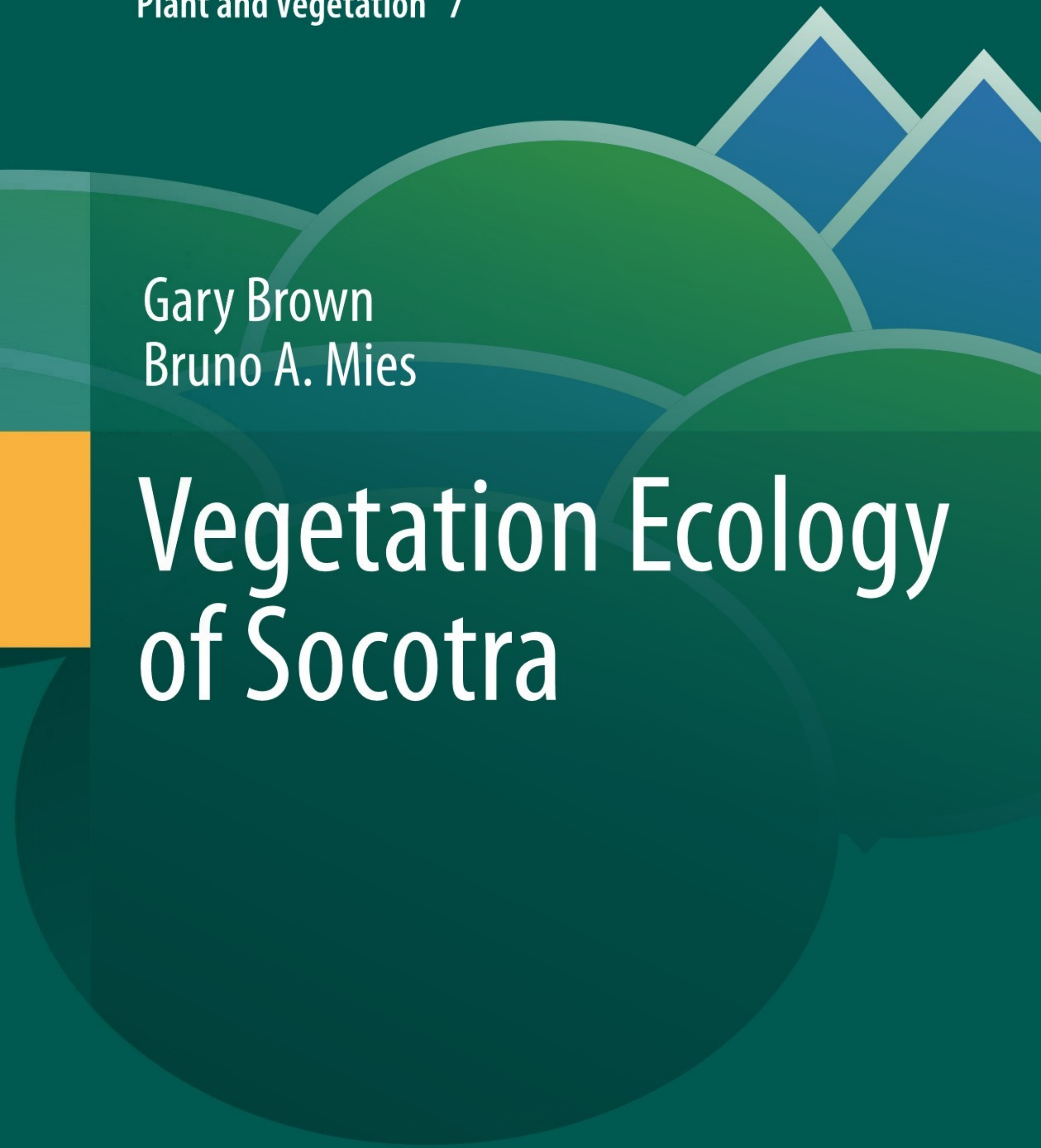

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Gary Brown
Bruno A. Mies

Vegetation Ecology of Socotra

Springer

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Vegetation Ecology of Socotra

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Preface and Acknowledgements

The impetus for this book came from the initial detailed studies carried out by Bruno A. Mies, which commenced with his first field trip to Socotra in the mid-1990s, nearly 20 years ago. Both authors have accumulated a considerable amount of field experience in the Arabian Peninsula, and Gary Brown has lived and carried out botanical research in three of its countries (Kuwait, UAE, Oman) for over 12 years since 1995, apart from travelling widely throughout the region.

As highlighted in the introduction, the Socotra Archipelago is a major biodiversity hotspot in the region on account of its remarkable endemic flora and fauna. Apart from dealing briefly with certain aspects of the flora itself, this book covers a variety of topics, including island biogeography, ecology, evolutionary biology, vegetation and conservation. Overviews of the lichen flora, based mainly on our own work, partly together with co-workers, and of the bryophytes are also given. There has been comparatively little vegetation work conducted throughout the entire region, even less so in an ecological context. Many of the studies that have been undertaken, some of which are of a very high standard, have been published in relatively obscure journals or volumes that are often difficult to access. Apart from summarising the results of our own work and more widely available publications, an important task of this book therefore was to trawl through lesser known information, filter out what appeared to us to be relevant, and present a comprehensive overview of the existing state of knowledge.

We hope that this book, in spite of its various shortcomings, will give a useful overview of the vegetation ecology of the remarkable island of Socotra. Furthermore, we hope that it will highlight the many gaps in our knowledge and therefore inspire more detailed studies. A final aim of this book, which we suspect might be viewed as being wildly optimistic given the reality on the ground, is that it will serve to promote conservation of the vegetation, and therefore a large part of the natural heritage of the archipelago as a whole, which is at serious risk of calamitous destruction and degradation.

Given the problems of transliterating Arabic/Socotri place names into English, we have striven at least to maintain consistency throughout the book, rather than to adhere to any of the “accepted” spellings, which are invariably a source of controversy.

We have even used the spelling “Socotra”, rather than the more correct transliteration, “Soqotra”, as most non-Arabic speakers would have difficulty in correctly pronouncing the Arabic “q”.

In carrying out the studies for this book and right up until its completion, a large number of people provided assistance in many different ways. Bruno A. Mies would like to thank the various persons who accompanied him in the field, in particular Gaby Beyer, Friedrich E. Beyhl, Peter Hein, Gary J. James, John J. Lavranos, Thomas A. McCoy, Christian Printzen, Matthias Schultz and Hans and Helga Zimmer. He also acknowledges financial support provided by the Heinrich and Erna Walter-Stiftung (Germany), the Cactus and Succulent Society of America, the Deutsche Kakteen-Gesellschaft and the German BMBF Program Biolog E14. Gary Brown thanks Mohammed Al-Khamis (assistance with literature acquisition), Ahmed Al-Saaed (accompaniment on field trips), his wife Ina, Richard Porter and Torsten Weber. Sultan Qaboos University, Muscat, Oman granted him research leave to enable completion of the book.

Several persons kindly allowed us to use their photographs, including AbdulRahman Al-Sirhan, Frank Boltz, Abdulkadir Elshafie, John J. Lavranos and Wolfgang Wranik. These persons are mentioned in the relevant figure captions.

John J. Lavranos provided various comments on the text, and identified a number of plant species for us. Bernhard Pracejus reviewed the initial draft of the geology chapter, and Fiona Sewell edited the final manuscript. Many thanks to all at Springer for their patience and support.

We are especially grateful for the substantial support of Professor Marinus J.A. Werger, who provided detailed comments on the draft manuscript and was a great source of encouragement. All remaining errors and omissions are claimed by the authors, and we would appreciate any feedback or corrections that improve the contents.

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University of Duisburg-Essen, Duisburg, Germany Bruno A. Mies

Contents

1 **Introduction** 1

2 **Topography, Climate and Soils** 5
  2.1 Introduction 5
  2.2 Topography 6
  2.3 Climate and Weather Patterns 10
  2.4 Soils 16

3 **Geology** 21
  3.1 Introduction 21
  3.2 General Geology and Structure 22
  3.3 Basement Rocks 22
  3.4 Triassic and Jurassic Strata 25
  3.5 Cretaceous Strata 25
  3.6 Tertiary Strata 26
  3.7 Quaternary Deposits 27
  3.8 Brief Geology of the Ancillary Islands 27
  3.9 Brief Tectonic and Climate History of the Region 28

4 **Flora and Biogeography** 33
  4.1 History of Botanical Exploration 33
  4.2 Vascular Plants 44
    4.2.1 General Attributes of the Flora of Socotra 44
    4.2.2 Characteristic Distribution Patterns 46
    4.2.3 Endemism 62
    4.2.4 Origins of the Socotra Flora and Colonisation of the Islands 68
  4.3 Ferns 83
  4.4 Non-Vascular Cryptogams 85
    4.4.1 Bryophytes 85
    4.4.2 Lichens 87

5 Ecology and Adaptive Strategies 93
5.1 Introduction 93
5.2 Adaptation of Plants to Desert Ecosystems 94
5.2.1 Photosynthetic Pathways 94
5.2.2 Plant Water Relations 95
5.2.3 Energy Balance 100
5.3 Adaptation of Plants to Highly Saline Ecosystems 104
5.4 Adaptation of Plants to High-Montane Ecosystems 109
5.5 Life and Growth-Forms 111
5.5.1 Raunkiaer Life-Form Classification 111
5.5.2 Growth-Form Classification of Socotran Plants 112
5.5.3 Life-Form Analysis 128
5.6 Adaptive Strategies 129
5.6.1 Relating Net Carbon Gain to Environmental Stress in Arid Ecosystems 130
5.6.2 Plant Strategies in Arid Ecosystems 131
5.6.3 r/K-Selection Theory and the Three-Strategy CSR Classification System of Grime 131
5.7 Pollination 132
5.8 Seed Dispersal and Germination 137

6 Vegetation 141
6.1 General Comments on the Vegetation 141
6.2 Broad Vegetation Classification 144
6.3 Vegetation of the Different Altitudinal Belts 153
6.3.1 Coastal Vegetation Types 153
6.3.2 Vegetation of the Coastal Plains 169
6.3.3 Vegetation of the Wadis at Lower and Middle Altitudes 185
6.3.4 Vegetation of Lower-Altitude Rocky Slopes 191
6.3.5 Vegetation of the Cliffs and Crevices 201
6.3.6 Vegetation of the Mid-Elevation Plateaus and Gentle Slopes 215
6.3.7 Vegetation of the Montane and High-Montane Cloud Zone 236
6.3.8 Other Montane Vegetation Types 241
6.3.9 Vegetation of the High-Montane Granite Peaks 243
6.3.10 Vegetation of Wet Flushes and Other Semi-Aquatic Habitats 251
6.4 Vegetation Map of Socotra 253
6.5 Potential Natural Vegetation 254

7 Environmental Management 259
7.1 General Introduction 259
7.2 Habitat Degradation and Desertification 260

7.3 Direct Causes of Ecosystem Degradation 262
7.3.1 Effects of Overgrazing 263
7.3.2 Soil Erosion 269
7.3.3 Wood-Collecting and Deforestation 276
7.3.4 Infrastructure Development 279
7.3.5 Impacts of Drought 282
7.3.6 Potential Impacts of Climate Change 282
7.3.7 Water Extraction 283
7.3.8 Invasive Species 284
7.3.9 Rubbish 286
7.4 Regeneration of the Natural Vegetation 286
7.4.1 Restoration 287
7.4.2 Native Plant Production 289
7.5 Conservation of the Flora of Socotra 290
7.5.1 The Conservation of *Dracaena cinnabari* 293
7.5.2 The Conservation of *Boswellia elongata* 300
7.6 Coordination of Conservation Efforts 302
7.6.1 Conservation Zoning Plan 302

Appendices 305
Appendix 1: List of Vascular Plant Species of the Socotra Archipelago 305
Appendix 2: List of Bryophytes of Socotra 327
Appendix 3: List of Lichens of Socotra 329

References 337

Index of Scientific Plant Names 357

Subject Index 367

Chapter 1
Introduction

Abstract Due to its remarkable flora and fauna, the Socotra Archipelago has been the focus of a number of ecological studies dating back to the beginning of the nineteenth century. Its unique biodiversity and – until very recently at least – relatively intact ecosystems have earned it the status of a World Heritage Site, and the islands are frequently referred to as the "Galápagos of the Indian Ocean". Despite its small size, the archipelago is one of the major island biodiversity hotspots in the world with respect to its endemic flora, with roughly 37% of plant species and 15 genera unknown from elsewhere. The objective of this book is to summarise the existing state of knowledge on the vegetation in an ecological context. Apart from providing descriptive accounts of the various vegetation units, the book also deals therefore with the factors, predominantly abiotic, affecting the distribution and abundance of species. As with other isolated islands or archipelagos, Socotra is an ideal model system, relatively unaffected by many complicating factors, to test fundamental ecological theories from a wide variety of biological disciplines (including biogeography, evolutionary biology and colonisation).

Due to its remarkable flora and fauna, the Socotra Archipelago, which lies in the north-western part of the Indian Ocean north-east of the Horn of Africa, has been the focus of a number of ecological studies dating back to the beginning of the nineteenth century. Indeed, its unique biodiversity and – until very recently at least – relatively intact ecosystems based on age-old traditional practices (Cronk 1986) have earned it the status of a World Heritage Site (UNESCO 2008), and the islands are frequently referred to as the "Galápagos of the Indian Ocean". Despite its small size, the archipelago is one of the major island biodiversity hotspots in the world with respect to its endemic flora, with roughly 37% of species and 15 genera unknown from elsewhere (see Chap. 4). Although Socotra itself, by far the largest of the islands and the main focus of this book, is undoubtedly the most important in terms of biodiversity, the smaller islands also harbour remarkable endemic species, such as the extremely local *Euphorbia abdelkuri* on Abdalkuri and *Begonia samhaensis* on Samhah. Even the rocky islet of Saboniya can boast a minor claim to

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fame, albeit from an ornithological perspective, hosting the only known breeding colony of the globally vulnerable Socotra cormorant in the archipelago, although it breeds elsewhere very locally along the coast of mainland Arabia (IUCN 2010).

The objective of this book is to summarise the existing state of knowledge on the vegetation in an ecological context. Apart from providing descriptive accounts of the various vegetation units, the book also deals therefore with the factors, predominantly abiotic, affecting the distribution and abundance of species. Very little information is forthcoming on biotic interactions concerning the plants of Socotra, and so this aspect, equally crucial for comprehending an underlying order to vegetation, has been rather neglected. Regarding species nomenclature, this book closely follows the *Ethnoflora of the Soqotra Archipelago* (Miller and Morris 2004), a truly excellent effort that will remain the reference work for the foreseeable future. A few newly recorded species for the archipelago have been added, and taxonomy at the family level has been updated somewhat in accordance with the most recent edition of the *Flowering Plant Families of the World* (Heywood et al. 2007). Some colleagues may be disappointed that we have not used the opportunity to be more adventurous in our approach to the taxonomy of the vascular plants, as the *Ethnoflora* is quite conservative. However, although we readily agree that a number of species in the *Ethnoflora* could indeed be further segregated, we felt that this would be beyond the scope and remit of this book. In addition, it is also clear that any further splitting of taxa would be unfairly biased towards species that are reasonably well studied on account of their high profile, in particular succulents.

The account of the vegetation in Chap. 6 is purely descriptive and highly subjective. Little attempt has been made to force the described vegetation units into the strait-jacket of the Braun-Blanquet floristic association system, which enjoys a wide following in Central Europe for reasons explained in that chapter. In the same vein, quantitative approaches to vegetation analysis and description involving multivariate procedures have not been utilized because suitable data are completely lacking. Given the potential power of quantitative approaches, carefully designed studies could, however, help in the development of reliable models to shed light on important plant community processes in the archipelago. In attempting to identify underlying patterns in the vegetation of Socotra, but also to uncover peculiarities that may elucidate interesting ecological processes, a certain emphasis has been placed on comparisons with other related ecosystems in the wider region, most prominently the Canary Islands and Dhofar in southern Oman.

As with other isolated islands or archipelagos, Socotra is an ideal model system, relatively unaffected by many complicating factors, to test fundamental ecological theories from a wide variety of biological disciplines (including biogeography, evolutionary biology, colonisation), as underlined by Whittaker and Fernández-Palacios (2007). Due to its relative geographic remoteness and the problems that formerly (and again more recently) existed for researchers in reaching the islands, much basic work remains to be undertaken, and this book occasionally emphasises the substantial gaps in our knowledge. A large part of this work has to be based on fieldwork – unpalatable as that may appear to many funding agencies in the current research climate, dominated almost exclusively by biotechnological and molecular approaches. Although such “modern” techniques are of great benefit, the significance of Socotra as a “natural laboratory” for carrying out field research, which also gives rise to the important basic questions for molecular studies, should not be underestimated. Meticulously documented field observations are generally of enormous scientific value, and we hope this book in particular has profited from them. They are at the heart of fundamental conceptual models relevant to various aspects of ecology, including efforts to restore seriously damaged ecosystems.

Basic ecological fieldwork is therefore essential, if – from an idealistic point of view – further information can help to protect the archipelago from the “anthropogenic tsunami” (van Damme and Banfield 2011) that is currently sweeping over it, or – from a more pessimistic, but perhaps realistic perspective – to document the natural history of the archipelago before it is irrevocably destroyed. Apart from the fact that very few exhaustive studies on the vegetation of the islands have been carried out to date, the rapid deterioration of many of the more accessible ecosystems means that we shall be forever ignorant of their true nature. In this context, extreme caution is required in the interpretation of results from ecological studies, as the current status quo may not represent what is presumed to be the intact situation. On the relevant time-scale, which is not necessarily always that of a human being, natural vegetation processes are highly dynamic. However, the rapid degradation of the landscape in recent years and the associated reduction of perennial plant cover and simplification of the vegetation structure are ominous indicators of the massive detrimental anthropogenic influences afflicting the archipelago, as has been comprehensively documented for the whole North-African–Arabian region by Le Houérou (1996). In this context, it should be emphasised that solutions to these problems will not be easy to achieve, because combating “desertification” is also a major socio-economic challenge (Agnew and Warren 1996).

Chapter 2
Topography, Climate and Soils

Abstract The Socotra Archipelago is located in the north-western part of the Indian Ocean, close to the Horn of Africa. Socotra itself (ca. 3,600 km^2) can be divided into three main topographical regions: (1) the granitic Hagghier mountains; (2) limestone plateaus, which occur between 300 and 700 m and occupy by far the largest part of the island; and (3) coastal plains. The arid tropical climate of Socotra is characterised by pronounced seasonal, altitudinal, spatial and inter-annual variability, with the seasonally reversing monsoons exerting a major influence on weather patterns. The overall arid macroclimate is also greatly modified by the diverse topography of the island and the extent of cloud cover. Rainfall is the chief form of available water at the lower elevations, either directly or indirectly through surface and subsurface redistribution. However, at higher altitudes, where forest is developed, fog and mist provide an important input of moisture, substantially augmenting the amount of plant-available water. Due to the arid nature of the climate, soils are poorly developed over much of the island. Pedogenesis involving chemical processes and the synthesis of organic matter is mainly restricted to the upper mesic montane zone where there is dense vegetation cover and the climate is more humid.

2.1 Introduction

The Socotra Archipelago is located in the north-western part of the Indian Ocean, close to the Horn of Africa and to the south of the Arabian mainland (Fig. 2.1). It consists of the main island of Socotra itself (ca. 3,600 km^2), the much smaller islands of Samhah (ca. 45 km^2) and Darsah (ca. 17 km^2), known together as "The Brothers", as well as Abdalkuri (ca. 150 km^2), the western-most island of the archipelago. Also included are the two islets of Ka'al Firawn and Saboniya. In total, the archipelago covers a surface area of about 3,800 km^2. A cartographical survey was conducted by the British military in the 1960s, leading to the production of the first detailed topographical map (Royal Geographical Society 1978). The project was subsequently continued by the Russian military (Russian Military Map 1978).

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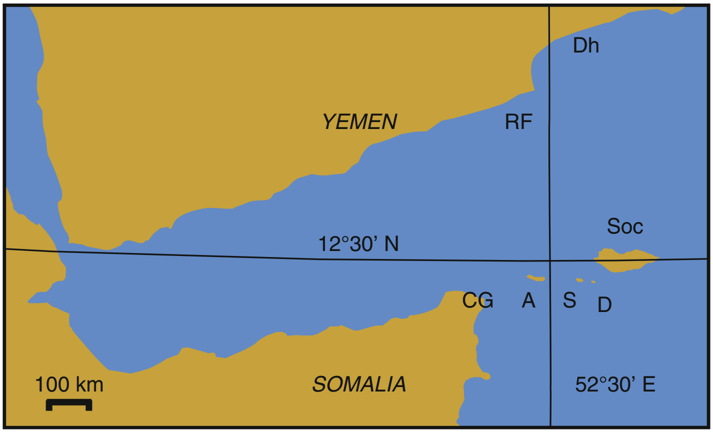

Fig. 2.1 Location of Socotra off the Horn of Africa. Abbreviations: *A* Abdalkuri, *CG* Cape Guardafui, *D* Darsah, *Dh* Dhofar, *RF* Ra's Fartaq, *S* Samhah, *Soc* Socotra

Socotra, by far the largest island, is about 133 km from west to east, has a maximum north–south breadth of 43 km, and accounts for ca. 94% of the surface area of the archipelago (Fig. 2.2). It is located between latitude 12°42′35″ in the north and 12°17′50″ in the south, roughly equidistant from the Tropic of Cancer in the north and the Equator in the south, and longitude 53°18′16″ in the west and 54°32′03″ in the east. The distance from Socotra to the nearest point on the African mainland, Cape Guardafui at the north-eastern tip of Somalia (Horn of Africa), is 232 km. The far west of Abdalkuri lies only about 95 km from Cape Guardafui, and is therefore a few kilometres closer to the African mainland than to Socotra. Although the archipelago belongs territorially to Yemen, the closest point on Socotra to the Arabian mainland is Ra's Fartaq in southern Yemen, some 351 km away. As noted in Chap. 4, a number of Socotran plant taxa have close relatives in Dhofar, southern Oman, possibly in part due to the geographical proximity of the two areas prior to the Gulf of Aden rifting (see Sect. 3.2), and some of these taxa also extend westwards into the adjacent Hawf region of southern Yemen. The Dhofar border with Yemen is about 440 km away from the nearest point on Socotra.

2.2 Topography

The present structure and morphology of Socotra are a result of post-Lower Miocene uplift with arching, block-faulting and tilting (Beydoun and Bichan 1970), although some authors (see Sect. 3.9) have suggested that the granite core of the Hagghier mountains was possibly subject to Cretaceous uplift. In accordance with Popov (1957), Socotra can be divided into three main topographical regions, as indicated in Fig. 2.2.

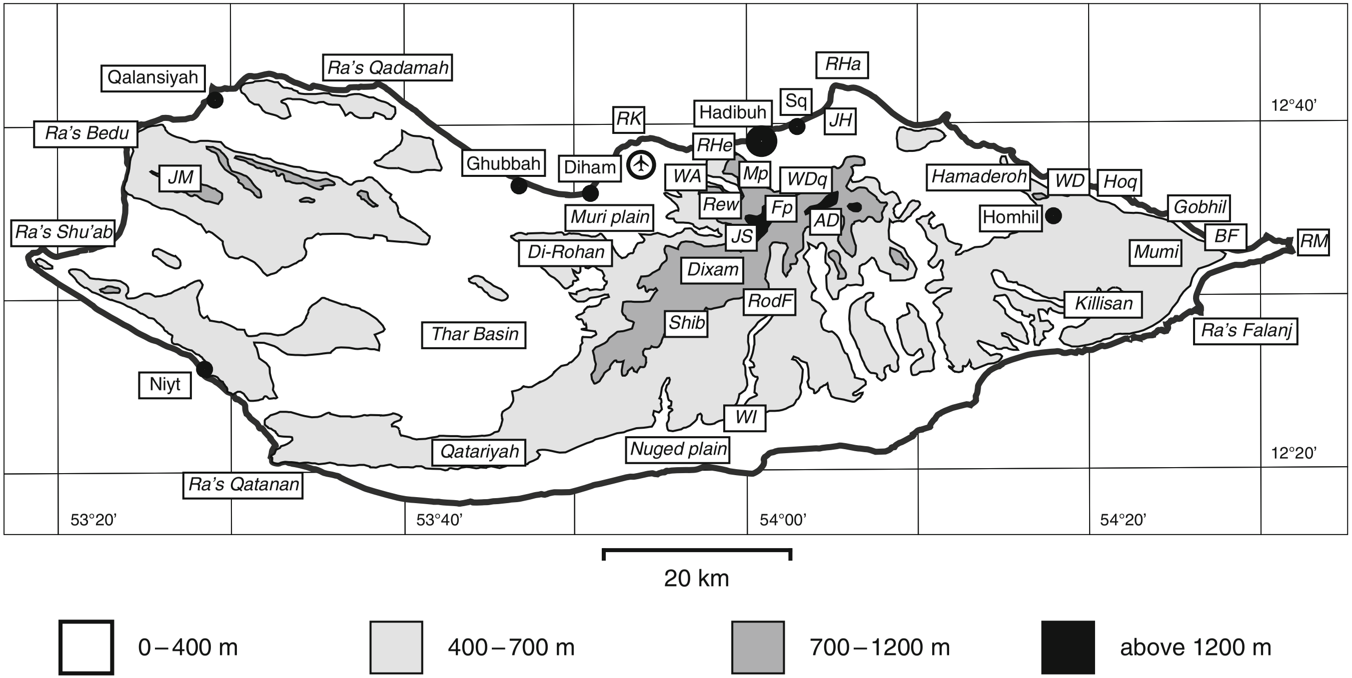

Fig. 2.2 Place names and locations mentioned in the text. Abbreviations: *AD* Adho Dimele, *BF* Bandar Fikhah, *Fp* Fieri peaks, *JH* Jebel Hauwari, *JM* Jebel Ma'alah, *JS* Jebel Skent, *Mp* Muqadrihon pass, *Rew* Rewged (Rughid), *RHa* Ra's Haulaf, *RHe* Ra's Hebak, *RK* Ra's Kharmah, *RM* Ra's Mumi, *RodF* Rokeb di Firmihin, *Shib* Shibehon plateau, *Sq* Suq (Shiq), *WA* Wadi Ayhaft, *WD* Wadi Dizyaf (Wadi Shi'faar), *WDq* Wadi Dihzafaq (Wadi Denegen), *WI* Wadi Ireh

Fig. 2.3 The granitic Hagghier mountains dominate the central and eastern parts of the island. They appear mainly white due to the dense growth of crustose lichens (especially *Pertusaria* spp.)

1. The granitic Hagghier mountains dominate the central and eastern parts, and are an impressive feature of the island, rising abruptly with their jagged pinnacles and peaks from the surrounding landscape (Fig. 2.3). It is only here on the island that the altitude exceeds 1,000 m, with the highest peak, Jebel Skent, at some 1,550 m. The area is strongly dissected by deep wadis, sheltered gullies and cliffs, but gentler slopes also occur. Boulder-strewn slopes at the base of the massif can be quite extensive. Soils are generally very thin and barely developed in the steeper parts, except in small sheltered pockets, but fertile red soils (cambisols – see Sect. 2.4) have accumulated locally in the wadis and on the more gentle slopes. Large amounts of gravels, cobbles, boulders and rocks that have been deposited in the wadis indicate the strong erosional forces of occasional heavy rain and flooding.
2. By far the largest part of the island is occupied by limestone plateaus, which occur between 300 and 700 m, locally up to about 900 m (Fig. 2.4). The individual plateaus are often undulating and cut by numerous gullies, ravines and cliffs, which makes walking in many areas, especially to the south of the Hagghier massif, very arduous. Extensive areas of bare limestone pavement are evident on many of the plateaus (e.g. Dixam, Qatariyah, Rewged), and sink holes and caves are scattered throughout. Karstification of the landscape is therefore a pronounced feature. In some places, the surface has been worn smooth, but it is

Fig. 2.4 Limestone plateaus occupy large parts of the island

usually rough and fissured, pockmarked by erosion. Locally, the limestone is interrupted by small areas of sandstone. In the east of the island, the limestone plateau extends to the coast, and impressive, steep cliffs are developed that plunge up to 400 m to the sea. To the south, the plateau drops abruptly up to several hundred metres onto the Nuged plain, forming an extensive escarpment. Soils are at best poorly developed on the limestone plateau, mainly in rock fissures, cracks and other such sheltered sites, but in some larger depressions, thin deposits of soil (rendzina) may accumulate. In general, however, the surface topography is characterised by the eroded limestone bedrock, and any soils that do form are usually seriously deficient in organic material.

3. Coastal plains are developed where the mountains and limestone plateaus do not reach the coast. The most extensive of these, the Nuged plain, runs parallel to the south coast and is about 70 km in length and up to 5 km wide (Fig. 2.5). Smaller plains, separated from each other where the limestone plateau juts out to the immediate coastline, are found along the northern and western coasts. They are typically quite narrow, usually less than a few kilometres in width, and in the north are dissected by numerous run-off channels, gullies and shallow wadis. The plains are covered by Pleistocene to Holocene sediments consisting of sands, gravels and coarser materials, depending on the location.

Fig. 2.5 Nuged plain on the south coast. December 2008

2.3 Climate and Weather Patterns

In-depth information on the climate of Socotra is largely lacking, and most published studies give rather general accounts, with more specific details restricted to localised areas. These studies have enabled broad statements to be made concerning variables such as wind and temperature, but contradictions and gaps remain, particularly in respect of precipitation. It is also possible to infer a certain amount of information on the climatic situation of specific ecosystems from the prevailing vegetation (at least where reasonably intact), especially when compared to analogous vegetation units from elsewhere in the world. However, detailed information on the climate and its variability, essential for an understanding of ecosystem processes and also for conservation purposes, requires a network of meteorological stations providing reliable measurements over a longer period of time from various parts of the island.

Useful overviews of the general climate have been provided by Kopp (1999), Mies (1999a, 2001), Miller and Morris (2004) and, in particular, Cheung and DeVantier (2006). An assessment of monsoonal influences on precipitation and vegetation, in part summarising the work of other authors, but also including recent data obtained from various weather stations over an altitudinal range from 3 to ca. 800 m asl from the year 2002 to 2006, has been presented by Scholte and de Geest (2010). Fleitmann et al. (2004) and Shakun et al. (2007) give details on the Quaternary climate history of Socotra.

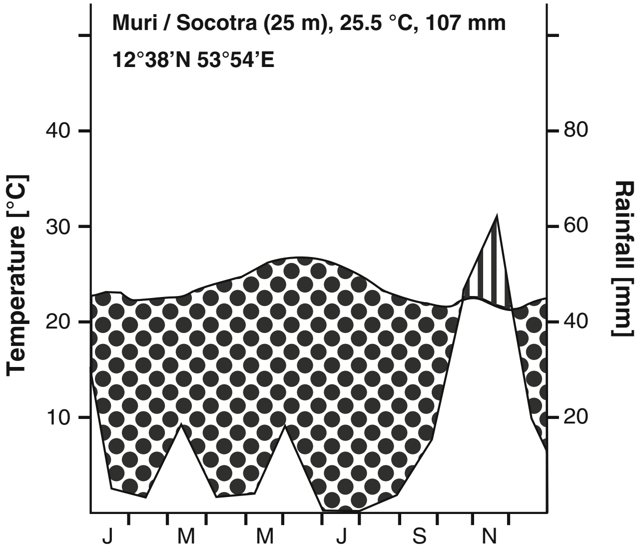

Fig. 2.6 Climate diagram based on data from various literature sources. Measurements were taken on the Muri plain in the north of the island

The arid tropical climate of Socotra is characterised by pronounced seasonal, altitudinal, spatial and inter-annual variability (Mies 1999a), with the seasonally reversing monsoons exerting a major influence on weather patterns (see Gadgil 2003). The overall macroclimate is also greatly modified by the diverse topography of the island and the extent of cloud cover, as reiterated by Mies (1999a) and by Scholte and de Geest (2010). The distinctly arid nature of the climate of large parts of the island is underlined by the fact that potential evapotranspiration greatly exceeds precipitation during most of the year (Fig. 2.6). Mies (2001) estimated that ca. 80% of Socotra receives a mean annual rainfall of less than 200 mm. More recent data reported by Scholte and de Geest (2010) show that mean annual rainfall from 2002 to 2006, measured at a network of stations below 800 m, was about 216 mm. However, there was considerable geographical variability, ranging from just 67 mm (Qalansiyah) to about 400 mm at Mathre on the northern coastal plain. Interestingly, the amount of rainfall does not appear to be correlated with altitude, as the station that registered the largest amount (Mathre) was located just 20 m asl, whereas a station at 760 m asl received only 168 mm.

Rainfall is generally essential for terrestrial plant growth, but due to its overriding importance in arid desert ecosystems, it has been described as the "master input" by Noy-Meier (1973), and three aspects deserve special mention: (1) arid deserts are systems with a discontinuous input; (2) arid deserts are systems with a stochastic input; (3) edaphic factors in arid ecosystems greatly modify the water regime, including infiltration and storage capacity, horizontal and vertical redistribution,

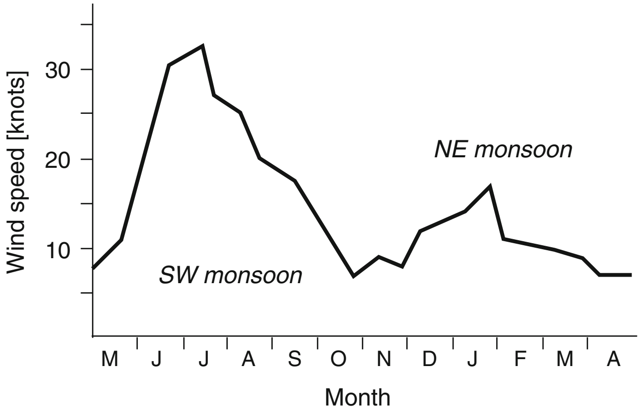

Fig. 2.7 Monsoon wind speeds in the northern Indian Ocean over the year (Based on Haake et al. 1993)

and the potential use of rainwater for biomass production. This last point is essential for understanding ecosystem processes, and also for vegetation restoration attempts (see Sect. 7.5.1).

As indicated above, the annual weather pattern of Socotra is governed to an overwhelming extent by the seasonal shift of the inter-tropical convergence zone (ITCZ), which gives rise to the predominance of the SW monsoon during the summer months, and the NE monsoon in the winter. The winds associated with the SW monsoon are overall much stronger than those of the NE monsoon, with a relatively calm period occurring during the spring and autumn transitional periods, i.e. from February to May as well as during September and October (Fig. 2.7). In the following, the complex weather patterns on Socotra are summarised in very general terms. Information on temperatures and rainfall applies mainly to the areas below 800 m.

In winter, moderate north-easterly winds are a consequence of the atmospheric pressure gradient that develops between the high-pressure cell over the Eurasian continent and the low-pressure cell over the southern Indian Ocean, at its furthest south situated at roughly the same latitude as northern Madagascar. This is the season of the north-east winter monsoon on Socotra, coinciding with the coolest months of the year, December to February. Mean monthly temperatures are usually below 28°C in most locations. At the highest elevations, nocturnal temperatures can drop to below 10°C on some days, although frosts appear to be unknown. Wind speeds rarely exceed 35 km h^{-1} during the winter. Due to the moist, cool air arriving from the north-east, the northern side of the Hagghier mountains is shrouded in rain clouds and mist (Fig. 2.8), whereas on the leeward side, only patchy cloud formation usually occurs, because the mountains act as an effective barrier to the clouds. Rainfall is therefore concentrated in the northern part of the island during the winter. As already indicated by Mies and Beyhl (1998), the main rainy period in the north is between November and February, and more specific data evaluated by Scholte and de Geest (2010) for the years 2002–2006 show that most rainfall was

Fig. 2.8 Dense cloud cover over the north of Socotra. December 2008

received in November. Typical rainfall amounts during the winter at lower to medium elevations range from about 45 to 350 mm.

In the spring transitional period between the two main monsoon seasons, and as the ITCZ has begun its seasonal shift northwards, moderate south-westerly winds predominate as the northern tropical and subtropical landmasses gradually warm up. North-westerly winds are also occasionally recorded. Late spring (late April and May) is the warmest period of the year, with mean daily temperatures reaching ca. 31°C during May. Relative humidity is generally high, with values sometimes exceeding 95%. A distinct rainy period occurs during the late spring, although the amounts received are much less than in the early winter.

In summer, the ITCZ has migrated northwards, and assumes its most northerly position over southern Pakistan by July. The summer monsoon has typically commenced by early May. The wind direction is from the south-west, and increases noticeably in speed as the month progresses. When the monsoon is at its most intense, wind speeds are on average more than 50 km h^{-1}, with substantially stronger gusts (up to hurricane-force) interspersed. Own measurements in the northern wadis of Socotra at the beginning of July 2002 recorded gale-force winds exceeding 160 km h^{-1}. These extreme windy conditions meant that in the past, Socotra was often cut off during the summer, and life in the northern part of the island still becomes exceedingly uncomfortable. Activities such as fishing virtually grind to a halt. The winds originate from Africa, and are mainly hot and dry as they pass over Socotra. As the summer progresses, the southern half of the island becomes increasingly affected by cloud cover, which often envelops large parts of the south and the

Hagghier mountains (see Scholte and de Geest 2010), although this is not accompanied by any significant amounts of rainfall, at the lower altitudes at least.

With the onset of the autumn in late September, the ITCZ retreats southwards, and this is marked by a decline in the intensity of the monsoon. During the autumn transitional period (mainly late September and throughout most of October), a second distinctly warm spell usually occurs, with mean temperatures around 29°C at the lower altitudes.

Rainfall is the chief form of available water at the lower elevations, either directly or indirectly through surface and subsurface redistribution. However, at higher altitudes, where forest is developed, fog and mist provide an important input of moisture, substantially augmenting the amount of plant-available water. No specific data are available to quantify this additional source, but Mies (2001) estimates it to be in the region of at least twice the amount of annual rainfall in the forested mesic montane zone (and so in excess of 800 mm, probably even equivalent to as much as 1,000 mm total precipitation). Beyhl and Mies (1996), Mies and Beyhl (1998) and Mies (2001) have emphasised the crucial role of fog for vegetation development at the higher altitudes, and also for the abundance of epiphytic and even epiphyllic lichens and bryophytes.

Quantifying the amount of fog precipitation is problematic for various methodological reasons, as is the precise assessment of its ecological significance in some cases, because of the close interrelationship with other factors. On the northern slopes of several of the Canary Islands, which receive a regular input of moisture from the trade winds, various types of evergreen laurel forests are developed. Mean annual rainfall on these slopes ranges from about 350 to 900 mm, and Kämmer (1974) estimated the amount of additional fog precipitation intercepted by the trees to be in the region of 300 mm. Miller and Morris (1988) underlined the importance of trees and vegetation in condensing moisture on the escarpment forest of Dhofar, a unique deciduous cloud-forest formation characterised by the endemic *Anogeissus dhofarica*, and located in an overall arid macroclimatic area. Rainfall is between 200 and 500 mm, and the coolest monthly mean temperatures (ca. 27–28°C) are recorded in January and February. This forest is undoubtedly developed below the lowest extreme in terms of rainfall requirements, as also shown by Hildebrandt et al. (2007), and therefore relies heavily on the monsoon mists in the summer for its survival. It is probably for this reason that it is a deciduous forest type, coming into leaf during the moist late-summer months, in contrast to the mainly evergreen types of Socotra and the Canary Islands. Equally important for the development of forest on Socotra and the other above-mentioned areas is regular high cloud cover, which dramatically reduces radiation loads, and thus temperatures and evapotranspiration, as made abundantly clear in the case of the escarpment forest in Dhofar, which is dormant during the cooler, but dry winter period. This has also been demonstrated in Dhofar by detailed ecohydrological studies (e.g. Hildebrandt et al. 2007).

Figure 2.9 shows a 24-h cycle of measurements (end of March 1996) of relevant climatic parameters from the Hagghier mountains at 1,050 m asl (taken from Mies and Beyhl 1998), which the authors believe to be representative of the situation for a large portion of the year, as supported by cloud cover data provided by Scholte and

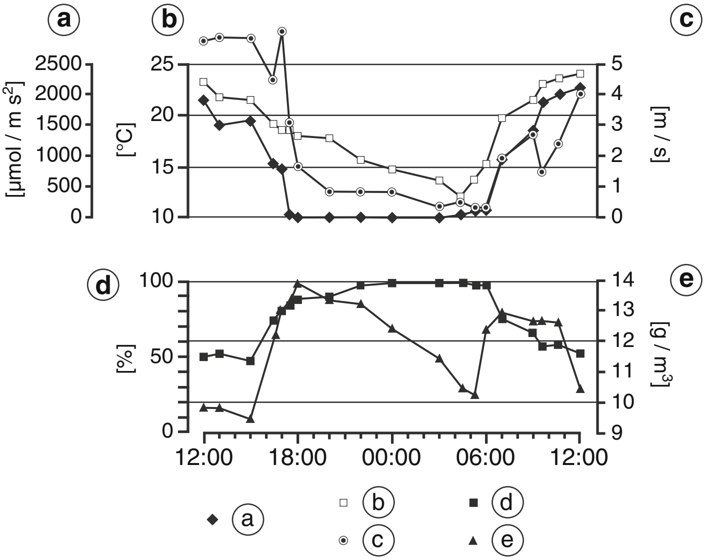

Fig. 2.9 Time course of important meteorological parameters over a 24-period in the Hagghier mountains at 1,050 m asl. Abbreviations: *a* global radiation, *b* air temperature, *c* wind speed, *d* relative humidity, *e* absolute humidity

de Geest (2010). It is interesting to note the sudden drop in temperature and wind speed after 18:00. This is accompanied by an equally steep rise in relative humidity, which is at, or close to, 100% for most of the period of darkness. The nocturnal longwave radiation loss to the atmosphere is so great that moisture will readily condense on any structures such as vegetation or the soil surface in the form of dewfall. One of the consequences of this additional input of moisture is that substrate-water availability is substantially higher in the mountains.

In their discussion of the cloud forest of the Canary Islands, Walter and Breckle (1999) emphasised an aspect that is probably also highly relevant to the cloud forest of Socotra, namely that the frequency of moisture input is just as important as the overall amounts of precipitation received, if not more so. As underlined by Mies (1999a), also important for the overall hydrological situation on Socotra is that the large amounts of precipitation received at higher altitudes are retained on the island due to absorption by the soil and vegetation, and at lower altitudes due to percolation into the karstic limestone.

Cloud cover also plays an important role at lower altitudes, i.e. on the limestone plateau (Fig. 2.10), as indicated by fog measurements taken during the SW monsoon by Scholte and de Geest (2010). Depending on aspect and location, these authors collected between 0.18 and 10.14 l m^{-2} per day, reaching up to the equivalent of 10 mm of rainfall per day. This moisture input, and in particular its regular occurrence, probably play a key role in the occurrence of a relative abundance of epiphytic lichens on trees on the plateau. However, as noted by Popov (1957), it is possible that the strong desiccating winds may prevent development of phanerogams on exposed limestone plateaus, which are often conspicuously poorly vegetated.

Fig. 2.10 Cloud cover and mist are a regular feature on many parts of the limestone plateau. December 2008

2.4 Soils

Due to the overall arid nature of the climate, soils are poorly developed over much of the island (Fig. 2.11). Pedogenesis involving chemical processes and the synthesis of organic matter is mainly restricted to the upper mesic montane zone (above ca. 800–1,000 m) where there is dense vegetation cover and the climate is more moist. At medium and lower altitudes, the parent bedrock is very much in evidence over extensive areas, but limited soil formation has taken place over large tracts on the plains and in basins. Small pockets of humus and “terra rossa”-like substrates (see below) accumulate in rock crevices and other such favourable microsites, and these are of enormous ecological significance for the establishment of many plant species. It is important to realise that large-scale soil formation involving chemical and biological processes once took place during more favourable climatic periods (pluvials), especially during the pre-Holocene. The last extended period of high rainfall in the region probably occurred between about 6,000 and 10,500 years ago (Fleitmann et al. 2003), but since the general aridification of the climate, soil degradation has occurred, exacerbated substantially by recent human activities (see Sect. 7.3.2), as has been the case in other arid and semi-arid parts of the world. Recent soil formation processes over much of the island are therefore restricted primarily to mechanical weathering, i.e. the disintegration of the parent rock into smaller particles with the same properties, rather than chemical or biological processes.

Fig. 2.11 Only very limited soil formation has taken place over large areas, so that the parent material is very much in evidence

However, an important physico-chemical process associated with the aridification of the climate in the Arabian region during the Quaternary is the secondary accumulation of calcium carbonate, which can be viewed as an indicator of soil degradation, along with loss of soil structure. Pietsch (2006) assumes that all the calcium-rich soils investigated by her on Socotra are of recent origin. Calcretes are near-surface accumulations of predominantly $CaCO_3$ in unconsolidated sediments, sedimentary rocks and soils (Goudie 1973), and various types are extensively distributed at lower altitudes on Socotra over carbonate-rich parent material. Rainfall chemistry appears to be a particularly important control on carbonate distribution in the regolith, and carbonates are generally thought to precipitate in areas where annual rainfall is less than about 400–500 mm. The regular alternation of short periods of excess water followed by drought is thought to be particularly beneficial for the formation of calcretes (Eren et al. 2008).

In accordance with the classification system of the recently published World Reference Base for Soil Resources (IUSS Working Group WRB 2006), a number of main reference soil groups (RSG) play an important role on Socotra, namely cambisols, calcisols, fluvisols, arenosols, leptosols and regosols. Detailed soil taxonomic information on several specific sites on Socotra is available from Pietsch (2006), Pietsch and Kühn (2009) and Pietsch and Morris (2010).

Cambisols, relatively young soils derived from various rock types, combine a wide range of different soil types, but all are characterised by at least the beginnings of horizon differentiation in the subsoil. Brownish discoloration, increasing clay fraction and carbonate removal are other general features of this group. These soils are the most widespread group on Socotra at lower altitudes, but also high in the mountains. At lower elevations, cambisols are often deep red in colour ("red soils", in part equivalent to the relictual "terra rossa" soils that are common in the Mediterranean region – see Pietsch 2006). This is due to the enhanced formation of haematite, and occurs when limestone-rich soils weather to liberate large amounts of iron oxide that was closely bound to clay minerals (Durn 2003). It involves the soil formation process known as "rubification", which is associated with cool, wet winters alternating with warm, dry summers, i.e. occurring in a typical Mediterranean-type climate. During the moist winter period, carbonate dissolution in the upper soil layers takes place, which in turn leads to the oxidation of iron (accounting for the orange to red colour), and in the summer, high evaporation rates lead to the accumulation of calcium carbonate and the precipitation and irreversible crystallisation of iron oxide (haematite).

The development of cambisols is usually associated with moist climatic conditions, which would have prevailed on Socotra during the last pluvial. Since this time, i.e. over the past ca. 6,000 years, soil evolution processes that can be interpreted as regressive have prevailed, including the accumulation of calcium carbonate and loss of soil structure, leading in part to the formation of calcisols.

Calcisols (which mainly belong to the calcids in the US soil taxonomy) are widespread in arid and semi-arid regions that have calcium carbonate-rich parent materials. Calcisols are developed where capillary action facilitates the movement of calcium carbonate to the soil surface, and are usually the result of more recent soil formation processes. On Socotra, they are fairly widely distributed, and have been described in detail by Pietsch (2006) and Pietsch and Morris (2010) at Homhil. They are generally silty, but also partly clayic.

Fluvisols are young, azonal soils typically formed in alluvial deposits. On Socotra, fluvisols are restricted to the wadis and coastal plains, and the parent material consists predominantly of recent fluvial or marine deposits. The sediments vary in size substantially, and this feature can be used to characterise the different types of fluvisols further.

Arenosols (sandy soils) are present locally, especially on the plains of the north and south coasts, and along the coastline itself. On Socotra, arenosols are mainly derived from calcareous parent material, but pockets of extremely weathered siliceous rock probably also occur. Sand dunes are typically characterised by arenosols. One of the most important characteristics is their coarse texture, which accounts for the generally high permeability and low water and nutrient storage capacity of these soils.

Leptosols are very shallow soils over continuous rock, and soils that are extremely gravelly and/or stony. Leptosols include lithosols in some soil classification systems. They strongly restrict the ability of plants to root, resulting in a very patchy vegetation cover. Leptosols are highly characteristic of strongly eroding landscapes, often in very hot (or very cold) climates, at medium to high altitudes. On Socotra, they are widely distributed on the limestone plateau, and also on the granite of the Hagghier massif. In some national systems, leptosols correspond with rendzinas over calcareous rocks and rankers over acidic ones (IUSS Working Group WRB 2006). The B-horizon in such soils is therefore absent or very poorly developed.

Regosols encompass a range of weakly developed mineral soils in unconsolidated material that are not rich in gravels (i.e. leptosols), sand (arenosols) or fluvic material (fluvisols). Regosols can be regarded as a soil-taxonomic remnant group and a convenient category in which to place many soils showing only incipient formation processes that are otherwise difficult to accommodate. Regosols are widespread, for instance, on the limestone plateau.

Over large tracts of the limestone plateau, continuous rock occurs at the surface and this is generally considered as non-soil in many soil classification systems.

As clearly outlined in Sect. 7.2, land degradation in the form of soil deterioration is a key element of "desertification", and in fact soil degradation and erosion are used as the primary indicators of this phenomenon in the *World Atlas of Desertification* (Middleton and Thomas 1997). Specific examples of the impacts and consequences of soil degradation on biodiversity are given in Sects. 7.3.2 and 7.5.1. Pietsch and Morris (2010) highlight the importance of soil protection for the preservation of biodiversity on Socotra, and give an account of traditional and modern techniques aimed at conserving soil resources.

Chapter 3
Geology

Abstract Socotra is a typical example of an ancient continental island, but in biological evolutionary terms, it is more akin to an oceanic island due its relatively long duration of isolation. Post-Lower Miocene uplift with arching, block-faulting and tilting has played a major role in the present structure and morphology of the island. Most parts of Socotra, with the possible exception of the central Hagghier mountains, were intermittently submerged until the Miocene. As a consequence, the Precambrian basement rocks are overlain unconformably by Cretaceous and Tertiary limestones, but are exposed in three main uplift areas, most prominently in the Hagghier mountains. Prior to the Gulf of Aden rifting in the Oligocene, Socotra was probably located adjacent to southern Arabia. The precise time at which the Socotra Archipelago became detached from the African mainland is unclear, but could be of considerable biogeographical significance. The climate history of the Horn of Africa, with Socotra, differed from that of the adjacent regions, because since about the Late Cretaceous, and extending into the Middle Eocene, the evidence suggests that arid conditions persisted there, at least intermittently. During the glacial phases of the Pleistocene, it seems that as the rainforests contracted, "arid corridors" existed between South Africa and the north-east of the continent, including the Horn of Africa, and that repeated plant migrations were taking place in both directions. Such corridors could help explain the present-day disjunct distributions of various taxa.

3.1 Introduction

In accordance with the classification of islands of Alfred Russel Wallace (1911), Socotra is a typical example of a continental fragment or ancient continental island. Tectonic drift caused the separation of fragments from the mainland tens of millions of years ago, and Socotra is one such fragment originating from Gondwana. Deep waters now isolate Socotra from the mainland landmasses of Arabia and Africa. Despite being a continental fragment, in biological evolutionary terms, Socotra is

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