened and disturbed areas. These will reduce sand movement to a minimum and restrict the ability of the wind to lift up dust.

It should be noted, however, that some farmers have both built foredunes and also let nature build foredunes in the same area. For example, a few kilometres west of Sawlah large foredune ridges have been built up naturally over a number of years using palisades. Nearby, other farmers in a critical area where sand was threatening the fields, hired bulldozers to construct an 'instant' foredune and have stabilised this with brushwood, plant residues and are encouraging *Cadaba rotundifolia*, and *Salvadora persica* bushes to grow. The secondary process of planting in many areas however is usually rather neglected due to either a lack of water supply, or a lack of understanding of the importance of establishing a plant cover and using a (precious) water supply to nourish the plants.

Thus, it is believed that the solution to the problem of the proposed foredunes is to implement their rapid construction in certain critical areas, but to let nature build the foredune ridge in other areas. Disruption of soil surfaces should be kept to a minimum. Establishment of fences should be undertaken at an early stage and will always require maintenance and probably periodic replacement as materials perish, or as the dune grows.

The plant cover should then be established once the fences are in place, and irrigation will be necessary for a number of years. Later, as plants become deeper rooted and reach the water table, irrigation can cease. Where shallower rooted plants or shrubs are used, or where a water table is too deep, irrigation may always be necessary. The use of indigenous plants which naturally aid in foredune / hummock construction sand stabilising properties, such as *Cadaba rotundifolia*, *Salvadora persica*, and *Tamerix aphylla* should be encouraged.

It should also be noted that the first rule of sand stabilisation is that it will never be possible to totally stop sand movement through an area. The importance of the stabilising measures described above is that they will stop most of the sand, but being permeable barriers will allow an acceptable fraction of sand and dust to blow or creep through the system. This is seen naturally in some of the zibar sand plain areas, down wind of the coastal dune belts, where sand hummocks allow a moderate but steady movement of sands inland. Development of large scale dunes here is absent. However, human disruption of the vegetation cover of the hummocks along the margins of the cultivated lands, appears to lead to extensive development of more mobile sand sheets and in turn these form sand dunes.

5.5 SOIL IMPROVEMENT.

Preliminary findings from the present study suggest that in the past stabilisation of the ancient sand sheets and dunes was accomplished by the formation of soils, formation of algal crusts, the addition of airborne dusts and an increased plant cover under a higher rainfall regime than at present. At the time these helped to transform a large part of the Tihama from mobile dunes into vegetated plains and allow settlement to be sited on what were crests of dunes.

Within the present period unfortunately it is thought that it will not be possible to duplicate these natural processes. The aim however of the sand stabilisation process should be to improve soil conditions wherever possible, as any process leading to the formation of stable soil aggregates will also reduce their capability to be moved by the wind.

As an example of what can be achieved in a similar climate to that of the Yemen the work described by Stephens (1974) is relevant and instructive. He reported on the successful stabilisation of strongly calcareous sands in the Al Hasa Oasis, Saudi Arabia, using *Tamerix aphylla*. Litter from the leaves was allowed to accumulate on the soil surface under the closed canopy of trees, which reached 8 metres after 8 years. The leaf litter decomposed to form an organic surface layer with stable soil aggregates, whilst organic acids resulted in a lowering of pH and thus more availability of plant nutrients held in the soil. The result was a wind-stable soil that protected the date palms in the oasis.

In the case of the Tihama sands, where the sand grains are seen to be a mixture of quartz, feldspars, pyroxenes, opaque minerals and rock fragments, there is a probably a greater potential (than the Saudi example) for long term nutrient availability if the soil conditions could be improved. Additionally, on a local scale the mixing of silty alluvium with the sands of the dunes would provide a solution for creating a soil, but practical difficulties exist in carrying out the actual mixing of the ingredients and also the costs of transporting materials. However, some farmers are understood to have tried this with some success and the matter deserves more attention. Any soil amelioration however needs to be implemented in a 'package' with addition of mulches, stabilisation of adjacent lands, irrigation of seedlings, etc.

Stabilisation of sands can be accomplished by spraying on latex or bitminous compounds. However, these are susceptible to damage from off-road vehicles and livestock herds leading to breaks in the surface skin and deflation of the untreated sands below. These materials usually do not allow the growth of plants, and environmental damage to the ecology of the Tihama plant and soil animal populations would also preclude their use.

Where sand stabilisation fences and shelterbelts are being established it is most important that surface accumulation of organic mulches produced from falling from leaf litter is preserved. Checkerboard fencing, and the application of other plant litter on the surface will reduce wind movement and encourage this. Additional useful inputs could be acquired from composting excess green matter, such as from *Prosopis juliflora* (mesquite) but it is not known if this has been attempted in Yemen yet. All such measures will aid in increasing the organic matter levels in the soils under the shelterbelts and increasing the stability of the sands

In a review of 30 years of sand stabilisation activities in north-central China, with annual rainfall of 100-200 mm, Mitchell and Fullen (1994), reported on the success of checkerboards and other measures to reclaim dunes and improve soils. The results are summarised below with conclusions for Tihama applications:

Levelling of Sand Dunes.

Levelling of sand dunes was carried out in the areas close to irrigation water supplies which had high silt loads. After the dunes were flattened, by bulldozer, silty waters covered the sands. This led to soil improvement and the creation of a suitable environment for plant growth.

In the Tihama, the marginal areas of the principal wadis long relied on irregular flooding to remove sands from fields and truncate advancing dunes. Since water regulation was implemented some areas no longer receive any supplies and sand movement is greatly enhanced. Pumped waters are by nature free of silts. It is suggested that some relaxation of water regulation, could release silt laden flood waters onto these marginals areas, where dunes were flattened.

Addition of Soils onto Sands.

In China the use of paleosols from adjacent deposits have mixed with sands to produce a more favourable soil.

The Tihama paleosols on the ancient sand dunes should not be used in this fashion as the surface stabilised soil is underlain by loose sands, which already show some evidence of remobilisation in unprotected areas. Adjacent deposits of alluvial silts, common in many areas of the flood plains, are used locally. This could be expanded but caution should be noted where saline soils exist.

Dune Stabilisation

The first stage of stabilisation is the establishment of windbreaks, in China made of bamboo or willow branches. Behind these barriers, straw or clay checkerboards are constructed on a 1m x 1m grid. Straw is placed to a depth of 20cm and protrudes some 15cm above the ground. Within the checkerboard, aerodynamic roughness is increased, surface wind velocity is reduced and sand movement is largely halted. Where the checkerboard grid was set at 3m x 3m size however, there was substantial wind erosion and deflation of sands to a depth of 20cm each year.

In the Tihama, the use of checkerboard systems is utilised, and this report has stressed the need for its universal adoption. The design being adopted by TDA is different than that of China and utilises a one metre high palisade windbreak of palm fronds on a 4m x 4m grid. It would be useful to attempt some trials using a finer gridded checkerboard, perhaps using millet and sorghum residues as low fences within the grid. It is likely that this would give highly significant results.

Vegetation Development and Formation of Soil Crusts.

The checkerboard system allows soil formation to commence and suitably adapted indigenous plants to become established without risk of deflation around root zones. At the same time soil organic matter is built up by decaying vegetation and algal crusts develop on the surface. The latter were found to be extremely important in soil formation and stabilisation of the dunes.

In the Tihama, algal crusts were only noticed on the ancient sand dune soils in the eastern parts of the Tihama. These appear to be related to higher rainfall close to the escarpment and, in summer, were not seen on other sands. Study of the possibilities for biocrust formation as a component of sand stabilisation on the Tihama sands needs further investigation.

Control of Livestock Densities.

The China experience showed that livestock densities on the stabilising sands were strictly controlled, with a density of one sheep per 0.87 ha. This led to recovery of vegetation in degraded areas within five years.

In the Tihama a programme such as this would require more participatory management involving the pastoralists and reclamation projects, than exists at the present.

5. 6 SUMMARY OF RECOMMENDATIONS FOR IMPROVEMENT TO METHODS.

The present study has concluded that a number of improvements can be made to the present methods being adopted for the Sand Dune Stabilisation Programme of the TEPP. These can be summarised as follows:

a). The checkerboard system of fencing on mobile dunes is recommended. Systems of parallel fences or fences with L-shaped design are unlikely to work in the Tihama where multidirectional winds blow throughout the year.

b). Checkerboard fencing should be extended onto all sand types in the affected areas and not just on the dune forms, as shallow sand sheets can develop into dunes and bury young plants. The use of checkerboard fences should be regarded as standard procedure in all areas, and not something that is constructed in one place but not another.

c). Attempts to stabilise routes through large areas of mobile dunes by flattening and then planting should be avoided, as changing wind directions, dry conditions of sands and general access will compromise efforts to stabilise a narrow pathway.

d). Confusion abounds when villagers and sometimes extension staff are asked to provide the wind direction. The only practical outcome is to install automatic stations with anenometers to record wind speed and wind directions on a continuous basis. Data can then be analysed to show wind directions throughout the year. Existing TDA stations require maintenance and/or upgrading to fulfil this requirement.

e). The use of *Prosopis juliflora* in areas remote from farms should be considered for sand dune stabilisation work. It already has an extensive presence in some areas, such as east of Hodeidah. It is not recommended for use in coastal foredune areas where dunes, and thus seeds, are moving inland. Seed pods could be manually collected but this has practical difficulties when large canopies are present.

f). The building of foredunes in the interior areas requires testing before this high cost operation is initiated. A pilot area should be initiated, prior to large scale construction work.

g). Foredunes should be considered for rapid construction in certain areas where there is a critical and timely need to stop sand. Elsewhere natural dune accumulation, following fence and checkerboard establishment, is desirable.

h). Any establishment of foredunes in coastal areas is best left to natural processes of sand accumulation aided by checkerboard palisades / fences and plant establishment.

i). Soil improvement through use of mulches and green manuring is to be encouraged as these will lead to formation of stable soil aggregates and release of plant nutrients from the minerals in sand grains. Mixing of silty and sandy soils should to be investigated as an additional method of helping to form a wind-stable soil.

j) Farmers should be strongly encouraged to establish shelterbelts over farmlands and in the farm or pastoral lands that exist upwind of dune belts. Tree-free zones, as advocated by some landowners, are leading to an increase in sand movement into various dunefields that lie adjacent to villages and benefits from reduced sand and dust movement on health of people and crops could well outweigh the as yet unquantified effect of increased bird populations on crop loss.

6 PROPOSALS FOR FUTURE INTERVENTIONS IN SAND DUNE STABILISATION

6.1 INTRODUCTION

This chapter discusses the need for sand dune stabilisation in the Tihama in areas other than those that are at present within the Tihama Environment Protection Programme, and also presents proposals for improving sand dune stabilisation techniques.

6.2 REDUCING SAND MOVEMENT IN COASTAL AREAS.

Coastal areas have been denied an input into the present programme because they have been said to play an insignificant role in the problems of movement sand dune onto agricultural land, and that the links with the inland dunes were distant enough to be unimportant (IFAD, 1992; HTS, 1993). It is considered that this is a generalisation which could have serious effects on certain rural economies in certain coastal areas of the Tihama. As was originally suggested in the Preparation Report (FAO-IC, 1990 and 1991), the present consultancy has also concluded that coastal areas should be included in the overall scheme, hopefully in a future programme adjustment.

In coastal areas there is a natural tendency for coastal dunes to evolve from sand hummock into foredune ridges and then parabolic dunes. The foredune appears to occur naturally along the coast in those areas where there is a continuous sand supply coming ashore, leading to sand accumulation parallel to the shore. Where the sand supply is diminished or the beach eroded by storms foredunes are locally destroyed, leading to blow-outs formation and the appearance of parabolic dunes.

Relatively finer textured sands then move off inland, as hummocks and barchans (or mixtures of these) and combine to form transverse dunes, complex network of transverse dunes and interdune sand sheets that are spreading rapidly into the irrigated agricultural lands. The sand dunes are not thought to have formed from recent deflation out of the main wadis, and although some reworking of aeolian sands is likely to be occurring from the ancient linear dunes that occupy the inter-wadi plains, the principal origin of the sands is held to be from alluvial sands washed into the sea during earlier, prehistoric, periods of extensive flooding.

There is thus a steady movement of sand north-eastwards inland and the formation of sand seas. Although it is impractical to consider the stabilisation of an entire sand sea, for example, from At Ta'if to Sawlah, an understanding of the process of relative movements of sand away from coastal areas is essential if one is consider stabilising the sands at selected areas along the coast where the rural economy is being damaged by sands. It is thus necessary to look in some detail at the ecology of the coastal lands and their modification by human interventions.

On high energy beaches sand is coming ashore and accumulating in drifts, hummocks and dunes. On the low lying sabkha fringe and low sand drifts immediately bordering the sea, the vegetation is dominated by halophytic shrubs (*Suaeda fruticosa, Suaeda monoica, Salsola spinescens,* and grasses (*Aeluropus lagepoides, Halopyrum mucronatum)*. In some sheltered areas, near Al Fazzah and immediately north of Hudeidah, reed beds (*Scirpus spp)* are found according to Barratt et al (1987).

On slightly higher sand hummocks the spiny grass *Odyssea mucronata* colonises sandy terrain within a few metres of the sea, especially in low energy beaches. This grass (Shawkam in Arabic) is largely unpalatable and can provide a luxurious cover over loose sands. On the more exposed coastal parabolic dunes, for example such as near Mutaynah and Mabar, this grass is responsible for the stabilisation of a large belts of fragile dune systems several kilometres inland and up to fifty meters above sea level. Tamerisk, *(Tamerix sp)* also occurs in association with Dom Palm (*Hypahene thebaica)* on the slightly elevated lands. Both of these latter plants are stabilisers of drifting sand where it emerges from the beaches along the coastal areas.

Halopyrum mucronatum, Qasabo in Arabic, is also particularly useful as a coloniser of sand dunes not just in Yemen but throughout the coastal areas from Eritrea to Kenya. Although it occurs at intervals on the coast north and south of Hodeidah it appears to be quite rare at present. It may be it has been excessively used for thatching. It is not generally grazed due to salt content. A study is needed to assess if its distribution can be increased.

The presence on the coast where sands are blowing inland of the natural sand colonising species *Halopyrum mucronatum, Odyssea mucronata, Tamerix sp*, and *Hyphaene thebaica* (Dom palm) need to be greatly enhanced in the future.

However, both the Dom Palm and Tamerisk are being extensively cut for home building materials, and the woody portions of the older bushes of *Odyssea mucronata* are cut and dug up for firewood. The result, in areas such as Mujaylis (Wadi Zabid) and the delta of the Wadi Siham (south of Hodeidah), is reactivation of stabilised hummocks, and mobilisation of parabolic dunes. At Mujaylis parabolic dunes are advancing at some 7 m per year over dwellings and burying date palms. In other rural communities, such as at Mutaynah, there is some degree of community protection and movement of the dunes appears to be minimal.

In the future, therefore, a prodigious human effort needs to be made to encourage the conservation of indigenous vegetation. This can only come about by a process of education amongst the coastal peoples as to the role of vegetation in stabilising sand dunes and, at the least, delaying the rapid movement of dunes onto farmland.

At present, although the cutting of vegetation is apparently forbidden on dunes and hummocks, the practice is widespread and often blatantly carried out. When questioned by the consultant the answer invariably was that they were only cutting old bushes for their own household use. Yet it was clear they were engaged in a rewarding business. The result however is leading to widespread desertification in an ever increasing radius from Hodeidah, and mobilisation of modern and erosion of ancient dunes in the coastal areas. A process of education to land users on the consequences of this destruction should be a forthcoming task for the Extension Officers, whose network already exists throughout the area.

Finally and perhaps most importantly, it is not felt necessary to actually construct artificial foredunes in coastal areas, as suggested in the Preparation Reports (FAO-IC, 1990 and 1991). Foredunes form and accumulate sand naturally when the appropriate vegetation is allowed to propagate. All along the coast there are examples of natural foredunes accumulating when stabilising vegetation is present.

By abandoning the concept, constructing a coastal foredune costs would be considerably reduced. The TDA is thus urged to reinvestigate the proposals for work in coastal areas, and specifically in the areas detailed in some of the following paragraphs.

6.3 PROPOSED PROTECTION AREAS.

6.3.1 Introduction.

A number of proposed protection areas are shown on the 1:50,000 scale image maps that accompany this report. These are areas which have very considerable problems with sand movement at the present time, but are not included in the funding IFAD programme. From field studies conducted throughout the Tihama during this consultancy it was concluded that these areas will need protection in the future. In some areas the situation is deteriorating and fields and rural communities could be overwhelmed by sand dunes sand lost. As it was not possible to visit every village in the seven weeks available for the field study it is likely that there are additional needy communities. Thus, prior to the writing of any proposal to draw funding for these areas a more detailed reconnaissance and review would need to be carried out by TDA staff.

6.3.2 Qutay to Munayli Area.

The margin of the ancient sand sheet to the east and north east of Quaty is a low scarp, where in the past the sands were eroded by the changing courses of the Wadi Siham. Alluvial silts thus lie to the east of the scarp and are important agricultural cropped lands. A problem exists, all along the edge of the scarp sand line, that sand sheets, and locally dunes, are moving off the sand plains and onto the alluvial lands where they lead to a deterioration of the soil quality and cause agronomic problems. On the ancient sand ridges, which have an east/west alignment in this area, there is dendritic gully erosion on the stabilised soils caused by rainfall events and this is supplying fine sand onto the fields.

In addition, sand sheets and transverse dunes are migrating eastwards from the extensive sand seas that occupy the lands to the west.

It is proposed that a policy of shelterbelt plantation, seen in the TDA areas further west in the Wadi Siham, be extended all along this zone. At several villages the inhabitants do already allow tree and shrub growth, and groves of *Acacia spp* are noted. In the lands between the villages however there is often no control of grazing and no planting of windbreaks. It is concluded that the first step in this area is to appraise the villagers on the deflating sand plains in the west and the sand-receiving silt lands to the east, on the long term consequences of these processes of sand movement. A solution, to be jointly managed by villages on both sides of the sand line, should then be worked out, in pilot areas at first to demonstrate the effectiveness of a conservation programme.

Gullied terrain in the old sand ridges requires controlling to reduce washing out of fine sands as fans onto the adjacent plains, and their local mobilisation into sand sheets and dunes. Gully stabilisation will require trials to select the most appropriate method. The most eroded areas could be fenced off to allow vegetation to colonise banks, but it is thought this would not be effective due to the harsh climate and pastoral needs. It may be possible to place dry brushwood or drystone dams at intervals in the gully floor to encourage infilling of gully floors but supply of materials are likely to be limiting. A problem is that the upper part of the sand ridge is a stabilised soil, no longer forming in the present climate, whilst there is loose sand at depth. Once the soil surface has been broken through erosion proceeds rapidly as piping and slumping of the loose sands result in headward erosion of the gully walls.

6.3.3 Kulzum Area, Wadi Siham.

This area in the western edge of the Wadi Siham is a relatively small area of date palms that are threatened with engulfment by transverse dunes that are moving inland from foredunes and parabolic dunes along the coast. The supply of sand from the sea in this area is moderate. Local efforts to stabilise the dunes with brushwood fences along the dune front are quite successful but need to be augmented with afforestation upwind of the dune front. Investigation of the devegetation of the hummocky terrain and parabolic dunes along the coast to the south-west is recommended. Reversal of these desertification trends could probably lead to a reduced mobility of the sands.

6.3.4 At Ta'if .

Coastal dunes move inland from the lands in the At Ta'if area and threaten farmlands along the whole length of the Wadi Rumman. Although sand dunes are moving at a rate of less than 10 metres per year into the plantations, it is very likely that individual sand grains are moving much faster. Grains will emerge from the sea and be blown onto farmland ten kilometres to the north within one or two years leading to a steady building up of the dunes that already threaten the farms. At the village of Al Ha'it a ten metre transverse ridge is moving into the farmlands.

In this future protection area it is proposed firstly, that the coastal parabolic dunes and hummocks, which occur on the lands south of the Wadi Rumman and extend south of At Ta'if for some five kilometres, are protected from land use pressure that leads to denudation of vegetative cover of the dunes and thus to increased mobility of sands. The aim of protection in this area will be to make local inhabitants aware of the process of sand movement and how they can assist in reducing movement. Secondly, attention should be given to the mobile dunes themselves at villages such as Al Ha'it, with assistance from TDA, for example to place date palm fronds in checkerboard fashion on the sands and introduction of plant species. Though the motivation will come from TDA workers in the field, much will depend on the will of the local people to carry out this work themselves.

6.3.5 Sawlah to Al Lawiyah Area, Wadi Rumman.

The southern edge of the Wadi Rumman receives sands that originated from the coast south of Ta'if. A huge sand sea of over 500 km^2 in size lies to the south. The annual drift resultant of sand appears to be towards the north east, and this therefore threatens a fifteen kilometre long strip westwards from Al Lawiyah. The neighbouring villages have, with little material assistance from the TDA project, carried out their own crash programme to stabilise the dunes. Efforts at the village of Al Manqam al A'la in particular need to be singled out for high praise.

Here, transverse dunes directly sweep onto the pump irrigated farmlands of the Wadi Naba / Wadi Kidiyah. The farmers in several localities have placed brushwood fencing along farm boundaries on upwind sides, but these are steadily building upwards, and now massive foredunes tower some ten metres over the fields. There is a danger that the dunes will blow over onto the farms and ruin the efforts of many years. Attempts must therefore be made to stabilise the sands further back, upwind, and past the adjacent village of Al Manqam al Asfal.

The use of borehole supplies to initiate planting of tree species following checkerboard construction is recommended. Unfortunately, the construction of a water tower at Manqam Al A'la village was not well planned (nor well constructed) and the supply is out of command of several potential areas for irrigated afforestation. The adjacent village could assist in joint effort to stabilise this area. The role of TDA would be through the extension service to make all parties aware of the possibilities that exist for solving a deteriorating situation for these villages.

6.3.6 Wadi Kuway Area.

The Wadi Kuway, lying to the north of Wadi Zabid, has important date palm plantations that are threatened by parabolic dunes originating on the coast some two to eight kilometres distance. The proposal in this area would be to protect the southern flanks of the Wadi Kuway with shelterbelts at the edge of the dates and attempt to stabilise the dune front, where it is moving into the plantations, with standard brushwood palisades in checkerboard pattern and reafforestation.

There are existing water supplies in this area which could be used for initial irrigation of stabilising species. Dunes are also threatening the north of the Wadi Kuway area in summer when sands are moving in a south-easterly direction, but the extent of this problem is not known.

6.3.7 Madaniyah to Wadi Ajji Area.

The southern edge of the Wadi Rimah suffers from the north-easterly drifting of sands into the Wadi Rimah floodplain. The sands originate on the coast to the south and migrate inland as transverse dunes. At the Wadi Rimah parabolic dunes form linear ridges that slowly move into the valley. Further east, away from the coast, transverse ridges replace the parabolics. Stabilisation of the dune front was given prominence in the World Bank funded study for the Wadi Rimah. But, although shelterbelts have been extensively developed on the irrigated alluvial soils of the Wadi Rimah plains, there has been no stabilisation of the dunes. Instead, as seen by a multitemporal study of the aerial photography (1973, 1987) and the SPOT satellite imagery (1997/98) there has been a very significant reduction in the natural vegetation along the edge of the Wadi Rimah. This vegetation, principally comprised of large bushes of *Salvadora persica*, has been progressively reduced in the past decades. In its natural state in this area it buffers the north-easterly advance of the transverse dunes and parabolic dunes into the Wadi Rimah. This situation is now changing. The dunes are advancing further into the farmlands of the Wadi Rimah, especially in the lands due south of Madaniyah. A study needs to assess the following questions:

a) Is the advance of the dunes progressing any faster in recent years?

b) Is the advance of dunes due to cutting vegetation down for fuelwood?

c) Or has the vegetation become desiccated due to drought and the drying up of shallow water tables?

d) If there is a lowering of water tables, is it due to overpumping in the valley or reduced recharge?

e) Has control of the irrigation system led to reduced 'flushing out' of the sand dunes, that have accumulated in the wadi floor, by occasional large floods?

f) What is the significance of the eastwards change from parabolic dunes to transverse dunes in terms of sand type and their ability to support stabilising vegetation?

These questions are appropriate to an investigation in any threatened area. In the lower Wadi Rimah there is a sharp boundary between dunes on the higher sand plains and farmland in the alluvial valley. There is also a good record of aerial photography on which to assess change. As the Wadi Rimah was chosen as the first sand dune field to be stabilised it is important that consideration is given to achieving this in the long term.

6.3.8 Mutayna Area.

In the Mutayna area large parabolic dunes threaten the date palm oasis lands to the north. The linear parabolic dunes are extending in a north-north-east direction. Parts of the village of Mutayna in fact lie on the dunes and deep wells extend down to freshwater some 13 m below. The villagers have adjusted to the presence of the parabolic dunes and it appears that there is a local policy of protecting the stabilising vegetation on the dunes. This needs to be investigated as it could provide a social model for use elsewhere in the Tihama, especially in those communities which do not (appear to) understand the importance of stabilising vegetation and shelterbelts.

6.3.9 Wadi Urfan Area.

The Wadi Urfan has a catchment in the mountains to the east of Hays. Sand dunes are moving inland and cross the main road where there is a conspicuous bend just to the north of the Wadi Urfan crossing. A plan to stabilise these sand dunes to the west of the main road is required, so as to reduce the impact of sands drifting across the road. The area of stabilisation should be developed some distance west of the road so as to allow the build up of vegetated dunes. Whilst the source of the sands is thought to be from the transverse dune sand seas lying to the west, it is possible that the Wadi Urfan is supplying sands that are deflated onto the plains, and this also requires some further study.

6.4 MONITORING WIND VELOCITIES AND THE MOVEMENT OF SAND.

No detailed study has yet been made of the actual threshold velocities to lift sand and dust particles in the Tihama (Williams, 1979). Whilst threshold velocities will probably be within the range experienced elsewhere in the world it is important to relate the recorded wind speeds to actual sand movement. Clearly, since sands are seen to be actively moving in the Tihama, the winds are strong enough during several seasons to move sand in several directions, especially towards the south-east and north-east. It would be useful, however, to quantify this by measuring the movement of the different types of Tihama sands under different wind velocity regimes. Such a study would require the establishment of several sand movement stations where the process could be investigated over the course of a year.

b). S2 SABKHA PLAIN.

The sabkha plains lies immediately inland of the coastal bars and occur on low energy coasts. They are flat plains with a limited ephemeral cover of drifting sand. Sands will move over the sabkha when wind speeds are high enough but if the winds drop the sands will fall into cavities in the rough crusted surface and be incorporated into the sabkha plain. Desiccation and buffeting by impacting sand grains will also, in turn, destroy the salt crust leading to movement inland of airborne salt particles and sand grains encrusted with salts.

On the lowest areas of the sabkha there is no vegetation, and this zone has saline crusts and moist sandy to silty soils extending from the surface. The watertable is usually within a metre of the surface and is usually highly saline. The lands are often within the range of extreme tides. Salt collecting pans in the areas around Salif, Luhayyah and south of Hodeidah provide witness to the hypersaline conditions. On the surface of the sabkha in these areas there are gypsum crystals and aeolian sand particles are often bound together by halite and gypsum crystals. On scattered hummocks of sand may accumulate on the sabkha plain and these are colonised by halophytic plants.

On higher grounds of the sabkhas, possibly where water tables are deeper or less saline, there is a 'sabkha fringe' where the vegetation cover appears. It is all halophytic with *Suaeda fruticosa* and *Salsola spinescens* common. The presence of shells and other materials suggest that these areas may have been flooded by tides in the past. These areas merge upslope into sand sheets with similar vegetation. Laterally they pass into the mangrove areas which are also present on low energy coasts.

7.2.5 Hills of the Tihama Escarpment.

a). H ROCKY AND HILLY TERRAIN.

The Tihama escarpment comprises many different types of rock, including granite, granodiorite, gneiss, schists, Basement metavolcanic and metasediment rocks, sandstones and shales, limestones, basic igneous intrusive and volcanic rocks. These have not been differentiated in the present study. The hills rises steeply from the alluvial plains, and include for example stepped slopes on layered volcanics, tors on granite, steeply dissected blocks and canyons on limestones and sandstones and steep stony slopes on Basement metamorphics. These rocks provide the sources of the sands that are emerging from the coast to form aeolian landforms in the Tihama.

7.2.6 Alluvial Landforms.

a). W WADI FLOOR.

The floors of many of the wadis of the Tihama are composed of loose sandy to gravelly sediments with a single or braided network of channels. In the upper parts of the catchments the floors are bouldery. In those streams which have a perennial base flow, such as at the headworks of Wadi Zabid, there are pools of water with *Tamerix* and aquatic grasses and sedges. Low sand and gravel banks lie adjacent to the channels and are regularly flooded.

In channels which may flood only once a year or less, such as the Wadi Nakhla, the floor is sandy to gravelly and perennial grasses and herbs may be established.

b). Wf FLOODPLAIN AND CHANNEL WITH LOW TERRACE

The floodplain of the larger wadis (Mawr, Surdud, Siham, Rimah and Zabid) is generally a broad plain in which lies a weakly sinuous wadi floor. The flood plain is rarely flooded at present, but is often under irrigation because of its relatively low position and a build up of silty soils. It also contains groves of woodland and aquatic grasses.

c). Fs SILTY ALLUVIAL FANS

Coalesced alluvial fans have formed recently over large parts of the Tihama where the principal wadis debouch onto the Tihama coastal plain. The transported material consists of a poorly sorted mixture of clay, silt, sand and gravel, derived from erosion of soils and slope mantles in the Yemen Highlands. It is thought that human management of the annual floods, by constructing earth dams and diversion canals, has over a long time been partly responsible for a steady alluviation of the finer textured piedmont plain with its largely silty to loamy soils. The coarser fractions either remain in the channels and are washed to the sea during periodic large floods, or are displaced laterally to form gravelly fans (for example on the southern flanks of the Wadi Zabid fan), or are deflated by wind from the channels, which is considered to be a minor process. The silty and gravelly fan surfaces slope down at 1 to 2 percent, but are broken by terraces of individual fields, whose purpose is to store irrigation water for cropping before passing it on to the next level downslope. In the silty soils these terraces may be several metres high and are either bare or planted with windbreaks.

d). Ft HIGH TERRACE.

A high terrace occurs on the edges of the escarpment and commonly comprises a surface loamy sediment that overlies gravelly and bouldery layers. The whole sequence may be 20 m thick, as noted in the Wadi Surdud valley, where it forms broad plains cut into by the river. The upper loamy layer, in the Wadi Surdud, at Suknah and elsewhere, has matured into deep fine loamy soils with terraced agricultural fields. In other areas, however, the surface may be gravelly and gullied with only scrub vegetation present. In the southern Tihama, such as on the flanks of the Wadi Rasyan, and on fans adjacent to the Mokha road, there are similar high level terraces, on which gravelly and bouldery surfaces have coatings of "desert varnish"; these fans have only a rangeland use.

e). Fg GRAVELLY FANS

The gravelly fans are most widespread at present in the southern parts of the Tihama where several of the drainage basins do not have large catchments extending into the Yemen Highlands. Rather, the fans are fed from the hills along the escarpment. The surfaces of these fans are sandy to gravelly and are partly overlain by aeolian landforms. They support a varied vegetation cover including *Acacia ehrenbergiana, Acacia tortilis, Commiphora sp.* and tussock grasses such as *Lasiurus scindicus.*.

f). Fh HIGH ANGLE FANS ON EDGE OF ESCARPMENT.

High angle fans occur as steep, narrow, fringing arpons along the margins of the Tihama escarpment in certain areas, and are often dissected by deep gullies. They may represent an earlier phase of colluvial and alluvial fan deposition which has been preserved in certain localities. In the higher rainfall areas in the central parts of the Tihama, these fans are cultivated using rainfall and spate irrigation, and flood deposits in the gully floors are conveyed onto the silt alluvial fans that lie downslope. Elsewhere they are utilised for rangeland.

g). Fd DISSECTED FANS AND TERRACES.

Dissected fans and alluvial terraces occur along the margins of the major wadis that drain the Tihama escarpment. They were not investigated in any detail but appear as distinctive features on the imagery and aerial photography. They are often not cultivated and this may be due to undulating terrain with gullies and an absence of arable soils.

h). F UNDIFFERENTIATED ALLUVIUM OF FS / FG.

This unit has been used where it was not possible to differentiate whether the alluvial plains are primarily composed of silty materials or are of sands and gravels. With more detailed field work the parent materials would probably be mapped separately.

7.3 LAND COVER CLASSES.

The symbols are identical to those on identified on the Tihana Land Cover Change study (HTS, 1993). A number of units from the earlier project were not mapped during the current study of sand dunes or formed small areas.

a). A 1 PARKLAND AGRICULTURE.

This class occurs on the alluvial lands bordering the mountain front, where there is annual flooding and some silt replenishment from runoff originating on the hills. The parkland nature of the piedmont fans is due to the presence of *Dobera glabra, Balanites aegyptiaca, Acacia sp.* and *Ziziphus spina-christi* trees which occur on field boundaries and also within fields. Flood waters are channelled into fields along small canals, often for many kilometres. The terrain is generally flat with a slight slope westwards. The main field crop is sorghum. Flood irrigation cropping is supplemented by pump irrigation and rainfed cropping.

b). A 2 WADI AGRICULTURE.

The pump and spate irrigated lands bordering the main wadi courses of the Tihama are covered by this mapping unit which occurs on the silty and loamy alluvial soils. The major crops are sorghum, cotton, sesame, vegetables, bananas and papaya. The natural vegetation cover includes scattered occurrences of *Acacia nilotica*, *Ziziphus spina-christi*, *Tamarindus indica*, and *Tamerix aphylla*. Shrubs include *Capparis decidua* and *Salvadora persica*. The introduced multipurpose and shade tree *Prosopis juliflora* is also present in fields as a weed. In the upper parts of the catchments, close to the offtake structures and if there is sufficient base flow, the lands receive irrigation water for much of the year. They will also receive supplementary water from rainfall. In the distal parts of the wadis, and often closer to the sea than the mountain front, there may only be spate irrigation once every few years and rainfall is negligible. Spate irrigation in many of the wadis is controlled by systems of concrete dams and canal systems leading off into the farmlands. These modern structures have replaced the traditional earth and gravel dams placed in the wadi floors.

c). A 3 RAINFED AGRICULTURE.

The areas of rainfed agriculture are mapped on the sandy soils of the ancient sand sheets (AP) that form the interdune areas and the broad sand ridges (AR) and their modern cover of loose drifting sands (D2). Planting of millet and cowpeas occurs during late summer when rainfall moistens the sands. Though rain may occur as far west as the coast, the limit of rainfed cropping on both sandy lands and silty soils is closer to the escarpment (rainfed agriculture on the latter is classed under Parkland Agriculture). There is a high risk of drifting sand on the sandy soil areas which increases to the west, and field bunds are built up on sands often only weakly stabilised by *Leptodenia pyrotechnica*.

d). A4 PUMP IRRIGATED AGRICULTURE.

Pump irrigated agricultural lands occur through the Tihama according to the supply and quality of groundwater, and small farms may be found in the middle of sandy areas where there is locally a suitable water source. Such areas usually also have found that the presence of a protective shelterbelt of suitable species provides considerable benefits to the farm, and probably help to divert mobile sands away from the irrigated lands. This mapping unit covers those areas where pump irrigation is the dominant land use. Some areas that were formerly spate irrigated are now largely under pump irrigation.

e). C1 MANGROVE WOODLAND.

The mangrove woodland forms dense thickets of *Avicennia marina*, associated with small pockets of *Rhizophora mucrionata*, along parts of the coast, and especially north of Hodeidah. The full extent of these formations were mapped in 1986 by Barratt et al (1987) and surveys conducted by Hunting Technical Services (HTS 1992 and 1993). The mangrove areas are important zones for shellfish and as breeding grounds for juvenile fish. They are also crucial in stabilising coastal mudflats and reducing the movement of sands inshore. The local fishing population understand the ecology of the mangrove, and felling of trees is reduced.

f). C2 CULTIVATED DATE PALM.

The cultivated date palm *Phoenix dactylifera* forms extensive plantations in the Tihama, and especially south of Hodeidah in the Wadi Siham, Wadi Rumman, Wadi Rimah', and Wadi Zabid. Close to the coast, these plantations are irrigated from shallow groundwater that is drawn by hand or pump. Farther inland pumping from open well and tubewells is common. The dates are commonly grown on the silty soils that form the distal plains of the wadis up to where they reach the sea. In some areas, where sands have migrated over the plains, the dates are now rooted in sands but their roots will extend into the silty subsoil. The dates are threatened in many areas by drifting sands, and numerous instances were observed of dates being progressively buried by sand dunes.

g). C3 HYPHAENE PALM WOODLANDS.

The Dom (Doum) Palm (*Hyphaene thebaica)* grows in the coastal areas, in similar environments to that of the date palm, but will also grow in areas with poorer quality groundwater and appears to have better drought resistance qualities compared to the date palm. The fronds of the Dom palm are extensively used for basket making and also have applications for sand dune stabilisation fences. The trunk, with its branching characteristic is used for holding up roofs in rural villages. Though the plant coppices well, poor management and a clear-felling policy in some areas has led to its decline. It is often associated with sand hummock formation with *Odyssea mucronata, Salsola spinescens* and other plants. Removal of the trees is often accompanied by damage to the hummocks, with wind erosion, movement of sands and associated deflation of underlying silty soils.

h). C4 SABKHAS AND BEACHES

The sabkhas and beaches are often bare of vegetation due to excessive salt spray or flooding by sea water. On the more elevated areas, and merging on to the sand sheets, there is colonisation by a range of plants *(Halopyrum mucronatum, Aeluropus lagepoides, Suaeda fruticosa, Suaeda spp., Salsola spinescens, Odyssea mucronata)*. *Propospis juliflora* can also exist on sabkha where it is transitional into mangrove. Land use includes grazing on carpets of *Aeolurous lagepoides* (Mujaylis), and salt collection (Wadi Siham mouth and Luhayyah).

i). E1 ACACIA-COMMIPHORA WOODLAND AND SHRUBLAND.

An association of *Acacia mellifera, A. tortilis, A. asak* and *Commiphora spp.* occurs over a large area of the foothills of the Tihama escarpment at low to middle elevations. There is a moderate canopy over the ground but runoff and erosion from floods was noted to be high.

j). E2 ACACIA - COMMIPHORA SHRUBLAND AND AGRICULTURE.

In this mapping unit the same vegetation association as E1 is mixed with pockets of terraced and valley agriculture in suitable locations.

k). E6 AGRICULTURE.

This unit covers the terraced agriculture that is present on the foothills of the escarpment. Crops are grown from rainfall and by diverting runoff from rocky terrain into fields.

l). E8 AGRICULTURE AND RANGELAND.

This mapping unit covers lands which has a combination of agriculture and rangeland use on the foothills of the escarpment.

m). E9 RANGELAND AND BARE AREAS.

These lands occur on the foothills of the escarpment where rainfall is too low to permit agriculture. The vegetation includes succulents, dwarf shrubs and grasses, and various species of *Acacia*.

n). R1 SALVADORA / CADABA / TAMERIX THICKET.

In the Wadi Rimah' there are very extensive thickets of *Salvadora persica*, that are grazed by camels. Elsewhere this plant, and also *Cadaba rotundifolia* and *Tamerix aphylla,* are characteristic stabilisers of sands, and are associated with sand hummocks from the coastal areas inland to the fringes of the sand plains. Despite their obvious benefits in stabilising sands these bushes continue to be cut down throughout the Tihama by land users. In some areas they appear to be protected and a coppicing policy, rather than wholesale removal of the wood for fuel, is pursued. The main benefit of the *Cadaba* and *Salvadora,* in particular, is that they produce broad all enveloping canopies that trap sand and dust. All plants produce considerable quantities of leaf litter and are thus valuable for initiating soil formation, soil structure and levels of organic matter.

o). R2 ACACIA WOODLAND.

This unit primarily covers *Acacia ehrenbergiana* woodland, which is fairly common along rangeland areas on both sandy and silty soils. Other species observed include *Acacia tortilis, Acacia seyal, Acacia nilotica*, and *Zizyphis spinachristi*. Often these appear to be associated with village sites and offer protection against drifting sands, but a frequent policy of clear felling of the *Acacia* groves leads to re-mobilisation of sands. Some of these woodland thickets receive flood waters as they lie in poor drainage areas between the sand plains and the silty lands.

p). R4 ACACIA - COMMIPHORA WOODLAND ON GRAVEL PLAINS.

In the southern parts of the Tihama, on the more gravelly plains, there is a broader range of woodland and shrub species than on the pure sands. These include *Acacia ehrenbergiana, A. hamulosa, A. tortilis, and Commiphora spp* trees, a wide range of thorny shrubs, more succulent shrubs closer to *the escarpment, and grasses notably Lasiurus scindicus, which is widely used for thatching and* basket making.

q). R5 RANGELAND.

This unit covers undifferentiated rangeland that occurs on the sandy and gravelly plains of the Tihama. The lands are extensively grazed by sheep, goats and to a lesser extent by camels. The main species include the grasses *Panicum turgidum, Odyssea mucronata*, on dunes and gravel plains, and *Lasiurus scindicus* specifically on gravel plains. Shrubs include *Leptadenia pyrotechnica, Dipterygium glaucum* in inland areas, and *Salsola spinescens, Suaeda fruticosa* on the coast. Arboreal vegetation includes scattered *Acacia ehrenbergiana, A. tortilis, Zizyphus spina-christi* and *Balanites aegyptiaca*.

r). R6 SHELTERBELTS AND AFFORESTED AREAS.

This mapping unit has been devised to indicate those areas where there has been extensive afforestation programmes, such as taking place within the TEPP, and also where there have been 'spontaneous' afforestation, due to the spread of introduced species.

In the first example the tree species are numerous and include, also *Tamerix aphylla, Acacia seyal, Acacia nubica, Capparis somaliensis, Cassia italica, Lucaena spp, Albizzia labada* and *Acacia mellifera, Acacia themeda, Conocarpus lancifolia, Parkinsonia sp, Zizyphus spina-christi*,and *Azadirachta indica*. These have been described in Chapter Five.

The second type of afforestation includes lands which have been planted or infested with the multipurpose tree mesquite, *Prosopis juliflora*. There are very substantial thickets of mesquite in many towns where they provide shade. In particular around Al Mokha and Hodeidah they provide useful protection against encroachment by wind blown sand. So luxuriant is the growth that it far exceeds any local needs to cut the tree for timber, charcoal etc. This is a benefit to the control of sand dune movement. In the area immediately north east of Hodeidah it appears as if there has been deliberate planting, but elsewhere the spread may have been unintended.

s). UR URBAN AND PERI-URBAN AREAS.

This unit covers the large industrialised and residential areas of Hodeidah.

t). V VILLAGES.

Village areas are mapped separately. Generally they lie over one type of landform but occasionally may straddle several. The sand drift hazard was also assessed for each settlement. These are highest on the sandy areas of the coastal plains and lowest on the silt plains close to the escarpment.

7.4 DRIFTING SAND HAZARD CLASSIFICATION.

A qualitative assessment was made for each mapping unit in the 1:50,000 scale mapping area. The classification is intended to aid planners of the distribution of mobile sands, ranging from the widespread nature of the drifting sand in some areas, to its absence elsewhere. Details are shown in Table 7.1.

7.5 OTHER FEATURES SHOWN ON MAPS.

The landform and land use maps also show where the principal existing sand stabilisation areas are being established as part of the TEPP. A number of areas, identified in this consultancy as warranting particular attention in the future, are also included.

The direction of winds, where these are apparent from features observed in the field or from satellite imagery and aerial photography are indicated. In some locations the overall drift directions for sand movement are also shown. The latter have not been calculated from sand velocity data, but are intended to provide an indicative display of the sand movement resulting from several wind directions.

7.6 EXTENT OF CLASSES.

Digitisation of the 1:50,000 maps has enabled the production of statistics on the area measurements of the central part of the Tihama. These are shown in Tables 7.2, 7.3 and 7.4.

TABLE 7. 2 EXTENT OF AREAS OF ACTIVE AEOLIAN LANDFORMS

CLASS (MAP CODE)	AEOLIAN FEATURE	AREA (KM^2)	%
D1s	Coastal Sand Sheets	93.1	2.2
D1n	Coastal Hummocks	157.5	3.8
D1p	Coastal Parabolics & Foredunes	145.5	3.5
D1b	Coastal Barchans	114.0	2.7
D1t	Coastal Transverse Dunes	74.5	1.8
D2s	Interior Sand Sheets	1,722.5	41.3
D2n	Interior Hummocks	89.1	2.1
D2b	Interior Barchans	35.4	0.9
D2t	Interior Transverse / Seif Dunes	1,739.0	41.7
TOTAL	-	4, 170.6	100.0

TABLE 7. 3 EXTENT OF AREAS OF UNDERLYING LANDFORMS

CLASS (MAP CODE)	LANDFORM FEATURE	AREA (KM^2)	%
W	Wadi floor	82.7	1.1
Wf	Floodplain & channel with low terrace	24.2	0.3
Fs	Silty alluvial fans	3,271.3	42.1
Fg	Gravelly fans	306.8	4.0
Fh	High angle fans on edge of Tihama Escarpment	91.8	1.2
Fd	Dissected fans and terraces	143.8	1.8
Ft	High terrace	22.2	0.3
F	Undifferentiated Fan Alluvium Fs / Fg	24.9	0.3
S1	Sandy beaches and sand bars	36.2	0.5
S2	Sabkha plain	50.7	0.6
Ar	Linear dune ridges	268.8	3.5
Ap	Undulating plain / interdune sand plain	2, 202.0	28.3
H	Rocky and hilly terrain	1, 246.6	16.0
TOTAL	-	7, 772.0	100.0

TABLE 7. 4 EXTENT OF AREAS OF LAND USE

CLASS (MAP CODE)	LAND USE TYPE	AREA (KM²)	%
E1	Acacia - Commiphora woodland & shrubland on foothills	230.0	2.9
E2	Acacia - Commiphora shrubland & agriculture on foothills	677.0	8.7
E6	Agriculture on foothills	77.7	1.0
E8	Agriculture and rangeland on foothills	130.0	1.7
E9	Rangeland and bare areas on foothills	294.0	3. 8
C1	Mangrove woodland	4.5	0.1
C2	Cultivated date palm (irrigated)	108.1	1.4
C3	Hyphaene palm woodlands	31.9	0.4
C4	Sabkha and beaches	81.4	1.1
A1	Parkland agriculture (spate irrigation with pump and rainfed)	1,069.8	13.8
A2	Wadi agriculture (rainfed & irrigation by spate , canal, pump)	858.0	11.0
A3	Rainfed agriculture (on sands)	702.0	9.0
A4	Pump irrigated agriculture	219.6	2.8
R1	Salvadora / Cadaba / Tamerix thicket in alluvial plains	30.7	0.4
R2	Acacia woodland on alluvial and sand plains	131.3	1.7
R4	Acacia - Commiphora woodland on gravel plains	95.2	1.2
R5	Rangeland on alluvial and sand plains	2,890.0	37.2
R6	Shelterbelts and afforested areas on plains	32.1	0.4
UR	Urban and Peri-urban industrial areas	36. 1	0.5
V	Villages	72.6	0.9
TOTAL	-	7,772.0	100.0

TABLE 7. 5 EXTENT OF AREAS OF DRIFTING SAND HAZARD CLASSIFICATION

MAP CODE	CLASS	SAND HAZARD DESCRIPTION	AREA (KM^2)	%
0	None	No loose sand present	2,831.8	36.5
1	Slight	Some sand present along wadi floors, old sand ridges, or drifting in from adjacent sand sheets.	679.3	8.7
2	Moderate	Limited supply of sand available. Often a seasonal problem	498.8	6.4
3	Severe	Deep loose mobile sands cover the area, as sand sheets or dunes	3,762.1	48.4
TOTAL	-	-	7,772.0	100.0

APPENDIX A TERMS OF REFERENCE.

Baseline Survey and Study of the Tihama Environmental Protection Project:
Dune Stabilisation/Farmland Protection.

Hunting Technical Services undertakes to perform the Services mentioned below.

1. Conduct a study of the dune dynamics to cover the whole of the Tihama area, with assessment of changes for those areas not covered by the five SPOT panchromatic scenes. Practical field work covers a period of seven weeks.
2. Investigate the origin of the dunes, the sediment source along the coast, the concentration of the dunes in semi-confined areas, the regional transfer of the sands into other parts of the Tihama.
3. Assess the effect of dune movement on farming and pastoral communities.
4. Characterise and classify the types of coastal and interior sand dunes and their dynamics.
5. Evaluate the effect of sand dunes on land use patterns.
6. Evaluate previous sand dune stabilisation activities and suggest improvement measures.
7. Specify the line of alignment of the dune stabilisation work in the areas which are covered by the SPOT scenes for the Tihama Environment Protection project (TEPP).
8. Prepare map sheets to cover the whole study area, with the most detailed coverage in areas covered by the SPOT scenes.
9. Produce ten copies of the complete technical report in both English and Arabic.
10. Supply both slides and print photographs for representative samples of the area covered by the study.
11. Deliver SPOT panchromatic images for the effective delimiting of the sand dunes and farm areas in the TEPP sites.
12. Produce a project map at 1:50,000 from SPOT with addition of orientation features and annotations.
13. Give an explanation of how the dunes are formed, how they become unstable and how they move.
14. Analyse the interaction of the mobilisation of the sand dunes and the agricultural development taking into consideration geomorphology, wind direction and land use.
15. Provide recommendations for the application of this information for the siting of the sand dune stabilisation and farm protection measures.

APPENDIX B WORK PROGRAMME DIARY OF HTS CONSULTANT (MR R. NEIL MUNRO) IN YEMEN (JUNE AND JULY 1998).

June 7	R.N. Munro travelled to Sana'a	July 4	Field: Southern Zone
June 8	Sana'a-Hodeidah (TDA Office)	July 5	Field: Southern Zone
June 9	TDA Office	July 6	Field: Southern Zone
June 10	Field:Wadi Siham	July 7	Field: Southern Zone
June 11	Field:Wadi Siham	July 8	Field: Southern Zone
June 12	Sanaa: Air freight	July 9	Field: Southern Zone
June 13	TDA Office	July 10	Field: Southern Zone
June 14	Field: Wadi Zabid	July 11	TDA Office.
June 15	Field: Wadi Zabid	July 12	TDA: Laboratory work
June 16	TDA Office	July 13	TDA: Laboratory work
June 17	Field: Wadi Mawr Area	July 14	TDA: Laboratory work
June 18	Field: Wadi Mawr Area	July 15	Field: Wadi Rima'
June 19	Hodeidah: Office work	July 16	TDA Office: Mapping
June 20	Field: Central Zone	July 17	Hodeidah: Mapping
June 21	Field: Central Zone	July 18	Sana'a: Visit to University
June 22	Field: Central Zone	July 19	Sana'a to Hodeidah
June 23	Field: Central Zone	July 20	TDA Office: Mapping / Lab.
June 24	Field: Central Zone	July 21	Field: Central Zone
June 25	Field: Central Zone	July 22	Field: Northern Zone
June 26	Hodeidah: Office Work	July 23	Field: Southern Zone
June 27	Field: Central Zone	July 24	Hodeidah: Friday
June 28	Field: Central Zone	July 25	Hodeidah: TDA Office
June 29	Field: Central Zone	July 26	Hodeidah: Seminar at TDA
June 30	Move to TDA Zabid	July 27	Hodeidah: TDA, depart to Sana'a
July 1	Field: Southern Zone	July 28	Sanaa: Air freight; visits to depts.
July 2	Field: Southern Zone	July 29	Sanaa: Visit Depts.; depart to UK
July 3	Field: Southern Zone	July 30	Arrive London

APPENDIX C SAND AND SOIL SAMPLES COLLECTED DURING JUNE AND JULY 1998.

TABLE C.1 LOCATION AND ANALYTICAL SCHEDULE OF SAMPLES.

Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M 28	R 19	-	Red Sea, Mutaynah 38P 0297330E. 1552900N	Hummock , 15m from shore	-	Small sample in 35mm film container
M 61	R 87	-	W Mawr, south of Zuhra on plains 38P 0280170E. 1724560N	Active sand sheet along stabilised dune	L, G.	Ditto
M 77	R 88	-	East of Luhayyah, on coastal plain 38P 0259300E. 1737530N	Hummock with Suaeda	L, G, S.	Ditto
M 78	R 89	-	East of Luhayyah, on coastal plain 38P 029300E. 1737520N	Hummock on edge of sabkha, lower than M78	-	Ditto
M 80	R 92	-	Luhayyah, edge of 'island' 38P 0253000 E. 1737100 N	Stabilised sand dune with concretions-Pleistocene?	L.	Section sampled 1: 0-30
M 80	R 93	-	Luhayyah, edge of 'island' 38P 0253000 E. 1737100 N	Stabilised sand dune with concretions-Pleistocene	L, G, C, S.	Section sampled 2: 30-90
M 80	R 94	-	Luhayyah, edge of 'island' 38P 0253000 E. 1737100 N	Stabilised sand dune with concretions-Pleistocene	L, T.	Section sampled 3: 90-150+
M 81	R 90	78	Luahaiyah, sabkha to east 38P 0258190E. 1737320N	Hummock on sabkha floor	D.	Saline
M 82	R 91	79	East of Luhayyah, on coastal plain 38P 0259200E. 1737520N	Active sand sheet with grasses, overlies old stabilised sand plain	D, C, T.	
M 95	R 56	23	Coast, S of Hodeidah airport 38P 0283600E. 1620660N	Crest of ancient coastal foredune	D.	Partly mixed in shell midden
M 96	R 57	14	ditto	Active hummock over ancient dune crest	D.	<1m high, Shawkam, Ashim *Panicum*
M 98	R 61	42	Coast, S of Hodeidah airport 38P 0283520. 1619320	Hummock on sabkha with saline crust <3 m high	D.	*Tamerix* trees (being cut)

Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M 99	R 59	15	ditto	Active transverse ridge on edge of sabkha fringe	D.	3-4 m high. No plant growth. See also M 168, 169 ,170
M 100	R 60	27	ditto	Hummock on margin of coast actively forming Up to 4m high	D.	*Tamerix*, Doum, Shawkam
M 115	R 69	40	Wadi Siham, SE of Hodeidah 38P 0308180E 1641460N	Sand drift in wadi sediment	D.	
M 118	R 70	39	E of Qutay 38P 0309350 E. 1644900 N	Ancient sand sheet + concretions	D, L, S.	
M 119	R 72	38	E of Qutay 38P 0309340 E. 1644900 N.	Active sand sheet	D, L.	
M 120	R 71	46	N of Qutay 38P 0311760E. 1653900N	Ancient stabilised sand sheet, gullied	D, L, S.	Sample on sand ridge
M 138	R 65	26	East of Dayr al Issa, N of Hodeidah 38P 0288500E. 1655990N	Hummock with *Panicum*	D.	Associated with M139 & M140
M 139	R 64	24	East of Dayr al Issa, N of Hodeidah 38P 0288510E. 1655990N	Transverse ridge with Shawkam from crest	D.	
M 140	R 63	13	East of Dayr al Issa, N of Hodeidah 38P 0288520E. 1655990N	Sand plain	D.	
M 141	R 76	34	Salif road, N of Hodeidah 38P 0259390E. 1684350N	Dark sand of seif ridge, from 60% slip face	D, L, X.	Close to road. Downwind of parabolic
M 142	R 77	29	Salif road, N of Hodeidah 38P 0253570E. 1690190N	Barchan, 72% slip face. Pale shell sands	D, L.	
M 143	R 78	3	Salif road, N of Hodeidah 38P 0253560E. 1690190N	Barchan, 2-5% crest. Pale shell sands	D.	Same dune as M142
M 144	R 79	11	West of Salif road, coast 38P 0252770E. 11683430N	Mobile sand between hummock	D.	Close to M145
M 145	R 80	32	West of Salif road, coast 38P 0252770E 1683430N	Stabilised hummock with Shawkam	D.	
M 146	R 81	41	West of Salif road, Red Sea coast 38P 0252600E. 1683430N	Beach sand	D, L.	Shells used for poultry industry
M 147	R 82	33	Salif road 38P 0257740E 1686660N	Black sand on seif like ridge	D.	Near M141

Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M148	R 83	48	Salif road 38P 0267170E. 1677490N	Dark beach sand	D, L, G, S.	Transect with 149, 150, 151
M149	R 84	16	Salif road ditto	Coastal sand hummock with *Cossabo* grass	D, L, S.	
M150	R 85	-	Salif road ditto	Ancient stabilised sand sheet	L, G, S, T.	Upper 30 cm of 5 m section
M151	R 86	-	Salif road ditto	Sub-recent nabkah with *Suaeda*	L, G, S.	Lower part of ca. 5 m section
M 158	R 68	2	W Siham 38P 0290300 - 1624630	Hummock with shawkam	D.	
M 168	R 58	58	Coast S of Hodeidah 38P 0283520E. 1619320N	Bare sabkha with accreting sand. Salt crust formation	D.	Salts make this very difficult to sieve
M 169	R 54	28	ditto	Hummock with faecal pellets	D, S.	Sieved
M 170	R 55	49	ditto	Saline material. sand sheet on sabkha 30 cm	D, S.	Not sieved – saline
M 178	R 49	7	At Ta'if, on beach 38P 0284710E. 1611020N	Low sand drift 10 m from sea	D, L, G, S.	
M 179	R 52	9	At Ta'if ditto	Hummock , 100 m from sea	D, L, G, C, S.	
M 180	R 50	4	At Ta'if, NE of the fort 38P 028530E. 1611820N	Hummock with shawkam grass	D, L, G, X, C.	
M 181	R 53	80	At Ta'if, NE of fort 38P 0286130E. 1612570N	Ancient sand sheet + shell midden. 0-5 cm	D, L.	
M 182	R 48	1	ditto	Ancient sand sheet 5-30 cm	D, L, G.	
M 183	R 51	10	At Ta'if, NE of fort 38P 0286420E. 1613150N	Transverse dune ridge slip face 65%	D, L, C	Isolated dunes NE of hummocks
M 184	R 44	5	Al Qaza village 38P 0288500E 1616440N	Barchan dune slip face, 15 m high	D, L, G, X.	Dune advancing into dates
M 194	R 46	12	Al Qaria, Wadi Kidiyah area 38P 0310460E 1618630N	Transverse dune slip face, 2 m high	D.	Dune field, NE of M 184
M 195	R 104	-	Al Qaria, Wadi Kidiyah 38P 0310460E. 1618630N	Blocky soil	L.	

Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M 197	R 45	6	Wadi Kidiya 38P 0310250E. 1616510N	Wadi floor sample	D.	
M 202	R 47	25	Sawlah village area 38P 0300940E. 1616330N	Active barchan, 2 m high	D, L, G, C, S.	
M 203	R 43	8	ditto	Ancient sand sheet surface below	D, L, G, X	
M 209	R 73	-	NE of Mansuriyah 38P 0322930E. 1627740N	Interdune ridge sand plain, rainfed millet	L.	
M 211	R 100		NE of Mansuriyah 38P 0322 E. 1627 N	$CaCO^3$ conc. in ancient sand ridge	T.	
M 214-A	R 75	31	NE of Mansuriyah 38P 0329400E. 1630900N	Ancient sand ridge soil 0-10 cm	D, L, S.	
M 214 - B	R 74	47	ditto	ditto, 10-30 cm	D, L, S.	
M 217	R 102	-	NE of Mansuriyah 38P 0329310E. 1633910N	Alluvial plain with *Dobera* Soil	L.	
M 218	R 103	-	NE of Mansuriyah 38P 0331200E. 1635760N	Clay loam soil on gravel terrace	L.	
M 220	R 32	53	Zabid area TDA well site 38P 0320260E. 1561710N	Transverse dune 3.5 m high, slip face	D.	Adjacent to well just finished
M 223	R 9	18	Al Mahdali, Wadi Ayn 38P	Drifting sand in Wadi Floor	D.	
M 226	R 7	20	Al Mahawi, S of Maqati 38P 0315780E. 1563440N	Aeolian dune on edge of fields	D.	Sands derived from wadi
M 228	R 31	19	Beyt al Mashareh 38P 0313530E. 1563520N	Slip face of barchan 2.5 m high	D	Site near half-buried old mosque
M 238	R 33	77	West of Tuhaytah 38P 0301620E. 1568120	Loose sand sheet near hummock	D.	
M 239	R 34	56	ditto	Stabilised hummock 1-2 m high	D.	Adjacent to M 238
M 243	R 27	67	Mujaylis oasis area 38P 0297550E. 1569690N	Transverse dunes	D.	
M 247	R 22	17	Mujaylis 38P 0293010E. 1569450N	Crest of parabolic dune, burying dates	D, L.	
M 248	R 24	21	ditto	Slip face with dark sand	D, L.	
M 249-A	R 26	50	Mujaylis, on Red Sea coast 38P 0292590E. 1568180N	Beach sand	D.	

Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M 249-B	R 23	70	Ditto	Beach strand occasionally flooded	D.	
M 249-C	R 21	57	Ditto	Hummock on beach plain	D.	
M 249-D	R 20	65	Ditto	1.2 m cliff section of older aeolian/alluvium	D.	
M 249-E	R 29	-	ditto	Hummock. "Older" hummock eroding. Salt crusted	X, T.	
M 249-F	R 30	-	ditto	Aeolianaite. Salt crusted. Coastal parabolic	T.	
M 250-A	R 28	76	Mujaylis. On Red Sea coast 38P 0292760E. 1568240N	Sand ripples of parabolic foredune. Fine sand	D.	
M 250-B	R 25	22	ditto	Sand ripples of parabolic foredune. Coarse sand	D.	
M 260	R 15	43	Village near Mutaynah 38P 0299000E. 1553920N	Sandsheet along edge of fields, downwind of transverse dunes, and also of M 262	D.	Dunes building up on field edge with brushwood fences
M 262-A	R 17	51	Mutaynah. S of village 38P 0298240E. 1551830N	Crest of parabolic dunes between hummocks	D, L, X, S.	A & B few metres apart
M 262-B	R 18	45	ditto	Crest of parabolic dunes on adjacent hummocks	D, L.	
M 263-A	R 14	44	North of Mutaynah 38P 0295880E. 1558220N	Large hummock accreting off sabkha	D.	
M 263-B	R 16	75	ditto	Sand sheet adjacent to hummock	D.	Few metres landward of 263-A
M 265-A	R 106	-	Fazzah, mosque site 38P 0294880E. 1559900N	Cliff section: 0-2 m. Brown aeolian sand + $CaCO^3$ concretions	L.	
M 265-B	R 107	-	ditto	Cliff section: 2-3.5 m. Alluvial sand	L.	
M 265-C	R 108	-	ditto	Cliff section: 3.5-4.7 m Loamy alluvium	L.	
M 266	R 12	61	East of Fazzah 38P 0296740E. 1560690N	Coastal barchan	D.	
M 267	R 13	-	ditto	Aeolianite. Dip at 10 deg to N	L, T.	
M 279-A	R 10	66	S of Hays on Taiz Road 38P 0330140E. 1527780	Transverse dune drifting across road	D.	Dunes 1-1.5 m high

Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M 279 - B	R 105	-	ditto	Grey gravely silt with *Melanoides sp*	L.	Fluvial sediment on fan overlain by dunes
M 291	R 8	68	Track to Yachtul 38P 0316690E. 1487810N	Hummock over gravel plains	D.	*Panicum*
M 293	R 6	54	5 km N of Mocha, coast 38P 0310760E. 1483220N	Hummock on sabkha fringe	D.	*Aeluropus*
M 297	R 3	55	East of Mocha, coastal plain 38P 0328030E. 1472990N	Barchans moving from NW over road	D.	<1.5 m high Source area unclear
M 299	R 1	52	Wadi Zabid. Ar Rawdah Headworks 38P 0337100 E. 1566050 N.	Sediment in wadi floor	D, L.	
M 302	R 5	60	Al Khawkah road 38P 0324950E. 1535800N	Sand drifts along field adjacent to wadi	D.	Reworked, blowing off wadi
M 306	R 109	-	Qatabah. Cliff section 38P	Old sand sheet with $CaCO^3$ concretions	L.	
M 308	R 11	59	W. Nakhla, N of Qatabah 38P 0309170E. 1536360N	Crest of landward edge of parabolic dune	D.	Hummocks form downwind
M 310	R 4	62	N of Al Jilab mosque. 38P 0307880E. 1547640N	Hummock field, <0.5 m high. Approx downwind of M 308	D.	Close to well along track. Water at 19 m depth
M 318	R 36	37	W Rimah valley - lower 38P 0301030E. 1579430N	Transverse Dunes in floor. <4m high	D.	Bare, with much plant debris
M 320	R 35	35	W Rimah valley - lower 38P 0292750E. 1579040N	Hummock <1 m high broad dome shaped mounds	D.	*Salvadora* dense bushland.
M 321	R 37	36	W Rimah valley - coast 38P 028980E. 1578500N	Seaward slope of parabolic - foredune	D.	
M 329-A	R 67	63	N of Hodeidah 38P 0283870E. 1643970N	Active transverse dune ridge	D.	
M 329-B	R 62	64	ditto	Ancient stabilised sand sheet	D.	
M 332 - A	R 95	71	N of W Mawr 38P 0273730E. 1749880N	Barchan 2 m high on edge of dunefields	D, L, G.	
M 332 - B	R 96	-	ditto	Soil, alluvial/aeolian plain overlain by dunes	L.	

Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M 340	R 97	73	Buhays, N of Wadi Mawr 38P 0267600E. 17665809N	Active sand sheet <1 m high	D.	
M 346-A	R 98	72	East of Buhays 38P 0290700E. 1766120N	Ancient linear sand ridge. Polygonal cracked soil surface	D, L, G, C, S.	
Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M 346-B	R 99	69	ditto	Active sand sheet at same site	D, L, G, C, S.	
M1000	R 2	30	Wadi Surdud Gorge 38P	Alluvial sediment from flood sand bar	D, L, X, S.	
M 1002	R 101	81	Zabid, TDA HQ 38P	Dust accumulated on veranda at TDA.	D, L.	Dust accumulation on July 15, 1996
M 1003	R 66	74	Hodeidah Beach 38P 0271800 E. 1644900 N.	Beach sediment	D.	
M 1004	R 110	-	Mujaylis area 38P 0298050 E. 1569050 N.	Silt on alluvial plain	L.	Flood deposit
M 1005 - A	R 38	-	Beit al Faqih Section 38P 0318450E. 1606860N	Active hummock on crest of sand ridge. (0 - 1.0 m)	L, G, C.	Loose sand
M 1005 - B	R 39	-	Ditto	Upper Sand. Recent. (1.0 - 3.0 m).	L, G, C.	Stratified with recent plastic detritus.
M 1005 - C	R 40	-	ditto	Upper Sand. Sand sheet with concretion detritus. (3.0 - 6.2 m).	L, G, C.	Startified, weakly stabilised
M 1005 - D	R 41	-	ditto	Lower Sand. (6.2 - 6.45 m) Weak soil formation	L, G, X, C.	Old land surface of ancient sand ridge
M 1005 - E	R 111	-	ditto	Lower Sand with $CaCO^3$ concrections (at 7.2 m depth)	L, C.	Massive structure of subsoil on ancient sand ridge
M 1005 - F	R 42	-	ditto	Lower Sand, with $CaCO^3$ concretions (at 8.4 m depth)	L, G, C, S.	Massive structure of subsoil.

Site No.	PRIS Lab. No.	TDA Lab. No.	Sample Location	Landform	Analysis	Notes
M 1005 - G	R 112	-	ditto	Lower Sand, with $CaCO^3$ concretions. (at 10.2 m depth)	L, C.	Massive structure of subsoil. Base deeper than 11.4 m

NOTES.

1. Explanation of Symbols for Analyses Carried Out on Samples:

   D = Particle Size Determination by Dry Sieving at TDA, Hodeidhah.

   L = Particle Size Determination by Laser Granulometry at PRIS.

   G = Geochemical Analyses at PRIS.

   X = X-Ray Diffraction at PRIS.

   C = $CaCO^3$ Equivalents Determined at PRIS.

   S = Examination by Scanning Electron Microscopy / Energy Diffuser X-Ray at PRIS.

   T = Resin Impregnated Thin Section Examined Under Microscope at PRIS.

2. PRIS is the Postgraduate Research Institute for Sedimentology at the University of Reading, UK.

3. Locations are given in UTM grid coordinates, with Easting and then Northing in metres.

APPENDIX D ANALYTICAL RESULTS DETERMINED BY SIEVING AT TDA, HODEIDAH.

TABLE D.1 PARTICLE SIZE DISTRIBUTION OF AEOLIAN SANDS.

Sample No.	Sediment Type	Silt +Clay % Weight (< 4 Phi)	Sand % Weight (+4 to -1 Phi)	Mean Grain Size (Phi)	Standard Deviation (Phi)	Skewness (Phi)	Mode of Peak (Phi)	Histogram, Principal Sand Classes and Other Notes
R 1	Sand drift in Wadi alluv.	2.5	97.5	2.58	0.624	0.095	2.6	Unimodal, FS / VFS
R 3	Inland barchan	0.5	99.5	2.57	0.564	0.084	2.9	Unimodal, FS, VFS
R 4	Inland hummock	3.5	96.5	1.86	0.670	0.831	1.5	Unimodal, MS, FS
R 5	Inland sand sheet	1.0	99.0	2.70	0.524	0.029	2.9	Unimodal, FS, VFS
R 6	Coastal hummock	3.0	97.0	1.87	0.574	0.298	1.6, 2.2	Bimodal, MS, FS
R 7	Inland sand sheet	2.5	97.5	2.38	0.734	0.356	1.6, 2.4	Bimodal, MS, FS, VFS
R 8	Inland hummock	6.0	94.0	2.81	0.765	-0.690	3.2	Unimodal, FS, VFS
R 9	Sand sheet - wadi floor	6.5	93.5	2.90	0.603	-0.292	2.9	Unimodal, FS, VFS
R 10	Inland transverse	4.0	96.0	3.09	0.488	-0.607	3.2	Unimodal, FS, VFS
R 11	Coastal parabolic	1.2	98.8	1.65	0.931	0.768	0.9, 1.4, 3.3	Complex, multimodal, CS to VFS
R 12	Coastal barchan	1.1	98.9	1.98	0.752	0.518	1.6	Unimodal, MS, FS, VFS
R 14	Coastal hummock	0.5	99.5	2.15	0.56	0.42	1.9	Unimodal, MS, FS
R 15	Coastal transverse	0.9	99.1	1.87	0.640	1.128	1.4	Unimodal, MS, FS, VFS
R 16	Coastal sand sheet	<0.2	99.8	1.73	0.60	0.532	1.4	Unimodal, MS, FS
R 20	Ancient aeol.-alluv.	0	100	1.91	0.503	0.119	1.6, 2.1	Bimodal, MS, FS
R 21	Ancient aeol.-alluv.	0	100	2.0	0.568	-0.202	1.6, 2.1	Bimodal, MS, FS
R 23	Sand sheet on beach	0	100	1.65	0.848	-0.767	1.6, 2.1	Bimodal, VCS to FS
R 25	Coastal sand ripple	0.4	99.6	0.85	0.951	0.868	0.2	Bimodal, VCS to VFS. Ripples of coarse sand
R 26	Beach sand deposit	<0.2	99.8	0.61	1.407	0.210	various	Multimodal, VCS to VFS
R 27	Coastal Tranverse	2.5	97.5	3.18	0.445	-0.189	3.2	Unimodal, FS, VFS
R 28	Coastal fine sand ripple	< 0.2	99.8	1.81	0.542	-0.095	1.6, 2.1	Bimodal, MS, FS. Ripples of fine sand
R 31	Inland barchan	1.2	98.8	2.63	0.492	-0.009	2.75	Unimodal, broad peak, FS, VFS
R 32	Inland transverse	1.0	99	2.69	0.483	-0.092	2.9	Unimodal, MS to VFS
R 33	Inland hummock	2.0	98.0	2.05	0.903	0.453	1.4, 3.2	Bimodal, CS to VFS
R 34	Inland hummock	2.0	98.0	2.70	0.597	-0.002	2.9	Unimodal, MS to VFS. Stabilised hummock

Sample No.	Sediment Type	Silt +Clay % Weight (< 4 Phi)	Sand % Weight (+4 to -1 Phi)	Mean Grain Size (Phi)	Standard Deviation (Phi)	Skewness (Phi)	Mode of Peak (Phi)	Histogram, Principal Sand Classes and Other Notes
R 35	Inland hummock	6.0	92.0	2.64	0.796	-0.108	1.9 ,3.0	Bimodal, MS to VFS
R 36	Inland transverse	2.0	98.0	2.78	0.576	-0.299	2.9	Unimodal, MS to VFS
R 37	Coastal foredune	0.5	99.5	1.86	0.726	0.421	1.5	Unimodal, CS to VFS
R 45	Wadi floor - alluvium	8.0	92.0	2.89	0.889	-1.521	3.2	Unimodal, MS to VFS
R 46	Inland transverse	1.0	99.0	2.78	0.402	0.165	2.6	Unimodal, FS VFS
R 54	Coastal hummock	1.0	99.0	2.56	0.483	-0.021	2.6	Unimodal, MS to VFS
R 56	Ancient foredune	1.5	98.5	2.86	0.435	-0.621	2.9	Unimodal, FS, VFS
R 57	Coastal hummock	1.0	99.0	2.65	0.499	-0.344	2.9	Unimodal, MS to VFS
R 59	Coastal Transverse	0.5	99.5	2.72	0.406	0.081	2.9	Unimodal, FS, VFS
R 60	Coastal hummock	3.0	97.0	2.95	0.447	0.120	2.9	Unimodal, FS, VFS
R 61	Coastal hummock	4.5	95.5	2.35	0.990	-0.493	2.9, 1.4, 3.9	Multimodal, CS to VFS. Salts binding particles
R 62	Ancient sand plain	1.5	98.5	2.58	0.728	-1.350	2.9	Unimodal,MS to VFS
R 63	Inland sand plain	3.0	97.0	2.71	0.789	-0.725	3.25	Unimodal, MS to VFS. Associated R64, R 65.
R 64	Inland transverse	3.5	96.5	2.43	0.869	0.006	3.2 & 1.9	Bimodal, CS to VFS
R 65	Inland hummock	0.5	99.5	1.94	0.70	0.671	1.4	Unimodal, MS to VFS
R 66	Coastal sand sheet	<0.1	99.9	2.12	0.548	-0.409	2.1	Unimodal, MS to VFS
R 67	Inland tranverse	0.3	99.7	2.39	0.445	0.442	2.4	Unimodal, MS to VFS
R 68	Inland hummock	1.0	99.0	2.74	0.407	-0.240	2.9	Unimodal, FS,VFS
R 69	Sand Drift in wadi	4.2	95.8	2.71	0.575	0.627	2.8	Unimodal, MS, FS, VFS
R 74	Ancient sand sheet 10-30 cm	5.0	95.0	2.75	0.635	-0.276	2.8 & 3.8	Bimodal, FS to Coarse silt
R 75	Ancient sand sheet 0-10 cm	7.5	92.5	2.89	0.712	-0.719	2.8 & 3.8	Bimodal, MS to coarse silt
R 78	Coastal barchan	0.2	99.8	1.90	0.553	0.829	1.6	Unimodal, MS, FS
R 79	Coastal sand sheet	<0.1	99.9	1.78	0.60	-0.414	2.1	Unimodal, CS, FS
R 80	Coastal hummock	<0.1	99.9	2.16	0.453	-0.242	2.1	Unimodal, MS, FS
R 81	Shelly beach sand	<0.1	99.9	1.47	0.593	-0.862	1.5	Unimodal, CS to FS
R 82	Coastal seif dune	<0.1	99.9	1.81	0.520	0.885	1.6	Unimodal, MS, FS
R 91	Coastal Sand sheet	3.0	97.0	2.71	0.632	-0.050	2.9	Unimodal, MS to VFS
R 97	Inland sand sheet	2.5	97.5	2.25	1.082	-0.094	1.1 & 3.2	Bimodal CS to VFS

Notes:

1. These samples were dry sieved at following mesh sizes (microns - μm):

Gravel:	2360; 2000;
Very Coarse Sand (VCS):	1400; 1000;
Coarse Sand (CS):	850; 710; 600; 500;
Medium Sand (MS):	425; 355; 300; 250;
Fine Sand (FS):	212; 180; 150; 125;
Very Fine Sand (VFS):	90; 75; 63;
Very Coarse Silt (CZ):	45;
Coarse to Very Fine Silt + Clay:	Pan.

These are shown as the dominant classes in each sample, eg FS, VFS. Where there is a range of particle sizes in the distribution curve of the histogram, eg VCS, CS, MS and FS, the range is shown thus: VCS - FS.

These μm data correspond to phi particle sizes from -1.485 to + 4.474 phi (μ). A statistical package, using the method of moments, was used at PRIS to convert the TDA derived data into phi classes.

2. A number of these samples were also examined by the laser granulometry method (see Table E.1). The distribution curves and modes can be compared, but Standard Deviation (SD), Mean and Skewness are not exactly comparable as a different statistical package has been used.

3. Some samples sieved at TDA have not been included in the above analysis, because aggregation due to salts and carbonates gave false readings. However, these have been examined using the laser granulometer method in which sediment is dispersed in Calgon solution prior to determination.

Conclusions:

The particle size analysis shows that all the sampled sands have over 90% sand content. Most sands have a unimodal distribution with one dominant peak in the Very Fine Sand to Coarse Sand range. Bimodal sands include certain types of hummocks and sand sheet near the coast and inland, and older sand sheets where there appears to have been secondary accumulation of finer particles.

The mean grain size of sands, in Phi units, increases away from the coast as particles become finer. Thus coastal sands generally range from 0.6 to about 2.0 phi, and rarely up to 3.2 phi; interior dunes and sand sheets from 1.9 to 2.7 phi; and ancient dunes from 2.6 to 2.9 phi. The Mode of Peak shows the grain size at the top of the distribution curve in Phi units. These often correlate to the Mean grain sizes of unimodal distributions, but will show several peaks for more complex bimodal or multimodal distributions. To convert these to millimetres refer to Table E.8.

The skewness of the samples is a statistical measure which characterises the symmetry of the distribution curve. It has negative or positive values according to whether more coarse or more fine materials are present than in a normal distribution. In the dry sieved Tihama sands there is a wide range of skewness values that appears to reflect the complex mixing of grain sizes derived from coastal areas, with additions of finer materials from dust and alluvial silts.

APPENDIX E ANALYTICAL WORK CARRIED OUT IN THE UNITED KINGDOM.

TABLE E.1 PARTICLE SIZE DISTRIBUTION DETERMINED BY LASER GRANULOMETRY.

Sample No.	Sediment Type	% Clay 0.1-2 μm (8-13.3 Phi)	% Silt 2 – 63 μm (4-8 Phi)	% Sand 63-900 μm (0.3 - 4 Phi)	Mean (Phi)	SD (Phi)	Skew -ness (Phi)	Mode Peaks (Phi)	Histogram of Particle Sizes	Principal Particle Size Classes	Notes
R 1	Sand drift	0.21	3.4	96.39	2.37	0.75	0.10	2.3	Unimodal	CS - VCZ	Reworked alluvium
R 2	Alluvial sand bank	0.11	1.14	98.75	4.40	2.13	0.51	1.0	Unimodal	CS - VFS	
R 13	Aeolianite	0.80	4.35	94.85	1.79	0.89	0.28	1.6	Unimodal	CS - VFS	$CaCO_3$ cement
R 17	Parabolic	0.07	0.49	99.44	1.61	0.49	0.12	1.5	Unimodal	CS - VFS	
R 18	Parabolic	0.06	0.38	99.56	1.53	0.54	0.09	1.5	Unimodal	VCS - FS	
R 22	Parabolic	0.11	1.44	98.46	1.97	0.64	0.24	1.75	Unimodal	CS - VFS	Crest of dune
R 24	Parabolic	0.08	1.73	98.20	2.37	0.55	0.20	2.25	Unimodal	MS - VFS	Slip face below
R 29	Hummock	4.36	14.66	80.98	2.52	2.08	0.74	1.5	Unimodal	CS - VFS + silt/clay	
R 30	Aeolianite	4.03	14.33	81.65	2.40	1.99	0.71	1.5	Unimodal	CS - VFS +silt/clay	$CaCO_3$ cement
R 38	Sand sheet	0.47	2.61	96.92	2.43	0.63	0.12	2.3	Unimodal	MS - VCZ	
R 39	Recent hummock	0.67	5.26	94.07	2.59	0.75	0.15	2.5	Unimodal	MS - VCZ	
R 40	Older hummock	1.04	8.16	90.80	2.82	0.84	0.15	2.6	Unimodal	MS - VCZ	
R 41	Ancient dune: soil	1.32	6.52	92.16	2.70	0.86	0.25	2.5	Unimodal	MS - VFS + sill/clay	Topsoil

Sample No.	Sediment Type	% Clay 0.1-2 µm (8-13.3 Phi)	% Silt 2 – 63 µm (4-8 Phi)	% Sand 63-900 µm (0.3 - 4 Phi)	Mean (Phi)	SD (Phi)	Skew -ness (Phi)	Mode Peaks (Phi)	Histogram of Particle Sizes	Principal Particle Size Classes	Notes
R 42	Ancient dune: soil	0.50	2.78	96.72	2.52	0.61	0.04	2.5	Unimodal	MS - VFS + silt	Subsoil
R 43	Ancient sand sheet	2.93	6.57	90.50	2.93	1.08	0.31	2.8	Unimodal	MS - VCZ + silt/clay	
R 44	Transverse dune	0	0	100.0	2.59	0.50	-0.04	2.6	Unimodal	MS - VFS	
R 47	Barchan	0.42	1.87	97.71	2.94	0.48	-0.02	3.0	Unimodal	MS - VCZ	
R 48	Ancient sand sheet	2.78	12.79	84.43	2.82	1.44	0.44	2.5	Unimodal	MS - VFS + silt	
R 49	Sand sheet on coast	0	0.36	99.64	1.74	0.50	0.06	1.75	Unimodal	CS - FS	
R 50	Recent hummock	0.21	1.59	98.20	2.34	0.49	0.07	2.3	Unimodal	MS - VFS	
R 51	Transverse dune	0.01	1.24	98.75	2.41	0.46	0.07	2.3	Unimodal	MS - VFS	
R 52	Hummock on coast	0.18	2.68	97.14	1.74	0.54	0.17	1.6	Unimodal	CS - VFS	
R 53	Ancient sand sheet	3.44	12.83	83.73	2.83	1.55	0.49	2.5	Unimodal	MS - VFS + silt/clay	Topsoil 0-5 cm
R 70	Ancient sand sheet	0.56	5.74	93.71	2.95	0.65	0.02	3.0	Unimodal	MS - VFZ	
R 71	Ancient sand sheet	1.29	11.24	87.47	3.20	0.72	0.09	3.25	Unimodal	MS - VCZ	Gullied surface
R 72	Active Sand sheet	0.26	2.95	96.79	2.61	0.62	0.12	1.4	Unimodal	MS – VCZ	Overlies R 70

Sample No.	Sediment Type	% Clay 0.1-2 µm (8-13.3 Phi)	% Silt 2 – 63 µ m (4-8 Phi)	% Sand 63-900 µm (0.3 - 4 Phi)	Mean (Phi)	SD (Phi)	Skew -ness (Phi)	Mode Peaks (Phi)	Histogram of Particle Sizes	Principal Particle Size Classes	Notes
R 73	Interdune sheet	2.94	16.32	80.74	3.10	1.49	0.46	2.6	Unimodal	MS – VFS + silt/clay	
R 76	Seif dune	0.16	1.31	98.53	2.19	0.47	0.06	2.2	Unimodal	MS - VFS	
R 77	Barchan	0.10	0.66	99.24	1.81	0.51	0.06	1.75	Unimodal	CS – FS	
R 83	Beach sand	0	0	100	1.62	0.46	0.06	1.5	Unimodal	CS - FS	
R 84	Hummock on coast	0	0	100	1.47	0.48	0.13	1.4	Unimodal	CS - FS	
R 85	Ancient sand sheet	4.58	14.61	80.81	2.90	1.67	0.61	2.25	Unimodal	CS - VFS + silt/clay	
R 86	Older hummock	1.63	6.01	92.36	2.36	1.07	0.30	2.3	Unimodal	CS - VFS +silt/clay	
R 87	Active sand sheet	1.17	7.78	91.06	2.59	1.12	-0.13	1.25 & 3.25	Strongly Bimodal	CS - VFS + VCZ	
R 88	Hummock on coast	8.48	35.25	56.26	4.58	2.47	0.57	2.8	Unimodal	MS - VFS + silt/clay	
R 92	Ancient dune	6.42	21.46	72.13	3.68	2.35	0.65	2.4	Unimodal	CS - VFS + silt/clay	
R 93	Ancient sand sheet	3.45	14.68	81.87	2.84	1.69	0.52	2.25	Unimodal	CS - VFS + silt/clay	
R 94	Ancient dune coast	5.92	33.56	60.51	3.67	2.63	0.48	2.0	Bimodal	CS - VFS +silt/clay	
R 95	Barchan	0.68	3.99	95.32	2.63	0.72	0.10	2.5	Unimodal	MS - VFS +VCZ	Overlies R 96
R 96	Aeol-alluv soil	5.33	34.94	59.73	3.98	2.51	0.41	1.75	Complex bimodal	CS - VFS + silt/clay	

Sample No.	Sediment Type	% Clay 0.1-2 μm (8-13.3 Phi)	% Silt 2 – 63 μm (4-8 Phi)	% Sand 63-900 μm (0.3 - 4 Phi)	Mean (Phi)	SD (Phi)	Skew -ness (Phi)	Mode Peaks (Phi)	Histogram of Particle Sizes	Principal Particle Size Classes	Notes
R 98	Ancient dune: soil	4.56	25.86	69.58	3.73	2.12	0.51	2.6	Unimodal	CS - VFS + silt/clay	
R 99	Active sand sheet	0.78	4.12	95.09	2.30	0.95	0.09	2.25	Unimodal	CS - VFS + VCZ	Overlies R 98
R 101	Aeolian dust-sand	3.22	48.09	48.69	4.11	1.06	0.37	3.8	Unimodal	FS - VFS +VCZ/CZ	Dust fall at Zabid
R 102	Alluvial soil	9.77	75.66	14.57	5.78	2.00	0.32	5.0	Weakly Bimodal	VCS-VFS +silt/clay	
R 103	Alluvial terrace soil	5.75	63.81	30.43	4.92	1.97	0.23	4.1	Unimodal	VFS + silt/clay	
R 104	Alluvial soil	5.50	40.37	54.13	4.40	2.13	0.51	3.0 & 5.25	Bimodal	CS - VFS +silt/clay	
R 105	Alluvial terrace soil	5.3	36.39	58.31	3.74	2.78	0.20	0.5 & 3.75	Bimodal	CS - VFS + silt/clay	
R 106	Ancient Aeol/All.	5.52	51.9	42.57	4.64	2.16	0.26	3.5	Broadly Unimodal	CS - VFS + silt/clay	Saline
R 107	Ancient Aeol/All.	8.36	50.43	41.22	4.99	2.21	0.47	3.5	Unimodal	FS - VFS +silt/clay	Saline
R 108	Ancient Alluvial	13.67	70.46	15.47	6.09	2.26	0.33	4.3	Unimodal	MS - VFS +silt/clay	Saline
R 110	Alluvial	8.22	47.65	44.14	4.67	2.51	0.28	2.25 4.2	Bimodal	MS - VFS + silt/clay	
R 111	Ancient dune	0.57	4.22	95.21	2.62	0.66	0.10	2.5	Unimodal	MS - VCZ	
R 112	Ancient dune	0.21	1.69	98.10	2.44	0.55	0.03	2.5	Unimodal	MS - VFS	

Notes:

1. Table E.1 provides a summary of particle size information obtained from a number of sand and soil samples that were analysed on a Coulter LS 130 Laser Granulometer at PRIS, UK. Laser granulometry provides a rapid method for the determination of particle sizes using 126 photodiode detectors that are set at intervals between 900□m and 0.1 microns (□m). For each sample, the data was displayed as a histogram (□m), with standard statistical parameters using the method of Folk and Ward (1957), and also grouped into standard classes of sand, silt and clay. Metric data (□m) was then converted into phi (Φ) units, more conventionally used in the analysis of sediments.
2. Particle size classes, VCS, CS, etc. are as indicated on Table D.1.

Conclusions:

The laser granulometry technique provides a far more precise method of determining the particle size distribution of a sediment than the traditional dry sieving methods. The samples show the detailed breakdown of the sand, silt and clay components of the sands. This is useful for sand stabilisation where the sands will be seeded with plants that will be maintained by irrigation.

Some active hummocks have over 5% clay which suggests fine materials blowing off sabkha. The alluvial origin of some sediments is characterised by high silt content, often over 30%. Ancient sand sheets have variable silt contents probably due to additions of airborne dust in the past.

The statistical analyses show broadly comparable results with the dry sieved sediments. Many of the sediments show positive skewness reflecting the presence of very fine materials, and only some active dunes and sand sheets are negatively skewed.

TABLE E.2 X-RAY DIFFRACTION DETERMINATIONS.

Sample No.	Location	Chlorite	Mica	Quartz	Amphibole	K Feldspar	Plagioclase Feldspar	Calcite	Pyroxene	Notes
R2	Wadi Surdud	Trace	-	Dominant	-	Present	Present	Trace	Present	Alluvial sand
R 76	Salif	Trace	-	Present	Present	-	-	-	Dominant	Dark seif dune near coast
R 17	Mutaynah	Trace	-	Dominant	-	Present	Present	Trace	Present	Parabolic dune crest
R 29	Mujaylis	Trace	-	Dominant	-	Present	Dominant	Present	Present	Coastal Hummock with salt crust
R 50	At Taif	Trace	Trace	Dominant	Trace	Dominant	Dominant	Present	Present	Hummock 1 km from sea
R 44	Al Qaza	Trace	-	Dominant	-	Dominant	Dominant	Trace	Present	Transverse dune
R 43	Sawlah	Trace	-	Dominant	-	Present	Dominant	Present	Present	Ancient sand dune
R 43	Sawlah	-	-	Present	-	Present	Present	Dominant	-	Concretion in ancient dune
R 41	Beit al Faqih	Trace	-	Dominant	Trace	Present	Dominant	Trace	Present	Ancient sand sheet, below paleosol

Conclusions:

These analyses provide an explanation of the mineral content of 9 sand samples. The mineral content of fresh samples from rivers entering the Tihama (R2) and those of the coattail dunes (R17, R29) and also that of the interior dunes (R44, R50) and ancient dunes (R41, R43) all show very similar X-Ray diffraction analyses. These suggest a common source of sediment.

The dark dunes of the Salif area (R76) are rich in amphiboles and pyroxenes which are clearly fresh sediments identical to those seen in the Wadi Surdud river bed and have been sorted by coastal processes.

TABLE E.3 GEOCHEMICAL DATA: ACID SOLUBLE CONCENTRATIONS (µg/g).

Sample No.	Site Location	Na	Mg	Al	Ca	Mn	Fe	Zn	K	Si
ANCIENT SAND SHEETS / DUNES: COASTAL AREAS										
R 48	Ta'if. 5-30cm. Sea 1 km	411.4	7398.0	7119.0	11497.0	225.9	10814.0	31.5	1234.0	877.0
R 85	Salif - B. 100 m to sea	1220.0	9052.0	6875.0	29891.0	247.2	10241.0	20.3	672.0	1007.0
R 93	Luhayyah. 250 m to sea	872.0	6340.0	3559.0	46126.0	124.6	7074.0	14.7	830.0	1725.0
ANCIENT SAND SHEETS / DUNES: INLAND AREAS										
R 41	Beit al Faqih	297.1	7695.0	7949.0	7538.0	266.2	11468.0	30.0	1112.0	1361.0
R 42	Beit al Faqih	313.3	7404.0	6446.0	20748.0	229.7	10310.0	25.7	905.0	1109.0
R 43	Sawlah	326.0	8641.0	7195.0	23204.0	235.3	10745.0	27.0	1061.0	3073.0
R 98	Ad Dawmah	92.9	4340.0	4289.0	4315.0	296.7	6252.0	14.9	1258.0	2029.0
RECENT AND SUB-RECENT STABILISED HUMMOCK HUMMOCKS: COASTAL AREAS										
R 52	Ta'if. 100m to sea	413.0	9077.0	7006.0	22749.0	229.1	11937.0	28.3	794.0	1019.0
R 86	Salif - B. 100 m to sea	694.0	9303.0	4483.0	10468.0	282.2	8878.0	19.4	956.0	1838.0
R 88	Luhayyah. 2 km to sea	3546.0	10253.0	4417.0	33054.0	216.8	8666.0	20.7	1550.0	1708.0
RECENT AND SUB-RECENT STABILISED HUMMOCK HUMMOCKS: INLAND AREAS										
R 50	NE of Taif. Sand hummock	369.2	7697.0	4424	21901.0	206.0	9600.0	23.4	771.0	2472.0
R 39	Beit al Faqih. Sand hummock	278.6	7241.0	6513	17019.0	245.8	11263.0	29.9	1293.0	1159.0
R 40	Beit al Faqih. Sand hummock	231.9	6317.0	6716	7863.0	253.6	10632.0	30.7	1194.0	1481.0

Sample No.	Site Location	Na	Mg	Al	Ca	Mn	Fe	Zn	K	Si
MOBILE SAND SHEETS AND DUNES: COASTAL AREAS										
R 49	Ta'if. Sand sheet, 10 m to sea	1880.0	8203.0	2900.0	43627.0	131.3	8632.0	21.8	681.0	889.0
R 83	Salif. Beach sand, sea 5 m	2329.0	9426.0	4217.0	15911.0	180.9	12661.0	46.0	531.0	480.5
R 84	Salif. Beach ridge; sea 7 m	1367.0	7718.0	3213.0	9975.0	137.4	9393.0	16.2	400.0	922.0
MOBILE SAND SHEETS & DUNES: INLAND AREA										
R 38	Beit al Faqih. Sand sheet	217.1	6286.0	5622.0	11398.0	225.4	9845.0	26.7	1020.0	1094.0
R 44	Al Qaza. Transverse dune	474.7	8292.0	7417.0	13070.0	230.9	11015.0	23.4	1039.0	976.0
R 47	Sawlah. Transverse dune	259.7	8189.0	8213.0	7418.0	262.8	12894.0	35.3	1232.0	1282.0
R 51	NE of Taif. Transverse dune	413.0	9077.0	7006.0	22749.0	229.1	11937.0	28.3	794.0	1019.0
R 95	S. of Buhays. Barchan dune	88.8	3462.0	2444.0	3203.0	170.3	4129.0	9.2	772.0	1575.0
R 87	S. of Zuhra. Sand sheet	206.0	5704.0	3715.0	23722.0	173.1	7603.0	16.8	1290.0	1879.0
R 99	Ad Dawmah. Sand sheet	78.1	2823.0	2321.0	2687.0	208.7	3914.0	9.4	721.0	1675.0

Conclusions:

Acid soluble concentrations were measure by inductively coupled plasma spectrometry (ICP) on filtered solutions derived from heating a sand sample with hydrochloric acid. The results show the range of elemental compositions for different groups of sand samples. No statistical work has been carried out on these analysis but the following observations can be made which support observations made in the field and in other determinations.

Low values of silicon and high Calcium near the coast generally appear to reflect the presence of coarser shell materials in coastal areas. Inland these calcium decline as calcium carbonate decreases and silicon becomes the more dominant constituent of the sands, either as quartz or as components of silicate minerals.

Values for Magnesium, Manganese, Iron, Zinc and Aluminium have similar concentrations throughout the area as they reflect the ubiquity of alumino-silicate minerals and rock fragments in the Tihama sands.

Values for Sodium, a constituent of soluble salts and feldspar minerals show higher values near the coast.

TABLE E.4 GEOCHEMICAL DATA: WATER SOLUBLE CONCENTRATIONS (µg/g).

Sample No.	Site Location	Na	Mg	Al	Ca	Mn	Fe	Zn	K	Si	Cl	Br	NO3	SO4
ANCIENT SAND SHEETS / DUNES: COASTAL AREAS														
R 48	Ta'if. 5-30 cm. 1 km to sea	203.1	93.40	129.30	124.5	0.699	67.00	<0.04	59.40	411.6	<3.0	<0.2	<0.50	<5.0
R 85	Salif - B. 100 m to sea	963.0	69.80	159.80	66.9	0.576	75.00	<0.04	37.09	408.0	23.5	<0.2	0.82	5.7
R 93	Luhayyah. 250 m to sea	722.0	28.04	28.05	76.3	<0.020	23.44	<0.04	51.90	87.7	39.1	<0.2	1.68	4.7
ANCIENT SAND SHEETS / DUNES: INLAND AREAS														
R 41	Beit al Faqih	58.2	35.37	71.90	107.0	0.430	42.31	<0.04	68.20	225.1	<3.0	<0.2	<0.50	<5
R 42	Beit al Faqih	59.3	17.28	27.61	90.0	0.063	19.69	<0.04	46.15	114.1	<3.0	<0.2	<0.50	<5
R 43	Sawlah	72.3	14.75	22.30	128.4	<0.020	11.79	<0.04	82.60	83.6	3.6	<0.2	2.38	<5
R 98	Ad Dawmah	57.5	31.72	113.00	113.3	0.517	56.10	<0.04	59.50	236.3	<3.0	<0.2	<0.50	<5
RECENT AND SUB-RECENT STABILISED HUMMOCK HUMMOCKS: COASTAL AREAS														
R 52	Ta'if. 100 m to sea	76.7	39.8	12.92	105.9	<0.020	11.180	<0.04	56.7	72.10	4.5	<0.20	1.48	<5.0
R 86	Salif - B. 100 m to sea	458.6	73.8	95.50	44.2	0.800	60.700	<0.04	80.8	293.60	7.6	<0.20	1.16	<5.0
R 88	Luhayyah. 2 km to sea	4104.0	1090.0	<0.01	2043.0	0.298	1.446	<0.04	167.4	17.12	567.0	1.21	26.20	22.2
RECENT AND SUB-RECENT STABILISED HUMMOCK HUMMOCKS: INLAND AREAS														
R 50	NE of Taif. Sand hummock.	106.40	18.58	22.53	86.1	<0.020	13.86	<0.04	43.89	101.1	4.4	<0.2	0.95	<5
R 39	Beit al Faqih. Sand hummock	45.10	44.57	76.40	91.3	0.561	49.51	<0.04	140.30	240.7	<3.0	<0.2	<0.50	<5
R 40	Beit al Faqih. Sand hummock	34.74	44.41	85.00	114.2	0.471	52.60	<0.04	77.20	262.4	<3.0	<0.2	<0.50	<5

Sample No.	Site Location	Na	Mg	Al	Ca	Mn	Fe	Zn	K	Si	Cl	Br	NO3	SO4
ACTIVE SAND SHEETS AND DUNES: COASTAL AREAS														
R 49	Ta'if. Sheet, 10 m to sea	1871	165.0	<0.01	149.5	<0.02	1.734	<0.04	119.4	7.200	131.0	0.51	0.6	23.7
R 83	Salif. Beach sand, sea 5 m	2557	249.5	<0.01	152.1	<0.02	1.474	<0.04	146.2	2.741	191.0	0.68	0.7	29.4
R 84	Salif. Beach ridge; sea 7 m	1316	77.6	<0.01	75.5	<0.02	2.343	<0.04	98.9	4.899	86.9	0.33	<0.5	14.6
ACTIVE SAND SHEETS AND DUNES: INLAND AREAS														
R 38	Beit al Faqih. Sand sheet	34.94	35.41	64.40	112.7	0.290	40.58	<0.04	112.30	209.2	3.7	<0.2	0.63	<5.0
R 44	Al Qaza. Transverse dune	222.20	54.30	68.80	92.6	0.453	41.58	<0.04	81.70	233.5	5.9	<0.2	4.75	5.1
R 47	Sawlah. Transverse dune	66.70	29.07	60.20	112.2	0.211	33.59	<0.04	79.10	188.9	3.6	<0.2	3.26	<5.0
R 51	NE of Ta'if. Transverse dune	146.40	28.41	36.17	104.8	<0.020	20.66	<0.04	43.33	138.9	5.0	<0.2	2.00	<5.0
R 95	S. of Buhays. Barchan dune	38.75	32.38	41.03	132.9	<0.020	31.25	<0.04	73.10	150.9	3.3	<0.2	2.13	8.1
R 87	S. of Zuhra. Sand sheet	51.20	50.30	111.30	148.1	0.928	68.50	<0.04	54.50	258.8	3.5	<0.2	1.09	<5.0
R 99	Ad Dawmah. Sand sheet.	19.83	14.84	40.87	64.2	<0.020	25.39	<0.04	35.62	115.3	<3.0	<0.2	0.81	<5.0

Conclusions:

The water soluble concentrations were measured by inductively-coupled plasma spectrometry (ICP) on centrifuged and filtered solutions derived from sand sample mixed with de-ionised water. The results show the range of elemental compositions for different groups of sand samples. No statistical analysis has been carried out on this analysis but the following observations can be made which support observations made in the field and in other determinations.

Levels of soluble Sodium and chloride reflect higher concentrations of soluble salts (halite) near the coast, but it is apparent that salts are also blown inland. Sodium is also a constituent of clay minerals that are present as airborne dust.

High levels of SO4 in some coastal areas reflect deposition of gypsum in these areas, and a general low level of incidence inland.

Levels of soluble Zinc, Manganese and Iron are all low and have a slight variation through the area. Aluminium reflecting clay minerals in fines, has moderate levels in most coastal and inland areas, but is notably very low in some coastal zones in beach deposits. Levels of Bromine, a constituent of sea water, are predictably higher at the coast but decline inland. Levels for Nitrate NO3 are generally low.

TABLE E.5 RESULTS OF % $CaCO_3$ EQUIVALENTS DETERMINED ON COASTAL AND INLAND SANDS.

PRIS Sample Number	Location	mg $CaCO_3$	% $CaCO_3$ Equivalent	Notes
R 38	Beit al Faqih (inland dunes section)	11.04	2.05	Active sand (0-1.0 m)
R 39	"	24.05	4.49	Recent hummock (1.0 -3.0 m)
R 40	"	6.88	1.52	Older hummock (3.0 - 6.2 m)
R 41	"	2.72	0.57	Paleosol (6.2 - 6.45 m)
R 111	"	28.73	5.75	Ancient dune (7.2 m depth)
R 42	"	24.05	5.18	Ancient dune (8.4 m depth)
R 112	"	25.61	5.24	Ancient dune (10.2 m depth)
R 49	Taif to Sawlah (coast-inland transect)	77.64	15.84	Hummock, at Ta'if, 10m from sea
R 52	"	45.90	9.33	Hummock, at Ta'if, 100m from sea
R 50	"	28.21	5.48	Hummock, close to Ta'if fort.
R 51	"	29.78	5.89	Transverse dune, North East of Ta'if village
R 44	"	13.65	2.78	Transverse dune at Al Qaza village
R 47	"	3.24	0.69	Transverse dune at Sawlah village
R 91	Luhayyah (coastal area transect)	4.28	0.88	Active sand sheet at coast
R 93	"	71.40	15.09	Ancient sand dune at coast
R 99	Ad Dawmah (inland dunes section)	0.00	0.00	Active sand sheet overlying ancient dune
R 98	"	4.28	0.88	Paleosol on ancient dune with polygonal cracks

Conclusions:

The results of the CaCO3 determinations suggest that in the majority of cases looked at the CaCO3 equivalent decreases inland with distance from the sea. The samples taken between At Taif and Sawlah show a decrease from 15.84 to 0.69% in the active dunes. This may be attributed to the crushing effects that take place as sand grains are saltated, rolled and wind abraded by other particles as they move inland from the coast. It is thought that much of this abrasion and loss of calcium carbonate as fine dust occurs close to the coast.

Very low values occurring on a paleosol developed on ancient dunes inland at Beit al Faqih (sample R41) suggest that carbonate has been leached during soil formation on these dunes.

Other low values such as on active dunes at Luhayyah near the coast, and inland at Ad Dawmah area, suggest that the modern dunes in this location are derived from sands that are depleted in calcium carbonate, such as the older dune sediments.

TABLE E.6 DATA FROM X-RAY ANALYSIS SCANNING ELECTRON MICROSCOPE.

Sample No.	Sediment Type and Location	Description
R 2	Alluvial sediment on sand bar, Wadi Surdud. Sediment source for wadis/sand dunes. Gorge of W. Surdud	Fresh grains with angular fractures caused by recent transportation in river bed.
R 17	Parabolic dune crest at Mutaynah on coast	Rounded to angular grains showing effect of aeolian abrasion. No obvious coatings on many grains which are generally fresh looking
R 47	Active barchan dune at Sawlah	Sand grains have sub-rounded features typical aeolian abrasion, and show presence of clay mineral and oxide coatings, with iron, aluminium, potassium. Grains may include older sands being re-worked. Fresh grains of mica also show that transportation from coastal source does not break down mica. Salts also present as NaCl in cavities of mineral grains
R 52	Active sand hummock on beach, At Ta'if area	Rounded grains with carbonate coatings may be oolitic grains from sea, but show secondary growth on surface; quartz grains with coatings showed absence of late-grain breakages from aeolian collisions
R 54	Active sand hummock on sabkha fringe terrain south of Hodeidah	Shows gypsum and halite crystals on own and as infillings of cavities in quartz grains. Typical of coastal environment high in soluble salts
R 55	Active sand sheet on sabkha with salt crystals. Coast, south of Hodeidah	Salt crystals show mixture of gypsum and halite, probably enclosing finer grained quartz and rock fragments. Quartz grains on own have few coatings and are quite angular showing lack of aeolian abrasion close to sea
R 71	Ancient sand sheet, stabilised by soil formation. North of Qutay.	Subrounded grains of quartz show thick clay mineral and iron oxide coatings, indicated by high Fe, Al, K, Mg, Ti
R 74	Ancient linear dune ridge, stabilised by soil formation. North-east of Mansuriyah. Sampled at 10-30 cm	Subrounded grains of quartz and feldspars with heavy clay mineral and iron oxide coatings. Crystals of NaCl (halite) show that salts have been leached down profile and crstallise.
R 75	Ancient linear dune ridge, stabilised by soil formation. North-east of Mansuriyah. Sampled at 0-10 cm	Rounded quartz and feldspar grains with thick coatings of iron oxides and clay minerals.
R 98	Ancient sand sheet, North of Wadi Mawr at Ad Dawham	Rounded to subrounded quartz and other mineral grains, with thick secondary coatings of clay minerals (K, Al, Mg,) and oxides (Fe, Ti, Mn). Also secondary crystals of calcite

Explanatory Note.

Sand grains were selected from a number of samples and attached to glass plates. These were then carbon coated under vacuum and examined in a scanning electron microscope at high magnification. X-ray bombardment of grain surfaces and individual crystals provided an analysis of major elements present. These were then related to grain characteristics and features to provide an identification of types of minerals and any surface coatings present.

TABLE E.7 THIN SECTION ANALYSIS.

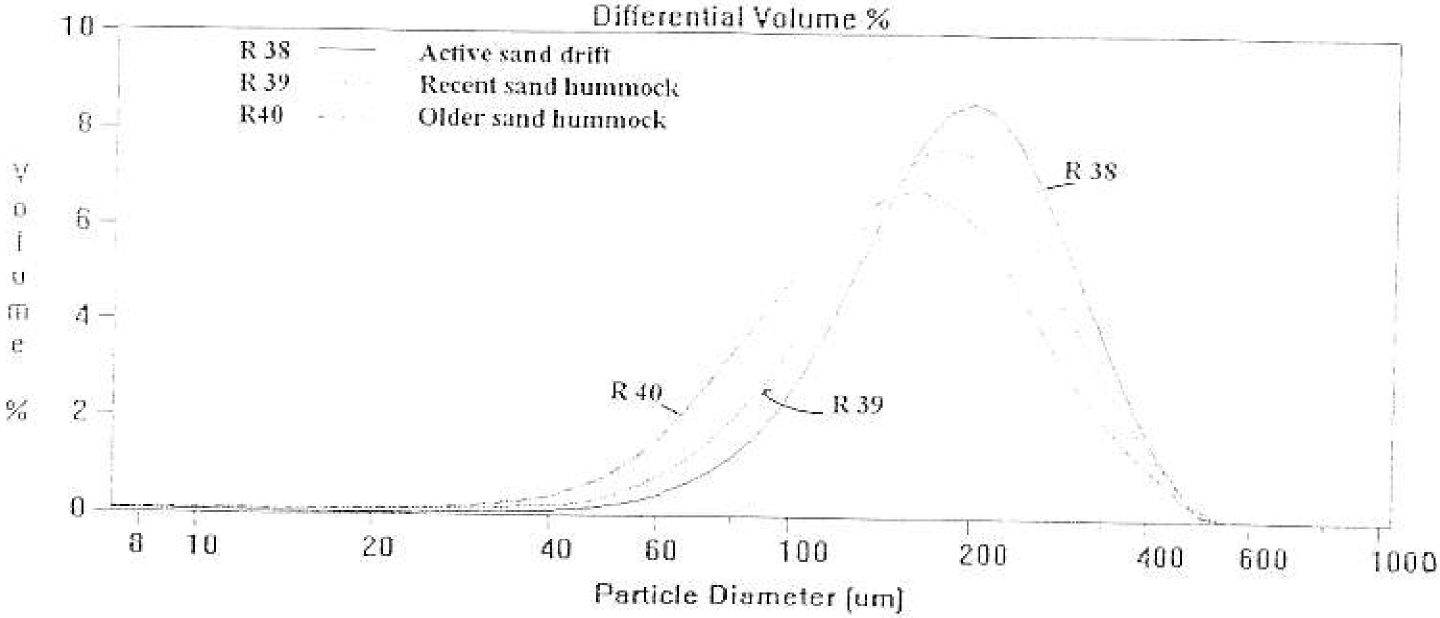
Sample No.	Sediment Type, Relative Age and Location	Field and Thin Section Description
R 13	Aeolianite. Coastal. Sub-recent. East of Fazzah	Finely stratified sandy deposit. Subangular to well rounded grains of Quartz, Opaques & Carbonate. $CaCO_3$ on rims of grains lightly cementing sediment.
R 29	Aeolianite. Coastal. Sub-recent. Mujaylis area	Thinly bedded sediment. Subangular to rounded grains of Quartz, Pyroxene, Opaques, Fe Oxide, Carbonate fragments and rock fragments. $CaCO_3$ on grain rims cementing sands.
R 30	Aeolianite. Coastal. Ancient. Mujaylis area	Thick bedded very hard sand overlain by alluvial silt deposit with 10 cm diameter polygons. Sand has subangular to rounded grains of Quartz, Carbonate, Feldpsar, Pyroxene and Opaques. $CaCO_3$ rims cementing the grains.
R 85	Aeolianite. Coastal. Ancient, former surface soil. Track to Salif. Salif-B section	Weakly angular blocky structure. Subangular to rounded grains of Quartz, Opaques, Fe oxides, shell fragments. Thin and weak $CaCO_3$ cement on rims of grains.
R 94	Concretions in soil formed in ancient aeolian sand. Coastal at Luhayyah	Soil developed in sands, sampled at 90-150 cm. Rounded grains of Quartz, Opaques & Fe-oxides. Large clasts of microcrystalline carbonate. $CaCO_3$ on grain rims are earlier phase of development.
R 100	Concretion in ancient aeolian sands up to 8 m thick of stabilised linear dune. Inland, NE of Mansuriyah	Sampled 5 m from surface in gully cut into aeolian sands. Subangular to rounded grains of Quartz, Pyroxene, and Opaques. $CaCO_3$ rims around grains and irregular patches of calcrete. Root channel features.

TABLE E.8 SUMMARY OF GRAIN SIZE CLASSIFICATION

	US Standard sieve mesh	Millimeters		Phi (φ) units	Wentworth size class
GRAVEL	Use wire squares	4096		-12	
		1024		-10	boulder
		256	256	-8	
		64	64	-6	cobble
		16		-4	pebble
	5	4	4	-2	
	6	3.36		-1.75	
	7	2.83		-1.5	granule
	8	2.38		-1.25	
	10	2.00	2	-1.0	
SAND	12	1.68		-0.75	
	14	1.41		-0.5	very coarse sand
	16	1.19		-0.25	
	18	1.00	1	0.0	
	20	0.84		0.25	
	25	0.71		0.5	coarse sand
	30	0.59		0.75	
	35	0.50	1/2	1.0	
	40	0.42		1.25	
	45	0.35		1.5	medium sand
	50	0.30		1.75	
	60	0.25	1/4	2.0	
	70	0.210		2.25	
	80	0.177		2.5	fine sand
	100	0.149		2.75	
	120	0.125	1/8	3.0	
	140	0.105		3.25	
	170	0.088		3.5	very fine sand
	200	0.074		3.75	
	230	0.0625	1/16	4.0	
SILT	270	0.053		4.25	
	325	0.044		4.5	coarse silt
		0.037		4.75	
		0.031	1/32	5.0	
		0.0156	1/64	6.0	medium silt
	Use	0.0078	1/128	7.0	fine silt
	pipette	0.0039	1/256	8.0	very fine silt
CLAY	or	0.0020		9.0	
	hydro-	0.00098		10.0	clay
	meter	0.00049		11.0	
		0.00024		12.0	
		0.00012		13.0	
		0.00006		14.0	

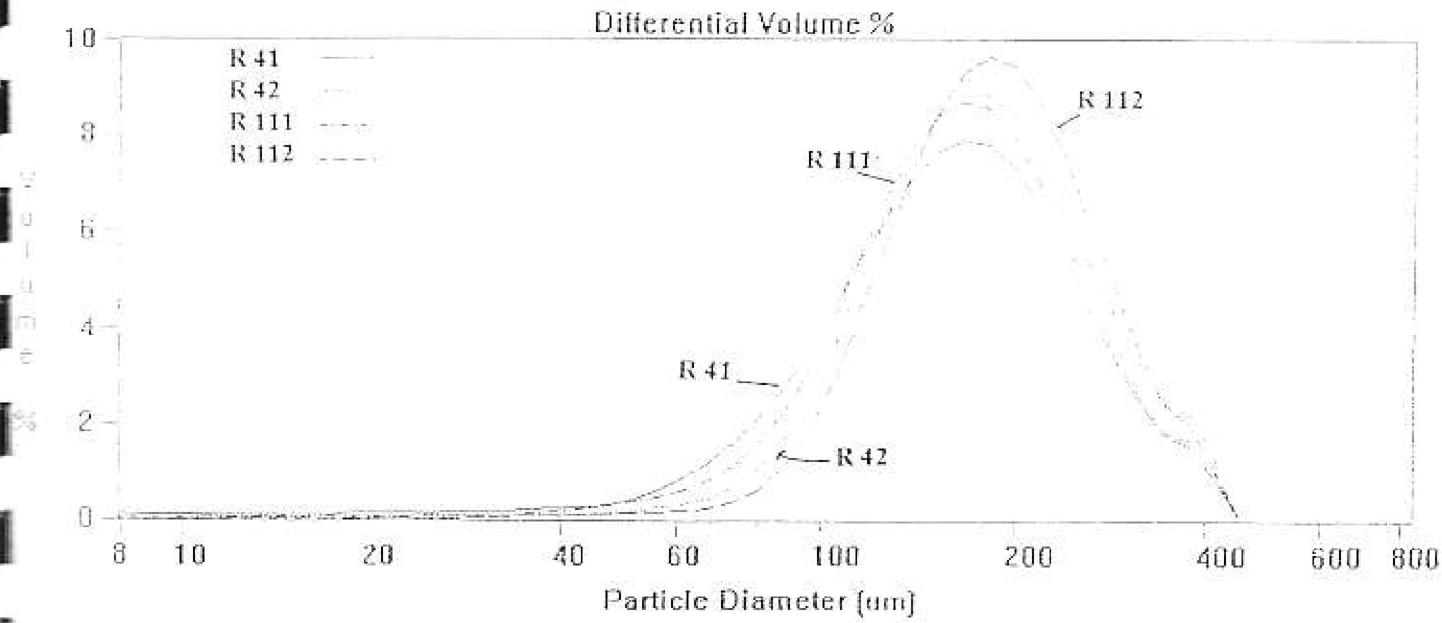
SOURCE: PYE and TSOAR, 1990.

FIGURE E.1A RESULTS OF LASER GRANULOMETRY ANALAYSIS OF DUNE SANDS AT BEIT AL FAQIH SECTION. UPPER LAYERS



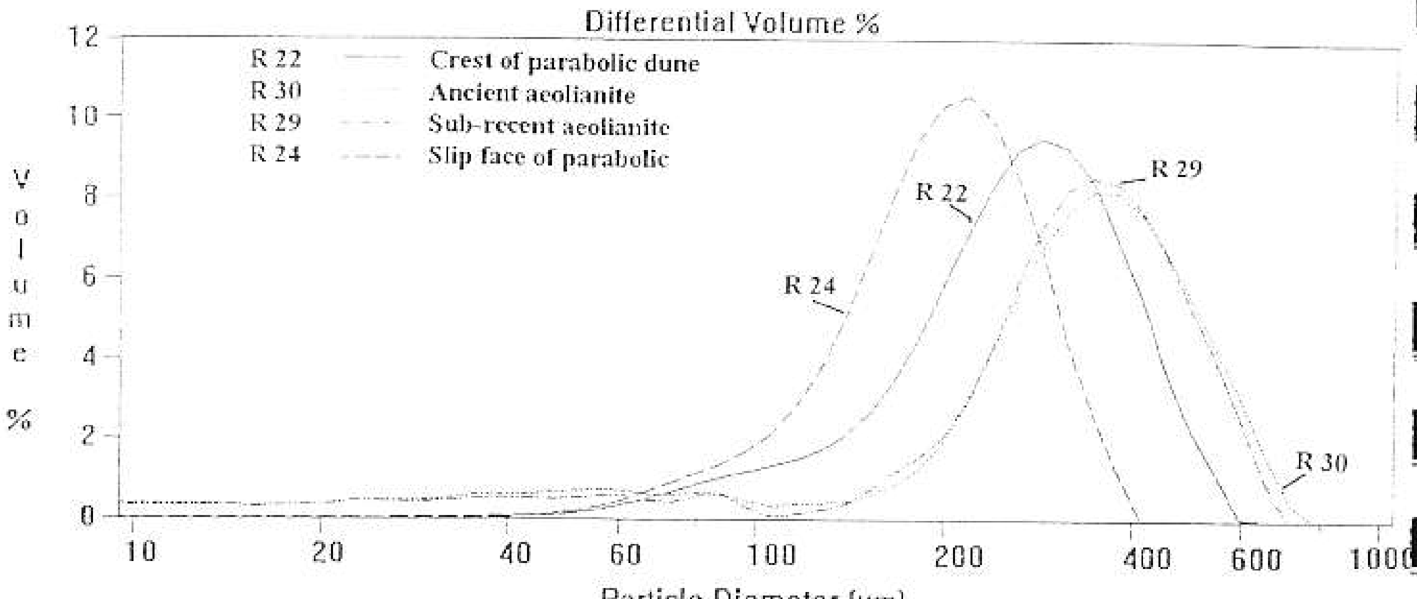
Explanatory Notes: The Beit al Faqih section was described in a quarry cut into a stabilised ancient sand ridge with active sands on the crest. The sequence is over 9 meters thick. In Figure E.1-A, an active sand drift (R 38) overlies weakly stabilised recent hummock sands (R 39) and an older sequence of sands with eroded coarse and fine particles (R 40). The analysis shows that the modern sands are coarser and better sorted than the layers below, whilst the layer with eroded materials (R 40) has appreciable silt and clay accumulation and has a mode which matches that of the underlying layers R 41 and R 111.

FIGURE E.1B RESULTS OF LASER GRANULOMETRY ANALAYSIS OF DUNE SANDS AT BEIT AL FAQIH SECTION. UPPER LAYERS



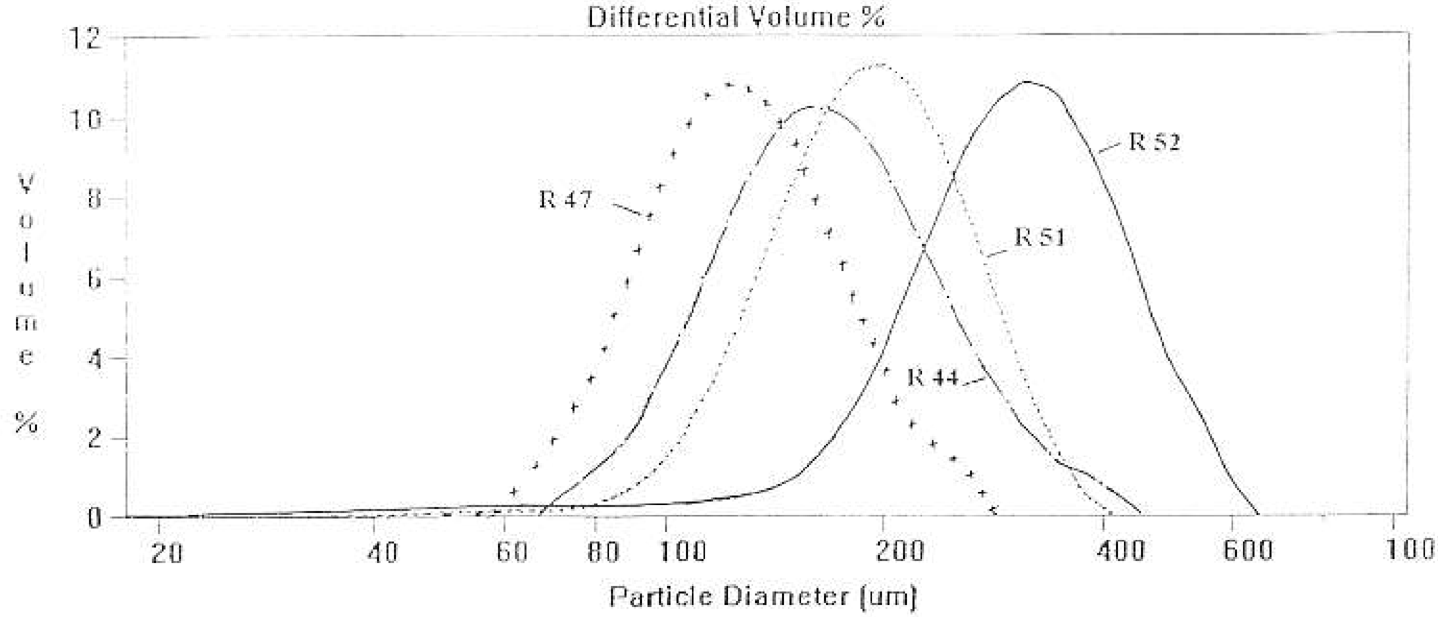
Explanatory Notes. Figure E.1-B. Beit al Faqih: Lower Layers. These represent the sediments of the ancient sand ridge dune surface with a stabilised soil (R 41) overlying softer sands (R111, R 42, R112). The analysis shows that silt and clay content decreases with depth. The modes of samples R 42 and R 112 indicate that basal layers are slightly coarser and more like the recent and active sands.

FIGURE E.2 RESULTS OF LASER GRANULOMETRY ANALYSIS OF SAND DUNE SAMPLES AT MUJAYLIS.



Explanatory Notes: The figure shows the particle size distribution curve of four aeolian sand samples from the Mujaylis area, Wadi Zabid. Sample R 24 and R 22 lie on the slip face and crest respectively of a parabolic dune that is burying date palms. Note that the slip face is composed of finer sand. The two samples on the right of the figure are from recent (R 29) and ancient (R 30) carbonate cemented aeolianites that occur close to the sea, 1 km from the parabolic dune, and suggest that coarser and comparatively poorer sorted sands of the aeolian sediments occur closer to the sea and sand source.

FIGURE E.3 RESULTS OF LASER GRANULOMETRY ANALYSIS OF DUNE SAMPLES ON TAIF - DURAYWIMI TRANSECT.



<u>Explanatory Notes</u>: The figure shows the particle size distribution curves of four aeolian sand samples collected along a transect from the beach at At Ta'il, inland to Al Sawlah. Sample R 52 is an active sand hummock located 100 m inland of the beach; sample R 51 is from a transverse dune overlying ancient sand plain, two kilometers inland; sample R 44 is from a barchan dune advancing onto dates at Qaza village, about 5 kms from the sea; and sample R 47 is a barchan closing on agricutlural lands at Sawlah, 16 km from the sea. The results strongly suggest that the modal diameter of sand grains rapidly decreases inland, from 316 microns (1. 9 Phi) at the coast to 127 microns (3. 0 Phi) at Sawlah. Thus, dunes threatening agricultural lands inland will be moved by lighter winds than those on the on the coast since the smaller sized grains will have lower threshold velocities for movement. This is borne out by wind speed records and recorded movements of sand in the Tihama.

FIGURE E.4 RESULTS OF LASER GRANULOMETRY ANALYSIS OF SAND DUNES IN THE SALIF AREA.

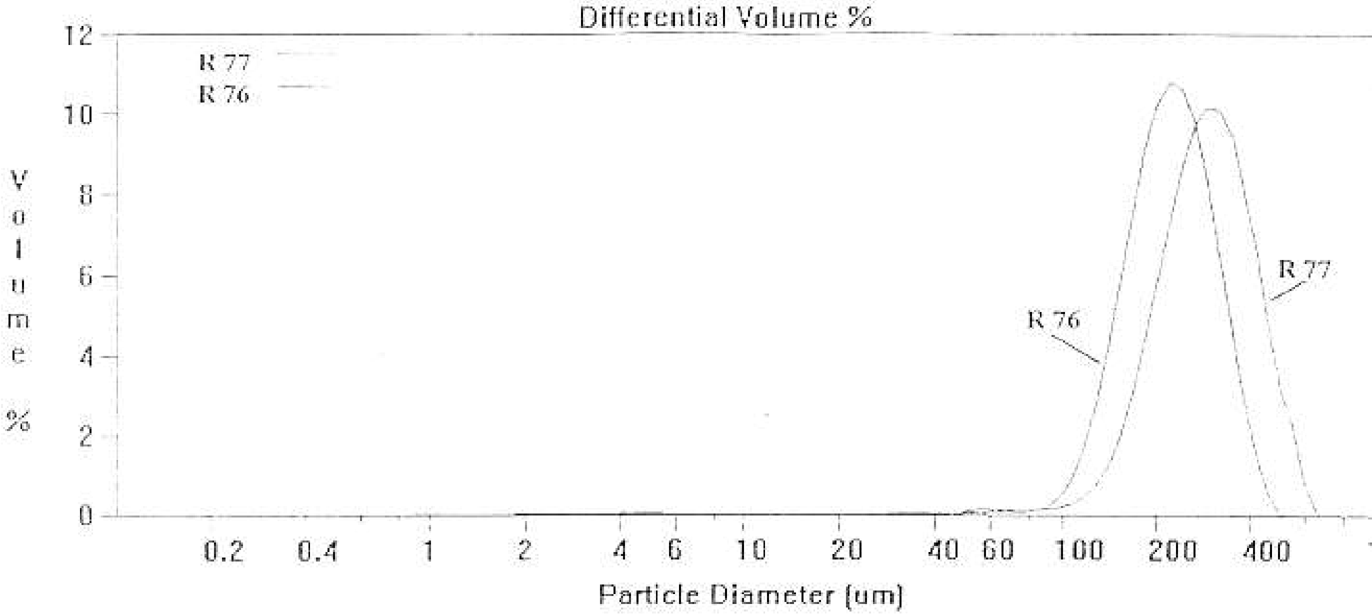
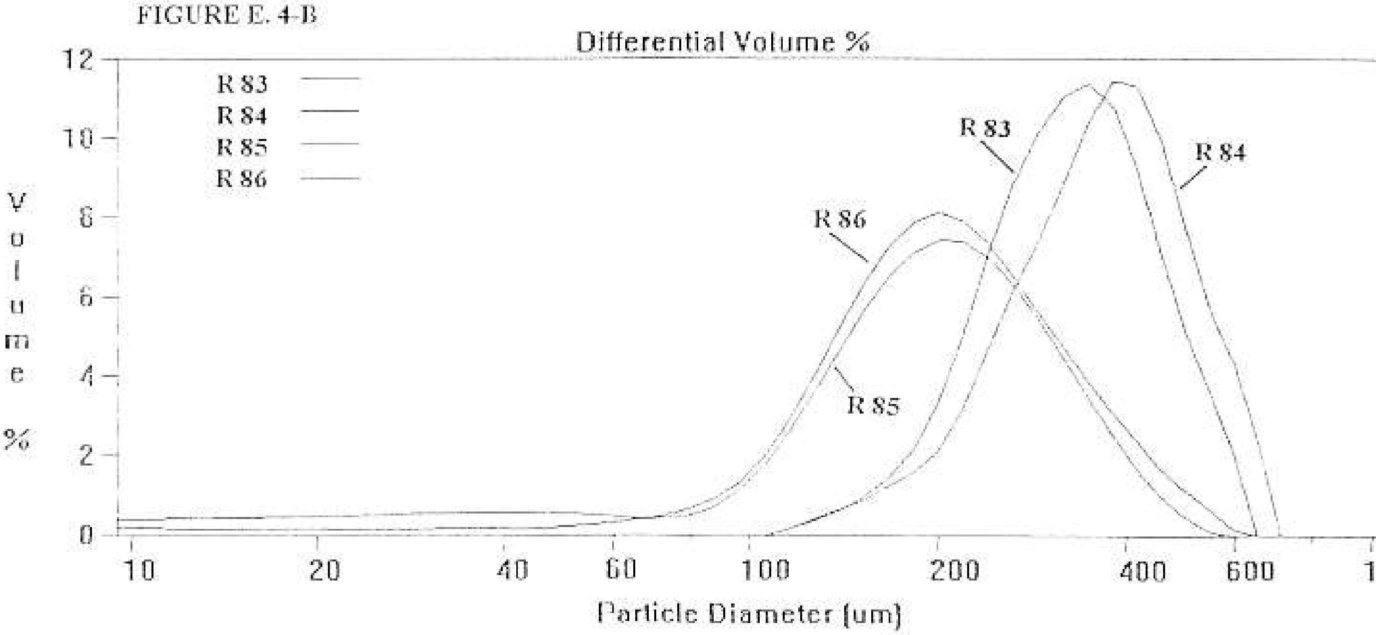
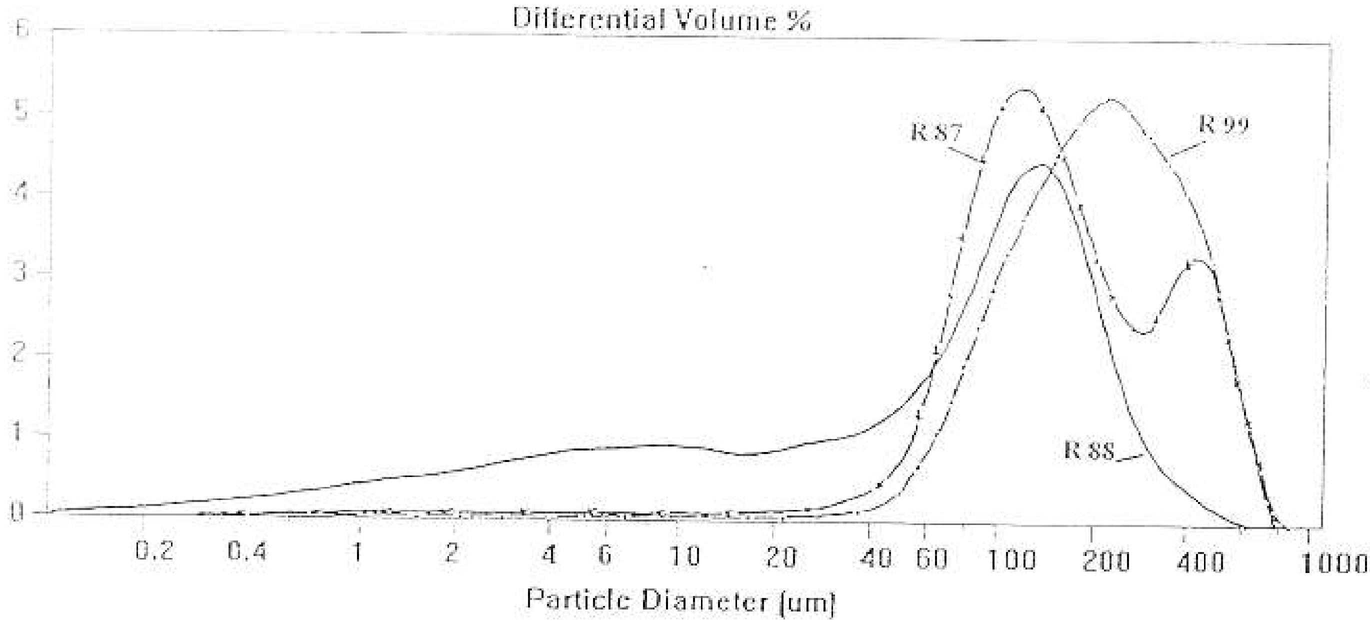


FIGURE E. 4-B



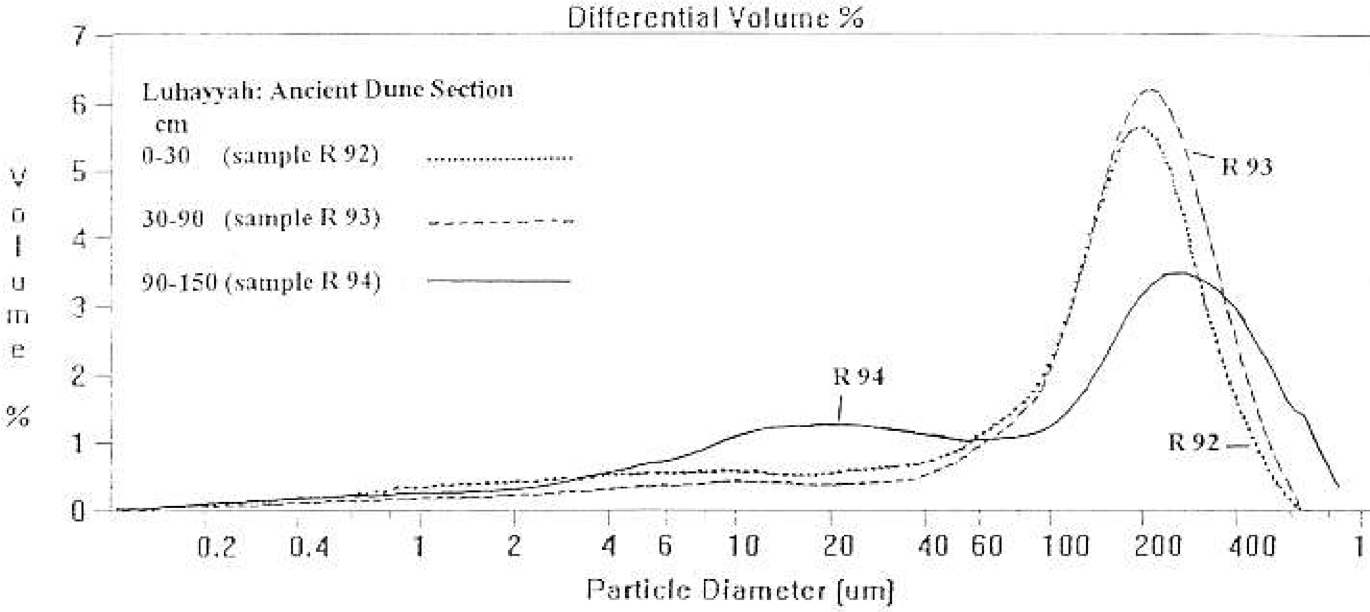
Explanatory Notes: The sand dunes in the bay south of Salif peninsula include shelly beach-sand sands forming parabolics and barchans (R 77) with darker sands, largely comprising heavy minerals, forming linear seif dunes (R 76), of Figure E. 4 A. The barchans are slightly coarser grained than the seif dunes. Further south, and shown in Figure E. 4-B, poorly sorted beach sands (R 83) pass into sand hummocks stabilised by *Halopyrum mucronatum* (R 84). These move inland past eroding sand hummocks (R 86) that in turn abruptly overlie a soil developed on the ancient aeolian sand plain formation (sample R 85). The modern sands are similar to the barchan and seif dunes to the north with strongly unimodal fine to medium sands, whereas the older sands (R 85 and R 86) show almost 20 % silt and clay accumulation and significantly, a much finer modal sand size of around 200 microns. This suggests that the sand fractions of the older aeolian formation accumulated at some distance inland from the source area, assuming they were derived from beaches.

FIGURE E.5 RESULTS OF LASER GRANULOMETRY ANALYSIS OF SAND DUNE SAMPLES IN THE LUHAYYAH - WADI MAWR – AD DAWMAH AREA.



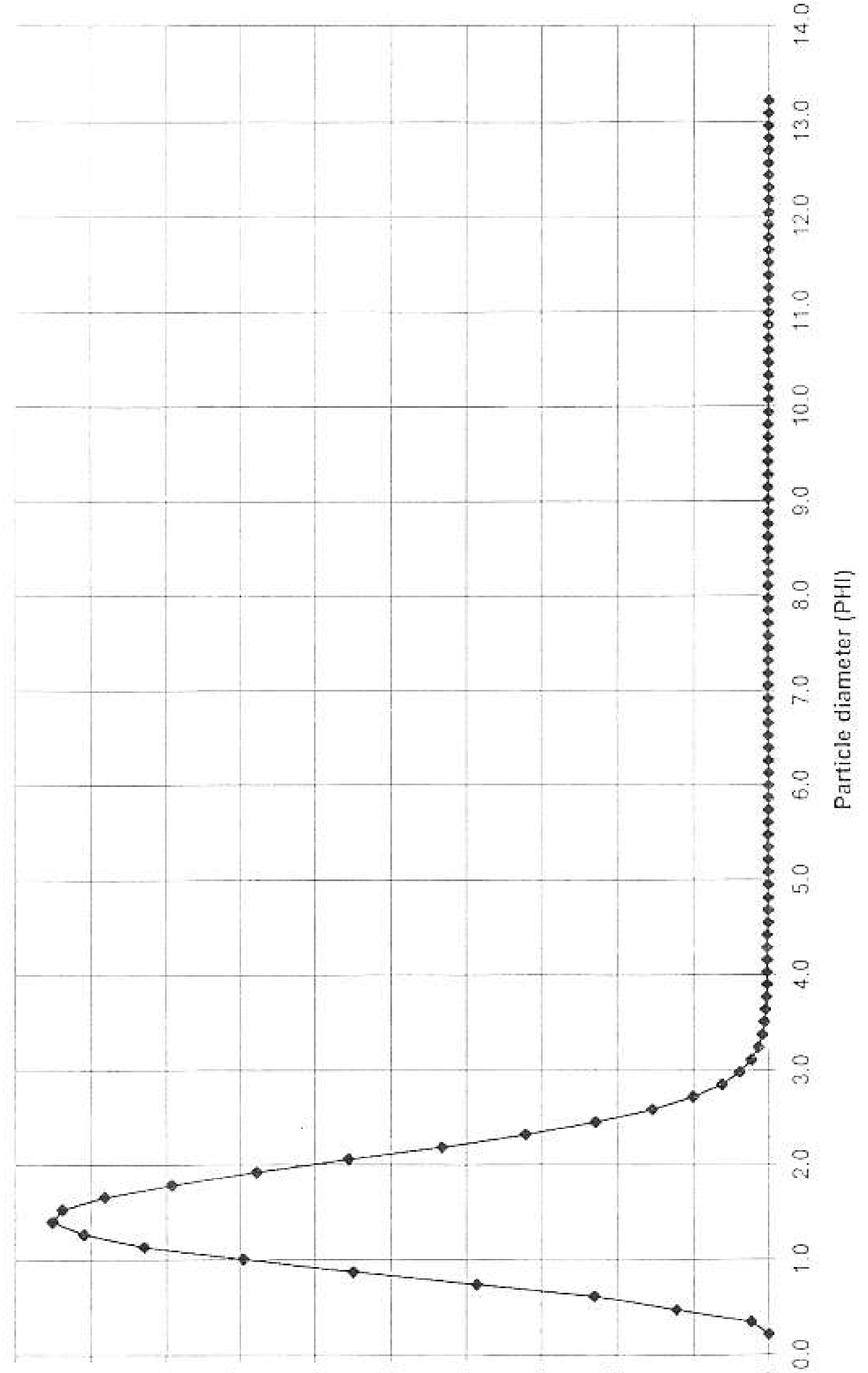
Explanatory Notes: This compares three samples collected in the northern part of the Tihama. Sample R 88 is a unimodal sand from a sand hummock on the coastal plain due east of Luhayyah. There is almost 44% of silt and clay, whose origin at present is not exactly determined, but it may be that fine sediments encased in salts are being deflated from the mangrove mudflats to the west. Sample R 99 is an active sand sheet that appears to be developed from cultivation of an ancient sand ridge in the Ad Dawmah area, and shows a broad unimodal peak of coarse to very fine sand. Finally, sample R 87 is a sand sheet encroaching onto rainfed farmland on the south side of Wadi Mawr. This shows a bimodal distribution, which is unusual in the Tihama aeolian sands collected but characteristic of sand sheets described elsewhere. In terms of sand stabilisation each of these sands will require a slightly different management technique.

FIGURE E.6 RESULTS OF LASER GRANULOMETRY ANALYSIS OF SAND SAMPLES FROM LUHAYYAH AREA.



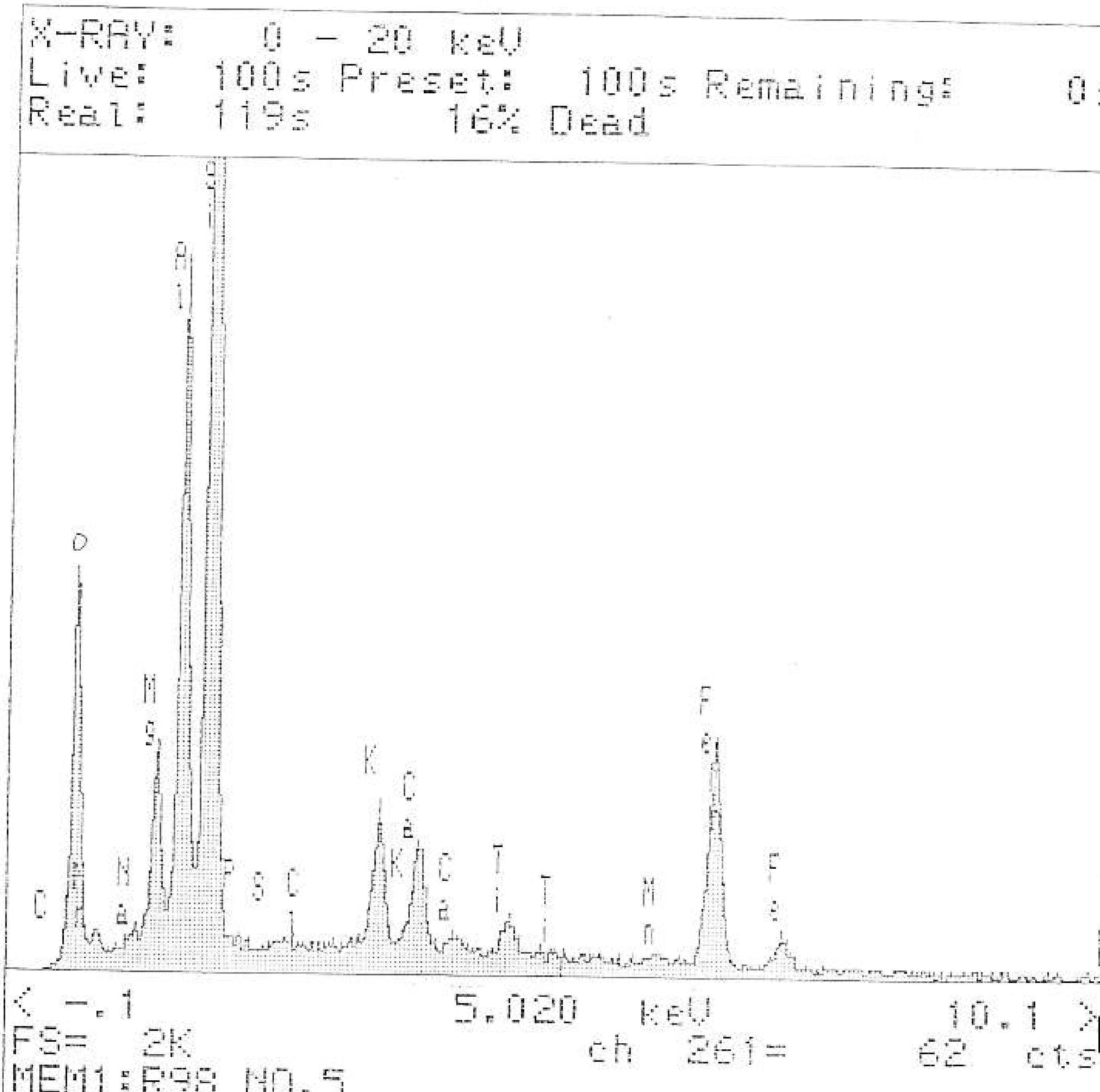
Explanatory Notes: The analysis shows the particle size distribution curves for three samples from a section in a stabilised ancient sand dune on the coast at Luhayyah. The surface samples (0-30 and 30-90 cm) show unimodal distribution at around 200 microns, with significant silt and clay. The lower horizon (90-150) shows a peak with coarser sand and a secondary peak with accumulation of silt, and may represent a buried soil.

FIGURE E.7 RESULT OF LASER GRANULOMETRY ANALYSIS OF SAND SAMPLE FROM MUTAYAH



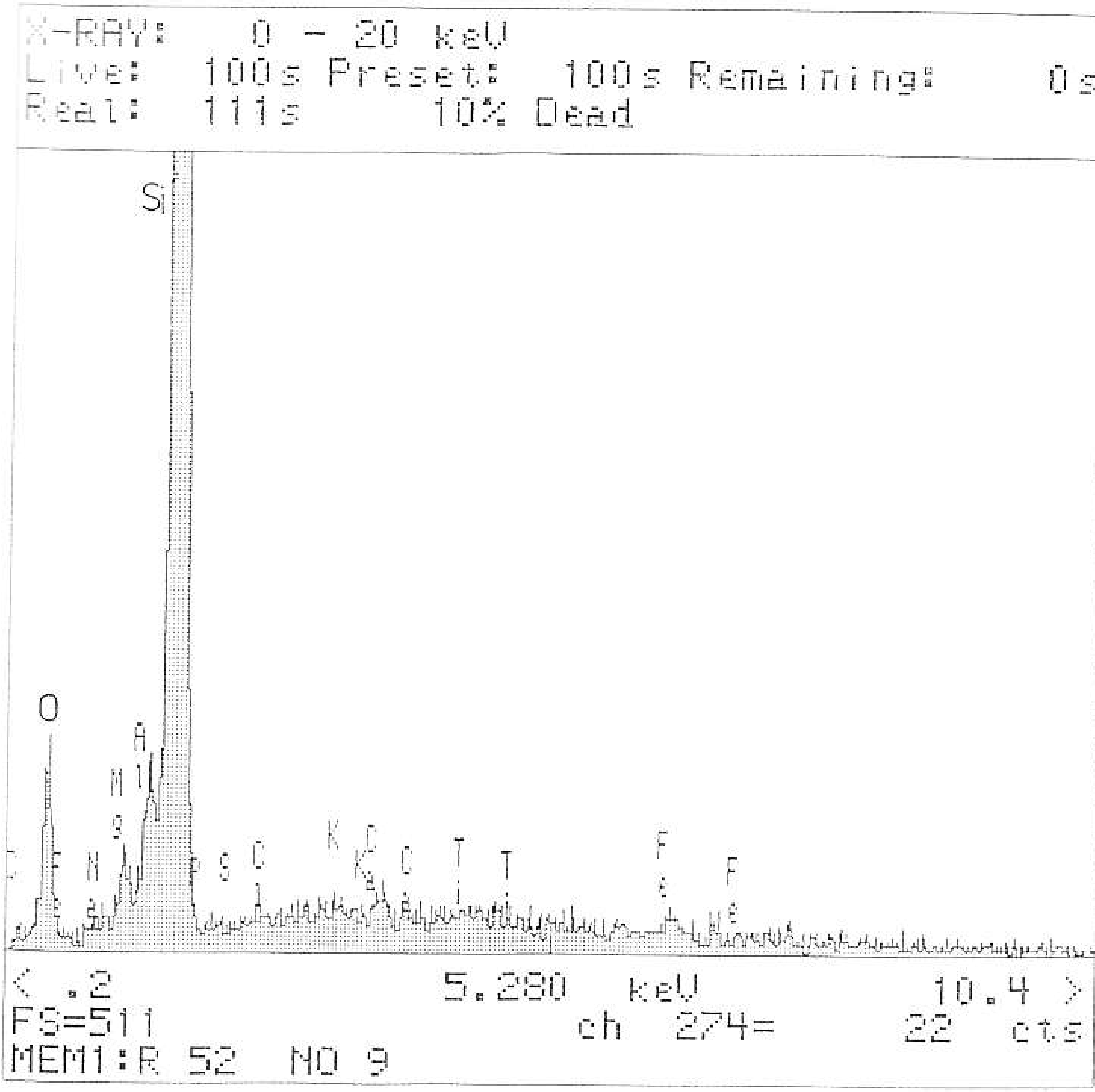
Explanatory Notes: This shows the particle distribution curve (in Phi) of sample R 17, located on the crest of a parabolic coastal dune at Mutaynah, Wadi Zabid. The analysed sand has a distinctive unimodal distribution mainly of medium sand with a modal peak at 1. 5 phi (0. 35 mm). The sample has 99. 44 % sand (4.0 to -1.0 phi). Analysis of the data in the long 'tail' of the curve shows that minute increments of silt and clay occur down to 9.0 phi (2 microns). From 9.0 to 13. 2 phi there is almost no clay present and the trace is flat. The laser granulometer measures from 0. 980 to 900 microns (approx. +13.2 to 0.0 phi). The finer materials on coastal dunes suggest that fine sorting is accomplished further inland.

FIGURE E.8 RESULT OF SCANNING ELECTRON MICROSCOPE EXAMINATION (S.E.M) OF A SAND GRAIN FROM AD DAWMAH, NORTH OF WADI MAWR



Explanatory Notes: The sand particle (sample R 98, site M346 A) was a sub-rounded grain of quartz with yellow staining, from a stabilised ancient aeolian sand ridge. The SEM showed secondary crystal growth and coatings on the surface. Dispersive X-Ray elemental qualitative analysis, illustrated in Figure E. 8, shows the high peaks of Si and O for the quartz grain, and suggests that clay mineral and oxides dust coatings are present, given by peaks in Al, K, Fe, Mg and Ti. In addition, there is secondary carbonate on the surface (Ca, C, O) and accumulation of airborne salts (Na Cl).

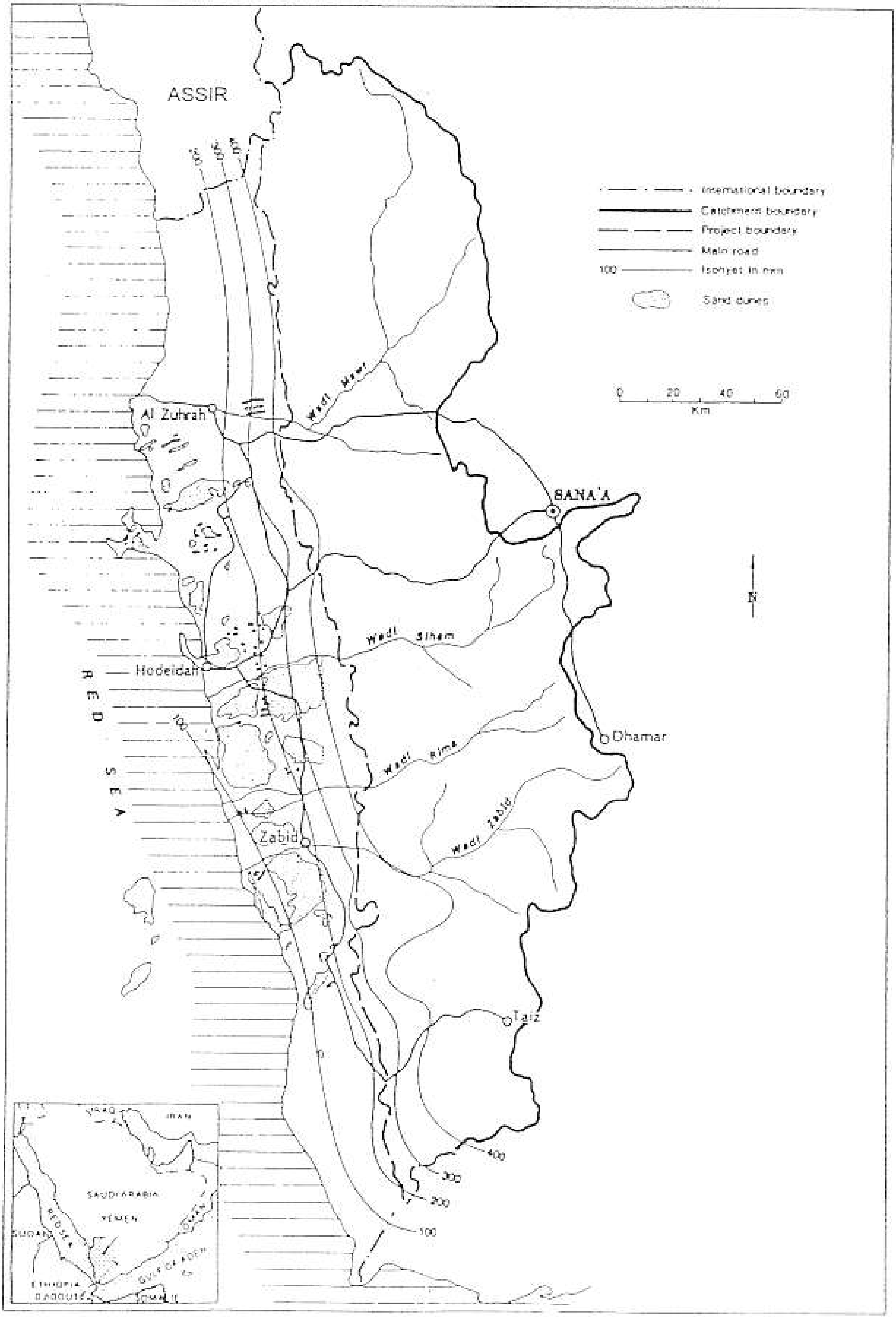
FIGURE E.9 RESULT OF S.E.M. EXAMINATION OF A SAND GRAIN FROM AT TA'IF, WADI RUMMAN



Explanatory Notes: This is a subrounded grain of clear quartz, from a sand hummock 100 m from the sea at At Ta'if (sample R 52, site M179. The S.E.M. shows that there are no obvious coatings, and an absence of late-grain breakages indicative of aeolian abrasion. The S.E.M. Dispersive X-ray elemental analysis shows high peaks of Si and O, for the quartz. Secondary small peaks of Ca, Al, Mg, Cl, and Na are most likely due to small quantities on the surface of biogenic shell fragments and salts acquired from wind-borne spray off the sea.

FIGURE E.10 LOCATION OF ACTIVE SAND DUNES ON THE TIHAMA

SAND DUNES LOCATION IN TIHAMA PLAIN



Source: FAO Investment Centre, 1990.

Abids, S.E.A.	1994	A study of sand stabilisation in eastern Saudi Arabia. Engineering Geology v. 38 (1994) p. 65-79.
Aitken, M.J.	1994	Optical Dating: A Non-Specialist Review. Quaternary Geochronology (Quaternary Science Reviews) v. 13, p. 503-508
Al-Anbaawy, M.I.H.	not known	Types and distribution of coastal sediments along the Al-Hudaydah, As-Salif area and Kamaran Island. Dept Geology, University Sana'a.
Al-Hubaishi A. & K. Muller-Hohenstein	1984	An Introduction to the Vegetation of Yemen. GTZ, Eschborn, Germany.
Al-Jamie, D., R. Missal, M. Al-Sudairawi, & A. Al-Dousari.	1995	Assessment of mobile sand and strategy for its control in Kuwait. Desertification Control Bulletin No 26 (1995), p. 44-54. Nairobi: UNEP.
Anderson, I.P.	1979	Soil Survey and Irrigation Suitability Classification of Wadi Rima. Montane Plains and Wadi Rima' Project. Project Record No. 30 (YAR-01-43/REC-30/79). Land Resources Division, ODA, UK.
Bagnold, R.A.	1941	The Physics of Blown Sand and Desert Dunes. Methuen, London.
Bagnold, R. A.	1951	Sand formations in southern Arabia. Geographical Journal, London. v. 117, p. 78-86.
Barratt, L., A. Dawson-Shepherd, R. Ormond, R. McDowell.	1987a	Marine Conservation Survey. I: Distribution of Habitats Species Along the Yemen Arab Republic Coastline. Report by the Tropical Marine Research Unit Ltd, York University. International Union for the Conservation of Nature, Geneva.
Barratt, L., A. Dawson-Shepherd, R. Ormond, R. McDowell.	1987b	Marine Conservation Survey. II: Preliminary Coastal Zone Management Recommendations for the Yemen Arab Republic. Report by the Tropical Marine Research Unit Ltd, York University. International Union for the Conservation of Nature, Geneva.
Batanouny, K.H.	1987	Current knowledge of plant ecology in the Arab Gulf countries. Catena, v. 14, p. 291-316. Catena-Verlag, Germany.
Beskök, T.E.	1971	Forestry problems of the Yemen Arab Republic and possibilities for afforestation. Highlands Farm Development Project. FAO. Report No. AGS:SF/YEM 9. December 1971. Rome: FAO.
Binda, P.L.	1983	On the skewness of some eolian sands from Saudi Arabia. p 27-39 in: Development in Sedimentology v. 38. ed. M.E. Brookfield and T.S. Ahlbrandt. Elsevier, Netherlands.
Bristow, S.	1996	A Social and Technical Guide to Irrigated Shelterbelt Establishment in Northern Sudan. London: SOS Sahel International (UK).
Brown, G.F., D.L. Schmidt, A.C. Huffman.	1989	Geology of the Arabian Peninsula: Shield Area of Western Saudi Arabia. USGS Professional Paper 560-A. USGS, Reston, Virginia.
Carter, R.W.G., T.G.F. Curtis, & M.J. Sheehy-Skeffington (eds)	1992	Coastal Dunes. Geomorphology, Ecology and Management for Conservation. Balkema, Rotterdam.

Cooke, R.U., D. Brunsden, J.C. Doornkamp, D.K.C. Jones.	1982	Urban geomorphology in drylands. Oxford: Oxford University Press.
Cooke, R.U. & A. Warren	1973	Geomorphology in Deserts. London: B.T. Batsford Ltd.
Cooke, R.U., A. Warren, & A. Goudie	1993	Desert Geomorphology. London: University College London Press.
Costin, E., A.S. Baleidi, M. Ezz, & N. Bazara.	1974	Sand dune fixation and afforestation in some semi-desert countries of the Middle East area. In: Report on the FAO/DANIDA inter-regional training centre on heathland and afforestation. FAO, Rome.
Davison, I., M. Al-Kadasi et al	1994.	Geological evolution of the southeastern Red Sea Rift margin, Republic of Yemen. Geological Society of America Bulletin, v. 106, p. 1474-1493.
DHV Consultants	1979	Wadi Rima Irrigation Development. Feasibility Study. DHV, Amersfoort, Netherlands.
DHV Consultants	1983	Water Resources Study of the Tihama Coastal Plain. v. 1 Main report. v. 2 Annexes. Central Planning Organisation, Sana'a. DHV, Netherlands.
DHV Consultants	1988	Tihama Basin Water Resources Study. Tihama Development Authority. DHV, Amersfoort, Netherlands.
DHV Consultants	1990	Environmental Profile Tihama. Edited by Robert Beck. Environment Protection Council and the Environmental Health Department, Ministry of Housing and Municipalities, Republic of Yemen. DHV Consultants, Amersforrt, Netherlands.
El-Baz, F. & M.H.A. Hassan (Editors).	1986	Physics of Desertification. Dordrecht, Holland: Martinus Nijhoff Publishers.
El-Demerdash, M.A., A.M. Zilay	1994	An introduction to the plant ecology of the Tihamah Plains of Jizan Region, Saudi Arabia. Arab Gulf Journal of Scientific Research, v. 12 (2), p. 285-299.
FAO	1974	Sand Dune Fixation. Report to the Government of Iran. Report No. TA 3252. (IRA/68/012). Based on work of C.P. Bhimaya. Rome: FAO.
FAO	1985	Sand dune stabilisation, shelterbelts and afforestation in dry zones. FAO Conservation Guide No. 10. (ISBN 92-5-102261-5). Rome: Food and Agricultural Organisation.
FAO	1997	Land quality indicators and their use in sustainable agriculture and rural development. FAO Land & Water Bulletin: 5. Rome: Food and Agricultural Organisation.
FAO - Investment Centre	1990	Tihama Environmental Protection Project. First Phase Preparation Mission. Environmental Protection. Report No. 61/90. IF-YEM 32. FAO-Investment Centre. Rome.
FAO - Investment Centre	1991	Tihama Environmental Protection Project. First Phase Preparation Report. FAO/IFAD Co-operative Programme. Report No. 148/91. IF-YEM 39. Annex 1. Land Protection. Annex 6. Assessment of Desertification through the use of aerial photography 1976-1987. FAO-Investment Centre, Rome.

FAO-Investment Centre.	1995	Agricultural investment to promote improved capture and use of rainfall in dryland farming. FAO Investment Centre Technical Paper: 10, FAO, Rome.
Folk, R.L. & W.C. Ward	1957	Brazos River Bar: a study in the significance of grain size parameters. Journal of Sedimentary Petrology, v.48, p. 611-624.
Forbes, T.R.	1985	Landforms, soils, and climate of wadi Zabid in the Tihama, p.10-13 in: Stone, F. (editor) 'Studies on the Tihamah: the Report of the Tihamah Expedition 1982 and Related Papers'. Longman Group Limited, Harlow, UK.
Fryberger, S.G. & G. Dean	1979	Dune forms and wind regime. In: 'A Study of Global Sand Seas', edited E. D. McKee p. 137-169. USGS Prof. Paper 1052.
Fryberger, S.G. ,A.M. Al-Sari, & T.J. Clisham.	1983	Eolian dune, Interdune, Sand Sheet, and Siliclastic sabkha Sediments of an Offshore Prograding Sand Sea, Dhahran, Saudi Arabia. American Assoc. of Petrol. Geol. Bull. v. 67, p. 280-312.
Fryberger,S.G., A.M. Al-Sari, T.J. Clisham, S. Rizvi & K.G. Al-Hinai	1984	Wind sedimentation in the Jafurah sand sea, Saudi Arabia. Sedimentology v. 31, p. 413-431.
Gardner, R.A.M.	1988	Aeolianites and marine deposits of the Wahiba Sands: character and palaeoenvironments. Journal of Oman Studies Special Report, v. 3 , p. 75-79.
Geukens, F.	1966	Geology of the Arabian Peninsula, Yemen. USGS Professional Paper 560-B. USGS, Reston, Virginia, USA.
Girgirah, A., A. Al-Dukail, & M. Smith.	1975	Peoples Democratic Republic of Yemen. pp 197-200 in: Sandy Soils, FAO Soils Bulletin No 25. Rome: FAO.
Goudie, A. S. (Editor).	1981	Geomorphological Techniques. British Geomorphological Research Group. Allen and Unwin, London.
Greeley, R. & J.D. Iverson	1985	Wind as a Geological Process. Cambridge Planetary Science Series 4, Cambridge University Press, UK.
Grolier, M.J. & W.C. Overstreet	1976	Geologic Map of the Yemen Arab Republic. 1: 500,000 . USGS Miscellaneous Investigation Series. Map I-1143-B. USGS, Reston, Virginia, USA.
GTZ	1977	Dune Stabilisation. A survey of literature on dune formation and dune stabilisation. Geographical Institute University Wurzburg, Germany. Eschborn: Deutsche Gesellschaft fur Technische Zusammenarbeit (GTZ).
Guilcher, A.	1952	Formes et processus d'erosion sur les recifs coralliens du nord du bac Farasan (Mer Rouge). Revue de Geomorphologie Dynamiques, An. 3 (6), p. 262-274.
Sir W. Halcrow & Partners	1978	Development of the Tihama. Wadi Surdud. Tihama Development Authority.
Hartley, B.J.	1976	Observations on institutional and related aspects of irrigation improvement in Wadi Rima' and on prospects for afforestation and livestock improvement. Montane Plains and Wadi Rima' Project. Land Resources Division, ODA, UK.

Holm, D. A.	1960	Desert Geomorphology in the Arabian Peninsula. Science, v. 132 (3437), p. 1369-1379.
Hudson, N.	1991	A study of the reasons for success or failure of soil conservation projects. FAO Soils Bulletin: 64. FAO, Rome.
Hudson, N.	1987	Soil and water conservation in semi-arid areas. FAO Soil Bull. 57, FAO, Rome.
HTS (Hunting Technical Services)	1992	National Land and Water Conservation Project - Woodland Resources Mapping project. Technical manual. Ministry of Agriculture and Water Resources, General Directorate of Forestry and Rangelands, Sana'a.
HTS (Hunting Technical Services)	1993	Tihama Land Cover Change Study. Tihama Development Authority, Yemen.
IFAD	1992	Tihama Environment Protection Project: Appraisal Report. Report No. 0423-YE. Rome: International Fund for Agricultural Development (IFAD).
Jado, A.R. & J.G. Zötl.	1984	Quaternary Period in Saudi Arabia. Volume 2. Springer Verlag, Vienna.
Jensen, A.M.	1977	A Review of some Dune Afforestation Procedures. In: Conservation in Arid and Semi-Arid Zone. FAO Conservation Guide No.3. FAO, Rome.
Jones, D.K.C., R.U. Cooke & A. Warren.	1986	Geomorphological investigation, for engineering purposes, of blowing sand and dust hazard. Quarterly Journal of Engineering Geology, London, v. 19, p. 251-270.
Kaul, R.N.	1985	Sand dune fixation and afforestation traditional procedures for dune fixation: the hedge system. p.65-69, in: FAO Conservation Guide No 10. FAO, Rome.
Kerr R.C. & J.O. Nigra	1951	Analysis of eolian sand control. New York: Arabian American Oil Company.
Kerr R.C. & J.O. Nigra	1952	Eolian sand control. American Assoc. of Petrol. Geol. Bull. v. 36, p. 1541-1573.
Khalaf, F.I.	1989	Desertification and aeolian processes in the Kuwait Desert. Journal of Arid Environments, v. 16, p.125-145
King, J.W. & A.E.A. Ghanem (eds)	1983	'Soil Survey of the Yemen Arab Republic'. USAID. Final Report. Cornell University. Ithaca, New York.
Kocurek, G.A.	1996	Desert aeolian systems. p 125-153, in: Sedimentary Environments, Processes, Facies and Stratigraphy, ed. H.G. Reading. Blackwells, Oxford.
Kruck, W.	1983	Geological Map of the Yemen Arab Republic. 1:250,000. Federal Institute for Geosciences & Natural Resources, Hannover, Germany.
Lancaster, N.	1995	Geomorphology of desert dunes. London: Routledge
Leblond, B. & L. Guerin	1983	Soil Conservation: Project design and implementation using labour intensive techniques. (UNDP-ILO-INT-81-044). Geneva: International Labour Organisation.

Le Houérou, H.N.	1976	An ecological assessment of the project areas with special reference to sand stabilisation in Wadi Rima' and prospects for fodder shrubs and trees. Montane Plain and Wadi Rima' Project. Special Report. Land Resources Division, ODA, UK.
Lozeau,D, S.Arbouille,S. Santiago, & J.P. Vernet.	1994	Evaluation of wide range laser diffraction grain size analyser for use with sediments. Sedimentology, v. 41, p. 353-361.
Mabbutt, J.A.	1977	Desert Landforms.An Introduction to Systematic Geomorphology, Volume Two. Cambridge, Massachusetts: The MIT Press.
Sir M. MacDonald & Partners	1982	Wadi Mawr Project. Inception Study. Sir M. MacDonald and Hunting Technical Services Ltd. Ministry of Agriculture and Fisheries Resources. Cambridge, UK.
Sir M. MacDonald & Partners	1983	Wadi Mawr Project. Notes and General Information. Sir M. MacDonald & Partners. Ministry of Agriculture & Fisheries Resources, Sana'a.
Makin, M.J. (editor)	1977	Irrigation and Agricultural Development in Wadi Rimah, Project Report No 16. (YAR-01-29/REP-16/77). Land Resources Division, ODA, UK.
McClure, H.A.	1978	Ar Rub'Al Khali. In: Quaternary Period in Saudi Arabia, v. 1. Al Sayari, S.S. & J.G. Zotl, eds. p. 252-263. Vienna, Springer-Verlag.
McKee, E. (editor).	1979	A Study of Global Sand Seas. United States Geological Survey (USGS) Professional Paper No. 1052. Washington, D.C.: USGS.
Meigs, P.	1966	Geography of Coastal Deserts. Arid Zone Research. vol. XXVIII. UNESCO, Paris.
Millington, A.C.	1988	Woody Biomass Resources Assessment. Final Report. Household Fuelwood Marketing Study, Phase 2. Department of Geography, University of Reading, UK. Energy Sector Management Programme. UNDP/ World Bank .
Mitchell, D.J. and M.A. Fullen. 1994.		Soil-Forming Processes on Reclaimed Desertified Land in North-Central China. In Environmental Change in Drylands: Biogeographical and Geomorphological Perspectives, A.C. Millington & K.Pye (eds.), 393-412. John Wiley and Son.
Munro, R.N., R.V.H. Morgan & W.J. Jobling	1997	Optical Dating and Landscape Chronology at ad-Disa, Southern Jordan , and its potential. In: Studies in the History & Archaeology of Jordan, VI. p. 97 - 103. Department of Antiquities, Amman.
Nettleton, W.D. & O.A. Chadwick	1996	Late Quaternary, redeposited loess-soil developmental sequences, South Yemen. Geoderma, v. 70, p. 21-36.
Overstreet, W.C. & M.M. Ibrahim	1979	Petrographic and Trace Element Data on Rocks from the Yemen Arab Republic. U.S.G.S. Open File Report (IR) Y-15. U.S.G.S., Reston, Virginia
Parry, M. L.	1990	Climatic Change and World Agriculture. Earthscan, London
Parry, M.L., T.R. Carter & N.T. Konijin (editors)	1988	The Impact of Climatic Variations on Agriculture. Vol 2: Assessments in Semi-Arid Regions. UNEP. Kluwer Academic Publishers, London.

Phillips C.J. & B.B. Willets.	1978	A review of selected literature on sand stabilisation. Coastal Engineering. v. 2 (1978) p. 133-147.
Pratt, D.J.	1975	Mid Term Review of the Montane Plains and Wadi Rima' Project. Report No. MTR / 3 / 75. Land Resources Division, ODA, UK.
Pratt, D.J.	1976	Initial Development Prospects. Montane Plains and Wadi Rima' Project. Project Report 1. Land Resources Division, ODA, UK.
Pratt, D.J.	1977	An Investment and Development Plan for Wadi Rima', Montane Plain and wadi Rima' Project. Project Report: 17. (YAR-01-30/Rep-17/77). Land Resources Division, ODA, UK.
Pye, K.	1987	Aeolian Dust and Dust Deposits. Academic Press, London.
Pye. K. (editor).	1993	The Dynamics and Environmental Context of Aeolian Sedimentary Systems. Geological Society London Special Publication No. 72.
Pye, K.	1995	The nature, origin and accumulation of loess. Quaternary Science Reviews, v. 14, p. 653-667.
Pye, K. & H. Tsoar	1990	Aeolian sand and sand dunes. London: Unwin Hyman.
Pye, K. & Lancaster, N.	1993	Aeolian Sediments Ancient and Modern. Int. Association of Sedimentologists Special Publication No. 16. Blackwell Scientific Publications, Oxford.
Reineck, H.E. & I.B. Singh	1975	Depositional Sedimentary Environments. Berlin: Springer-Verlag.
Rhebergen, G.J., E. Van Waveren, & O.A. Bafadel	1990	Agro-climatic characterisation of the Northern Governorates of Yemen. FAO/UNDP Soil Survey & Land Classification Project. AG: YEM 87/002. Field Document 5. Ministry of Agriculture and Water Resources, Dhamar.
Robertson Research Minerals	1993a	Reconnaissance Beach Sand Prospecting of the Red Sea Coast (Al Mukha to Al Luhayyah)., Yemen. Interim Report No 8. Minerals Exploration Board. Sana'a. Report No 4459 of Robertson Research Minerals Ltd, UK.
Robertson Research Minerals	1993b	Laboratory Evaluation of Four Heavy Mineral Sand Samples from Yemen. Report No 4448. Robertson Research Minerals Ltd. Minerals Exploration Board. Sana'a.
Scharpensel, H.W. & A. Ayoub (editors)	1990	Soils on a Warmer Earth. Developments in Soil Science, v. 20, Elsevier and UNEP, Nairobi.
Scholte, P., A.W. Al Khuleidi, & J.J. Kessler	1991	The Vegetation of the Republic of Yemen (Western Part). Agricultural Research Authority, Sanaa, DHV Consultants, Holland.
Stevens, J.H.	1974	Stabilisation of aeolian sands in Saudi Arabia's Al-Hasa Oasis. Journal of Soil and Water Conservation. v. 29 (3), p. 129 - 133
Stipho, A.S.	1992	Aeolian sand hazards and engineering design for desert regions. Quarterly Journal of Engineering Geology, v. 25, p. 83-92.
Stone, F. L. (editor)	1985	Studies on the Tihamah: the Report of the Tihamah Expedition 1982 and Related Papers. Longman Group Limited, Harlow, UK.

Tag, R.T., M. Abouof, A. El-Shater	1990	Nature and occurrence of heavy minerals in the recent sediments of the Al Fagh - Al Qundufah Coast of the Saudi Arabian Red Sea. Indian Journal of Marine Sciences, 1990, v. 19, p. 265-268.
TESCO	1971	Survey of the Agricultural Potential of the Wadi Zabid. Final Report. TESCO, VISITERV & VITUKI, Budapest.
Thomas, D.S.G. (editor).	1989	Arid Zone Geomorphology. Belhaven Press, London.
(TDA) Tihama Development Authority	1998	Tihama Environment Protection Project. Stabilisation and Monitoring of Sand Dune Dynamics. Work Plan for July to December 1998. Hodeidah: Tihama Development Authority.
Tipton & Kalmbach Inc.	1974	Wadi Zabid Irrigation Project. Proposed plan for water allocation. Denver and Hodeidah.
Tipton & Kalmbach Inc.	1979	Development of Wadi Mawr. Tihama development Authority. Denver and Hodeida.
TNO - DGV	1988	Water Resources of the Wadi Surdud Area. Institute of Applied Sciences, Delft, and Department of hydrology, Sana'a.
Trossel, C.J.	1981	Eolian sand control in Saudi Arabia as experienced by ARAMCO. 34 pp. Arabian American Oil Company, Dhahran.
Tsoar, H. & Pye, K.	1987	Dust transport and the question of desert loess formation. Sedimentology v. 34, p. 134-153.
Tucker, M.E. (editor).	1988	Techniques in Sedimentology. Oxford: Blackwell Scientific Publications.
UNCSD	1996	Indicators of Sustainable Development: Framework and Methodologies. UN Commission on Sustainable Development. (Sales No. E.96.II.A.16). New York: United Nations.
Van der Maarel, E. (Editor).	1997	Ecosystems of the World. Dry Coastal Ecosystems, Volume 2C. Elsevier, Amsterdam.
Vesey-Fitzgerald, D. F.	1955	Vegetation of the Red Sea Coast South of Jeddah, Saudi Arabia. Journal of Ecology, v. 43, p. 477-489.
Watson, A.	1985	The control of wind blown sand and moving dunes: a review of the methods of sand control in deserts, with observations from Saudi Arabia. Quart. Journal of Engin. Geol. v. 18, p. 237-252.
Watson, A.	1990	The Control of Blowing Sand and Mobile Desert Dunes. In: 'Techniques for Desert Reclamation', edited by A.S. Goudie. p. 35-85. John Wiley & Sons Ltd., Chichester.
Whitney, J.W. D.J. Faulkkender & M. Rubin.	1983	The Environmental History and present Conditions of the Northern Sand Seas of Saudi Arabia. USGS Open File Report: USGS-OF-03-95. Ministry of Petroleum & Mineral Resources, Jeddah, Saudi Arabia.
Williams, J.B.	1979	Climate of the Montane Plains and Wadi Rima'. Montane Plains and Wadi Rima' Project. Project Record 42. (YAR-01-48/REC-42/79). Land Resources Development Centre, ODA. UK
Wood, J.R.L.	1983	An outline of the vegetation of the Yemen Arab Republic. In: King, J.W. & A.E.A. Ghanem (eds) 'Soil Survey of the Yemen Arab Republic'. Dept. of Agronomy, Cornell University / USAID.

World Bank	1979	Staff Appraisal Report: Tihama Development Project IV (Wadi Rima II). Report No. 2613-YAR. Washington D.C.: World Bank.
Zahran, M.A., H.F. Al-Kaf	1996	Introduction to the ecology of the littoral halophytes of Yemen. Arab Gulf Journal of Scientific Research. v. 14 (3), p. 691-703.