2 Historical Perspective of Dutch Geomorphological Research in the Gutland Region in Luxembourg

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Abstract

In the 1950s, geomorphological research by the University of Amsterdam broke with the traditional way of studying landforms by introducing laboratory research. Starting with *grain size analysis* and *standard chemical analysis*, it gradually extended to *clay mineralogy*, *heavy mineral analysis*, *palynology* and *micromorphology*. These methods were also used in Luxembourg, where research concentrated on past conditions: tropical weathering during the Tertiary and periglacial phenomena during the Pleistocene. In the 1970s, the emphasis in Luxembourg swung to present-day processes. This was a major parameter shift again requiring new research methods such as soil profile analysis for geomorphological reconstructions, and setting up hydrological field stations. Prevailing research subjects included cuesta formation by differential soil erosion, soil erosion in agricultural lands, and soil formation and erosion under forest with the role of rodents and earthworms. It was a prelude to the last decades, in which the role of litter quality and differences in pH, decomposition and mineralization of nutrients have been addressed.

2.1 Introduction and Aim

Luxembourg has always attracted Dutch geomorphologists. There are several explanations for this popularity: the characteristic European mountainous relief which is not found in the Netherlands, the absence of a Luxembourg University where earth sciences were taught, and the presence of a cooperative geological survey.

Geomorphologists of the University of Utrecht were among the first to produce valuable studies of the geomorphology of Luxembourg, mainly on the development of river terraces as a response to tectonic uplift. Their promotor was prof.dr. Jacoba Hol whose Ph.D. thesis was devoted to the hydrology of the Ardennes. The

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University of Amsterdam followed in the 1960s. Over the years, their research developed into two methodological directions, the *bio-geomorphological approach* based on soil studies which is examined in this chapter, and the *hydro-geomorphological approach* dealt with in later chapters.

The aim of this chapter is twofold:

- Presentation of a number of methods developed by the University of Amsterdam for investigating the many past and present processes active in a characteristic European cuesta landscape.
- The contribution of these processes to the geomorphological development of European secondary mountain chains ('Mittelgebirge').

2.2 The Setting

The Grand-Duchy of Luxembourg can be subdivided into two main regions (Fig. 2.1): the Oesling, which is the northern part with a substratum of Devonian rocks (Lucius 1950) and the southern Gutland, which has a substratum of divers Mesozoic sedimentary rocks (Lucius 1948). The Gutland is situated at the NE border of the Paris basin and is a characteristic cuesta landscape surrounding a major tectonic basin. A sequence of cuesta steps that is present is related to outcrops of Triassic and Jurassic sedimentary strata, which slightly dip inwards towards the centre of the Paris Basin. In between the outcropping dolomite, limestone and sandstone formations, marls and claystones are present of which the Keuper marls proved to be particularly important. The marls underlie one of the most prominent cuestas, the Luxemburger Sandstone or Lias cuesta, which is developed in the Lower Lias. The highest parts of the cuesta landscape rise to altitudes of about 420 m and cover large slightly sloping plateau-like areas. The lowest parts are adapted to the level of the Mosel river which is about 140 m at the confluence with the Sauer.

The Gutland of Luxembourg has a temperate humid climate with an annual rainfall ranging from less than 700 mm in the east to 1000 mm in the utmost southwest (Atlas du Luxembourg 1971). Average annual temperature is around 9 °C. Evapotranspiration rates are typically about 400–500 mm $year^{-1}$ depending on land use. Rainfall intensities over 60 mm h^{-1} are relatively rare (Lahr 1964). From recent data, it is becoming clear that rainfall amounts increase through time, especially under the prevailing westerly winds (Pfister et al. 2000).

The Gutland has a miscellaneous land use, which is strongly related to substrate and slope. The steep slopes of the cuestas are mainly covered with deciduous forests. Important tree species are beech (*Fagus sylvatica* L.) and hornbeam (*Carpinus betulus* L.) because they regulate geomorphological processes, either directly such as by stem flow, or indirectly through the palatability of their leaves for earthworms. The dip slopes in between the cuesta escarpments are now under different types of crops, but grasslands are becoming more common. Conversely, the former grassland on heavy marl soils is increasingly used for the cultivation of maize.

2.3 Historic Overview, in the Footsteps of Davis

To appreciate the scope of the geomorphological and soil research of the University of Amsterdam in Luxembourg, it is necessary to put this research in a historical perspective. Starting point is the maxim of Davis (1899), who was the founder of geomorphology as a systematic discipline:

$$\text{Landform} = \int (\text{structure, process, stage})$$

Each of the terms on the right side of this equation has its own aficionados, to the extent that the main aim of the equation— explaining the landform—often recedes to the background.

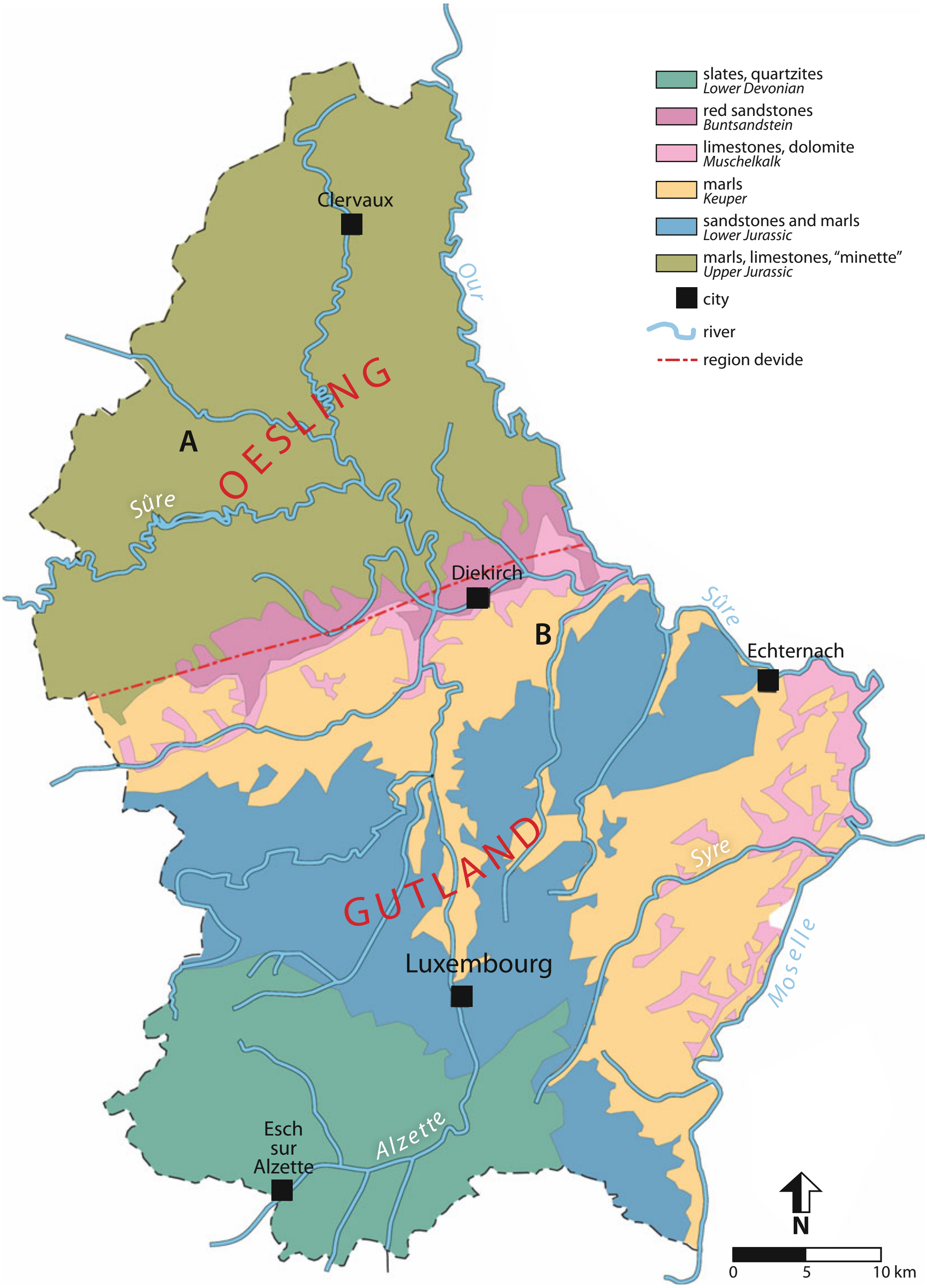

Fig. 2.1 The two main regions of Luxembourg, Oesling and Gutling and the main geological subdivision of the country

2.3.1 Stage ≈ Time

Davis, a geologist himself, emphasized the role of time in the explanation of landforms. He brought order in the apparently chaotic appearance of the Earth's landforms by postulating a time sequence and subdividing the landforms in sequential developments stages (Davis 1899). Starting with uplift in the juvenile stage, a mountain range reaches maximum relief during maturity, and ends up as a gently undulating peneplain in the old age. This approach dominated geomorphological research in Europe for the next five decades. Especially German geomorphologists went out of their way to show that Davis' model was much too simple. They argued that the sequential development could be interrupted at any time by tectonic movements or by climate change. They coined the terms *Morphotektonics* and *Klimamorphologie,* respectively, for the two specializations that emerged from their research. With their studies of stream terraces, the geomorphologists of the University of Utrecht contributed to morphotectonics. The University of Amsterdam emphasized the climatic control of the Klimamorphology.

2.3.2 Structure ≈ Materials

Jan Pieter Bakker was the founder of geomorphology at the University of Amsterdam in the 1930s. He gave geomorphological research a drastic twist by expanding the significance of the first independent term of Davis' conceptual equation. He discovered that earth materials reveal much more of the origin of the landforms than geological structure alone. Also, these materials contain a wide diversity of information that is not visible in the field but can be extracted from samples in the laboratory. In 1951, he established the Laboratory of Physical Geography and Soil Science and started with applying to geomorphology the sedimentological methods then in use for soil research in the newly established Dutch polders (Jungerius 2002). It started with *grain size analysis* and *standard chemical analysis*, to be extended later to *clay mineralogy* and *heavy mineral analysis*.

Bakker introduced laboratory studies not to explain landforms, but to support his 'Klimamorphological' theory, in his case by detecting past tropical and subtropical climates in weathering profiles. Clay mineralogy was used to study the changes in the Tertiary climate which had influenced the development of the European low mountain ranges ('Mittelgebirge'). Climate in that period shifted from warm-humid to relatively dry periods (Bakker and Levelt 1964). In the first case, strong chemical weathering led to the development of the Tertiary plateau loams investigated by Levelt (1965). The dry climates affected the higher parts of the landscape through denudation in the absence of an uninterrupted vegetation cover. Hermans (1955) extended the concept of 'denudative altiplanation' to the Oesling, the crystalline northern part of Luxembourg. He argued that the relatively level summits were not remnants of a peneplain as was the current theory at the time, but the result of periglacial denudation processes affect the higher parts of the relief. This was what Bakker taught his pupils: being critical of established theories often opens exciting new avenues of research.

Our realization of the importance of soil profiles began when we followed a course in soil survey methods with the soil survey of Belgium, which was part of the obligatory curriculum of the study physical geography at the University of Amsterdam. All geomorphological research of physical geographers that followed the line of Bakker in Luxembourg started by making a soil map of their fieldwork area. It makes students familiar with the pattern of erosion (=down wearing) and colluviation (=raising). Soil erosion cum colluviation is, therefore, a process that has direct consequences for the geomorphological dynamics of a terrain: it links soil science to geomorphology (Jungerius 1958). Formal training in geomorphological methods and remote sensing started years later when the Vorarlberg group shifted their field practicals to Luxembourg (see also Chap. 5). More than 60 years ago, in the Soil Survey Manual of the US Departure of

Agriculture of 1951, soil erosion in need of conservation was called *accelerated soil erosion,* to distinguish this anthropogenic variety of the process from natural soil erosion. Natural soil erosion was defined on page 251 of the Soil Survey Manual as *a* ***constructive*** *as well as* ***destructive*** *process, geologically speaking responsible for* ***wearing down*** *higher points and* ***elevating*** *lower points*. Admittedly this two-pronged effect of the erosion process is confusing, but it is familiar to most members of the European Society of Soil Conservation (SSSC) with a geomorphological background because they are aware that erosion processes include downwearing as well as raising parts of the landscape. Deposition of colluvium is the agricultural counterpart of elevating the land as part of the natural erosion process.

Unfortunately, in applied soil science and agriculture generally, the term soil erosion is now used in the restricted, anthropogenic sense. This overlooks the fact that natural soil erosion has formed most landscapes that are affected by accelerated soil erosion, and continues to do so, because natural erosion never stops as long as there is relief. Even where the accelerated soil erosion processes are dramatically visible as gullies or rills, the natural erosion processes that have shaped the relief in the course of geologic time usually remain evident in the shape of the land. Moreover, the total output of waste from watersheds is often more dependent on natural processes than on agricultural activities.

2.3.3 Process

The concern for processes, the second term in Davis' equation, began in the USA in the middle of the twentieth century, with the hydro-geomorphological studies of Leopold, Wolman and Schumm, soon to be adopted in the UK. In Amsterdam, this methodological turn came in the early 70s of last century, when Anton Imeson joined the staff and introduced in Luxembourg the methods of process research developed in the UK. It involved a further shift from laboratory to field research. Adopting the drainage basin approach, Amsterdam geomorphologists established a number of hydrological and meteorological stations (Duijsings 1985; Cammeraat 1992). These stations served to obtain data on discharge of water and sediments, needed to test hypotheses of the effect of various geomorphological processes in the drainage basin. Research concentrated on forests, which have been the most common vegetation type since the formation of the Luxembourg landscape, with arable land and grassland as derivates. In contrast to the proliferation of erosion studies elsewhere in Europe, emphasis was not on the production of output figures for models developed elsewhere, such as the widely used Wischmeier equation, but on understanding the processes involved. This necessitated the concentration of the research on the smallest spatial units of the drainage basin, the first- and second-order watersheds.

This meant that all three dependent parameters of Davis' equation were investigated in one integrated research programme. And not only that: Davis' essentially physical method was supplemented with a biological approach to determine the geomorphological and pedological significance of plant growth and soil life. The appointment of Annemieke Kooijman filled in the biological gap. The wide range of specialists and methods available made it possible to embark upon the classical quest of geomorphology, the explanation of the landform, which is the quintessence of Davis' equation. The research gave answers to a number of hitherto unsolved questions in geomorphology. These questions included cuesta formation, dating of Holocene soil erosion and the role of soil fauna in the erosion process. In this chapter, we discuss these subjects as they emerged in the early years. Together they contribute to a consistent picture of the development of a typical Western-European cuesta landscape since its origin in the middle of the Tertiary, that will be amplified in other chapters.

2.4 The Formation of a Cuesta by Differential Soil Erosion

The role that is traditionally ascribed to qualities of the underling rock is in point of fact, often due to the response of soil material at the surface to subaerial erosion processes. Where concordant sedimentary rocks dip gently—which they do over enormous expanses of the earth's surface—they give rise to asymmetric hill ridges known as cuestas. It is the stubborn belief of authors of geological and geomorphological textbooks that these landforms are due to differences in 'hardness' of the underlying beds. They fail to realize that rocks are seldom exposed on the dip slope or in the foreland of cuesta landscapes, with the exception of the steep front which is not subject to downwearing but to backwearing and plays a passive role in the development of the cuesta. If there has been any differentiating process at work in carving out the cuesta, it is much more plausible to hold the resistance of the weathering and soil materials responsible, because they are exposed to the subaerial erosion processes. **In other words, a cuesta is shaped by differential soil erosion**.

The significance of this principle is evident in situations where a 'weak' rock develops into a soil which resists erosion. The escarpment in the soft Upper Coal Measures in Nigeria is a case in point (Fig. 2.2). The resistance is due to a protective armour formed in the soil of the Upper Coal Measures by plinthite that hardened on exposure into ironstone concretions. The concretions make the soil over the soft rock more resistant to erosion than the sandy soil of the false-bedded sandstones underneath. The layer of ironstone concretions is the result of the poor drainage of the subsoil (Jungerius 1964, 2011). Termites bring the clay in between the ironstone concretions to the surface where it is removed by the prevailing slope wash processes, leaving the concretions behind. In the course of geologic time, this protective ironstone cap turns the originally soft rock into a 30 m high cuesta front.

The origin of the Lias cuesta in Luxembourg is in a way comparable. This impressive cuesta has been attributed to the 'hard' Luxembourg sandstone consisting mainly of quartz sand embedded in calcium carbonate which provides the 'hardness'. This explanation is questionable, in view of the fact that the Lias cuesta continues across the border with Germany where the sandstone is not impregnated with calcium carbonate and has a rather loose consistency (R. Hansen, pers. comm.).

The Laacher See explosion

A great help for dating the eroded slope materials in Luxembourg proved to be the ash produced by the explosion of the Laacher See in the Eastern Eifel at the transition of the Pleistocene to the Holocene (12,000–11,000 B.P.). At that time, a layer of these minerals covered all the land for thousands of square kilometres around the Laacher See with a characteristic heavy mineral assemblage of brown amphibole, poxene and sphene. The original deposit was found to be 4 cm thick in peat deposits in and around Luxembourg (Jungerius et al. 1968). The present distribution of these minerals reflects the pattern of the Holocene soil erosion: where soil erosion removed much of the surface soil, the volcanic minerals are scarce or absent. For the same reason, colluvial deposits of Holocene age contain these minerals and can, therefore, be separated from Pleistocene slope deposits in which they are absent (Jungerius 1964).

Jungerius and Mücher (1970) tested the hypothesis that the Lias cuesta is formed by differential erosion of the surface soils. They analysed the erosion rates of the various slope elements of the cuesta by studying the remaining concentration of volcanic minerals left behind in the surface soil by the Laacher See eruption (Laacher see explosion 2.1). Compared to the Sandstone on top of the cuesta, the soils of the marly Steinmergelkeuper at the base of the escarpment slope showed highest erosion rates (Fig. 2.3). In a later paper, Jungerius (1980)

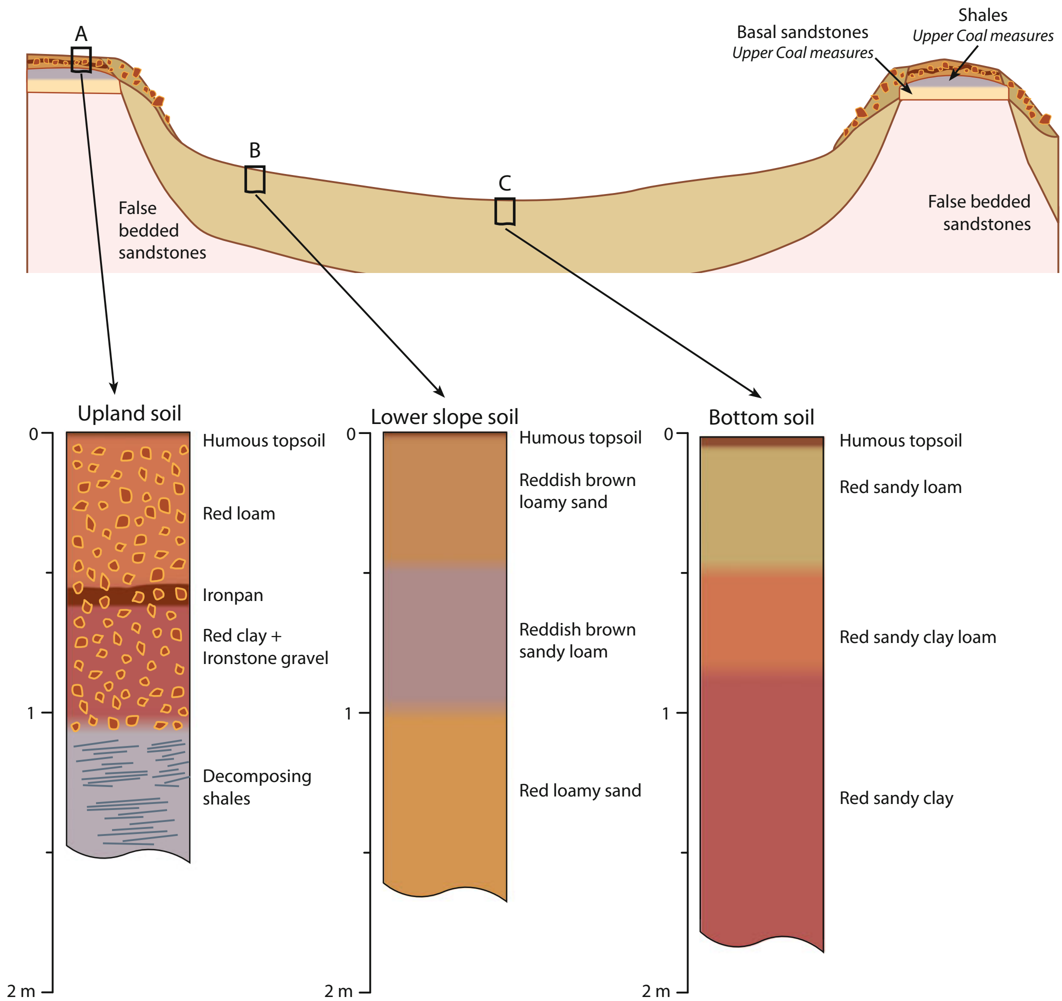

Fig. 2.2 Upper Coal Measures cuesta in Nigeria (after Jungerius 1964)

refined these results by quantifying the Holocene surface lowering with a simulation model using the amount of volcanic minerals left in the surface soil as a measure of soil erosion. Relative to the soils in the Luxembourg sandstone on top, the soils of the Steinmergelkeuper marls were lowered 44–57 cm (Fig. 2.3). Extrapolating this for the whole 2.8 million years long Quaternary, this would amount to 116 m. This amount is of the same order of magnitude as the approximately 100 m difference in elevation actually found. The surplus is presumably due to the fact that the calculated Holocene lowering includes the effects of soil erosion on bare agricultural lands during the last two or three millennia.

Several authors presented current erosion rates for small catchments on the forested Keuper marl areas (Van Hooff and Jungerius 1984; Imeson and Vis 1984a; Duijsings 1987). According to these authors, the small watersheds under forest in question show suspended solid outputs to be a factor 2–5 lower than the agricultural watersheds on the same substratum. However, the influence of land use on sediment production in Luxembourg is ambiguous. Imeson and Vis (1984b) found that soil erodibility, determined by rainfall

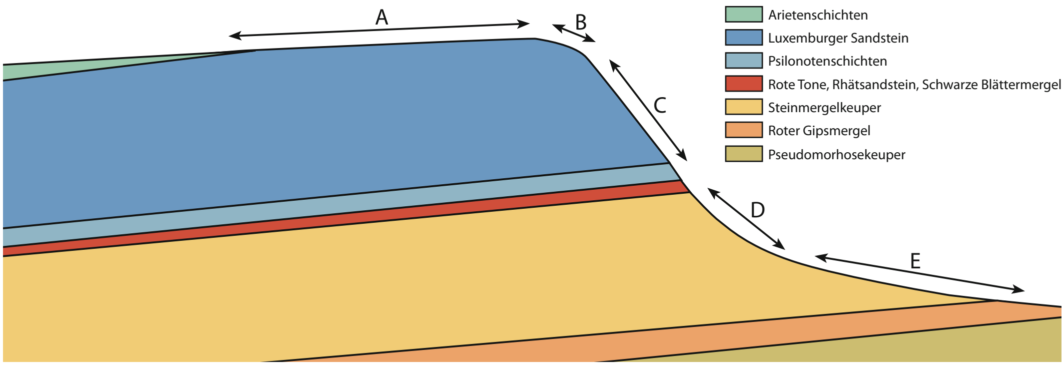

Fig. 2.3 Relative Holocene surface lowering across the Lias cuesta calculated from the frequency of Laacher See minerals of Allerød age remaining in residual soils. After Jungerius (1970)

simulator experiments, aggregate stability and splash erosion measurements, was largest for arable farmland, followed by forest colluvium and undisturbed forest topsoil, and that pasture was least erodible. They further found that erodibility showed a strong seasonal variation.

For these reasons, the erosion processes under agriculture and under forest are discussed separately in the following sections.

2.5 Soil Erosion in Agricultural Lands (Current Erosion Rates)

At the time, every student of the University of Amsterdam started his or her field work in Luxembourg by preparing a soil map of the allocated field work area from soil profile descriptions. There is hardly a better way to get acquainted with the 'population', to use a statistical term. In the second year, they were free to study a preferred process. As most field work areas included forest and agricultural areas, the maps provided much insight in the role of land use.

The general presence in the farmland of truncated soil profiles and associated colluvial deposits, with no sign of soil development, indicates ongoing soil erosion resulting from agricultural practices such as vegetation removal and tillage. Erosion processes on farmed land include splash, rill and gully erosion. Generally, these features are found on slopes with low vegetation cover, such as recently ploughed, fallow fields and fields with maize crops. Figure 2.4 shows the result of gully formation in a fallow agricultural field on marls near the village of Nommern that was subjected to an extreme rainstorm in June 2003, with rainfall intensity of approximately 9 mm in 30 min. The sediment yield of this event was approximated at 15–18 tonne ha^{-1} (Cammeraat 2006).

Soil profile truncation under agricultural land use is common in the marl areas, especially on Steinmergelkeuper. Whereas soil profiles under forest are typically developed with a clear B horizon (see Chap. 6), the profiles on agricultural fields with the same gentle slopes often show no more than a thin Ap horizon directly on top of the C material, or even directly on the weathered bedrock. Evidence of soil erosion is also seen in the occurrence of colluvial deposits on foot slopes and in the dry valleys, and the deposition of alluvium along the stream of third and higher order catchments. The influence of human occupation is clearly demonstrated by the presence of charcoal in the colluvial and alluvial sediments. Holocene fluvial sedimentation in the valley bottoms may reach a depth of several metres and is still continuing these days, as is demonstrated by the presence of a well-layered level of 75 cm thickness depth deposited on a paved road dating from the 1960s near Reisdorf.

To quantify surface lowering by soil erosion, Van Hooff and Jungerius (1984) combined data on extent and depth of soil truncation of 11 first

Fig. 2.4 Fresh gully developed in slope deposits on marls in a fallow field as generated during an intense storm on 10th of June 2003, near the village of Nommern. Reproduced with permission from Wiley Cammeraat (2006)

order watersheds in the Gutland with marl substratum, as shown on detailed soil maps prepared by the students, and compared the results with extent and thickness of nearby colluvial deposits shown on the same maps. This study covered an area of nearly 40 km^2. Only 6% of the area showed complete soil profiles, 44% of the area truncated profiles, 46% colluvial deposits and 4% alluvial deposits. They calculated an average soil truncation of 55 cm for the whole area. This is a conservative measure, as in places where the whole solum was lost, the total degree of truncation could not be established. The figure agrees fairly well with the 44–57 cm value calculated from the presence of volcanic minerals (Jungerius 1980). It appeared that roughly 60% of the eroded material left the second-order catchments, and 40% stayed behind. Similar results were obtained in the USA (Beer et al. 1966; Piest et al. 1975). The material that stayed behind in the catchments filled up the depressions as colluvium and raised the valley bottom with alluvium.

The dating of erosion by pollen analysis

Poeteray et al. (1984) used pollen analysis to date the colluvial deposits in closed depressions. A colluvial layer on slopes in northern Luxembourg which we initially interpreted as a periglacial deposit proved by them to be Subatlantic. They investigated the content of several closed depressions, which have been acting as traps for sediment and pollen. Several cores were analysed, some of which date back as far as the Roman period, based on palynological dating. From these deposits, the surface lowering rates were calculated, showing two clear peaks between 1200–1350 AD (0.086–0.215 mm year^{-1}) and between 1460–1600 AD (0.100–0.279 mm year^{-1}). In the first period, many forest areas were converted to arable land to provide food for the rapidly growing population of the many newly founded cities. This course of events is not restricted to Luxembourg: according to Bork and Lang (2003), extreme soil loss occurred in Germany during the first half of the fourteenth century and—less pronounced—in the second half of the eighteenth century.

The intervening period of recovery of the forest and decrease of soil erosion is probably the effects of outbreaks of pest and the thirty-year war, reducing the intensity of agriculture. It is interesting to note that the sudden enormous supply of eroded material that fed the streams in the hinterland coincides with the palynologically dated formation of the Younger Dunes between the eleventh and fourteenth century (Jelgersma et al. 1970). The rivers transported the eroded material from the catchments to the sea, longshore drift spread it out along the coast, surf deposited it on the beach and the wind blew it inward to dunes. The latest method of sand suppletion is based on the postulated course of events: the so-called Zandmotor mimics the output of a river mouth from where longshore drift, surf and wind take over to bring the sand to the required location.

After the sixteenth century, sedimentation rates declined to 0.055–0.156 mm year^{-1} from 1600–1800 AD. After 1800 AD, this rate declined further to 0.020–0.054 mm year^{-1}, as a result of decreased land use due to the introduction of potatoes, which have a higher calorific yield per ha. This lead to land abandonment and reforestation (Poeteray et al. 1984). In the Chap. 3, this technique is applied to new records of Holocene sediments to disentangle the landscape evolution in the Holocene and the impact of man on the landscape.

In general, it can be concluded that the soil erosion levels in Luxembourg are low to moderate for natural areas. For the agricultural areas, this also seems to be the case, except for some problem areas. The low to moderate erosion rates are consistent with the results provided by Kirkby et al. (2000), for adjoining France.

2.6 Soil Erosion Under Forest, the Bio-Geomorphological Approach

For the development of the cuesta landscape, the rate of soil erosion under woodland is geomorphologically more meaningful than accelerated erosion by agriculture. This type of vegetation, mostly deciduous forest, has dominated the Gutland over long geological time spans, and largely controlled the development of the present landforms. The study of soil erosion under forest was, therefore, one of the focal points of the

University of Amsterdam. Two approaches can be distinguished, depending on the methods used. The *bio-geomorphological* approach maps and monitors slope-forming processes and studies soil profiles, highlighting the role of soil fauna, mainly rodents and earthworms (see also Chaps. 10). The biotic factor, with its manifold effects on soil and landscape development in Luxembourg, was introduced as a major research theme in the early 1970s (Imeson 1976, 1977). The *hydro-geomorphological* approach collects data from instrumented catchments on partial areas (shallow depressions), piping and the role of forest trees such as beech and hornbeam. The methodology was worked out by Cammeraat (1992) and is further dealt with in Chaps. 9 and 10.

In the absence of overland flow, the most important process of sediment supply in forests is splash erosion (Kwaad 1977). Splash impact is particularly heavy in forest because rainwater drips from the leaves in large drops. Measurements showed these drops to have diameters of up to 6 mm. When they fall on the ground from the tree crowns, which are often more than 10 m high, they have reached their theoretical terminal velocity. Splash erosion is confined to areas of exposed mineral soil, produced mainly by the activity of burrowing animals. The amount of splashed material reflects not only burrowing, but also the yearly cycle of litter-fall and decay because splash erosion is impeded by the protection of the soil surface by low vegetation as well as by litter. Two types of animals contributed directly to sediment production and slope formation: burrowing rodents and earthworms. Cammeraat and Kooijman elaborated on this (Cammeraat 2002; Cammeraat and Kooijman 2009; Kooijman and Cammeraat 2010) by coupling forest tree community to dominant bio-geo-hydrological processes (see also Chap. 10).

2.6.1 Rodents

Burrowing rodents, mostly moles, enhance the erodibility of slopes by bringing material with a loose structure and often low organic matter content to the surface. They also play an important role in enhancing hydrological connectivity by connecting soil shrinkage cracks, creating semi-permanent pipes and enabling the transfer of water and sediment downslope to the streams (Imeson 1986; Cammeraat 2002). The effects of splash erosion on bare soil material were extensively studied in experimental plots on a 22° upper slope in a representative valley of the Luxembourg Ardennes, about 15 m from the river, grading abruptly to a 30–35° lower slope (Imeson and Kwaad 1976). The area was completely forested. It is noted that most of the bare soil was found within 10 m or so from the river and that 95% of the bare soil was the result of animal activity, predominantly moles and voles. These animals apparently prefer to live in the moist soils near the river bed and in shallow depressions. The splashed material is the main source of the suspended load in the river.

Aggregate stability was investigated with micromorphological techniques (Imeson and Jungerius 1974). The aggregate stability of the crumb structure of the mounds is low. Splash removed preferentially the particles <2 mm. With longer exposure, the stoniness of the exposed soil increased from 25–50% to 100% when the erosion stopped. Erosion was measured with erosion pins and splash boards. By combining the measurements of soil exposure with those of splash erosion for the same period, the lowering of the slopes by splash erosion was estimated to be 0.33 mm per 1000 years (330 kg km^{-2} $year^{-1}$), near the river increasing to 91.6 mm per 1000 years (Imeson and Kwaad 1976). The geomorphological implications are quite interesting: the convexity of the break in the lower slope is in proportion to the rate of lowering due to the activity of the rodents. A timespan of about 18,000 years would be required to explain the difference in elevation between the projection of the straight slope above the break of slope to a point above the river bed and the present river bed.

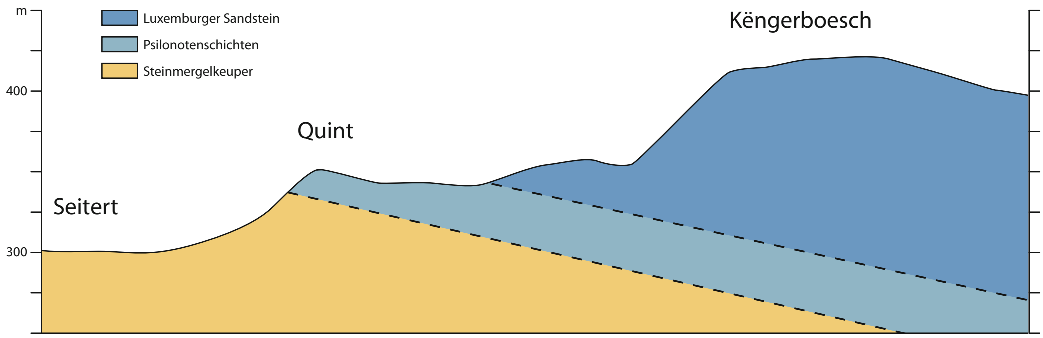

Fig. 2.5 One of the five investigated sections. The names refer to the topographical map 1:20,000. Administration du Cadastre de G.D. de Luxmbourg. LS = Luxembourg Sandstone, PM = Psilinoten marls, KM = Keuper marls. After Jungerius and van Zon (1982

2.6.2 Earthworms

A leading part in the biotic factor of the Gutland is played by earthworms, mainly *Lumbricus terrestris* L. and to a lesser extent *Allolobophora longa* L. They are significant in two respects. First, they are responsible for much of the bioturbation in the surface soils. In this way, they contribute to the contrast between the surface soil and the subsoil, which is characteristic for the soils of the Steinmergelkeuper Formation. Second, they are responsible for removing litter (Satchell 1961, see also Chap. 10), which results in the forest floor being bare and exposed to splash erosion and occasional overland flow.

To investigate the long-term effects of these two earthworm activities, two research projects were set up in Luxembourg. The first of these projects ran from 1980 to 1987 and investigated the area of bare forest floor exposed by earth worms, along five transects across the level parts of the three main steps of the Lias escarpment: Luxembourg sandstone which forms the main escarpment, Psilonoten marls which forms a secondary step and the Keuper marls at the base (Fig. 2.5). The beginning of each transect was marked on the topographical map 1:25,000 and in the field.

Each year before the new leaf fall, estimates of the percentage soil cover were made in squares of 4 m^2, 10 m apart along each transect's length of 400 m, numbering a total of 600 observations each year. The beginning and end of each transect were marked; deviations from the line between successive years were random but never more than a few metres. Leaf consumption by earth worms was the main cause of the observed differences in exposure, which in turn depended on ecological conditions of the soil: sand and moisture content (Jungerius and Van Zon 1982, 1984; Jungerius et al. 1989). The experiment was stopped after 1987 because local deforestation, heavy storms and a road building project had spoilt the experimental design. Over the measuring period, forest floor exposure in summer averaged over 40% on the Keuper marls, 11% on the somewhat more sandy Psilonoten marls and 0–3% on the sandy soil of the Luxembourg Sandstone. These results support the hypothesis that the cuesta formation is a function of the activity of earth worms, which in turn is controlled by the geological conditions.

2.6.3 Soil Creep

The second project focused on soil creep. On slopes in the Keuper marls, there is evidence of soil creep affecting the surface soil, which appears to shift slowly downslope as a result of the continuous bioturbation by worms in combination with gravitational forces (see Chap. 10). An important factor is the abrupt textural contrast between the AE and B horizon (see Chap. 9). The reason is that the soil material is easy to disperse, due to the presence of swelling and dispersible smectite in

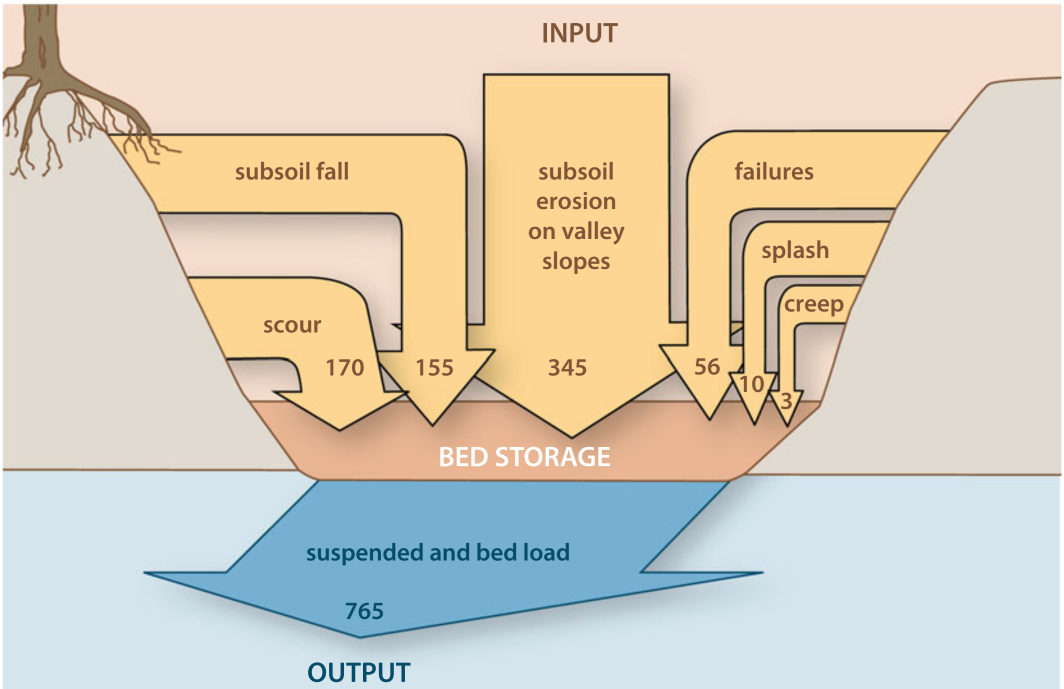

Fig. 2.6 Sediment budget for the Schrondweilerbaach catchment 1979–1981. Numbers are in kg ha^{-1} $year^{-1}$. Reproduced with permission from Wiley after Duijsings (1985)

the fine clay fraction and the relatively high pH, in combination with a complex saturation of divalent cations (no active Al^{3+}).

Soil creep was studied in the Schrondweiler catchment with so-called Rudberg pillars (Jungerius et al. 1989). At five locations along a catenary sequence of 200 m length, from the upper slope across the 2° slope to the bottom, small boreholes 50 cm deep and 2 cm wide were filled with contrasting yellow sand in April 1981. With this method, downward creep of the surface soil can be detected by dislocation of the sand columns. Two columns were dug up after 14 months. Both columns showed definite bending in the upper 15 cm indicating downslope movement varying between 2 and 8 mm. More columns were excavated after 6 years. Bioturbation in that period had been so intensive that the sand columns could no longer be detected in any of the surface horizons, and the experiment had to be terminated. Vestiges of the soil in the lowest member of the transect suggested a downslope displacement of 22 mm since the start of the experiment 7 years before. The type of mass movements was classified as seasonal creep which is produced by the combined action of gravity stresses and expansion or contraction stresses due to changing moisture content (Carson and Kirkby 1972). Part of the clay minerals in the Keuper are particularly prone to swelling and shrinking as could be shown by the presence of slickensides in thin sections, and produced movement on slopes as low as 2°. The exerted forces were manifest from the way an aluminium weir from an abandoned experiment, dug into the soil to collect surface runoff, became more and more distorted (Photo 1 in Jungerius et al. 1989).

2.6.4 Outline of the Erosion Processes on the Keuper Marls

The natural erosion here is due to the specific nature of the substratum, especially the swell and shrink properties of the soil, the type of

Table 2.1 Sediment budget for the Schrondweilerbaach catchment 1979–1981.

		Process	Sediment supply kg (2 years)$^{-1}$	%
Input	Stream banks	Lateral corrasion	20,650	22.9
		Subsoil fall	18,860	21.0
		Mass movements	6850	7.6
		Rainsplash erosion	1240	1.4
		Soil creep	400	0.4
		Overland flow	–	–
		Streambank total	**48,000**	**53.3**
	Valley slopes	Splash detachment + overland flow	38,000	42.2
		Throughflow	4000	4.5
		Slopes total	**42,000**	**46.7**
		Total sediment input	**90,000**	
Output		Suspended load	86,300	92.8
		Bed load	6700	7.2
		Total sediment output	**93,000**	
		Net dissolved output	**180,400**	

From Duijsings (1985)
Figures in bold denote totals

vegetation and soil faunal activity and the hydrological regime (Hazelhoff et al. 1981; Van den Broek 1989; Cammeraat 2002). Apart from splash, overland flow and creep on soils with burrowing animals, there are a number of other processes active on the forest-covered slopes of Luxembourg. After 2 years of monthly measurements in a 60.8 ha catchment, Duijsings (1985, 1987) found that sediment transfer from the Schrondweilerbaach on Keuper marls was determined by three types of processes active on the valley slope and six types of processes active on the streambank (Fig. 2.6 and Table 2.1). Valley slope processes such as splash erosion and overland flow contributed with 46.7% of the sediment budget of the Schrondweilerbaach, but throughflow with 4.5%. This process is controlled by the texture difference between the AE and B horizon of the Keuper soil, which promotes the process of subsurface erosion of dispersive clay (see Chap. 9). The streambanks contributed 53.3% to the supply of sediment, with lateral corrosion and subsoil fall being the main bank processes contributing, respectively, 22.9 and 21.0%. Each process could be related to a specific condition: lateral corrosion and splash erosion to summer thunderstorms, subsoil fall to frost periods, soil creep to biological activity. In terms of surface lowering, the output of 0.765 tonne ha^{-1} (Duijsings 1987; Table 2.1) approximates 0.05 mm year^{-1}. This value agrees with the average rates of slope denudation given by Poeteray et al. (1984) for the last 200 years: 0.020–0.054 mm year^{-1}.

2.6.5 Erosion Processes on the Luxembourg Sandstone

By comparison, erosion of the sandy soils of the Luxemburger Sandstone is relatively low, but not absent. Van Zon (1980) gives denudation rates for a small forested catchment on the Luxemburg sandstone on the scarp slope. Measured denudation was found to be very low: only 0.010 tonne ha^{-1} year^{-1}. An important factor is the presence of bare spots where the sandy soil was subject to splash erosion. Unexpectedly, he found that about a quarter of the amount was transported by the leaves of the forest floor, which may well be an important factor in the explanation of the presence of colluvium on forest slopes covered with litter (Van Zon 1978).

Although soil life is practically non-existent in the sandy soils of the Luxemburg sandstone, especially those under the widespread beech forests, but soil formation is not without interest. At a depth of 50–70 cm in beech forest on almost level dipslopes, the soil is often compacted to a mottled *fragipan*, which restricts water flow and root penetration (Jungerius 1980). True to theory current at the time, this fragipan was attributed to periglacial conditions during the last glaciation (Van Vliet and Langohr 1981*)*, but the close relationship with beech trees indicates that it is related to the beech forest. The even distribution of volcanic minerals of the Laacher See above the fragipan shows that the profile layer above the fragipan is completely homogenized, whereas roots and volcanic minerals are absent below the fragipan. In the absence of worms, this distribution must have been caused by the roots of the trees. It is apparently a slow process because the formation of a brown B2 horizon above the fragipan can outpace the effects of the homogenization. The cause of the abrupt increase in density is open to debate. It is possible that it is caused by fluctuating pressure exercised by the horizontal root mat during storms, but that would need further research.

2.7 Back to Davis, the Explanation of the Landforms

We can now see how far our research can explain the morphology of cuesta landscape, which was Davis' ultimate goal. Van Zon (1980) gives current denudation rates for a forested catchment on the Luxembourg sandstone on top of the scarp slope. Measured denudation after 2 years was found to be very low, in total only 0.010 tonne ha^{-1} year^{-1}, which means 5 m in 1 million years. Several authors presented current denudation rates for small catchments on the forested Keuper marls. The most detailed catchment study, the Schrondweilerbaach, showed values of 0.765 tonne ha^{-1} year^{-1}, equalling approximately 0.05 mm of annual soil surface lowering, equivalent to 50 m in 1 million years (Duijsings 1987). There is local variation: in Keuper forests, estimated denuation rates are 1.46–2.0 tonne ha^{-1} year^{-1} in areas where the forest floor is bare in summer, in contrast to 0.13–0.26 tonne ha^{-1} year^{-1} in areas with full litter cover under beech, which may lead to local development of shallow depressions and ridges (see Chap. 10). However, the difference in lowering of forest soils on the Luxembourg Sandstone on top of the escarpment and on the Steinmergelkeuper at the bottom is at least 45 m in 1 million years. The experiments in the forests on the Luxembourg sandstone were carried out where the cuesta has a height of 416 m, those in the forests of the Schrondweilerbaach at the base had an average height of 310–318 m. This means an altitude difference of roughly 100 m. When we apply Lyell's concept that the present is the key to the past and assume that forests have existed as long as the Keuper has been exposed in Luxembourg, worms would need about 2 million years to bring about this relief configuration. This brings us back to the early Pleistocene. There are indications that the environment of the geomorphological processes in this area has not much changed since the Pliocene and even the Miocene (Frenzel 1967; Van Hooff and Jungerius 1984).

It is a mental quantum leap from 2 years monitoring the sediment production by slope processes to extrapolating the results over millions of years. All the more admiration deserves Darwin (1881), who concluded the experiments with earthworms in his garden with the statement: '*…if a small fraction of the layer of fine earth, 0.2 of an inch in thickness* (±*5 mm*)*, which is annually brought to the surface by worms, is carried away, a great result cannot fail to be produced within a period of time which no geologist considers extremely long'* Or, in the words of Jose Rubio (2009) past president of the ESSC: '*we can interpret the history of the world through the observation of minuscule processes, that largely* *pass unnoticed but have the enormous dimension of time to originate major changes'.*

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