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Landslides at the Tertiary escarpments in Rheinhessen, Southwest Germany

Thomas Glade, Bonn, Annette Kadereit, Heidelberg, and Richard Dikau, Bonn

with 9 figures and 4 tables

Summary. Episodic landslide occurrence is widespread on the slopes of the Tertiary escarpment in Rheinhessen. Former investigations have mapped landslide locations following a serious landslide-triggering rainstorm during the winter of 1981/82, compiled further information on additional landslide events and created a landslide inventory for this area. This data base was further extended and used for regional scale analysis within this study. In addition, weather patterns were correlated with landslide occurrences.

Detailed investigations on three representative landslides have demonstrated recent and past landslide movement. Applied geomorphological techniques include aerial photograph interpretation, ground surveys, geomorphological mapping, and dendrogeomorphological analysis. Subsurface exploration includes geophysical investigations (seismic refraction methods and geoelectric techniques), reconnaissance drillings, drop-penetration tests, and inclinometer measurements.

Large rotational deep-seated landslides of, in some cases, Pleistocene age involving Tertiary parent bedrock and numerous small recent shallow translational landslides consisting of regolith, mostly colluvium, can be differentiated. Dendrogeomorphological results demonstrate that besides the well documented landslide events of 1881, 1940/41 and 1982 in the study area, reactivation of both landslide types has occurred episodically every 2 to 5 years with varying rates of movements. Additionally, a very slow, episodic displacement of all landslides instrumented with inclinometers could be demonstrated. This observation gives further support to the hypothesis that landslide movement contributes significantly to backwearing of the Tertiary Rheinhessen escarpments as one of the most important geomorphic erosion processes.

Zusammenfassung. *Hangrutschungen an der tertiären Schichtstufe Rheinhessens, Südwest-Deutschland.* An der tertiären Schichtstufe Rheinhessens treten Hangrutschungen episodisch auf. Frühere Untersuchungen kartierten Hangrutschungen, die durch ein Niederschlagsereignis im Winter 1981/82 ausgelöst wurden. Unter Einbezug von älteren Hangrutschungsereignissen wurde für dieses Gebiet ein Hangrutschungsinventar aufgebaut. Es wurde im Rahmen der vorliegenden Studie erweitert und für regionale Analysen verwandt. Zusätzlich wurde die Abhängigkeit der Hangrutschungen von Wetterlagen analysiert. Detaillierte lokale Untersuchungen an drei exemplarisch ausgewählten Hangrutschungen zeigen rezente und frühere Bewegungen der Hangrutschungskörper. Angewandte geomorphologische Techniken

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umfassen Luftbildauswertung, geodätische Vermessungen, und dendrogeomorphologische Untersuchungen. Die Erkundung des Untergrundes erfolgte durch Erkundungsbohrungen, Rammsondierungen, geophysikalischen Methoden (Refraktionsseismik und Geoelektrik) und mit Inklinometermessungen.

Im Arbeitsgebiet können grosse, tiefgreifende Rotationsrutschungen, die teilweise pleistozänen Alters sind und im anstehenden Tertiär entwickelt sind, von rezenten, flachgründigen Translationsrutschungen, die in den meisetn Fällen aus Kolluvien bestehen, unterschieden werden. Dendrogeomorphologische Ergebnisse zeigen, dass neben den gut dokumentierten Hangrutschungsereignissen von 1881, 1940/41 und 1982 beide Hangrutschungstypen episodisch alle 2 bis 5 Jahre mit unterschiedlicher räumlicher Ausprägung auftreten. Durch Inklinometermessungen konnte im Untersuchungszeitraum eine episodische Bewegung aller instrumentierten Hangrutschungskörper dokumentiert werden. Diese Ergebnisse stützen die Hypothese, dass Hangrutschungen als einer der wichtigsten geomorphologischen Prozesse der rückschreitenden Erosion des tertiären rheinhessischen Hügellandes angesehen werden können.

Résumé. *Des glissements de terrain sur l' escarpement de la couche tertiaire de la Hesse rhénane, sudouest Allemagne.* Sur l' escarpement de la couche tertiaire de la Hesse rhénane, des glissements de terrain apparaissent périodiquement. Lors d'anciennes études, les glissements de terrains déclenchés par de fortes précipitations lors de l'hiver 1981/82 ont étés cartographiés. Un inventaire des glissements de terrain a été développé pour ce secteur en prenant en compte d'anciens événements. Cet inventaire a été étendu dans le cadre de ce projet et utilisé pour des analyses régionales. En plus, la relation glissement de terrain et situations atmosphériques a été analysée.

Des études locales détaillées sur trois glissements de terrain ont démontré des mouvements actuel et anciens des corps en glissement. Nous avons employé les techniques géomorphologiques suivantes: interprétations de photographies aériennes, mesures géodésiques et études dendrogéomorphologiques. La prospection du sous-sol a été effectuée au moyen de méthodes géophysiques telles la seismique-réfraction et la géoelectrique ainsi qu' à l'aide de forages, de sondages de battage et de mesures inclinométriques.

Sur le terrain d'étude, de profonds glissements rotationnels provenant en partie du Pléistocène et entraînant en partie la roche en place, peuvent être différenciées des glissements de terrain translationnels récents. Ces derniers se composent largement de colluvions. Les résultats des mesures dendrogéomorphologiques montrent que, outre les événements bien documentés de 1881, de 1940/41 et 1982, les deux types de glissements de terrain apparaissent périodiquement tous les 2 à 5 ans avec des différences temporelles et spatiales. Au cours de la période d'étude, les mesures inclinométriques ont démontré un mouvement continu de tous les corps en glissement. Ces résultats soutiennent l'hypothèse que les glissements de terrain peuvent être considérés comme un des processus géomorphologiques les plus importants de l'érosion régressive de l'escarpement de la couche tertiaire.

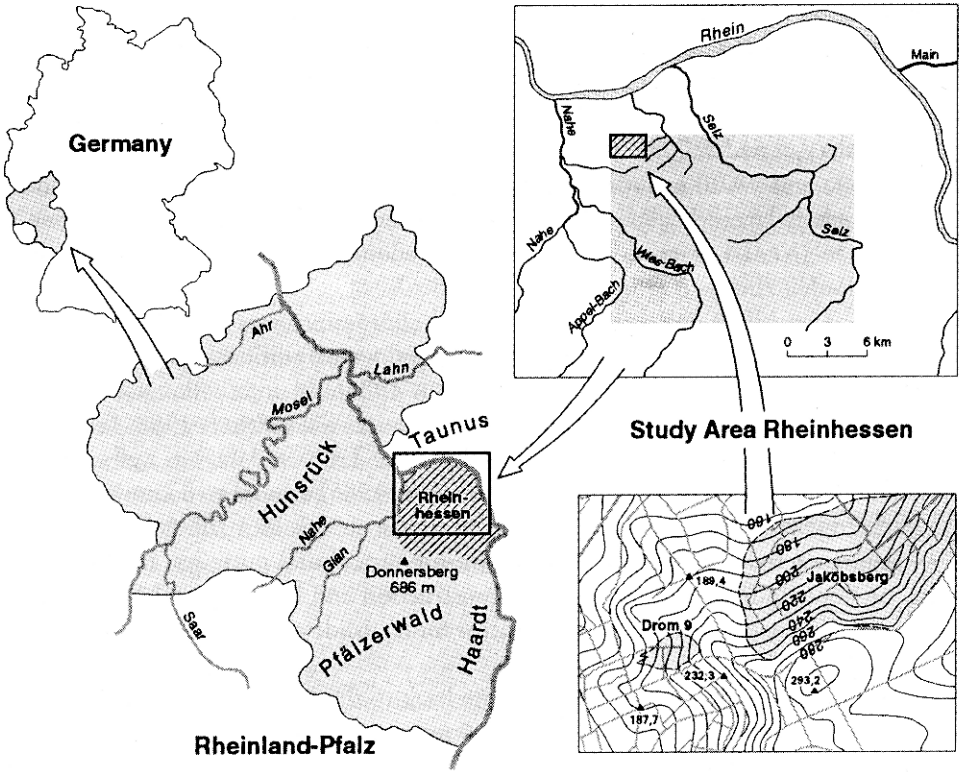

Fig. 1. Location of the study area in northwestern Rheinhessen,Germany.

Introduction

Although not well known internationally, landslides constitute a problem for the physical and social environment of Germany, and have drawn legislative responses in some regions (KRAUTER et al. 1996). KRAUTER (1994) suggests a yearly average of 150 Mio. US$ for damage caused by landslides in Germany. As one of the consequences of this pressure, a general project entitled *Mass Movements in South and West Germany* (project acronym MABIS) was established including several groups examing landslides in most affected areas of Germany. These regions prone to landsliding are discussed in this special volume of the Zeitschrift für Geomorphologie.

The area of interest in this study is Rheinhessen, located in southwest Germany (Fig. 1). While there have been numerous German language publications on this issue, international recognition of landslides and associated problems in this area, and respective research and results has been limited. Thus, this paper intends to give an overview of past and current research on landslide locations and characteristics in Rheinhessen. Various research issues are addressed, discussed and results of the current project are presented. Based on these analyses, research deficits are identified and future research directions are suggested in the conclusion.

Landslides have occurred episodically on slopes of the Tertiary escarpment. Slow moving continuous failures were rather unknown in this region. Types of landslides found are, according to the classifications of DIKAU et al. (1996) and CRUDEN & VARNES (1996), either small shallow translational earth slides or large deep-seated complex rock slides and earthflows. The deep-seated failures with shear surfaces at depths ranging from 10 to 25 m (HIDDEMANN et al. 1979) include bedrock, which consists mainly of clay and marl interconnected with sandy layers. Shallow translational landslides with average depths ranging from 0.5 m to 5 m (KRAUTER et al. 1985) involve predominantly regolith consisting of soils formed in weathered clays and marls, and in particular of colluvium.

Triggers of landslides in Rheinhessen are either short rainstorms with high rainfall intensities (ANDRES 1977, LESER 1965) or long prolonged wet conditions prior to failure (ANDRES 1977, DIKAU & JÄGER 1995, STEINGÖTTER 1984). In international contexts, both intense short term meteorological conditions (ELLEN & WIECZOREK 1988, GLADE 1998, JACOBSON et al. 1989, SIMON et al. 1990, SLOSSON & LARSON 1995) as well as prolonged wet conditions (CHURCH & MILES 1987, SIDLE et al. 1985) are also well known as common triggers. Seismicity is not known as a landslide trigger in this area (BECK 1994, KRAUTER 1987). Human activity such as slope reduction for agricultural purposes, in particular viticulture, or slope undercutting due to road construction and both industrial and residential developments is a widespread preparatory factor for landslide occurrence, as it is in any highly populated region.

First landslide occurrences in this area date back to the Pleistocene (BECK 1994). Shear planes explored during construction of the A60 motor way 5 km north of the recent escarpment indicate Pleistocene movements (ANDRES & PREUß 1983, HIDDEMANN et al. 1979, ROSENTHAL et al. 1988).

To increase productivity in the beginning of the 20th century, viticulture was extended into landslide prone areas, in particular onto steeper slopes and quite often without consideration of small perennial runoff channels and springs. Consequently, normal water percolation was disrupted which leads after either intense or prolonged rainfall to wetter soil moisture conditions and consequently to increased probability of failure. Since the 1930s, geotechnical stabilization work has been carried out in various areas to reduce or even stop landslide movements (ANDRES 1977, KRAUTER & STEINGÖTTER 1983). This has included construction of stop banks and slope nailing (ROSENTHAL et al. 1988) as well as drainage of slopes through well construction, overland channels and within-slope drainage pipes.

In addition to increased viticultural use of this area, residential developments within recent decades were preferentially located on slopes. Through slope cuts for building sites and roads, the shear strength determining the stability of slopes was reduced and consequently the probability of either reactivation of landslides or new failures was enhanced. To counter these problems, residential development is subject to building code requirements such as use of flexible supply lines, strengthened foundations, low building height, etc. (BECK 1994, STEINGÖTTER 1984).

One classical example of such a procedure is the Jakobsberg landslide, located near Ockenheim (refer to Fig. 1 for location). An investigation of this landslide undertaken by the Geological Survey of Rheinland-Pfalz lead to a recommendation against building on this

landslide. However, with strong political interest in allowing suburban development on this slope, a road and numerous houses were constructed, notwithstanding considerable problems associated with the landsliding processes. These problems included partial destruction of the road, failures into building sites under construction, and destruction of retaining walls. Consequently, although restricted building codes were not able to avoid damage through landslides, it can be speculated that the total amount of damage costs in the Rheinhessen region could be reduced by an increased awareness of the landslide problem on the part of the respective organizations.

Despite investigations of other similar situations, e.g. in the Gulden Valley (KRAUTER & STEINGÖTTER 1983), a realistic remediation of the resulting damage is generally not possible, as the issue of landsliding does not receive wide attention. These events and their effects are currently not archived; information is only available through personal communications with involved parties, either directly as eye witnesses or affected persons, or indirectly through Councils, private consultancies or Geological Surveys. Thus movement takes place, but very few detailed analyses of movement rates or causes and triggers are available. Consequently, public and institutional awareness seems to neglect landslides as a significant natural hazard for this region.

Previous work

Landslides in Rheinhessen have long been under investigation, mostly due to damage to houses, infrastructure, or other capital assets (e.g. vineyards). First investigations of landslides were carried out by STEUER (1911, 1934). After a major landslide event occurred in 1940/1941 at Jakobsberg, northwest Rheinhessen more detailed geotechnical investigations followed (WAGNER 1940, 1941, LAUBER 1941). Since then, local landslides causing considerable damage were reported sporadically. Despite the absence of standardized reporting schemes, KRAUTER (1994) calculates a total economic cost through landslides damage of 10 Mio. US$ per year for the Rheinhessen region. As this amount indicates, slope failures are not a local problem only.

Besides the landslides of Pleistocene age near Ockenheim, past landslides are reported from throughout the whole Rheinhessen region. As records demonstrate, landslide occurred in Petersberg in the Selz valley (ANDRES 1977, BECK 1994, KRAUTER & STEINGÖTTER 1983) and the Gulden valley (KRAUTER & STEINGÖTTER 1983); near Spiesheim (BECK 1994); on the Bosenberg (BECK 1994); in the Pfrimm valley (Zeller valley) near Mölsheim (STEUER 1911), near Zell (KRAUTER & STEINGÖTTER 1983, STEUER 1934) and between Albisheim and Wachenheim (LESER 1965); nearby Oppenheim and Dienheim (KRAUTER & STEINGÖTTER 1983); at the Wißberg near Sprendlingen (MATTHESIUS 1994, STEINGÖTTER 1984); southwest of Ober-Olm (KRAUTER & STEINGÖTTER 1983); and in the northwestern region of the Rheinhessen escarpment near Dromersheim and Ockenheim (LAUBER 1941, PREUß et al. 1997, WAGNER 1940, 1941), to name the most important only.

Systematic landslide research started with the landslide-triggering rainfall event in the winter of 1981/1982. A very low intensity rainstorm accompanied by an increase in temperature and corresponding snow melting triggered more than 212 landslides of >500 m^3, cov-

ering an area of approximately 200 ha and displacing a total volume of approx. 9 Mio. m^3 for the whole Rheinhessen region. This combination of low rainfall totals and snowmelt is also recognized as crucial landslide-triggering conditions in other countries (BERGMAN 1987, DEGRAFF et al. 1984, WIECZOREK et al. 1989). The Rheinhessen landslides were mapped by the Geological Survey in field surveys as well as from aerial photography (KRAUTER & STEINGÖTTER 1983).

Archives of the City, District, and Regional Councils were surveyed by the Geological Survey for former landslide events and added to this inventory. Analysis based on landslide locations, slope and bedrock geology derived from this database resulted in a first landslide susceptibility map at a scale of 1:50,000 (KRAUTER & STEINGÖTTER 1983, STEINGÖTTER 1984). Results show that 8% (110 km^2) of the total investigation area (1400 km^2) is susceptible to landslides. Most of the failures were translational shallow landslides with an average depth of 4 m, with slope angles ranging from less than 5° up to 48°. Resulting damage of up to 10 Mio. US$ was calculated (KRAUTER 1994). As KRAUTER et al. (1985) suggest, more than 90% of failures are reactivated landslides, which move episodically with long dormant intervening periods. As discussed later, however, this study indicates that both deep-seated rotational and shallow translational landslides move with very slow rates during these apparently dormant periods, thus with greater frequency than previously expected.

Research at site scale by MATTHESIUS (1994) on the Wißberg landslide as well as by PREUß et al. (1997) on the Jakobsberg landslide suggests episodic movements. Rates of movement were measured by KRAUTER & STEINGÖTTER (1983) for various landslides and range from 13 mm/month to 1.5 cm/minute. Maximum displacements were up to 60 m. On average, however, displacement is less than 10 m in active periods. The role of cracks and fissures in the ground for landslide initiation was recognized by LAUBER (1941). He investigated surface cracks of up to 30 cm width. Later investigations by STEINGÖTTER (1984) showed that crack widths at 4 m depth can still be up to 10 mm. It was suggested that these cracks play an important role in landslide movement by enabling the fast percolation of surface water through the ground to potential shear planes.

Recently continuous landsliding and Pleistocene landslides raise also the question of landform development in this area. It is suggested by various authors (ANDRES 1977, ANDRES & PREUß 1983, BECK 1994, KLUG 1961, KRAUTER & STEINGÖTTER 1983, PREUß 1983, STEINGÖTTER 1984) that landslide occurrence is one of the dominant geomorphic erosion processes responsible for landform evolution in this area. This argument was strengthened by the findings of shear planes in cores during construction work for the A61 motor way as well as reactivation of dormant landslides of probably Pleistocene age (HIDDEMANN et al. 1979). In Japan, YAMADA (1999) demonstrates the importance of soil creep and slope failures for landscape evolution. However, the hypothesis that landslides are an important factor in landform development needs to be addressed in more detail within this study.

Aims and previous results of the Rheinhessen project

Within the MABIS project, landslide research in Rheinhessen was focused on analysis based on local and regional scales. On the *local scale*, previous work aimed to

- identify shear planes on landslide DROM9;
- map cracks and fissures visible on the surface of DROM9;
- install soil moisture and soil temperature probes; and
- install an inclinometer.

First reconnaissance drillings suggested the contact between colluvium and underlying Oligocene clays and marls at approx. 5 m depth as the shear surface of the landslide DROM9. More detailed stratigraphical information was necessary to verify this hypothesis.

All cracks and fissures visible on the surface were mapped by determining distance from each crack to the base line of a 10 m grid. By marking the nodes of this artificial raster with poles in the field, it was anticipated to remeasure the cracks within defined periods. Unfortunately, vandals destroyed these poles and made further observations impossible.

An inclinometer, soil moisture and soil temperature probes were installed at two locations on the landslide and at a reference station on top of a ridge nearby the landslide DROM9. While soil temperature is still measured, soil moisture probes dried out and were destroyed. Thus, anticipated observations of slope water movement in relation to climatic variables and comparisons with landslide movement rates were not possible. However, inclinometer measurements based on installations from this period are available and are discussed later in this study.

On the *regional scale*, the first phase of the project aimed to

- supplement the already available landslide database through more detailed search of newspapers and in chronicles and archives of villages, churches and monasteries;
- perform geomorphometric analysis to define terrain conditions favoring landslide occurrence;
- analyse the climate record with respect to general climatic trends and to landslide occurrences; and
- digitise maps of geology, landslide locations, infrastructure, and vegetation to be used in addition with DEM derivates in regional landslide hazard assessment.

The already available landslide database LDB1 (GLA 1989) with 1290 entries and 28 parameters was expanded to include weather pattern and causes (natural/human). This database was the core of the regional landslide information and was subsequently used in further regional scale investigations.

Results of the geomorphometric analysis indicate that the landslide type itself gives a first indication of location on the slopes. While the deep seated slides involve parts of the plateau and are thus more or less independent of slope geometry, shallow slides occur mostly in planar or concave slope profiles (PREUß 1983). Geomorphometric analysis of landslide location and slope geometry has shown that in particular south, southwest, and west facing slopes contribute to landslide occurrence. Affected slopes commonly have planar profile curvatures, with a dominant concave plan curvature, followed by planar, and convex forms (DIKAU 1990). This analysis clearly demonstrates the favorable location of landslides in depressions, which are mostly filled with colluvium, as earlier discussed. Landslides occur in particular on slope angles ranging between 9° and 11° and on elevations between 180 and 220 m.a.s.l.

The influence of climatic variables on temporal landslide occurrence was examined by DIKAU et al. (1994), JÄGER (1997) and JÄGER & DIKAU (1994). Annual climatic indices were calculated on the basis of specific climatic parameters (rainfall, temperature, potential evapotranspiration) and compared with landslide records. Results demonstrate that landslides occurred in the past in particular in years following wet antecedent conditions and with annual precipitation above average (DIKAU et al. 1994, JÄGER 1997). A preliminary analysis of general weather patterns and historic landslides lead to the suggestion that various types of weather conditions are responsible for landslide initiation. This hypothesis, however, had to be examined in more detail.

Regional landslide hazard assessments are rather rare in Rheinhessen. A first attempt at deriving landslide hazard using digital spatial landform morphometry data (DIKAU et al. 1994) and GIS technology was performed for a 12 km^2 test area by DIKAU (1990). This approach was followed up by enlarging the catchment area and including the extended spatial and temporal landslide database into the hazard modelling procedure (JÄGER 1997, JÄGER & DIKAU 1994). The methodology and results of statistically based landslide hazard modeling were published by DIKAU & JÄGER (1995) and JÄGER (1997). Results show that upper slope positions on Oligocene bedrock with $>8°$ slope angle are particularly prone to landsliding.

Objectives of the current study

The previously defined aims and the respective results were the basis for further research objectives and goals, which are presented in more detail in the following. This study attempts specifically to:

- explore the subsurface structure of three representative landslides;
- investigate the type and kinematics of these landslides;
- determine recent landslide movement rates;
- analyze former movement behaviour and determine movement frequency;
- relate movement rates to climatic variables;
- introduce a physically based slope stability model into regional landslide hazard assessment; and
- develop a conceptual model of landform development.

Study area

The study area is located on the northwestern part of the main escarpment of Rheinhessen (Fig. 1). The morphometry of northwest Rheinhessen is characterized by the classical escarpment sequence of a flat plateau at the top followed by cuesta, pediments and fluvial terraces (ANDRES & PREUß 1983). Vertical profiles of the cuesta are subdivided into low angle upper surfaces, steep upper slopes, moderate mid slopes, gentle lower slopes and adjacent flat pediments. As indicated in Fig. 2, horizontal slope profiles resemble a sine curve with a continuous pattern of spurs and depressions. DIKAU (1990) showed using GIS techniques the importance of the upper mid slope section for landslide initiation.

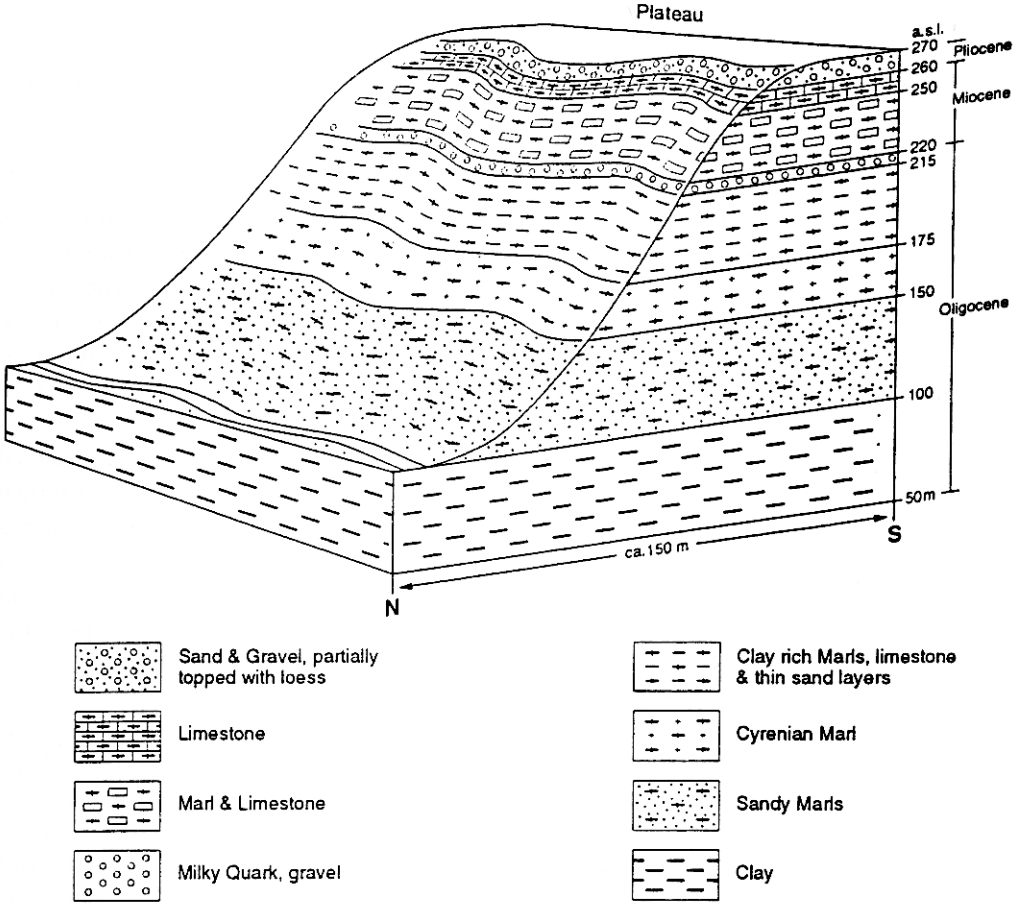

Fig. 2. Schematic geologic structure of the northwestern escarpment in Rheinhessen.

It is suggested by BECK (1994) and PREUß (1983) that this pattern of horizontal and vertical curvature is related to the periglacial conditions which formed this landscape during the Pleistocene. Permafrost conditions lead to intensive backwearing of the main escarpment, in particular due to frost weathering, solifluction, rill erosion, and landslides (BECK 1994, BRÜNING 1973). In addition, both tectonic faults and springs on the slopes increased local vulnerability to backwearing. In front of the slopes large pediments with low angles developed in the Pleistocene. Transport of material to the pediment was through periglacial processes, in particular through solifluction and gelifluction (BECK 1977). Probable Pleistocene landslides and shear planes have been covered by these pediments (HIDDEMANN et al. 1979).

The geology of this region is characterized by gently north-east dipping lithostratigraphic units ROTHAUSEN & SONNE (1984) (Fig. 2). The lower unit is based on over consolidated Oligocene Rupelian clays and marls with embedded fine sand layers and is up to 300 m

thick. These mudstones are composed mainly of pelites. The upper unit with an approximate thickness of 120 m, consists mainly of fissured limestone and marls of Miocene age. These carbonate rich alternate bedding layers are covered with Pliocene and Pleistocene sand and gravel and topped with an extensive loess cover with thicknesses of 0.5 m to >5 m. The whole area is characterized by fracture tectonics and has been continuously uplifted throughout the Quaternary.

High infiltration capacities within the Miocene units allow quick percolation of water down to the almost non-permeable Oligocene layers. These Miocene units function as an aquifer. Consequently ground water moves along the horizontally layered Oligocene clays to the slopes and emerges in numerous springs on the upper midslopes. Due to this water supply, most villages are based in convergences in mid slope positions. As work of KRAUTER & STEINGÖTTER (1983) has shown, most of the landslides occur on slopes underlain by Oligocene lithostratigraphy.

Typical soils of the Rheinhessen plateau are Chernosems developed on loess and formed during postglacial times (ZAKOSEK 1991, ZAKOSEK et al. 1991). Brown soils and Para-brown earth, which are occasionally eroded to Pararendzinas, are found on the slopes. Ploughing has reworked soils and thus transformed Rendzinas and Pararendzinas into Rigosols (LUDWIG 1977). Spurs with thin soil columns show Pelosols, which have been developed mainly on Rupelian mudstones (BECK 1994). The floors of the depressions which incise the slope of the escarpment vertically are filled with colluvium related to human induced erosion (sheet erosion and gravitational mass movements (WAGNER 1940)).

Vegetation is dominated by the viticultural land use introduced by the Romans approximately 2000 BP. Small patches of pine forests and shrubs can be found on steep slopes. During the Pleistocene ice ages tundra vegetation was dominant. Whether Rheinhessen was under forest cover in the Holocene as suggested by ZIEHEN (1970), which was then removed by early settlers or whether this area was never naturally reforested after the last glacial is still under discussion (KLAER 1977). Recently, winemakers have abandoned their vineyards located on active landslides, thus changing vegetation types from wine grapes to fast growing shrubs (*Crataegus oxyacantha*). Within this project these shrubs were used to identify landslide movements within the last two decades. Results of this preliminary investigation are given in this volume by GERS et al.

Climate in this area is continental and characterized by a high yearly temperature amplitude of 17–19° C, with a yearly average of 9.6° C, one of the highest temperatures in central Europe. Annual rainfall magnitudes are low, ranging between 400 mm and 700 mm, with precipitation maxima occurring in July/August and October/November. These large precipitation events in the summer months expose this region to erosional processes.

Hot and dry summers allow the development of deep cracks in clay soils, which promote fast movement of rainfall into the soil. Although these cracks are smaller in winter, snowmelt water can also percolate much faster into the soil, and in particular to potential or already existing shear surfaces. Soil moisture is thus not only dependent on infiltration rates, it is also influenced by the width and the depth of cracks. This preparatory slope destabilisation factor was already recognized by WAGNER (1941). Since then, the importance of cracks for landslide reactivation have been supported by various observations from numerous authors

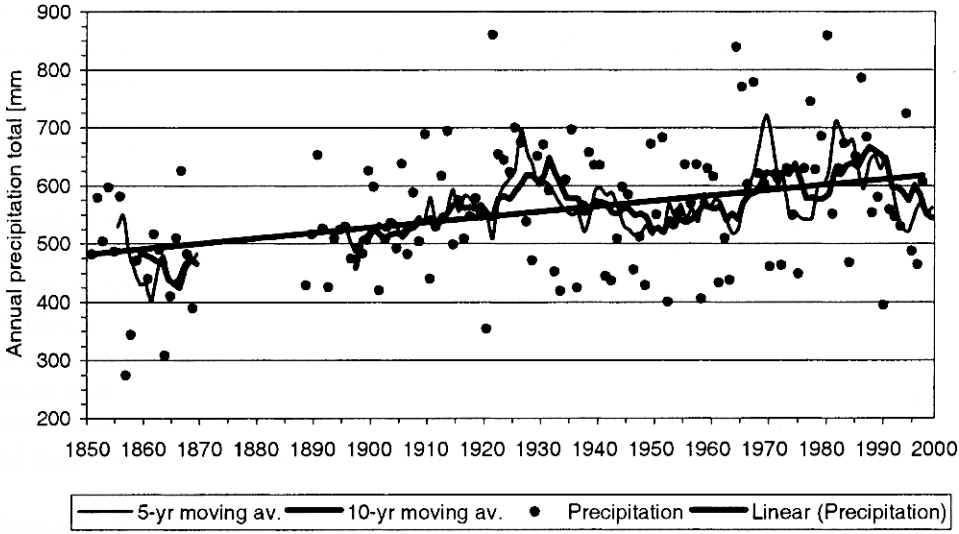

Fig. 3. Trend of total yearly precipitation in Büdesheim, 4 km northwest of study area (refer to Fig. 1 for location). The station is maintained by the German Meteorological Service (Deutscher Wetterdienst – DWD).

(HIDDEMANN et al. 1979, ROSENTHAL et al. 1988, STEINGÖTTER 1984). However, research on modeling the role of cracks for landslide initiation or reactivation has so far not been carried out in Rheinhessen.

Method

Local scale analysis

To investigate past and recent movement rates of landslides, techniques applicable to the specific conditions in Rheinhessen include field mapping, field surveys, subsurface exploration through drilling, drop-penetration tests and geophysical methods (seismic and geoelectric techniques), inclinometer measurements, dendrogeomorphology and climatological analysis. Within this paper, a brief overview of results is given.

Field mapping was performed to define the extent and form of the displaced landslide mass in more detail. As mentioned previously, special emphasis was given to mapping of cracks, which are believed to be an important factor influencing landslide movement.

Field surveys using laser-tachymetry equipment with a resolution of ±0.1 mm allow the determination of exact locations of boreholes, drop-penetration sites, stems used within dendrogeomorphological analysis, sensors for geophysical investigations and slope profiles.

Subsurface exploration was performed through drilling and drop-penetration tests with a weight of 50 kg (Drop Penetration Test Heavy – DPH). Resulting graphs plot the amount of blows necessary to drive the penetration head (15 cm^2) 10 cm into the ground, thus reveal-

ing differences in density at 10 cm increments. In addition to the resulting point information, geophysical methods such as geoelectric profiles and hammer refraction seismic surveys were applied. Former geophysical investigations using seismicity for determination of the boundary between undisturbed and disturbed material within the same lithology were unsuccessful (STEINGÖTTER 1984). However, the type of landslide investigated with these techniques consists of colluvium, thus the shear plane is at the boundary between underlying lithology and colluvium and could be readily determined using both geophysical techniques.

Recent landslide movements were derived from inclinometer measurements. In total eight boreholes in three landslides were equipped with inclinometer tubes ranging from 5 m to 10 m depth (refer to Fig. 4 for locations). The inclinometer has an instrument accuracy of ±0.01 mm in horizontal and vertical slope direction. Measurements of inclination were performed in the first half year on a weekly basis to allow detailed analysis of rainfall amount and movement rates. In the second half year, field measures were undertaken every month. Displacement rates were compared with cumulative rainfall amounts to define critical rainfall conditions.

In addition to recent investigations of landslide movement and historical information from landslide activity, the project applied dendrogeomorphological techniques to determine surface movements over longer periods. For the first time, shrubs were used as indicators for movements. Further methodological details and preliminary results are given by GERS et al. (this volume).

Regional scale analysis

In addition to site specific information, regional scale analyses have been performed. Following JÄGER & DIKAU's (1994) temporal analysis of landslide occurrences with respect to specific climatic parameters (rainfall, temperature, potential evapotranspiration and derived indices), a combination of general weather patterns and historic landslides lead to the characterization of various types of weather conditions responsible for landslide initiation.

In addition to landslide hazard assessment based on logistic regression analysis of different information layers such as geology, slope position, curvature, slope angle, etc. as performed by JÄGER (1997), a new concept of introducing a physically based slope stability model to landslide hazard assessments has been developed. The latter approach adapts the concept of hydrological response units to slope stability problems and delineates *Soil Mechanical Response Units* (SMRU). This methodology defines categories with different degrees of landslide hazard purely based on modeled soil mechanical behavior and verified through comparison with the past landslide-triggering event in the winter of 1981/1982. A full description of background, methodology and results of this research is discussed by MÖLLER et al. (this volume).

Landform development

Following observations of the current processes and its modeling, a genetic model for landform evolution based on landslide occurrence is suggested. This qualitative approach is a first

attempt to extrapolate results of process studies into long-term perspectives for this region. Coupling of geomorphogenetic analysis with the recent process data may result in a much better understanding of long-term landform evolution.

The variety of applied techniques demonstrates the detailed analysis of various aspects related to the landslide problem in Rheinhessen. The following results represent a selection of the overall project (refer to DIKAU et al. (1994); JÄGER & DIKAU (1994); DIKAU & JÄGER (1995); JÄGER (1997); MÖLLER et al. (this volume); GERS et al. (this volume)

Results and discussion

Local and temporal investigations

The investigated landslides Jakobsberg, DROM9, and OCK3 are all located on the slope of the northwestern part of the Tertiary crust zone between the two villages Dromersheim and Ockenheim, approximately 10 km south of Bingen (Fig. 4). Each landslide represents a specific landslide type. Following the definitions of DIKAU et al. (1996) and CRUDEN & VARNES (1996), the Jakobsberg landslide is a complex landslide with rotational structures including tilted blocks and cracks at the top and flow characteristics with compression per-

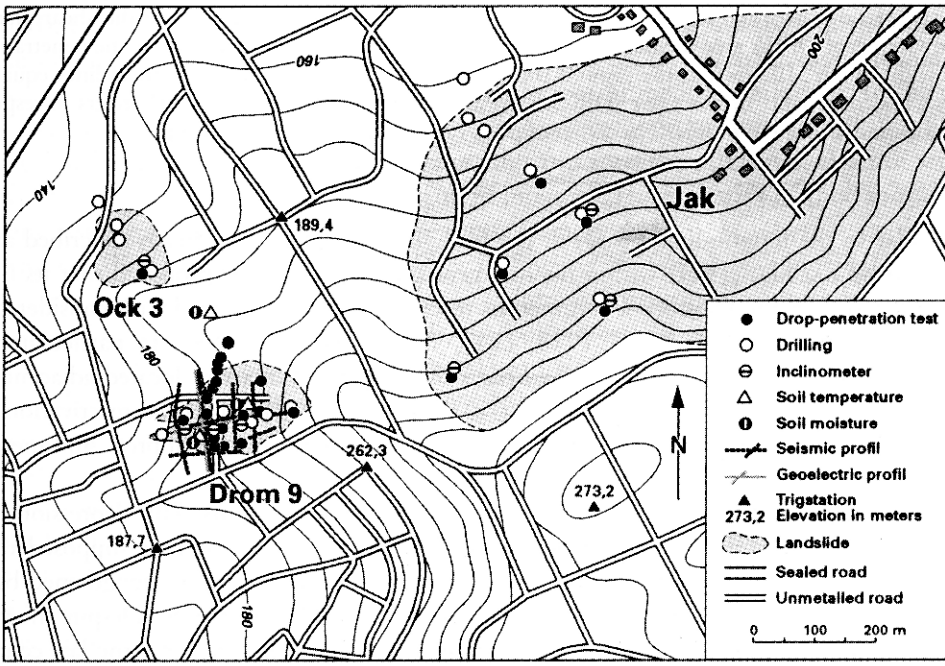

Fig. 4. Location of the landslides Jakobsberg, OCK3 and DROM9 at the northwestern slope of the Rheinhessen plateau (refer to Fig. 1 for exact location). Sites of drop-penetration tests, drillings, inclinometers, soil temperature and soil moisture probes and geophysical surveys (seismic and geoelectric profiles) are given for each landslide.

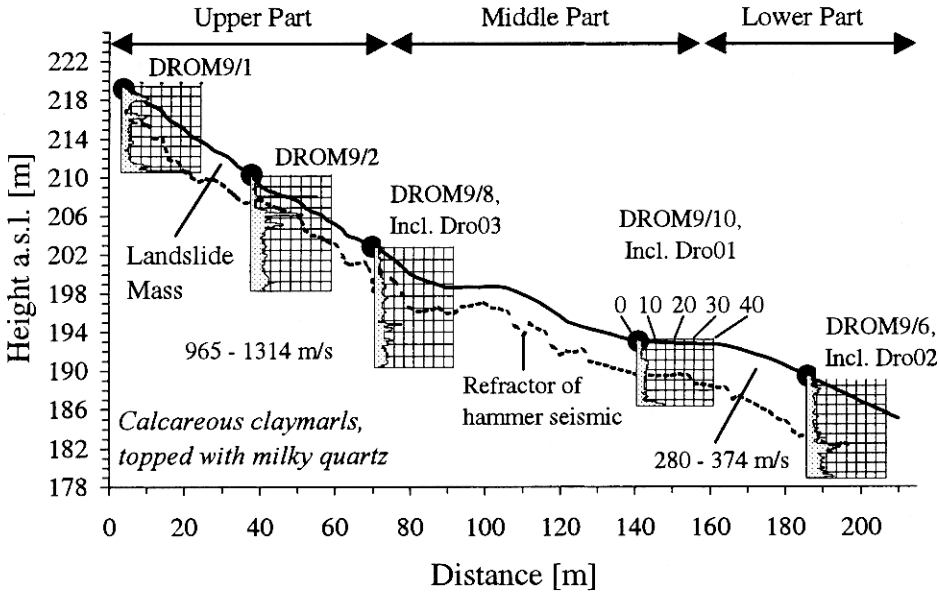

Fig. 5. Longitudinal profile of the landslide DROM9. Refractor of seismic survey shows approximate location of the contact between colluvium and bedrock. This boundary is verified by drop-penetration tests (DPH), drillings and inclinometer measurements and can be assumed to be the shear plane. (*Note*: Graphs of DPH's give the depth versus the number of blows necessary to drive the penetration head with 15 cm^2 10 cm into the ground (Horizontal lines equal 1 m depth; vertical lines equal 5 blows). Location name of cores (e.g. DROM9/1) and of inclinometers (e.g. Dro01) refers to respective positions within the profile. The different parts of the landslide is given at top.)

pendicular to the longitudinal profile at the foot. This landslide was already described and examined by LAUBER (1941) within his first geologic mapping. It is proposed that its first failure occurred in the Pleistocene. Numerous reactivations have occurred with considerable damage reported for 1860, 1880, 1924, 1941, 1944, 1949, and 1981. In particular the events of 1860, 1949 and 1981 destroyed parts of walls of a monastery located adjacent to the main head scarp (KRAUTER & STEINGÖTTER 1983). In 1944, a partial reactivation of this landslide took place with a run-out length of the displaced mass of approx. 400 meters (PREUß et al. 1997).

The landslide DROM9 is located in a concavity between two spurs. This depression has been filled by wash processes and probably shallow landslide failures. It is supposed that human activity in this region increased these processes. This argument is strengthened by a ceramic artefact, found at a depth of 5 m at bore point DROM9/10 (Fig. 5). Despite the fact that no dating was possible, this find suggests large accumulation rates over the last centuries. However, further detailed dating studies are necessary to verify this hypothesis.

The colluvium body was activated during the winter 81/82 event. Whether any movement prior to this event took place is unknown. As dendrogeomorphological analysis suggests, various parts of this landslide have been moving episodically since then (refer to GERS

et al. in this volume for more details). Results from drillings, drop-penetration tests and geophysical techniques prove that the contact between colluvium and underlying Oligocene marls and clays acts as a shear plane.

DROM9 can be subdivided into three main parts, each exhibiting different processes (Fig. 5). The upper part consists of shallow, 1 to 3 meter thick colluvial deposits interbedded with 5 to 10 cm thick clay bands. As dendrogeomorphological analysis shows, this regolith is slowly creeping downslope due to the displacement of the midslope unit, which was displaced during the 1981/82 event through rotations of single blocks. The first inclinometer Dro03 is situated immediately upslope of the highest of these blocks. Downslope the landslide shows a sequence of horizontal concavities and compressions. While the inclinometer Dro01 is located in a concavity, Dro02 is within a convexity. Due to the form of the lower part it is suggested that this area is displaced by a coupled slide-flow process.

The main shear surface was identified in the drill cores by reworked clay materials and reflects simply the boundary between bedrock and colluvium. Therefore geophysical investigations were carried out to determine the shear plane location in the longitudinal profile in more detail. A distinct difference between materials could be identified by the variations of seismic wave speed ranging between 280 m/s to 374 m/s in colluvium and 965 m/s to 1314 m/s in Oligocene clays and marls. The derived refractor is shown in Fig. 5 and indicates the thickness of the colluvium and consequently, of the landslide mass. Refractor location is compared with detailed point information from both drill cores and drop-penetration tests (DPH). DPH results are also given in Fig. 5 for each drilling site and show distinct changes in subsurface structure. Comparison shows that refractor depth and depth derived from drill cores as well as from DPH correspond very well, except in the lower mid part. In this area, the colluvium is compressed through downwards pressures from small rotational slide blocks located above and thus the material is disturbed. Consequently, a diffusion effect of seismic waves can be expected which is very difficult to interpret. However, this method showed satisfying results, and will be explored in the future in more detail.

Recent displacement is measured using inclinometers. Locations of inclinometers are given in Fig. 4. Measurements demonstrate a continuous movement of the whole landslide mass. Within the short measuring periods, total displacements ranged from 1.2 cm during 258 days (Dro02), 2.9 cm in 291 days (Dro01) to 1.6 cm in 362 days (Dro03) (Fig. 6). Following the terminology suggested by CRUDEN & VARNES (1996), the DROM9 landslide can be classified as extremely slow moving. The values suggest, however, that the middle part of the landslide is moving slightly faster than the upper and lower part. Whether this is a temporary condition only, or if it reflects a specific kinematic of this landslide has yet to be shown in the future with additional measurements. Nevertheless, measurements to date indicate that the landslide moves continuously downhill, which had not been recognized previously. Depth of shear planes determined through inclinometer measurements correspond to results derived from drill cores, drop-penetration tests and refraction seismic.

The second landslide presented in more detail in this study is named OCK3. This landslide is located at the end of a spur (Fig. 4) and occurred in calcareous marl with alternating fine sand and marl below and calcareous clay marl above. As determined in the core Ock3/1, the shear plane occurs within the underlying bedrock and was identified by a distinct

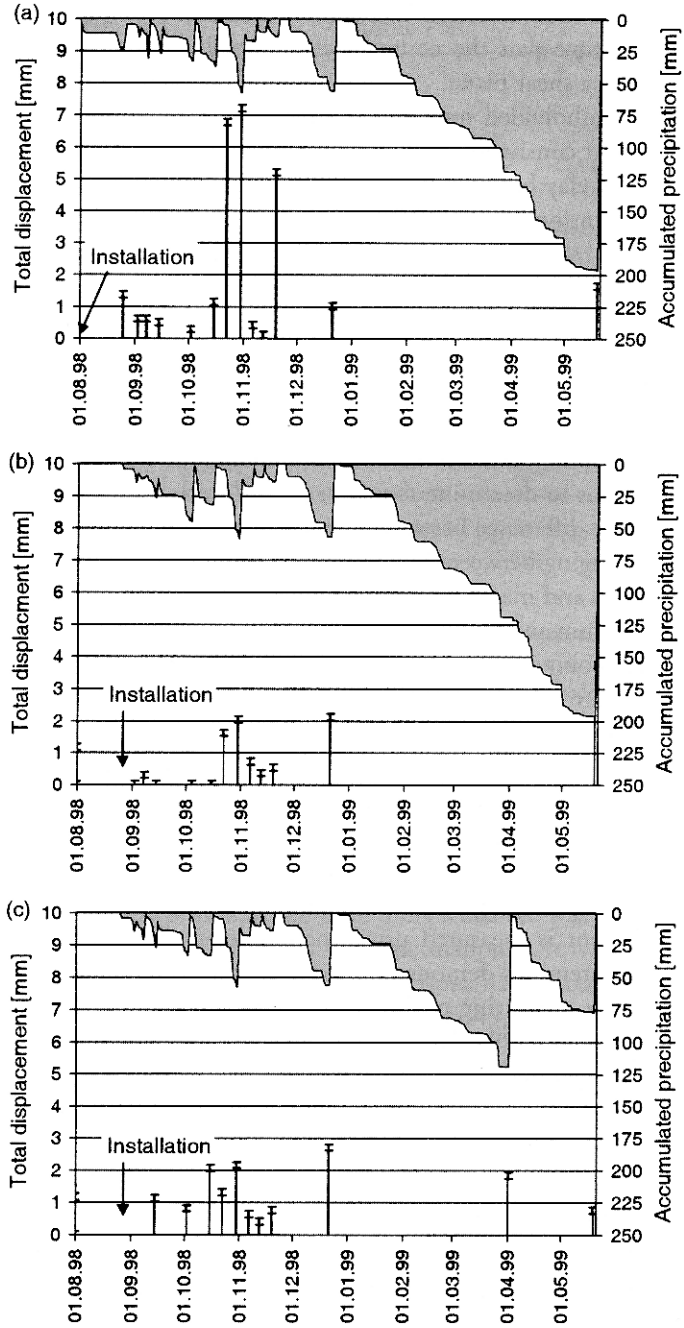

Fig. 6. Cumulated precipitation within the measuring interval (dotted area) and landslide displacement measured at the DROM9 inclinometers dro02 (a), dro01 (b), and dro03 (c). (*Note*: Small lines at top of bars give the accuracy of the inclinometer. Cumulation of precipitation starts after each inclinometer reading with zero.)

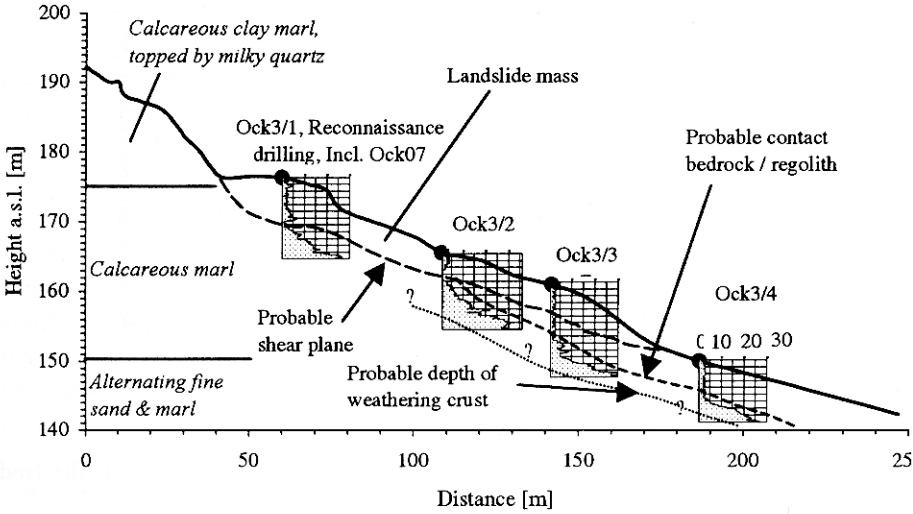

Fig. 7. Longitudinal profile of the landslide OCK3. Probable shear plane is marked with long dashes, contact between regolith and bedrock with short dashes and probable lower depth to weathering crust is indicated by a dotted line. (*Note*: Graphs of DPH's give the depth versus the number of blows necessary to drive the penetration head with 15 cm^2 10 cm into the ground (Horizontal lines equal 1 m depth; vertical lines equal 5 blows). Location name of DPH's (e.g. Ock3/1) and of inclinometers (e.g. Ock07) refers to respective positions within the profile.)

reworked layer within the Tertiary sediments. Consequently, geophysical techniques were not applied, because the shear plane does not represent a distinct change in material composition. However, drop-penetration tests were successfully applied to establish a longitudinal profile of the landslide (Fig. 7). As the penetration diagrams show clearly, there is a distinct change of penetration resistance with depth at two different levels. This leads to the hypothesis that below the shear plane, there is possibly a weathering front within the Tertiary sediments. This hypothesis needs further and more detailed investigations.

The depth of shear plane as indicated by the drill core Ock3/1 (9.7 m) corresponds very well with the DPH results and the depth of displacement as derived from the inclinometer measurements (Fig. 7). Displacement was 0.7 mm over 194 days (Fig. 8), thus even slower than DROM9. Nevertheless, it can be concluded that this landslide is also continuously moving, which was previously unknown.

Despite the lack of more data, correlations between antecedent conditions and movement rates indicate for OCK3 as well that the accumulated rainfall between measurements is most significant in explaining movement rates. For the same reasons already given for DROM9, this conclusion needs verification in the future through further measurements and modeling.

Besides information on the location of shear planes it is of particular interest to link landslide displacement rate to rainfall magnitude (Fig. 6). Daily rainfall magnitudes from the nearest climate station in Büdesheim, operated by the German Weather Service (Deutscher

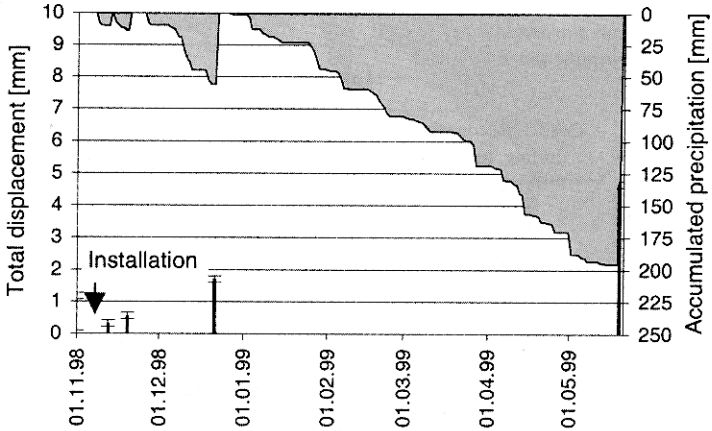

Fig. 8. Relationship between landslide movement and cumulated precipitation on the landslide OCK3.

Table 1. Correlation coefficients of landslide displacement and cumulated precipitation for different periods prior to measurement. Precipitation is measured at the climatic station Büdesheim (refer to Fig. 3 for location), maintained by DWD (German Weather Service). (*Note: n* = total numbers of observations).

Inclinometer (*n*)	Correlation coefficient of movement and cumulated precipitation over					
	2 weeks	4 weeks	6 weeks	8 weeks	12 weeks	period between inclinometer measurements
Dro01 (13)	–0.08	0.27	0.22	**0.44**	0.27	–0.08
Dro02 (12)	–0.25	–0.22	–0.15	0.14	<0.01	**0.78**
Dro03 (13)	0.18	0.09	0.1	0.35	0.2	**0.46**
Ock07 (4)	–0.73	–0.9	–0.83	–0.97	–0.99	**0.97**

Wetterdienst – DWD), were used for this study (refer to Fig. 3 for location). For the landslides in Rheinhessen, not only is daily precipitation important for displacement, antecedent climatic conditions also play a vital role in landslide initiation as well as in determining the rate of movement (DIKAU & JÄGER 1995, JÄGER & DIKAU 1994, JÄGER 1997). Consequently, displacement rates were correlated with different lengths of antecedent periods. Because local percolation behavior of water through the soil is not known, the assumption was made that there is no water loss, either through drainage or through evaporation and evapotranspiration. Thus, antecedent conditions reflect the accumulated amount of rainfall within each specified period. Each displacement rate was then correlated with the antecedent climatic condition. The corresponding correlation coefficients are given in Table 1.

Correlation coefficients vary strongly. Displacement of Dro01, located in the center part of the landslide DROM9 (Fig. 5), seems to correlate best with 8 weeks antecedent rainfall. However, it is the accumulated rainfall between the inclinometer measurements which gives the highest correlation coefficients for the inclinometers Dro02 (lower part) and Dro03 (upper part). Correlation coefficients for fixed antecedent periods are significantly lower. Although the higher correlation coefficients for the landslide OCK3 for all considered antecedent periods suggest better responses of landslide movement to antecedent rainfall over 12 weeks, these values have to be considered carefully due to the low data population (n = 4!).

It has not been possible to establish a general trend between movement and precipitation. Although investigations at Dro01 strengthens the argument that long-term rainfalls are more important for movement rate than short-term events, it is not possible to justify this trend by the displacement of the other inclinometers and the corresponding precipitation events. This is in particular due to the short period of records. In addition, negative correlations suggest a trend towards larger displacements coupled with drier periods. This might indicate, that even longer antecedent conditions are important for landslide movement.

Further measurements, which are currently carried out, might help to understand the complex input-response system of precipitation and landslide movement much better. In addition, further work involving more detailed measurements of water pathways through the soil must be carried out to determine the permeability of the soil, the routing of water through the slope, the loss of water through drainage and to the atmosphere and thus, the length of antecedent conditions important for movement.

Temporal and regional analysis

Regional analysis of weather pattern and landslide events in Rheinhessen was performed for the period 1931 to 1992. A fundamental problem in such an analysis is the different quantity and quality of data. Information on daily weather patterns is generated by the German Meteorological Service and has been classified by GERSTENGARBE et al. (1993). Accuracy of historical landslide data ranges from exact time of occurrence at a given day to a large landslide in a known year (GLA 1989). Thus a criterion had to be developed for linking both datasets to get further information on which weather patterns are responsible for landslide initiation.

First analysis of weather patterns and amount of rainfall introduced the Rainfall Index as a basis for separating weather patterns with low rainfall magnitude from those with high magnitudes. The Rainfall Index is defined as the relation between the proportion of percentage rainfall within one weather pattern to the proportion of percentage of this specific weather pattern to all weather patterns (JÄGER 1997). Analysis shows that weather patterns *tm* and *ws* are characterized by high rainfalls.

In addition to weather pattern and corresponding rainfall magnitudes, landslide data had to be included into the analysis. After analysis of all available landslide data, clusters of landslide data within a three months period could be differentiated. Due to the quality and quantity of data, a resolution of seasons was the best possible denominator. Consequently, daily rainfall magnitudes were also classified in four classes of rainfall. The fifth class refers to no

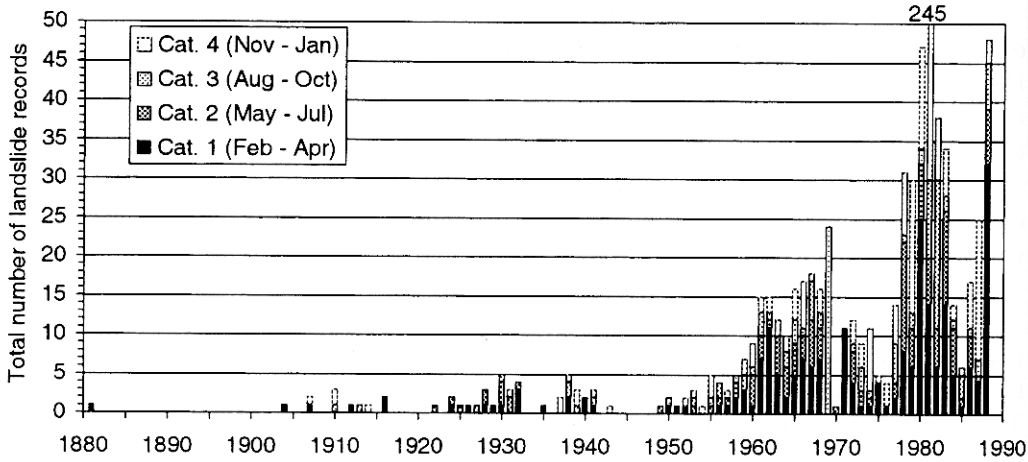

Fig. 9. Number of recorded landslide events in Rheinland-Pfalz classified in 3 month periods. For 209 entries only the year of occurrence is recorded.

Table 2. Classes of parameters season, rainfall and landslides. (*Note:* Not all categories are applicable for any parameter. Please refer to text for detailed explanation.)

Parameter	Category 0	Category 1	Category 2	Category 3	Category 4
Season	–	Feb – Apr	May – Jul	Aug – Oct	Nov – Jan
Precipitation	No Rain	0.1 – 10 mm	10.1 – 20 mm	20.1 – 30 mm	> 30 mm
Landslides	No	Yes	–	–	–

rain (category 0 in Table 2). For the parameter season, category 0 is not used. Landslides fail (category 1) or are stable (category 0), therefore categories 2 to 4 are not applicable. Table 2 gives an overview of categories used. Weather patterns have already been categorized into 30 classes by GERSTENGARBE et al. (1993).

The available landslide data are summarized in Fig. 9. Within each season, the number of records were counted independent of landslide type and landslide magnitude. As is common to such historical landslide databases, such detailed differentiation would not have been successful due to data quality. It can be noted, however, that most of the landslides occur during autumn and winter periods. Bearing the occurrence of short-term heavy precipitation during summer periods in mind, this observation supports the argument that long prolonged wet conditions are the most dominant climatic dispositions for landslide initiation in Rheinhessen.

Analysis of these data was carried out in two stages. In a first step, frequency of occurrence of each weather pattern was determined. Table 3 shows clearly that weather pattern *wz* occurred most commonly in all seasons of the year, although it delivered only small rainfall amounts. Weather patterns *hm* and *bm* follow a similar trend. It is surprising that despite the small amounts of rainfall, landslides occurred regularly within this season. This supports the

Table 3. Most common combinations of weather patterns and corresponding season, rainfall, and landslide occurrence. (*Note:* Table is ranked by frequency of weather patterns in descending order and gives 19 largest values only. Abbreviations of weather pattern are adopted from GERSTENGARBE et al. (1993). Refer to Table 2 for parameter classes.)

Weather Pattern	Season	Rain	Landslides	Frequency
WZ	4	1	1	485
HM	3	0	1	417
WZ	3	1	1	389
BM	3	0	1	387
HM	4	0	1	363
WZ	2	1	1	362
HM	2	0	1	350
BM	2	0	1	334
WZ	2	0	1	334
WZ	3	0	1	319
WZ	1	1	1	311
WA	2	0	1	306
BM	4	0	1	299
HM	1	0	1	254
WA	3	0	1	252
BM	1	0	1	246
WZ	4	0	1	229
WZ	1	0	1	200
NWZ	4	1	1	199

Note: WZ – Westerly cyclonal; HM – High Mideurope; BM – High ridge Mideurope; WA – Westerly anti cyclonal, NWZ – Northwesterly cyclonal

findings of JÄGER (1997) , who showed that landslide activation is not only dependent on daily rainfall magnitudes; it is clearly related to long-term antecedent climatic conditions. This may lead to situations where landslides take place although no rainfall is recorded for that day.

The second stage involved the analysis of the dependence of the other variables on rainfall magnitude. Thus the dataset was ranked according to the largest precipitation classes. The results given in Table 4 demonstrate the predominance of high rainfall magnitudes during weather patterns *ww*, *nz*, and *sez*, in particular during May and July. Although these are singular events, these have always triggered landslides in the past. It can be concluded that besides long-term antecedent conditions, high daily rainfall magnitudes do influence landslide activity as well. In the summer period, deep cracks as described previously are well developed and allow high infiltration rates into deep surfaces, which may act as shear planes. Thus existing landslides are highly susceptible to these summer rainfalls.

These results support the previously published hypothesis on climatic conditions necessary to trigger landslides (DIKAU & JÄGER 1995). However, further analysis, in particular with respect to different combinations of weather patterns prior to an event, is necessary to

Table 4. Most common combinations of precipitation and corresponding weather patterns, season, and landslide occurrence. (*Note:* Table is ranked by rainfall magnitude and frequency in descending order and gives 19 largest values only. Abbreviations of weather pattern are adopted from GERSTENGARBE et al. (1993). Refer to Table 2 for parameter classes.)

Weather Pattern	Season	Rain	Landslides	Frequency
WW	2	4	1	2
NZ	2	4	1	1
SEZ	2	4	1	1
SWZ	3	4	1	1
TM	1	4	1	1
TRM	2	4	1	1
WZ	2	4	1	1
HNFA	1	4	0	1
NEZ	2	3	1	6
WZ	2	3	1	5
SWZ	3	3	1	4
BM	2	3	1	3
HFZ	2	3	1	3
TRW	3	3	1	3
WS	3	3	1	3
WZ	3	3	1	3
HNFZ	2	3	1	2
SEA	1	3	1	2
TM	1	3	1	2

Note: WW – Angular Westerly, NZ – Northerly Cyclonal; SEZ – Southeasterly Cyclonal; SWZ – Southeasterly Cyclonal; TM – Low Center Europe; TRM – Trough Center Europe; WZ – Westerly cyclonal; HNFA – High Northsea-Fennoscandinavia Anticyclonal; NEZ – Northeasterly Cyclonal; BM – High ridge Center Europe; HFZ – High Fennoscandinavia Cyclonal; TRW – Trough West Europe; WS – Southwesterly; HNFZ – High Northsea-Fennoscandinavia Cyclonal; DEA – Southeasterly Anticyclonal

allow a characterization of typical weather patterns, or combinations thereof responsible for landslide initiation. Additionally, it would be an advance to link this information to more detailed landslide data, such as first time event or re-activation, magnitude of landslide, location of landslides, etc. However, as is true for most study areas, the landslide database available for this study is not detailed and comprehensive enough to allow such detailed analysis.

The previously given results demonstrate recent episodic movement determined by inclinometer as well as episodic movement in the last decades proved through a preliminary dendrogeomorphological study (GERS et al., this volume). Additionally, these findings are supported by the entries in the landslide data inventory. Consequently, it was envisaged to discuss these findings with respect to a long-term assessment of slope evolution, thus extending the considered time period from a few months and decades to millennia. Due to the lack of more detailed data, discussion of the role of landslides for landform evolution in Rheinhessen remains qualitative.

Role of landslides for landform evolution in Rheinhessen

Traditionally, the most important geomorphic processes influencing slope evolution in our study area include:

- sheet, rill and gully erosion;
- fluvial erosion and accumulation;
- landslides;
- aeolian loess accumulation during the Pleistocene;
- tectonic activities; and
- periglacial processes.

So far, it has not been possible to reconstruct the importance of each single process type for slope evolution based on empirical analysis. As this study suggests, however, landslides seem to contribute significantly to long-term landform development in Rheinhessen.

Based on these general statements, the following hypothesis is developed. From field evidence it appears that large magnitude landslides occurring with lower frequency involve the more resistant calcareous stratigraphy from the Miocene. These large events destabilize complete slope sections. The disturbed material has significantly lower shear resistance and is thus more susceptible to continuous movement. Smaller and more frequent landslides remove the displaced mass from the lower and middle parts of the slopes over time. This leads to an increase of slope angle, thus creating greater instability for the overall slope including the more resistant Miocene cap. Consequently, through removal of material there is a change over time in the balance of stresses that define the internal stability threshold, until eventually an input capable of triggering the next large event occurs. Thus landslide initiation is not always dependent on changing external conditions; similar climatic conditions over long periods may cause a series of small landslides, affecting the internal threshold (balance of stresses) and eventually resulting in a high magnitude landslide event.

A second hypothesis stresses the importance of changing material properties over time. As already suggested by LAUBER (1941), over consolidated clays may lose their strength over time as they lose their overburden with surface exposure. This hypothesis was tested by comparing soil mechanical properties from undisturbed samples with those taken from surface exposures of the same stratum. The undisturbed sample was taken from a core which was drilled through the plateau, while the latter sample was gathered from the same height on the slope. Results from the laboratory tests suggest that the exposed samples have changed from the over consolidated condition to a lower degree of consolidation. Thus erosional processes removed the covering strata and, over time, weathering processes decreased the strength of the material. Consequently, landslides may occur more frequently without changing external conditions. Laboratory analysis is currently still in progress and will lead to more detailed results in the future.

Inherent in both hypotheses is the premise that internal thresholds are changing over time and influence landslide occurrence without any necessary change of external conditions. This theory is based on the theoretical system concept introduced by SCHUMM (1979). Although this concept was originally developed for fluvial systems, numerous authors have adopted this approach to landslides (e.g. POPESCU 1996).

However, scientific evidence supporting these hypotheses are still rare. Nevertheless, examples can be found. PRESTON (1999) demonstrated that despite identical rainfall inputs, susceptibility to landslide failure changed over time, and concluded that internal mechanisms operate, such that triggering thresholds of external variables are of limited relevance. CROZIER (1999) interpreted this in terms of systematic evolution.

To examine these hypotheses in more detail, further research is currently being undertaken. Of particular interest is how erosion affects the degree of consolidation, and thus changes the shear resistance of a given slope over time. If it can be shown that geotechnical properties are changing over time, this analysis will help to determine in more detail the long-term landscape evolution.

Conclusions

The study has shown that landslides incidents are not only singular large magnitude events. Although not very well recognized by local authorities, landslides are a continuous threat in Rheinhessen. Certainly, the speed of movement is very slow during a year without extreme climatic events. However, it has been demonstrated through dendrogeomorphological analysis and inclinometer measurements that the three investigated landslides are in constant motion. Consequently, there is always the potential of increasing movement rates with changing climatic conditions and thus causing considerable damage to the environment as well as to economy and society. Therefore, further research is necessary to understand the process behavior, and consequently, to be able to predict landslide behavior in the future.

Future research issues include for specific locations:

- more detailed knowledge on landslide kinematics using physically based slope stability models,
- the influence of vegetation cover, and consequently the result of land use change for a given landslide,
- a better understanding of slope hydrology, in particular related to permeability and infiltration, role of cracks for water routing, length of antecedent climatic conditions influencing landslide movement, and the role of groundwater movement for landslide initiation,
- longer and higher resolution inclinometer measurements allowing more precise analysis of the relationship between climatic input and landslide displacement,
- more detailed laboratory analysis of soil mechanical properties of undisturbed and exposed overconsolidated clays.

On a regional scale, research should include:

- analysis of weather patterns, specifically including conditions prior to an event,
- linkage of weather pattern to rainfall conditions and further to landslide displacements, and on a temporal scale
- better understanding of the role of landslides for landform evolution in this area.

In addition to these research issues resulting from previous investigation, there is another need identified which relates to a comprehensive risk assessment. A proposed risk study for the Rheinhessen region involves the identification of elements at risk, their vulnerability as well as the perception and management of these risks. Such an integrated and interdisciplinary project would ensure the transfer of knowledge and expertise to a broader community.

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Addresses of the authors: Dr. Thomas Glade and Prof. Dr. Richard Dikau, Universität Bonn, Geographisches Institut, Meckenheimer Allee 166, D-53115 Bonn. Dr. Annette Kadereit, Forschungsstelle Archäometrie der Heidelberger Akademie der Wissenschaften, Max-Planck-Institut – Kernphysik, Postfach 103980, D-69029 Heidelberg.