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Preface

This book is a tribute to the Luxembourg Cuesta landscape that inspired so many researchers. It integrates more than 50 years of study on the long and short-term evolution and functioning of the cuesta landscape in central Luxembourg. A landscape that reveals large contrasts in lithology, geomorphology, soils and forest vegetation over short distances. An attractive landscape with a high biodiversity and geodiversity that entices many tourists. It is a showcase for education, both students and laymen. By presenting a scientific overview of the knowledge obtained over these past decades we hope to attract more scientific attention for the area and to inspire students and scientists to explore new pathways of research.

The area of study is part of the north-eastern margin of the Paris Basin, a characteristic cuesta landscape. A beautiful landscape with wide, slightly undulating plateaus under grassland and agriculture, deep river incisions, forested rims and steep sandstone cliffs. In the lower parts of the cuesta, marly strata give rise to more gentle slopes, a rolling landscape with numerous small brooks and mixed land-use.

The area did not only attract the attention of researchers from Luxemburg, such as geologists, soil scientists and hydrologists. It also has been a key study area for physical geographers and landscape ecologists of the University of Amsterdam for more than five decades. The geological diversity and tectonic history of the area provide excellent opportunities to study the interactions between landscape development, hydrology, geomorphological processes, soil formation and forest vegetation at multiple scales. Numerous scientific papers, Ph.D. dissertations and students reports have been published that highlight the cuesta landscape. Over the years, the focus has shifted from the use of traditional field methods and descriptive techniques, towards more quantitative approaches, including field monitoring and digital mapping. Modern research and information techniques, such as remote sensing data in combination with computer modelling, field observations and laboratory measurements, make it possible to maintain high standards in educational and research programs.

The book is organized around three themes that are closely interrelated. The first theme (Chapters 1–5) addresses the *long-term geological, geomorphological and hydrological development* of the Luxembourg cuesta landscape, as well as the scientific historical perspective of research in this area. The second theme (Chapters 6–8) focusses on *the geo-ecological system functioning of the landscape*, including soil development, nutrient availability and forest ecology. The third theme (Chaps 9 and 10) illustrates the *biological and physico-chemical control of natural erosion processes*, including the impact of fauna and vegetation and the substrate on soil erosion processes. Chapter 11 is a showcase of how *obtained knowledge can be applied*. Chapter 12 presents *impressions of students* whom have been working in the area. In several chapters student work is integrated in the scientific results.

Finally, we would like to thank the forestry departments and local communities for their permission and support and all those that in one way or another contributed to this book.

Amsterdam, The Netherlands

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Contents

About the Editors

A.M. Kooijman received her Ph.D. in Biology in 1993 at the University of Utrecht on changes in nutrient availability and vegetation in rich fens due to environmental stress. She has been working at the University of Amsterdam as a landscape ecologist, currently at the Ecosystem and Landscape Dynamics Department of the Institute for Biodiversity and Ecosystem Dynamics at the University of Amsterdam, The Netherlands. She works on interactions between soils and biota in ecosystems with gradients in geology and pH, such as semi-terrestrial wetlands, coastal dune grasslands and Luxembourg forests, with particular focus on ecosystem nutrition. For the Luxembourg forests, she has published a number of studies about the impact of geology and litter quality on ecosystem functioning. She has been teaching (field) courses on soils and landscape ecology in various ecosystems for more than 25 years.

L.H. Cammeraat received his Ph.D. in Environmental Sciences in 1992 at the University of Amsterdam on work in hydro-geomophological processes in a forested marl catchment in Luxembourg. He worked next as a postdoc and PI on EU- and Dutch-funded projects related to Mediterranean desertification and degradation remediation. Currently he is appointed as Associate professor in geomorphology and land degradation at the Ecosystem and Landscape Dynamics Department of the Institute for Biodiversity and Ecosystem Dynamics at the University of Amsterdam, The Netherlands. He works on soil-geomorphology-vegetation interactions in both humid and dryland areas, as well as on degradation remediation strategies using ecoengineering approaches, and on the fate of carbon in soils. He has been teaching (field) courses on geomorphology, soils, landscape ecology, and hydrology for more than 20 years.

A.C. Seijmonsbergen was born in 1961 in Amsterdam (The Netherlands) and studied Physical Geography at the University of Amsterdam. During his Master- and Ph.D. research he developed methods for the evaluation of natural hazards based on detailed geomorphological mapping in Austria. He has over 30 years of experience in teaching field courses, remote sensing and GIS tools and techniques.

Currently his research in the Theoretical Computational Ecology group at the University of Amsterdam is focusing on the functioning of Geo-Ecosystems by analyzing the 3D structure of both the landscape and the vegetation cover using air-born and terrestrial LiDAR-based high resolution elevation data as well as geodiversity mapping at multiple scales.

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Geological and Geomorphological Evolution of Luxembourg and Its Cuesta Landscape

B. Kausch and R. Maquil

Abstract

Two different regions in Luxembourg are characterized by different substrates and landscapes. In the north, the plateaus with deeply incised valleys of the Eislek have developed in folded Devonian rocks. These rocks constitute the geological basement of the country. In the southern Gutland region, the Devonian basement is covered by a succession of Mesozoic sedimentary formations, gently dipping to the southwest. This succession of sedimentary rocks is expressed by an alternation of hard and soft rocks, which is responsible for the characteristic geomorphology of the cuesta landscape of the Gutland. The hard relief-building rocks are pervious, while the soft rocks of impervious nature form gentle slopes. The latter are of clayey and marly constitution and are sensible to variation in water content. Differential uplift and climatic changes have influenced the landscape development and fluvial incision processes since the Tertiary. The epigenetically developed drainage network has sculptured the present landscape. Generally, slope evolution is largely controlled by soil erosion and mass movements, rock fall in hard rocks and landslides in soft rocks. The intensity of landscape forming processes depends on the local climatic and hydrogeological conditions. Nowadays man's influence is not negligible any more, as expressed by the displacement of soil and rocks, as well as in triggering mass movements and agricultural induced soil erosion. This chapter introduces the general geological evolution of Luxembourg and surroundings, as well as the various geomorphological processes acting during the Tertiary and Quaternary. This will be illustrated by examples from the present landscape, which is the result of the interplay between geology, geomorphology, climate and the relatively recent influence by man.

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1.1 Geology and Geomorphology of Luxembourg

1.1.1 Geological Overview

Two distinct geologic-geomorphologic regions dominate the landscape of Luxembourg.

The northern part, the Eislek, is part of the Belgian Ardennes and the Rhenish Massif in Germany (Fig. 1.1). It is built of folded lower Devonian rocks of Pragian (Siegenian) and Emsian age. The marine sediments were originally deposited in the Devonian seas as weathered material of the Old-Red-continent, a part of which is still exposed in the Stavelot Massif, located just a couple of kilometres north of Luxembourg. Marine sediments with a thickness of several ten thousand metres were successively deposited, lithified and then folded during the Hercynian Orogeny. The Eislek substrate is built of schists, quartzites, sandstones and locally slates. The different proportions of rocks vary locally, schists being the dominant lithology. The central part of the Eislek is formed

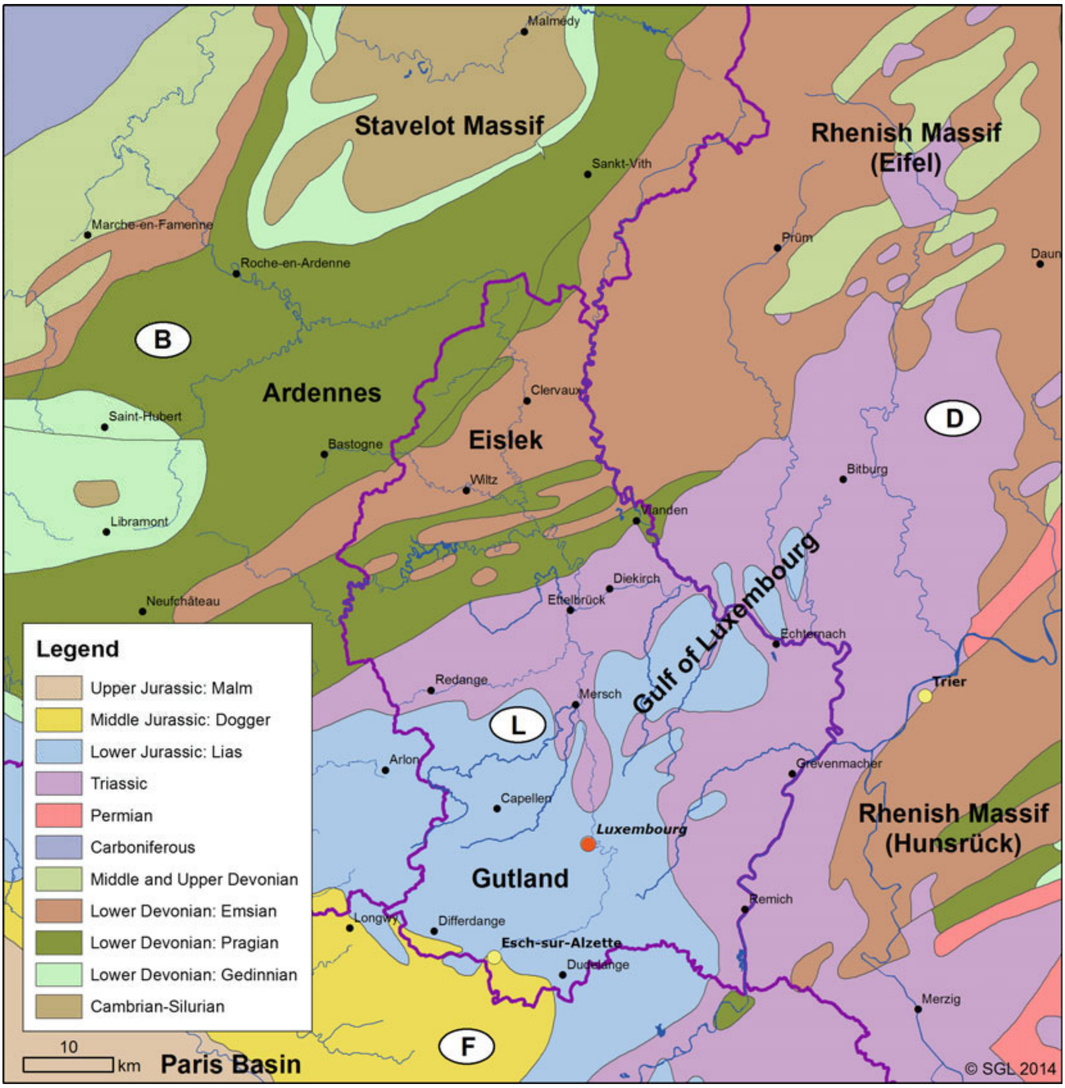

Fig. 1.1 General overview of the regional geology, with geological and geographical subdivisions, © SGL 2014

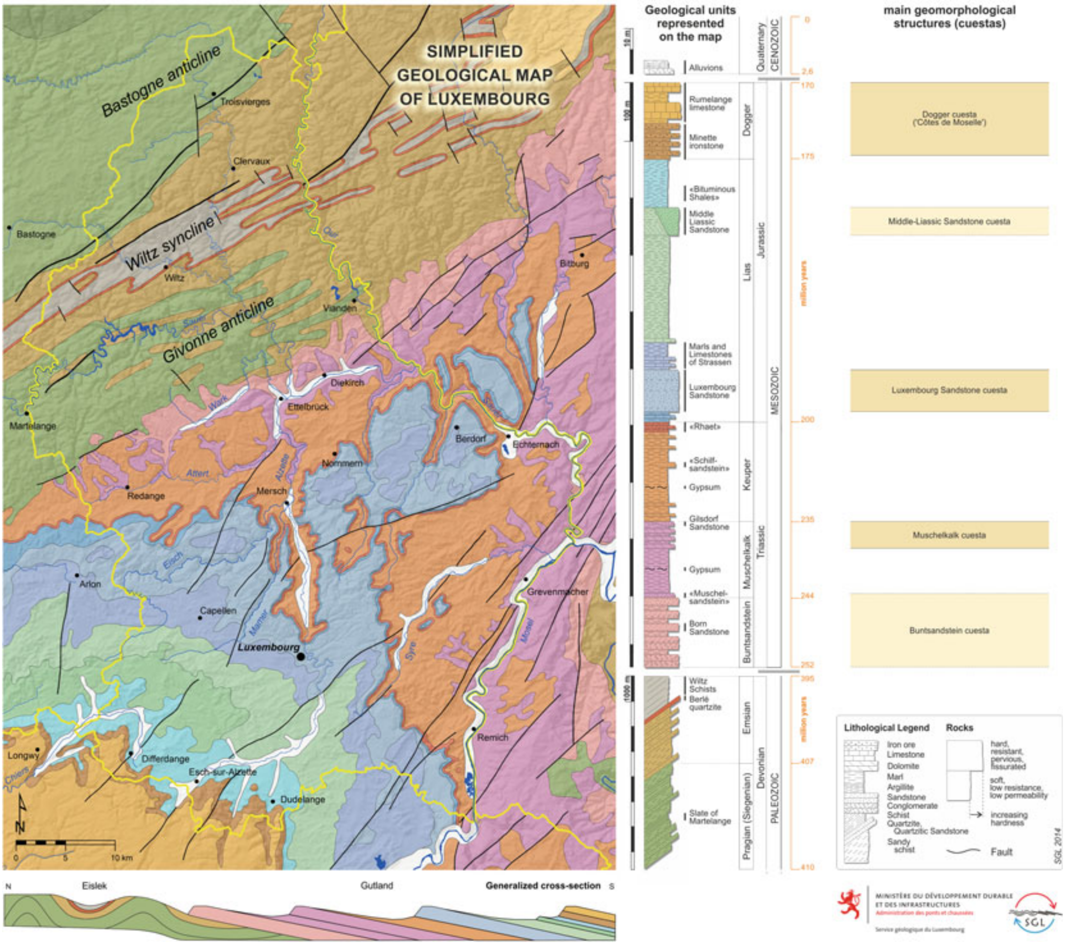

Fig. 1.2 Geological map of Luxembourg, © SGL 2014

by the Wiltz syncline, which is essentially composed of shales, with well-expressed schistosity. The shales are more erodible than the surrounding quartzite dominated rocks and thus form large topographical low-lying areas. To the north and south, the anticlines of Bastogne (N) and Givonne (S) are formed by rocks with a more quartzitic nature (Lucius 1950). Due to intense folding, schistosity is very well developed and oriented parallel to the axial planes of the folds. In the southwestern part of the Eislek, in the Martelange region (Fig. 1.2), more fine grained, clayey, pelitic rocks are present in a slate facies, which have been exploited extensively (Maquil et al. 1984).

By the end of the Perm, the Hercynian massif in this region had been largely eroded, forming the so-called pre-triassic peneplain (Lucius 1950). During the lower Trias, the Buntsandstein seas transgressed over the eroded Hercynian massif and coarse-grained fluvial material was deposited in an arid environment (Mader 1982; Guillocheau et al. 2002), forming a lithological (angular) unconformity. The coastlines of the following and transgressing Mesozoic seas moved progressively to the west, covering the flooded areas with new sediments. The area, forming the Gulf of Luxembourg, belongs to the north-eastern rim of the Paris Basin (Fig. 1.1). These sediments, starting at the Buntsandstein, dip slowly to the central part of the Basin (Fig. 1.2, cross section). Due to the sedimentation history, the lower strata are not developed beneath the entire basin. This can nicely be seen in Fig. 1.2 west of Redange, in Belgium, where only sediments of Keuper age rest discordantly on Devonian rocks. The Mesozoic sediments are characterized by an alternation of hard rocks of sandy, dolomitic or calcareous nature, and of soft rocks of clayey nature like (clayey) marls and claystones. Due to new uplift processes, probably in relation with alpine orogeny by lithospheric buckling as well as a mantle plume beneath the Eifel (Demoulin 2005), the Hercynian basement and its Mesozoic cover was incorporated in the continental environment and erosion processes started again. In the Eislek, the Mesozoic sediments have been eroded since. In today's Gutland, one observes in its most southern part a maximum thickness of 1000 m (Fig. 1.2).

The lithological log in Fig. 1.2 shows the succession of sediments, the hard–soft property is emphasized. The main mineralogical components of the rocks are quartz, clay minerals and carbonates. Important accessory minerals are gypsum and pyrite. All the rocks are of the consolidated type. The hard ones are resistant to weathering, fractured and pervious to water. The soft ones are much less resistant to weathering, not very fractured and quite impervious to water. Soft rocks like marls and claystones consist of different proportions of clay minerals and carbonates. The latter ones are also soluble in water and dissolution leaves residual clays. Gypsum veins ($CaSO_4 \cdot 2\ H_2O$) of variable thickness occur in the marly Trias formations of Muschelkalk and Keuper age. They were largely exploited in underground quarries. Dissolution of gypsum induces higher permeability in the substrate and the sensibility to landsliding is largely increased. Weathering processes form rocks of an unconsolidated type, which can be coarse (sand and gravel) or fine grained, the latter being of clayey nature, cohesive and quite impervious to water. Hard rock formations form steep slopes and are expressed in the landscape as cuestas. The soft rocks are sensitive to variations in water content, form shallow slopes and are, in case of extreme meteorological conditions, very prone to landslides.

At the Mesozoic, due to the disposition of the coast lines, large variations in facies and thickness may occur. Close to the former coast lines, the sediments are often very coarsely grained (sandy and conglomeratic), becoming more and more marly and clayey to the open sea (Lucius 1948). This facies variation is seen on the map of Fig. 1.2 in the Middle-Liassic rocks, the sandstone changing from west to east to a more marly facies.

Jurassic and Triassic rocks differ in the type of carbonates of their marls. The carbonate of the Jurassic rocks is calcite ($CaCO_3$), while the carbonate building the Triassic rocks is dolomite ($CaMg(CO_3)_2$). The solubility of the two carbonates is very different. The solubility of calcite is much larger than that of dolomite, which induces different weathering rates. On marly (dolomitic) sediments of Keuper age, the thickness of the regolith is often just a couple of centimetres, while it might be several metres thick on Jurassic (calcitic) marls, due to different weathering and erosion rates. The dissolution of carbonates and gypsum gives the groundwater a very typical hydrochemical signature. The Ca/Mg-ratio allows to distinguish groundwater from Triassic (dolomitic) and Jurassic (calcareous) rocks, while high concentrations of sulphates (SO_4^{2-}) characterize groundwater from substrates rich in gypsum.

The tectonic structure of the Gutland is characterized by a NE-SW oriented succession of undulations, building the Gulf of Luxembourg (Figs. 1.1 and 1.2) submerging from the Eifel region to the centre of the Paris Basin. The local dip of the strata towards the axis of the undulations, combined with the presence of faults, determine the topographical features and the main direction of groundwater flow. Groundwater emerges as springs at the surface of the underlying impervious rocks, such as marls. The discharge rate depends essentially on the thickness of the strata as well as the type and size of the catchment area. A simple calculation allows to evaluate discharge rates for the Luxembourg Sandstone (outcrop area: about 300 km^2). By admitting an infiltration rate of 25% of a mean annual rainfall of 800 mm, one square kilometre produces about 550 m^3 per day.

1.1.2 Geomorphological Overview

The Eislek and Gutland can be discriminated on Fig. 1.3, clearly showing the correspondence of the geological structure (Figs. 1.1 and 1.2) with the general geomorphology of the landscape.

The rivers of Luxembourg belong with the Alzette, Sauer and Mosel to the catchment of the river Rhine. The Chiers in the southwest, as well as a small river in the north, flow to the west and are part of the drainage network of the river Meuse. The relief of Luxembourg spans heights from 129 m at the confluence of Sauer and Mosel to 559 m at Buergplaz north-east of Troisvierges (Fig. 1.2).

The Eislek is formed by broad plateaus at about 500 m altitude dipping gently to the south and by deeply incised V-shaped valleys. In the north-western Eislek, the plateaus at higher altitudes are covered by a much thicker weathering mantle than in the south, as these surfaces are believed to correspond to one of the older erosion surfaces (Lucius 1950; Demoulin 1995). In the Wiltz syncline, heights of 350–450 m dominate, which correspond to a younger erosion surface (Lucius 1950; Demoulin 1995). Locally, as in the region of Vianden, in front and below today's outcrop of the Buntsandstein rocks at the border of Gutland and Eislek (Fig. 1.3), one might observe residues of the oldest pre-Triassic weathering mantle.

Due to the domination of surface or near surface runoff on the largely impervious substrate of the Eislek, the plateaus were dissected by a dense network of small streams (Fig. 1.4a), following often hercynian structural directions (NE-SW). The valley heads mostly are trough-shaped valleys, whereas the slopes at the lower sections of the rivers are V-shaped and have frequently inclinations of more than 70° (Désiré-Marchand 1985). The valleys often have an asymmetrical cross section with steep cliffs at one side, which are subject to undercutting and denudation by rock fall.

In the Gutland, the slightly sloping alternation of resistant hard and non-resistant soft sedimentary strata, with differences in weathering and soil erosion rates (Jungerius 1980; see also Chap. 2), led to the formation of three important cuestas (Figs. 1.2 and 1.3). They developed in different stratigraphic units, running from north to south. The Muschelkalk cuesta follows the geological outcrop of the Muschelkalk dolomites to the east, and passes into Germany, surrounding the Gulf of Luxembourg. The cuesta of the Luxembourg Sandstone is the most important one, the sandstone having generally a thickness varying from 60 to 80 m. The topography is influenced by the large synclinal structure of the Gutland sediments, as well as the dipping and local undulations of the Gulf of Luxembourg strata. Secondary undulations induce the formation of numerous buttes in front of the cuesta (Fig. 1.4b), separated from the cuesta by the regressive erosion of smaller rivers. The Dogger cuesta (Fig. 1.3), facing north-east, is formed in the youngest Mesozoic rocks of Luxembourg, the iron ore Minette and its overlying limestones. It passes to France and there it forms the north–south-oriented Côtes de Moselle. Also here, several buttes are developed. Two smaller escarpments are observed: the Buntsandstein cuesta is developed in the north-east. To the west, it merges with the Muschelkalk one, the facies of both units becoming mostly sandy and conglomeratic and grouped as 'Trias in border facies'. The Middle-Liassic Sandstone cuesta is developed only in the southwest of Luxembourg, in the more sandy facies of the unit. Numerous secondary steps may be observed locally in thicker strata of more weathering and erosion resistant harder rocks, their importance varying with the thickness of the strata.

The top of the main escarpments culminates at altitudes of about 400 m, independent of their stratigraphic position. The lower lying, undulating and less resistant marls associated with the escarpments lie at about 300 m (Fig. 1.5).

The density of the drainage network depends on the permeability of the substrate. It is less dense but much more accentuated on permeable rocks than on impervious ones, where surface

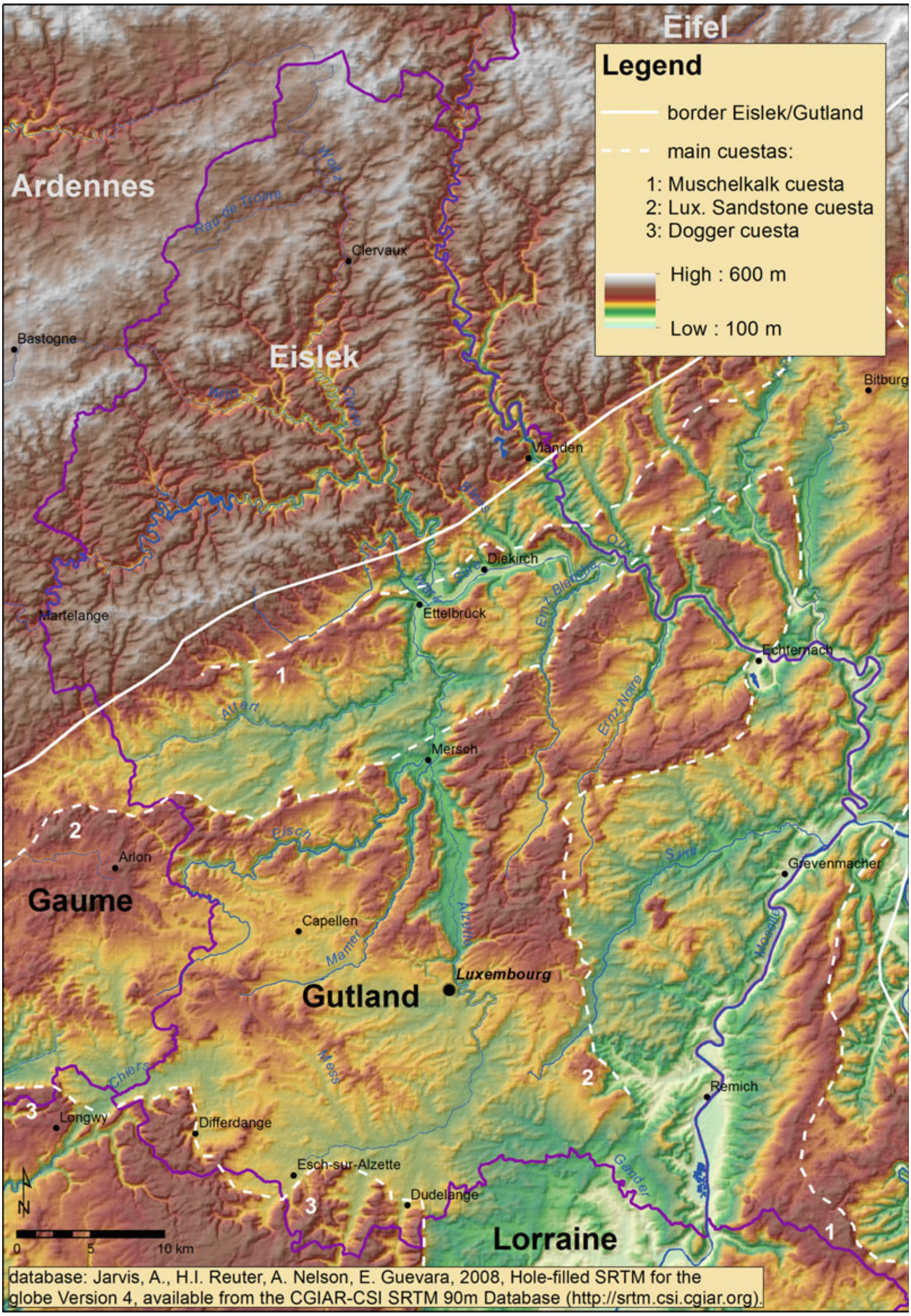

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Fig. 1.3 Relief map of the Luxembourg region with its geographical subdivisions and main cuestas, © SGL 2014

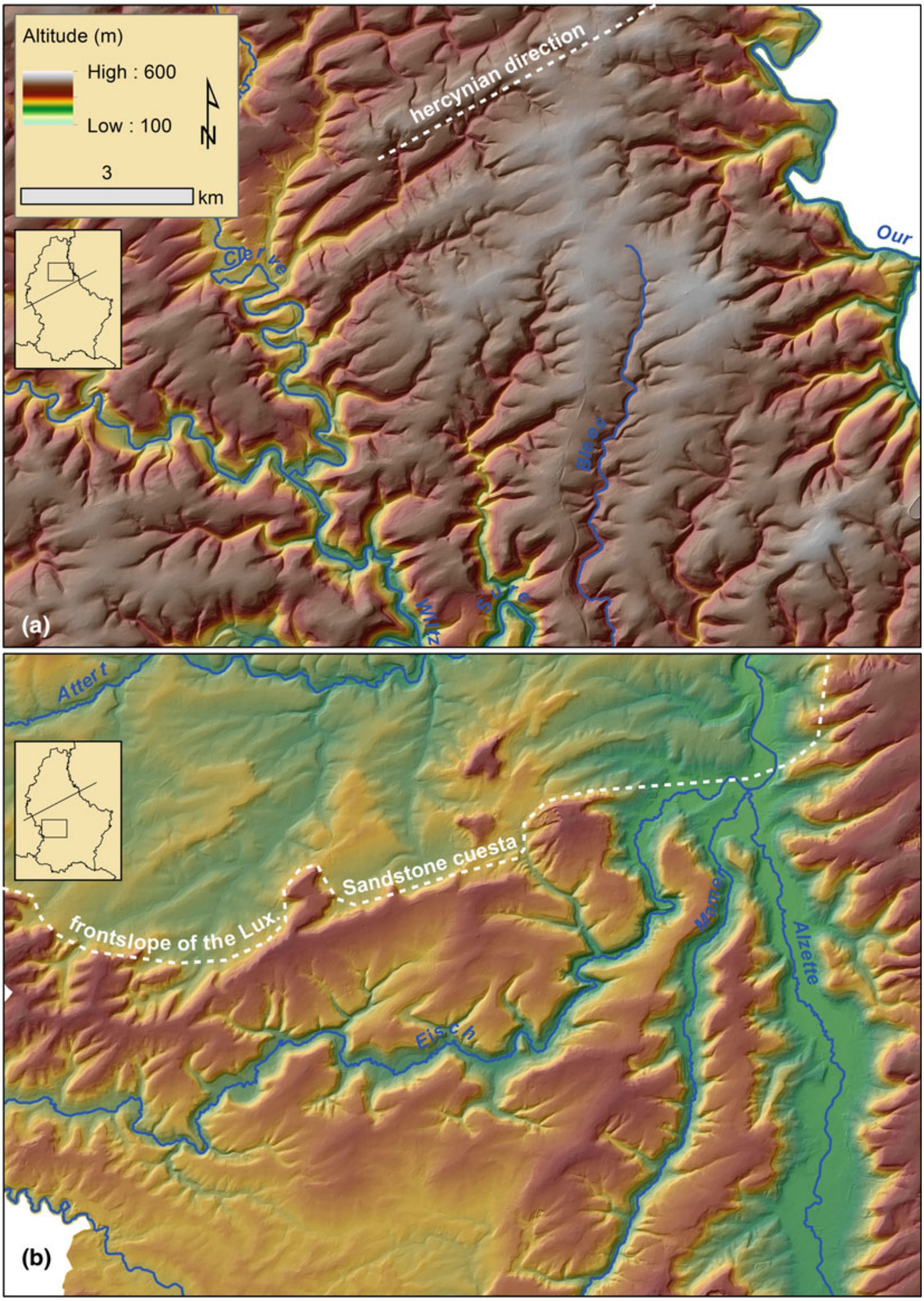

Fig. 1.4 Typical details of the two contrasting landscapes in Luxembourg (shaded DEM, © ATC 2014). **a** The plateaus of the Eislek, dissected by deeply incised rivers, with preferred hercynian (NE–SW) directions of the small streams. **b** The Gutland with the cuesta of the Luxembourg Sandstone, with the deeply incised main rivers and the dense drainage network of the small streams on the marls e.g. north of the cuesta, flowing to the north

Fig. 1.5 The stepped cuesta landscape at the border of Luxembourg and Germany, viewed from the foot of the Luxembourg Sandstone cuesta to the east beyond the Sauer valley on the Muschelkalk cuesta (*photo* BK)

runoff dominates (Fig. 1.4b). The drainage pattern of the Gutland is, however, independent of the geological structures. Particular observations support this: the Alzette flows to the north and cuts through the Lias plateau, the Sauer flows to the south-east to Echternach. It dissects the Lias plateau into the Mullerthal region in Luxembourg and the Ferschweiler Plateau in Germany. In the Ferschweiler Plateau, developed in the northern outcrop of the south dipping Sandstone, the dissection is largely completed. The south flowing Prüm river has, as have the other rivers, created nicely developed escarpments on both sides of the valleys. The Eisch river flows from the region of Arlon to the east and flows on the back of the cuesta, the Attert flows quite parallel, but in front of the cuesta (Figs. 1.2 and 1.4b). The Wark River west of Ettelbrück shows an even more complicated pattern with an incursion into Devonian substrate.

1.2 General Landscape Evolution

Landscape evolution started at the moment, when the freshly formed, compacted and lithified Mesozoic sediments emerged from the sea and were integrated in the landmass. Weathering and geomorphological processes have been active since. It is commonly admitted that the depositional area of the youngest strata of Dogger age, nowadays limited to the southern border of Luxembourg, may have covered large parts of the Gutland (Siehl and Thein 1989). There are not many relicts of ancient landscape evolution from the Mesozoic. They start to become more abundant from Tertiary to Quaternary times. The compiled Fig. 1.6 shows the time scale, in which landscape evolution, tectonic movements, eustatic sea level changes and climatic change took place.

The Palaeogene was characterized by a tropical warm-humid climate, inducing a deep chemical weathering of the bedrock. The alteration is essentially characterized by dissolution of carbonates and oxidation of iron minerals, in function of the rock types and their mineralogical composition. This produced several tens of metres of regolith with typical red and brown colours forming a planation surface. Thick deposits of altered material in the north-west and some relicts on other plateaus of the Eislek are interpreted as remnants of this alteration. In the Gutland, only relicts might be observed on top of the erosional surfaces of the cuesta plateaus. In the late Eocene, an up to 200 m deep incised drainage network developed on the new land surface in the Eifel, flowing to the north and triggered by tectonic uplift, forming the Buntsandstein cuesta in this region. In the later Eislek and Gutland, the general direction of surface water flow was probably still to the Paris Basin (Löhnertz 1994; Löhnertz et al. 2011).

During Eocene and Oligocene times, the Eifel valleys refilled partially by ingressions due to eustatic sea level rises, forming a flat relief of less than 200 m differences in altitude, known as the great valley filling (Louis 1953; Löhnertz 2003).

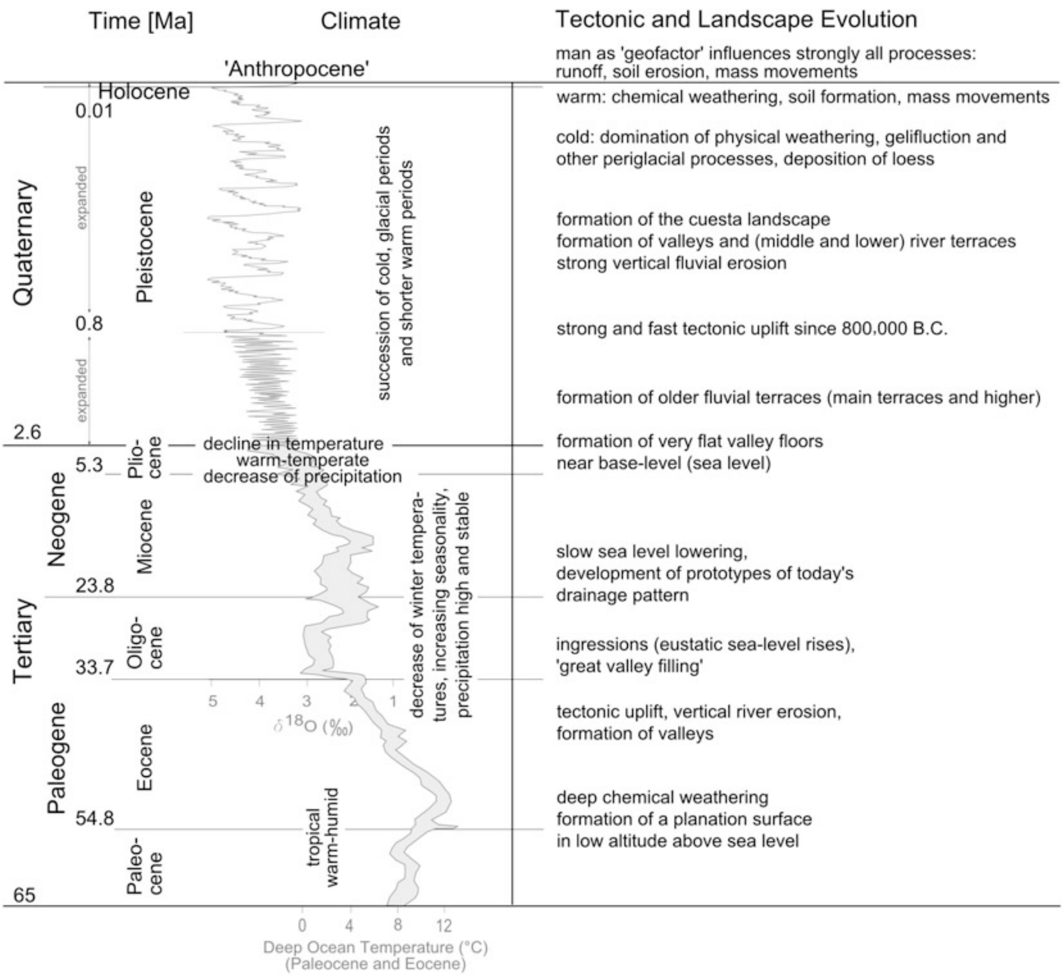

Fig. 1.6 Tertiary and Quaternary evolution of climate, tectonic and landscape (climate modified according to Jansen et al. (2007) (Fig. 6.1), Lisiecki and Raymo (2005), Moosbrugger et al. (2005), tectonic and landscape evolution according to Löhnertz (1994, 2003), Löhnertz et al. (2011), time: STDKe 2012) (*compilation* BK)

In a slightly different geological setting, Le Roux and Harmand (2014) describe a polygenetic infra-cretaceous surface in the eastern Paris Basin, from which today's landscape developed. As a consequence of sea level lowering during the late Oligocene and Neogene, the predecessor of the present-day drainage system incised epigenetically and independent from the nature and structure of the underlying basement, partially in the old river beds. At the beginning, the cuestas were not yet exposed respectively buried under Tertiary sediments. According to Löhnertz (2003) and Löhnertz et al. (2011), the slow lowering of the base level led to the development of vast valley floors in different altitudes. These are marked by relicts of gravel deposits, currently located at high topographical terrain positions.

The first Luxembourg river system, evolved in the central part of the Luxembourg Gulf area, may have been less accentuated, due to the proximity to the water divide, and a greater distance to the base level in the central Paris Basin. A general cooling of the climate took place since the mid-Eocene. This became more pronounced at the end of Pliocene (Moosbrugger et al. 2005), followed in the Pleistocene by a succession of cold, glacial periods and shorter warmer periods, and leading to a warm climate in the Holocene. An abrupt change in evolution took place in the Pleistocene, about 800,000 years ago, with a strong and fast tectonic uplift (Meyer and Stets 1998). This uplift was caused by an active mantel plume under the Eifel region (Garcia-Castellanos et al. 2000; van Balen et al. 2000), and induced an accelerated vertical fluvial erosion and formation of deeper and narrower valleys in both the Eislek and the cuesta landscape of the Gutland (Löhnertz et al. 2011). Differential uplift processes of the Eislek and Gutland (Lucius 1948) accelerated the river incision and sculptured the present relief. At that time, the different resistance of rocks to weathering became important. Physical weathering and mass transport were active on slopes under periglacial cold conditions, while under temperate conditions chemical weathering and soil formation were predominant. Newly formed regolith was removed, the landscape evolved, locally strongly influenced by groundwater flow, determined by the geological structure and lithological properties.

Today's position of the main escarpments developed progressively on the boundary of two different rock types, the more resistant hard one like sandstone or dolomite formations and the less resistant soft marls (Figs. 1.2 and 1.3). There is consensus that the position of the main cuesta escarpments has moved slightly since their formation, as described by Busche et al. (2005) and Tricart (in Liedtke et al. 2010). Jungerius et al. (1970, 1982) showed that the surface lowering of the Steinmergelkeuper landscapes was about 50 cm during the Holocene if compared to the top of the Luxembourg sandstone plateau, and about 100 m maximum for the whole of the Quaternary (see also Chap. 2). Rivers cut in function of the nature of the substrate, and also in relation with the tectonic setting and the time available for development. One observes narrow valleys in resistant rocks, while the valleys are wider in marly strata. A nice example is seen in Hesperange south of Luxembourg city (Figs. 1.2 and 1.3), where an important fault, even seen on satellite images, separates a narrow-incised valley less than 150 m wide and 40 m deep in the Luxembourg Sandstone (N) from an almost 1 km wide shallow valley in the Liassic marls (S).

Holocene landscape evolution can also be derived from palynological reconstruction (see also Chap. 3). This showed that, before the Subatlantic, denudation and fluvial processes were in balance. However, this balance was disturbed after the arrival of man, as evidenced by colluvial slope deposits and alluvial beds in first order catchments.

Geomorphological relicts of the Quaternary landscape evolution are abundant in the actual landscape. Section 1.3 shows several regional examples, differentiated by processes and forms.

1.3 Geomorphological Processes and Landforms

1.3.1 Introduction

The principal geomorphological processes are dominated by fluvial erosion and mass movements. The intensity of the geomorphological processes varied during the Quaternary, largely in relation to cold glacial and relatively warm interglacial conditions, and more recently by human impact (Fig. 1.6).

During glacial periods, the region was affected by periglacial conditions and permafrost. Rocks were fractured due to frost weathering by the freezing of water in cracks and pores, and subsequently disintegrated into fragments of different sizes. Mechanical weathering and mass movements reworked the produced regolith. Gelifluction and solifluction or faster mass movements transported hillslope material downhill. The typical coarse-grained debris deposits with large blocks occurring along major escarpments and valley slopes are thought to be relicts of this periglacial degradation. Weathered material was transported to the valley bottoms, where it accumulated in the floodplain because of the reduced discharge rate of the rivers. Tectonic uplift and incision of the rivers, following increase of discharge during climatic transition phases, deepened the valleys and left behind fluvial terraces in now higher topographical positions. Winds in the cold and dry pleniglacial climate transported fine-grained particles, which were deposited locally as loess.

While physical weathering was most intensive during the cold phases of the Pleistocene, the chemical weathering was more dominant in the warmer and wetter interglacial periods such as the Holocene. At that time, dissolution of carbonates and sulphates played an important role in the Gutland, by transforming marly substrates to a clayey regolith. Oxidation of iron and manganese minerals changed the initially grey and bluish colours to brownish. Carbonates in the limestones, dolomites and marls were dissolved by infiltrated rainwater, which subsequently was also enriched in CO_2 by root respiration. Many small closed natural depressions called Mardellen have developed through this processes on marly Keuper and Lias substrate. However, some of the sinkholes on the Keuper are also man made (see also Chap. 3).

The geomorphologic position and the processes acting on the plateaus or slopes dictate the nature and thickness of the weathering mantle that covers the substrate. On the plateaus, the weathering mantle is still in a large part in situ and reflects the composition of the original substrate. On the slopes, however, the regolith is transported at different speeds as a function of the inclination and moisture conditions and reflects the composition of the upslope available substrates. This regolith material has different geotechnical properties, such as the angle of internal friction and cohesion, as a function of its clay and water content. The disposition of the regolith can be homogenous or formed by a layered mixture of different materials. The speed of regolith movement, through creep or slide processes, is strongly influenced by shallow groundwater circulation within regolith layers of variable permeability.

The regolith observed below escarpments is often formed by an alternation of pervious coarse textured layers and impervious clay lenses. Groundwater emerges from the hard rocks at variable rates, as a function of prevailing meteorological conditions and infiltration rates. Rainwater infiltrates directly into the ground or might be introduced locally into open joints. In that last case, it is incorporated rapidly into the groundwater, which leads to increased hydraulic pressure in the pervious layers and reduction of shear strength. The triggering occurs in natural conditions during extreme rainfall periods, and/or reduced down-flow in the pervious layers of the regolith, e.g. due to frozen ground.

Taking the period of the late Quaternary and the variation of meteorological and hydrological conditions into account, it is likely that all sensitive slopes have been affected by different types of mass movements. Today, a first localization of regions sensitive to mass movements is done by considering the geological map with respect to lithology, in combination with field observations (Fig. 1.2). Geological areas sensitive to landslides lie on clayey or marly strata below pervious hard rocks. The slope angle has to be generally less than 20° to be stable. Stability then depends largely on the angle of internal friction of the clayey regolith material and on the quantity of water controlled by the dip of the pervious strata towards or away from the slope.

In the floodplains, Holocene alluvium of up to 8 m valley fill occur, e.g. in the Mosel valley. Valley fill accumulated as a result of agricultural induced soil erosion in the watersheds, but nowadays stabilizes the foot of the slopes against mass wasting in large areas. Slopes are generally stable under the prevailing meteorological conditions, but this might change in the future, as extreme meteorological conditions are predicted to occur more frequently.

Currently, but effectively since the beginning of the Anthropocene (Fig. 1.6), man plays an important role as geofactor, when considering the rapid development of settlements and construction of transport roads, and also by the effects of land use change and deforestation. The valleys of the Gutland were preferred settlement areas, and the influence of man on triggering mass movements is growing since its first active presence. Some dormant Pleistocene landslides have already been reactivated in the valleys by deep excavations.

Man's influence on the water cycle is increasing, and affects also fluvial erosion and deposition processes.

1.3.2 Fluvial Processes and Landforms

Fluvial terraces have developed during the Pleistocene along the larger river valleys in Luxembourg. Numerous publications deal with the development of these valleys. Generally, they distinguish between high, main, middle and lower terraces (e.g. de Ridder 1957; Verhoef 1966; Wiese 1969). The latest research by Cordier (2005) distinguishes six middle and two lower terraces in the Mosel valley of France, Luxembourg and Germany. Terraces in catchments of smaller tributary rivers are occasionally observed in temporary road outcrops or construction sites. An example is described by Kausch and Maquil (2006) from the Syre river. Duijsings (1987) described in detail the current processes of a small stream, which is currently incising itself in Keuper marls including fine scale terraces.

In the river systems of the Attert and the Wark, there is evidence for a stream capture east of Redange, which took place during the Pliocene (Verhoef 1966). In the Sauer valley at Echternach (Fig. 1.2), a meander cut-off took place at the end of the last glacial period (Würm-Dryas). This is dated by pollen analysis, leaving the Thull hill as meander core (Coûteaux 1970). The Sauer river shows more abandoned meanders, such as those near Bettendorf (e.g. Fig. 5.6 in Chap. 5). Also, the Alzette river started to connect to the Sauer not earlier than the late Pliocene, as on the older terraces sediments containing Raseneisenerze (Riezebos et al. 1990) are completely absent, whereas they start to appear lower down the slope at the high and main terraces (level T9 of Verhoef 1966). This difference indicates the establishment of a connection of the Alzette to the Sauer, bringing material originating from the southern part of Luxembourg to the north. At the edge of the Luxembourg Sandstone plateaus, numerous small and actual dry valleys are observed. They are filled with ancient alluvial deposits.

1.3.3 Periglacial Landforms and Processes

Loess deposits are present as isolated relicts of primary aeolian deposits on nearly all plateaus of the Gutland, while they are very rare in the Eislek. Loess is frequently found on slopes as an important constituent in material reworked by gelifluction processes, and the thickness of primary loess is normally only 1–2 metres (Storoni 1980). Some reworked loess deposits have been mostly accumulated on the foot of the slopes.

On the Merscherberg (near Mersch, Fig. 1.2), an exceptionally, up to 12 m thick layer of loess, lying on the level of the middle terrace, is preserved and has been investigated (Maquil and Postolache 2005). At its base, lacustrine sediments show initial deposition on a more or less flat, partially inundated surface. In these layers, one finds locally reworked grains of Raseneisenerz of Tertiary origin (Riezebos et al. 1990). The loess accumulation took place in the shadow of the Lias cuesta, showing that the escarpment had probably at that time its present-day position.

On the slope of the Merscherberg, reworked loess deposits have been exploited in pits (Heuertz 1969; Heyart 1964). Similar sediments were observed in a temporary outcrop in the Mosel valley at Remerschen (south of Remich, Fig. 1.2). There, one finds lenticular shaped layers of weathered marls, included in an up to 4 m thick loess-like regolith. The marls crop out on the upper part of the slope, and its presence within the loess is interpreted as the result of pull-out of marls flakes by solifluction and earth flow. These deposits are nowadays still prone to sliding.

One particular observation can be made on the site of the 'Champignon' north-east of Nommern (Fig. 1.2). The huge sandstone block is wind shaped, and rests as a regular sculpture on a large surface of rounded sandstone, lying below and a

Fig. 1.7 An outcrop of about 2 m in height showing bending of sedimentary layers, interpreted as the result of periglacial creep (near Remerschen, south of Remich, *photo* BK)

couple of hundreds of metres in front of the Lias cuesta.

Evidence of Pleistocene permafrost conditions like creep, earth flow, gelifluction, patterned ground, ice wedges exist. Such evidence, however, is seldom visible on the surface and is usually observed in small, short-lived outcrops, on building sites, in road cuts or in quarries.

Periglacial creep on slopes has often affected and deformed the underlying substrate. On the Mosel slopes near Remerschen, a large outcrop has been opened during a land consolidation project. The slope on Keuper marls was largely affected by ancient and recent slides, and the authors surveyed, planned and attended the numerous drainage and consolidation works. The slope shows undulations and shearing deformation of the marly and dolomitic strata of Keuper age, covered by a thin cover of Holocene regolith (Fig. 1.7). The slight original dipping of the strata has been dragged and folded by gelifluidal movements. Movements of this kind might pull out fragments of the substrate including it into the regolith. This phenomenon has also been described by Cammeraat for Keuper marls in a much flatter landscape in the Stegen-Schrondweiler region (Cammeraat 1992).

Fig. 1.8 Bending of the schistosity by creep in the Eislek near Michelau (*photo* SGL)

A similar process is known from the Devonian shale of the Eislek (Fig. 1.8). The original schistosity is broken up and bent parallel to the slopes by creep (bended outcrop; Hakenschlagen). The thickness of the deformed layer can be one to several metres and depends on the steepness of the slope. This phenomenon is still active today, but at a much slower intensity than by periglacial creep (Wiese 1969). Intense fracturing as a result of frost weathering simultaneously affected the schists, leading to thin and elongated fragments of a few centimetres in size in well sorted sediments, called grèze-lithée (Riezebos 1987). Nice outcrops might be observed in the Our valley south of Vianden

Fig. 1.9 Up to 5 m deep incised active gully in a sandy valley fill near Kopstal (west of Luxembourg city) as a consequence of concentrated discharge of surface water, the front part of the concrete tube itself is eroded (*photo* BK)

(Fig. 1.2). This material, transported by gelifluction processes, has extensively filled up small and dry valleys in the Eislek. Some of these deposits were exploited in gravel pits.

The shallow valley heads, observed in the Eislek as well as on the Luxembourg sandstone plateau, are nowadays characterized by the absence of water flow. Introduction of additional surface water in these valleys by man will induce intense gully formation downslope, especially in the sandstone substrate (Fig. 1.9), transporting fine-grained material to the river system.

Cryoturbation structures are observed locally as well. This process was active in places characterized by the alternation of rocks of different permeability and water contents (Fig. 1.10). The observed structure in the outcrop near Frisange (south of Luxembourg city) can be explained by the local freezing of water in the altered marls, lifting up thin overlying limestone strata.

Fossil ice wedge polygons can be seen on numerous places in the Gutland on aerial images. An example is shown on the hill Thull on the meander core of the Sauer at Echternach, where patterns of darker colours, induced by soil moisture and vegetation, indicate a system of fossil ice wedge polygons in the terrace sediments (Fig. 1.11).

Asymmetric valleys are very common all over the landscape. In the Eislek, the small valleys are often oriented parallel to the geological structures of the Devonian bedrock (Fig. 1.4a). They show asymmetrical cross sections due to structural characteristics of the bedrock, such as the dip of the stratification or orientation of the schistosity, as well as to the topographical exposition. On south to east exposed slopes, melting and freezing was more active under periglacial conditions, inducing more freeze–thaw-induced fracturing and faster transport of the regolith to the valley bottom. Slopes exposed from north to west received less energy from the sun and were more stable (Wiese 1969).

In the Gutland, asymmetric valleys are developed in relation to the structural disposition. The local dip of the strata affects largely water circulation. Groundwater emerges rather on one side of the valley while it infiltrates on the other side. Slopes rich in groundwater, emerging as springs or as diffuse exfiltration, evolve more rapidly than the opposite ones. This might lead on one side to active slope movements, while the other side is relatively stable.

1.3.4 Mass Movement and Hillslope Processes and Landforms

Gravitational mass movements are strongly influenced by the geological structure of the Gutland. Landslides dominate in soft and impermeable clayey rocks, rockfalls in hard and

Fig. 1.10 Cryoturbation structures in a new road cut in the altered Marls and Limestones of Strassen (li3). Three layers of dislocated limestones can be observed. (*photo* SGL)

permeable rocks, and one process might affect the other one. Several examples of mass movements have been observed and studied by the authors in different geological positions.

Sliding is a particular movement observed in many parts of the cuesta of the Luxembourg Sandstone (Fig. 1.3), e.g. in the region around Berdorf (Fig. 1.2). Fracturing during regional uplift, inducing a pattern of joints, has broken up the sandstone strata in rock monoliths with sections varying from 25 to 400 m^2 in plan surface, often with an almost rectangular pattern. The Marls of Elvange (li1) and especially the Rhät--claystone (ko2), underlying the Luxembourg sandstone, are incompetent and particularly sensitive to deformation. About 70% of the actual landslides, mostly influenced by man, were active on these two formations. Sliding at the base of larger sandstone monoliths, over these marly beds, might occur if stratification is dipping towards the topographical slope, or by pressure release after erosion of the rock face. Different movements of the monoliths are observed, depending on the localization of the sliding plane, relative to the base or the centre of gravity of the monoliths. Toppling of a sandstone block will occur when the slide surface is located close to its outer edge. Sliding at its base will occur when a large part of the base is affected. The latter movement opens joints to narrow caves, as nicely seen in Fig. 1.12.

A recent example of man-induced mass movements is that of Deysermillen (Fig. 1.13), south of Grevenmacher (Fig. 1.2), where an about 50 m thick dolomite package of the upper Muschelkalk forms an impressive escarpment.

Fig. 1.11 Fossil patterned ground near Echternach, © SGL 2014

Gypsiferous marls of the middle Muschelkalk are underlying the dolomitic unit. This unit is, due to its clayey character and the presence of gypsum veins, very sensitive to landsliding. Local dissolution of gypsum develops a secondary permeability, inducing progressively new groundwater circulation paths in a normally quite impervious material. In the winter of 1964–1965, a very large movement has been triggered, affecting progressively the entire slope, destroying several buildings and pushing the valley road into the river. Works on the Mosel waterway have been done since the beginning of the 1960s. The water level of the Mosel had been raised up to 4 m by the Grevenmacher lock gate. The higher water table reduced the groundwater down-flow rate, and raised hydraulic pressure at the toe of the slope. At the same time, earthworks at the new Mosel road reduced the load on the toe. A first slope slice started to move towards the Mosel. This affected the upper parts of the slope by reducing the retaining forces. A second destabilized slope slice of about 200 m length (2 in Fig. 1.13) moved very rapidly to the river, up to 20 m during one night. The movement progressed uphill over a couple of months up to the dolomitic escarpment, dragging down even some dolomite monoliths.

A couple of hundreds of metres north of this site, the historical landslide of Longkaul is located in a similar position. Its contours can nicely be seen on the 1:25,000 topographical map (Grevenmacher). A thick cover of marly Keuper sediments (ku on Fig. 1.13), overlying the dolomitic cuesta, regularly glides over the escarpment and falls on the regolith below. This progressively loads the top of the regolith below the escarpment, thereby reducing its stability. A first natural movement is believed to have started off in medieval times, and it has been reactivated numerous times by extreme meteorological conditions.

Fig. 1.12 A sandstone block slid at its base on the underlying marls and is vertically displaced by several metres and now leans against the Lias escarpment (Raiberhiel near Berdorf) (*photo* BK)

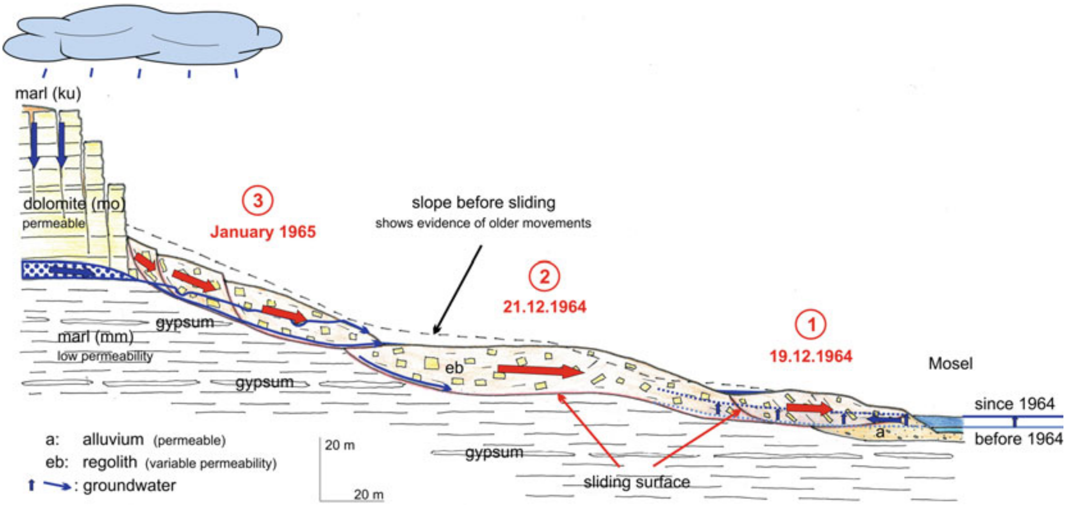

Fig. 1.13 The movement of Deysermillen south of Grevenmacher in winter 1964/65 (*cross-section* BK)

1.3.5 Anthropogenic Processes

Evidence for **soil erosion processes** is documented by truncated soil profiles on erosion sites, as well as by sediment traps like colluvial deposits on (the foot of) slopes (see also Chap. 6) floodplains or small closed depressions such as Mardellen (e.g. Poeteray et al. 1984). A relation between the history of soil erosion and the history of land use is shown on different sites on arable land and under forest (see also Chap. 3). A compendium of soil erosion studies in Luxembourg is given by Cammeraat (2006) and in Chap. 2.

Besides the Lias cuesta, man has also intensely affected the appearance of the Dogger cuesta (Fig. 1.3) that developed in the south of Luxembourg in the iron ore Minette and the overlying limestones. The iron ore has been largely exploited, dissecting the natural cuesta front towards the south, and exposing local large bedrock cliffs in the quarries. The new escarpments are now exposed to natural processes, such as weathering and rock fall. With time, these cliffs and the slopes below will become even more stable than before, since the influence of water has also been strongly reduced. Before exploitation, groundwater flow was to the north, to the Alzette basin. However, mine drainage changed the groundwater circulation, and waters are now conducted underground to the south-east into the basin of the Mosel. This reduces the discharge to, or dry out the small streams initially flowing down the slopes in front of the cuesta.

Chapter 3 discusses the human impact on the Gutland landscape, which becomes visible in sedimentological records from the late Holocene. In Chap. 5, examples of the complex nature of the Luxembourgian landscape are shown for some sample areas along the cuesta landscape near Diekirch (Fig. 1.2). For these landscapes, the complex spatio-temporal evolution and interaction between different geomorphological processes is illustrated. The described processes were active and sculptured the landscape under changing climatic conditions. Since the Holocene, some of the processes are still active on a finer scale. Nowadays man's influence is more and more visible. Also, the predicted more extreme climatic conditions might influence the intensity of the processes.

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