Effects of increasing humidity on slope geomorphology: cuesta scarps on the Colorado Plateau, USA

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Abstract Cuesta scarp slopes on the Colorado Plateau developed in various lithological contexts and in different altitudinal belts were the subject of a long-term study. Specific attributes of the scarp slopes such as vegetation and soil cover, dissection density, activity of mass movements, talus production and general morphometry were documented. The principal aim was to investigate how these slope attributes change with increasing altitude and precipitation under the present climatic conditions and to use this information as an indicator of morphoclimatic changes during the Quaternary in a space–time substitution. Altitudinal shifts of the hydrological environment during the Wisconsin resulted in associated shifts of vegetation and morphoclimatic belts, and the lower elevations were affected by present high-altitude process combinations. Corresponding to their intrinsic lithological characteristics individual types of scarp slopes show different reactions to changing moisture availability. The specific response to changes in humidity is discussed using the example of a sandstone/mudstone (Dakota Sandstone/Brushy Basin Facies) scarp slope. This scarp slope was studied on the sides of a canyon (Cottonwood Canyon, Colorado), which follows the structural dip on the flank of a major uplift (Uncompahgre Uplift). Thus, as in an experimental setup, an elevation range from 1500 to 3000 m and an annual precipitation range from 200 to 600 mm are covered. In the semiarid altitudinal belt the moderately dissected slope has a convex profile with an average inclination of about 30°. With increasing humidity the convex slope profile disappears and mass movement activity and associated irregular slope forms become more and more obvious on the scarp slope, beginning with inactive or dormant landslides at elevations below 2500 m and precipitation amounts below 500 mm. In higher areas with rainfall amounts exceeding 500 mm, present-day mass movement activity can be observed. The lower limit of inactive landslides is indicative of how far humid phase mass movement processes extended down the sides of the canyon.

Key words altitudinal zonation; climatic change; Colorado Plateau; cuestas; dissection density; mass movements; scarp slopes; slope geomorphology

INTRODUCTION AND AIMS OF THE INVESTIGATION

Forms and processes of cuesta scarp slopes were investigated on the Colorado Plateau in the southwestern United States. In this long-term study the combined influence of lithology and climate on the morphodynamics and morphometry of scarp slopes was analysed at a number of different locations covering diverse lithological and climatic settings. One of these locations was Cottonwood Canyon in western Colorado (Fig. 1). Special attention was given to slope attributes characterizing changes of material input, storage, transfer and output. On the Colorado Plateau, cuesta scarps have developed at elevations ranging from 1300 to 3000 m with corresponding mean annual precipitation...
amounts of between less than 150 and more than 600 mm (Schmidt & Meitz, 1996). There is also a wide lithological variety of caprocks and soft lower slope substrates composing the cuesta scarps (Barth & Blume, 1973; Hunt, 1974; Schumm & Chorley, 1966; Schmidt, 1988).

In the semiarid parts (<250 mm) in the lower elevations (1300-2000 m), four different slope types were identified (concave, convex, straight and vertical) (cf. Schmidt, 1987, 1988; Schmidt & Meitz, 1996). The classification in this altitudinal belt refers essentially to the form and process characteristics of the lower scarp slope, which are mainly dependent on the lithological and structural attributes of the soft lower slope substrates. The form variations of the upper scarp slopes are not as pronounced because in the semiarid belt, with its selective weathering and erosion, all the resistant caprocks tend to form nearly vertical cliffs.

After identifying the lithologically controlled slope types, their form and process response to changes in climatic conditions was systematically investigated in the higher elevations of the Colorado Plateau as well. Specific slope attributes (Table 1) were mapped and measured in the field and on air photographs in different altitudinal belts. The complete elevation (1300-3000 m) and precipitation ranges (<150 to >600 mm) were included in the analysis of an overall slope length of several hundreds of km (Schmidt, 1996; Schmidt & Meitz, 1996; Meitz, 1998).
The principal aims of the investigations were:
- to show how slope attributes change with increasing altitude and increasing moisture availability in the present climatic regime,
- to analyse how these changes influence processes of material input, transfer, storage and output on the slope,
- to define morphoclimatic thresholds separating distinct form and process regimes,
- to use the information collected under present climatic conditions as an indicator of morphoclimatic changes during the late Quaternary in a space–time substitution,
- to provide specific information on a classic geomorphological question, i.e. how the combined influence of lithology and climate on landforming processes can be differentiated.

STUDY AREA AND MAIN FEATURES OF THE CONVEX SLOPE TYPE

This paper focuses on the form and process variations found on the convex slope type. The convex lower slope (slope type 2) is developed in a number of different lithologies (Petrified Forest Member and Monitor Butte Member of the Triassic Chinle Formation, Brushy Basin Member of the Jurassic Morrison Formation) at the lower elevations of the Colorado Plateau. One of the main features of these rocks is their content of swelling clay minerals, which cause shrinking processes after longer periods of dry weather (Shawe et al., 1968; Stewart et al., 1972). Subsequently subsurface drainage, piping and tunnel erosion processes occur on the lower slope, leading to decreasing water availability and surface runoff with increasing downslope distance. This in turn results in the formation of convex slope profiles (Ahnert, 1988, 1998) as typically found in the bentonitic clays in the semiarid portions of the Colorado Plateau.

Individual sites for studying the effects of increasing humidity on morphodynamics and morphometry were located in the northeastern and central parts of the Colorado Plateau, adjacent to the flanks of major uplifts or laccolithic centres, where the cuesta scarps have developed in a great variety of altitudinal zones and hydrological conditions, and where morphoclimatic changes during the Pleistocene cold phases are likely to have occurred. One of the study sites, which was investigated in great detail, is located in Cottonwood Canyon near Grand Junction in Western Colorado (Fig. 1). Here slope type 2 is found in the Brushy Basin Member of the Morrison Formation with the Dakota Sandstone (including the Burro Canyon Formation) as caprock. The cliff-forming Dakota Sandstone is composed mainly of sandstone and some conglomerate beds firmly cemented with silica and carbonate minerals and with iron oxides. The Brushy Basin Member consists dominantly of multi-coloured bentonitic mudstones with some interbedded sandstone lenses. The Brushy Basin Member is

<table>
<thead>
<tr>
<th>Table 1 Slope attributes.</th>
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<tr>
<td>Density of the vegetation cover</td>
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<tr>
<td>Soil cover and thickness</td>
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<tr>
<td>Morphometry (inclination, curvature)</td>
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underlain by the Salt Wash Member of the Morrison Formation, a cliff-forming resistant sandstone, which is exposed in the deeper parts of Cottonwood Canyon.

Cottonwood Canyon is a consequent valley running down the eastern flank of the Uncompahgre Uplift following the direction of structural dip. Structural relief is almost identical with topographic relief, which is adjusted to the top of the Dakota Sandstone, from which the overlying less resistant strata (Mancos Shale) have been removed by erosion. Thus the canyon rims and the top of the scarp slopes on both sides of the canyon lie in the same stratigraphic position at elevations ranging from 1500 to 2800 m (Fig. 1); an altitude of 3000 m is reached near the top of the Uncompahgre Uplift. Annual precipitation amounts range from 200 to 550 mm along the canyon walls (Fig. 2(a)) and to more than 550 mm on the highest parts of the Uncompahgre Plateau (Schmidt & Meitz, 1996).

The present precipitation distribution on the northeastern and central Colorado Plateau was calculated by processing the data collected for 153 climatological stations in the entire study area and its vicinity. For the calculation of a regression with precipitation as the dependent and elevation as the independent variable, 59 stations from the central study area were selected to reduce the influence of surrounding areas with different precipitation regimes. The correlation coefficient \( r = 0.83 \) shows a strong relation between precipitation and elevation. The regression was used to estimate precipitation data for additional points. The data of the 59 reference stations plus 320 calculated points in the central part of the study area and 94 other stations in the surrounding regions were gridded with the Kriging method (Schmidt & Meitz, 1996). The precipitation amounts shown for Cottonwood Canyon (Fig. 2(a)) originate from this calculation procedure. However, the dataset did not allow us to account for the influence of prevailing wind directions on precipitation distribution.

As a consequence of the specific structural and stratigraphic setting of Cottonwood Canyon, the variation of scarp slope attributes induced by changes in humidity can be studied as in an experimental setup over a distance of 30 km. Moreover, the left side of the canyon faces southeastward and the right side northwestward (Fig. 1), which offers the possibility of studying the influence of aspect on slope attributes.

**RESULTS OF THE ANALYSIS OF SLOPE ATTRIBUTES IN DIFFERENT ALTITUDDINAL BELTS**

Slope attributes of the Dakota Sandstone/Brushy Basin Member cuesta scarp were mapped and measured in the field and on air photographs. Mapping did not include parts of the canyon lying in lower stratigraphic units (e.g. Salt Wash Sandstone). These areas are shown in white on the maps. Digital elevation models (7.5 min DEM of the US Geological Survey) were used for some topographic attributes. The grid \((30 \times 30 \text{ m})\), however, was too large for detailed mapping of slope microrelief and inclination. In Cottonwood Canyon large-scale \((1:3000)\) air photographs were produced with the support of an airphoto service in Fruita, Colorado, which carried out a low altitude flight specially ordered for the project. These photographs helped to improve the precision of mapping very much. More detailed information on the methods of mapping and classification of the slope attributes, on data sources and acquisition are given in the individual sections of this chapter.
Fig. 2 (a) Distribution of mean annual precipitation in Cottonwood Canyon. (The inner parts of the canyon, which lie stratigraphically below the Brushy Basin Member have not been mapped, this also applies to Figs 2(b) and 5(a and b)). (b) Vegetation density in Cottonwood Canyon.
Vegetation density

The analysis of the distribution of vegetation densities will be preceded by a brief description of the different vegetation zones included in the altitudinal range of Cottonwood Canyon. The desert shrub belt is found in the lower parts of the canyon and adjacent plateaus generally extending up to 1650–1700 m. At elevations with annual precipitation greater than 180 mm, sagebrush communities (Artemisia spp.) prevail and can extend up to 3000 m into other vegetation belts. In the study area the pinyon-juniper woodland (Pinus edulis, Juniperus osteosperma) is dominant at elevations between 1650 and 1950 m. The lower limit of the pinyon-juniper woodland is determined by lack of moisture and poor soil quality. Annual precipitation is generally above 300 mm. Juniper can be found in pure stands in the transition zone between sagebrush communities and pinyon-juniper woodland.

At higher elevations pinyon and juniper form a mixed woodland, and pinyon replaces the juniper in the transition zone to the pine-oak belt. This belt with its characteristic species gambel oak (Quercus gambelli), mountain mahogany (Cercocarpus spp.) and ponderosa pine (Pinus ponderosa) has its lower elevation limit at about 1850 m and its upper limit at 3000 m. The lower precipitation limit is about 400 mm. Gambel oak and mountain mahogany form impenetrable thickets on the slopes. The uppermost vegetation zone in the study area is the spruce-fir belt at elevations above 2500 m and an annual precipitation above 500 mm. The vegetation association is dominated by the Douglas fir (Pseudotsuga menziesii) in the dryer areas, blue spruce (Picea pungens), white fir (Abies concolor) and aspen (Populus tremuloides) in mesophytic areas.

It was not the main purpose of this study to map the distribution of plant species or plant communities. The more important morphodynamical and hydrological factor is the density of the vegetation cover, which was mapped independently of the individual species involved. Vegetation protects surfaces from direct raindrop impact, promotes infiltration, soil formation and stability, and reduces surface runoff through interception losses and runoff velocity by roughness increase (cf. Francis, 1994; Selby, 1993). Six categories of vegetation density were classified: (1) bare areas; (2) 1–20%; (3) 20–40%; (4) 40–60%; (5) 60–80%; (6) 80–100% (Fig. 2(b)). Vegetation density decreases with decreasing altitude. There are extended bare areas on the scarp slopes at lower elevations (Fig. 3). The distribution of bare areas is also influenced by the lithological characteristics of the Brushy Basin facies, which are extremely unfavourable for plant growth. At elevations between 1750 and 2100 m (northwest-facing slope) the cover with pinyon and juniper becomes increasingly dense. A density of 60–80% is reached at elevations of about 2250 m with corresponding precipitation amounts of about 400 mm. A full vegetation cover with 100% density is found in the highest parts of the canyon (Fig. 4) and in the upland areas of the Uncompahgre Uplift. The influence of aspect becomes obvious when comparing vegetation density on northwest-facing slopes to southeast-facing slopes (cf. Fig. 2(b)). There is also a shift in the altitudinal zonation of the individual vegetation belts of about 100 m. At elevations below 1750 and above 2350 m the difference in vegetation density caused by aspect loses its importance, since in the dry lowland areas humidity thresholds are not transgressed on either side of the canyon and in the humid highlands thresholds for density class 6 are exceeded on both sides of the canyon.
Fig. 3 Southeast-facing side of Cottonwood Canyon at an elevation of about 1850 m. In this location semiarid morphodynamic processes are still dominant. Vegetation is sparse, the slope has a convex profile, it is moderately dissected and no mass movements occur on the lower slope.

Fig. 4 Upper part of Cottonwood Canyon at an elevation of about 2350 m. The area is very densely vegetated (up to 100%). The slope profile is mass movement controlled. Several generations of movements can be distinguished. The slope is divided into ridges with intervening depressions. In the lowest parts of the slope the depressions are filled with small lakes. There are no continuous slope rills.
Soil cover and thickness

For soil mapping, information supplied by the soil surveys of different services of the USDA (US Department of Agriculture) was used (USDA, 1981, 1993, 1995). The soil map is not shown in this paper. Six soil depth categories were distinguished: (1) badlands, rock outcrops; (2) <25 cm; (3) 25–50 cm; (4) 50–100 cm; (5) 100–150 cm, (6) >150 cm. Soil depth is defined as "depth of soil over bedrock or a cemented hardpan" (USDA, 1993, p.123). There is no soil cover in large parts of the study area, even at higher elevations where the rocky parts of the Dakota Sandstone form cliffs, steep slopes and ledges. On the Brushy Basin clays no soils have developed in wide areas (badlands) below 2000 m. These bare areas are more frequent on southeast-facing than on northwest-facing slopes. Soil thicknesses increase starting at elevations of 2000 m. They reach the highest categories on the slopes in the upland areas. Great soil depths are also found at the foot of the scarp slopes. The thickest soils (category 6) developed in slope depressions, which are generally caused by mass movements (see below). These depressions are more frequent on northwest-facing slopes.

Dissection density

Slope dissection was measured directly in the field and on large scale air photographs. The latter measurements were tested by ground checks. Slope rills have the function to transport material from the slope to the scarp foreland and/or to the main channel. The denser the drainage net, the more effective the organization of material output from the slope system during times of high precipitation input and erosive activity. Dissection density is expressed as the number of slope rills per 1000 m of scarp length. Intensities were classified into eight categories: (1) no dissection, (2) 1–2 rills, (3) 3–4 rills, (4) 5–7 rills, (5) 8–12 rills, (6) 13–19 rills, (7) 20–30 rills, (8) 31–50 rills. This slope attribute was only mapped on straight scarp segments (Fig. 5(a)). Spurs and embayments were not included because of two reasons: (a) aspect, which itself is a controlling variable for dissection, varies in these curved scarp sections, and (b) for geometrical reasons there are more rills per unit scarp length on spurs than in embayments (Meitz, 1998; Schipull, 1980).

Owing to its specific lithological attributes, dissection is relatively low on the convex slope type in comparison with the concave lower slope, where the highest dissection rates are found. Categories 4 and 5 are reached only at the lower elevations of Cottonwood Canyon. At the lower end of the canyon (up to 1700 m, top of scarp slope) there are no differences between northwest-facing and southeast-facing slopes. On the northwest-facing slopes a clear decrease in dissection is noticeable at elevations above 1700 m, and the zone of highly reduced and no dissection begins at elevations of 2100 m (Fig. 5(a)). On the southeast-facing slopes, however, dissection densities remain in categories 4 and 5 up to 2150 m (cf. Fig. 3). A short transition interval follows with dissection class 3. With increasing altitude, dissection decreases rapidly and, in the highest parts of the basin also on the southeast-facing slopes, there are very few or no slope rills. Irregularities in inclination caused by mass movement accumulations impede parallel slope drainage in the higher elevations (see below). The influence of aspect becomes highly conspicuous regarding the overall distribution of
Fig. 5 (a) Dissection density in Cottonwood Canyon. (b) Distribution of mass movement accumulations in Cottonwood Canyon.
drainage densities along the sides of the canyon. Generally there is a close correspondence between altitudinal boundaries of categories of vegetation and dissection densities (cf. Figs 2(b) and 5(a)). The detailed mapping of the slope attributes convincingly demonstrates that drainage density decreases and erosional slope stability increases with increasing vegetation cover. There is a strong inverse correlation between vegetation and dissection densities (rank correlation, Spearman) for this slope type as well as the others (Meitz, 1998).

Mass movements and talus production

On the Colorado Plateau landslides are frequently observed on lower scarp slopes, which are developed in bentonitic clays (Colton et al., 1975a,b). They have been described in greater detail from slopes in the clays of the Petrified Forest Member of the Chinle Formation on the Vermilion and Echo Cliffs, Arizona (Strahler, 1940), and from the Clay Hills area, Utah (Mullens, 1960), and also for the Brushy Basin Member of the Morrison Formation in the Slick Rock District, Colorado (Shawe et al., 1968), which is situated in the vicinity of the study area. Landsliding processes are a typical feature of the convex slope type. In Cottonwood Canyon mass movement accumulations are found at elevations above 1900 m (top of the scarp) on northwest-facing scarp slopes and above 2200 m on southeast-facing slopes. Sickle-shaped ridges with their concave sides directed towards the scarp slope can easily be identified in the field or on air photographs. The distribution of mass movement accumulations reveals a clear asymmetry between north and south facing slopes (Fig. 5(b)). There are no landslides in the lower parts of the canyon. The only mass movements found here are small scale rockfalls or topples in the Dakota Sandstone with the displaced material only covering the upper part of the lower scarp slope.

Up to four generations of landslides can be found on slope profiles in the uppermost parts of the canyon (Fig. 5(b)). The accumulations cause breaks in the continuous slope profile and interrupt the usual parallel drainage pattern (cf. Fig. 4). They promote sediment storage on the slope and prevent material export in the affected slope segments (Fig. 6). As a result of the downslope transport of great masses of rock material, the scarp slope is characterized by specific associations of landforms. Block movements result in a heterogeneous relief arrangement, which is composed of a pattern of pairs of convex and concave elements, which run parallel to the scarp and perpendicular to the original slope inclination (cf. Fig. 7(b–d), Fig. 4). These paired relief elements have been categorized according to their degree of preservation and their transport distance away from the present top of the main scarp on the Muschelkalk scarp in Hesse and Thuringia, central Germany, where the lower slope rocks also consist of swelling clays that promote landsliding processes (Kirbis, 1950; Beyer & Schmidt, 1999).

Fresh caprock blocks with steep cliffs on both sides, which lie close to the scarp front, are called walls. They are separated from the main scarp by gaps (Fig. 7(c)). In the initial phase of detachment they have deep holes at their bottom and are filled with organic debris. With greater horizontal and vertical distance the walls are transformed into ridges with intervening trenches (Fig. 4) and eventually to low ridges with intervening hollows, which are characterized by greater moisture availabilities with adapted plant communities and thicker soil profiles (cf. Fig. 7(c,d)). At higher
Slope segment Cottonwood Canyon

Elevation of cliff: about 2100 m a.s.l.
Elevation of base of slope: about 1900 m a.s.l.
Length: about 990 m

Fig. 6 Digital elevation model (5 × 5 m) of a slope segment, which was affected by mass movement processes (rotational slide). The parallel downslope drainage and material output are disturbed. Drainage is deflected into a slope depression which has been formed by mass displacements and runs perpendicular to the original slope inclination. On the left side of the depression at the toe of the mass movement accumulation, Brushy Basin clays are squeezed out and form a bulge. The steep slope in the inner canyon is developed in Salt Wash Sandstone.

elevations the depressions are often filled with small lakes (Fig. 4). Mass movement processes on the slopes of Cottonwood Canyon are presently inactive or dormant. Only at elevations above 2500 m near the top of the Uncompahgre Uplift, where precipitation reaches more than 500 mm, are landslides presently active as documented by tumbled trees and caprock blocks drifting away from the scarp.

Movements are caused by water percolating through the widely jointed Dakota Sandstone to the underlying impervious Brushy Basin clays. Water saturation near the sandstone-claystone interface in times of high moisture availability results in increasing plasticity of the clays and reduced shear resistance and greater susceptibility to mass movements. Initial displacements of the sandstone blocks are effected by very slow processes of lateral rock spreading over the plastified argillaceous Brushy Basin facies. This process has been defined as the “creep of blocks over soft rocks” by Radbruch-Hall (1978). The overburden of the blocks of resistant rock is generally assumed to be the cause of plastic deformation in the soft rock. The horizontal to subhorizontal overposition of a thick block of competent rock, affected by a dense network of joints, on clayey material, which can behave as a visco-plastic medium, is
Fig. 7 Altitudinal zonation of slope characteristics on the Dakota Sandstone/Brushy Basin Facies cuesta scarp in Cottonwood Canyon. (a) Semiarid convex slope. (b) and (c) Irregular, mass movement controlled slope profiles with inactive and dormant mass movement accumulations. (d) Irregular, mass movement controlled slope profile with multiple generations of mass movements and active displacement processes in the highest parts of the basin.
required for the creep process to take place (Dikau et al., 1996, p.133). Lateral spreading leads to joint widening and block detachment from the main scarp with subsequent rotational or translational sliding of competent caprock over incompetent rock. Clays are often squeezed out in bulges at the foot of the slide block (Fig. 6).

**Altitudinal zonation of slope attributes and morphometry**

Using the results of field investigations and air photograph interpretation, a general altitudinal zonation of slope attributes and morphometry can be derived for slope type 2 (Fig. 7). The general model has been corroborated by findings in other locations on the Colorado Plateau (Meitz, 1998). This altitudinal zonation helps to show how the changes in slope attributes influence processes of material input, transfer, storage and output, and also helps to define morphoclimatic thresholds separating distinct form and process regimes.

In the semiarid altitudinal belt with rainfall amounts of less than 300 mm, no higher vegetation developed on the lower scarp slope. The slope is moderately dissected (cf. Fig. 5(a)) by parallel slope rills and has an overall convex profile with an average inclination of about 30° (Fig. 7(a)). Mass movement accumulations are only found in the upper portions of the lower scarp slope and are derived from rockfalls and topples in the caprock. Talus is destroyed by weathering and transported downslope by erosional undermining and subsequent sliding. It is eventually exported to the scarp foot and foreland via the slope rills. With greater humidity the smooth convex profile disappears and mass movement controlled irregular slope profiles become more and more characteristic for the increasingly densely vegetated lower scarp slope (Fig. 7(b–d)). The irregular profiles are first observed at elevations above 1900 m on northwest-facing slopes (above 2200 m on southeast-facing slopes). In this elevation belt only one generation of landslides is found (Fig. 7(b)). With increasing altitude, multiple sequences of mass movement accumulations with intervening slope depressions have developed (Fig. 7(c, d), and Figs 4 and 5(b)). Parallel slope drainage is completely disturbed in this altitudinal belt. Landslides are presently inactive or dormant at elevations below 2500 m and precipitation amounts of less than 500 mm. In the highest parts of the basin, with rainfall amounts exceeding 500 mm, a fundamental change of present-day morphodynamics takes place (Table 2) and creep blocks and slide masses are actively moving. The morphodynamically most active parts, with respect to mass movement processes, lie in the higher altitudes of the catchment which receive the greatest precipitation amounts.

**Table 2** Thresholds of morphoclimatic regimes on the Dakota-Sandstone/Brushy-Basin-Facies cuesta scarp (northwest-facing slopes).

<table>
<thead>
<tr>
<th>Threshold Description</th>
<th>Present-day Precipitation</th>
<th>Cold (Humid) Phase Moisture Equivalent</th>
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<tbody>
<tr>
<td>Arid to semiarid convex slope (Fig. 7(a)) (&lt;1900 m*)</td>
<td>≤ 200–300 mm</td>
<td>≤ 500 mm</td>
</tr>
<tr>
<td>Irregular slope profile with inactive and dormant mass movement accumulations (Fig. 7(b, c) (1900–2500 m)</td>
<td>≤ 500 mm</td>
<td>≥ 500 mm</td>
</tr>
<tr>
<td>Irregular slope profile with active mass movements and multiple landslide generations (Fig. 7(d)) (&gt;2500 m)</td>
<td>≥ 500 mm</td>
<td>≥ 500 mm</td>
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*Altitudes given refer to the top of the scarp slope.
IMPLICATIONS FOR LATE QUATERNARY MORPHOCLIMATIC CHANGE

At present, changes in vegetation and geomorphological forms and processes with increasing altitude are mainly the result of variations in precipitation. However, the existing palaeoclimatic and palaeobotanic evidence shows that on the Colorado Plateau there was no significant increase in precipitation during the cold (humid) phases of the late Pleistocene (Brakenridge, 1978; Galloway, 1983; Thompson et al., 1993). More moisture was available owing to reduced evapotranspiration. Temperatures during the Wisconsin full glacial (18 ka) were much cooler than today. Estimates range from 5 –10°C according to different sources (cf. Schmidt & Meitz, 1996; Thompson et al., 1993).

In order to obtain information on moisture availability during the Wisconsin, present potential evapotranspiration rates were estimated using data from the 153 climatological stations, which were also used in the analysis of the spatial distribution of precipitation (see above). The same was done for the Wisconsin cold phase using a temperature reduction of 7°C. The Thornthwaite method (Thornthwaite, 1948) proved to be suitable (cf. Schmidt & Meitz, 1996), with the advantages of easy processing and wide application. Assuming that precipitation remained essentially constant, as most authors imply, we were able to calculate the Wisconsin moisture gain for the study area by subtracting the computed values for the Wisconsin cold phase from present-day evapotranspiration rates. The moisture gain obtained in this way was added to the present precipitation data to get at least an approximate idea of the cold phase moisture equivalent. Generally hydrological conditions in the Cottonwood Canyon area were characterized by an additional moisture availability of about 200 mm. Altitudinal shifts of the hydrological environment resulted in associated shifts of vegetation zones (Betancourt, 1990; Wright et al., 1973) and morphoclimatic belts.

The altitudinal variation observed in the present configuration of form and process regimes may serve as an indicator and analogue for late Pleistocene climatic change in a space–time substitution. Process control and slope characteristics presently found in the higher altitudes migrated downwards during the cold (humid) phases as a consequence of reduced temperatures and resulting greater effective moisture availability. This must have provided conditions for vegetation growth, soil formation and dissection in the lower parts of the canyon, which were similar to the hydrological environment found today at the higher altitudes where precipitation amounts exceed the morphoclimatic threshold of 500 mm (Table 2). The lower limit of inactive mass movement accumulations is indicative of how far down the canyon slopes humid phase landslide activity reached. Moisture gain was not sufficient to generate mass movement activity at elevations below 1900 m (northwest-facing scarps) and 2200 m (southeast-facing scarps). In this altitudinal belt dryland morphodynamics persisted throughout the late Pleistocene and the moisture equivalent never exceeded 500 mm. In the altitudinal belt with only one generation of mass movement accumulations, conditions favourable for landsliding have only been present for relatively short periods of time, whereas in the areas with two or more generations of landslides (cf. Fig. 5(b)) the morphoclimatic threshold must have been transgressed for considerable periods of time.

The space–time substitution for the morphoclimatic conditions is a sound argument for the assumption that the landslides in lower altitudes were active during
the Wisconsinan cold (humid) phase, but the precise age of the landslides is not known. Some of the landslide accumulations farther downslope may also have originated during the Illinoian cold phase. A possible method for obtaining absolute age determinations is surface exposure dating (SED) (e.g. Elmore & Phillips, 1987; Nishiizumi et al., 1993) of the Dakota Sandstone slide blocks. As the Dakota Sandstone is very resistant to weathering, the application of SED may yield more reliable results for this caprock than those obtained by dating the more friable Mesaverde Sandstone blocks on the talus flatirons on the concave slope type (Schmidt & Meitz, 1997). Pollen analysis of the lake sediments in the slope depressions (Fig. 4) may also prove to be a successful dating tool in future research. With the onset of drier conditions the sequence of form and process changes was reversed and the semi-arid morphoclimatic system was re-established in the central and lower parts of the study area and on the Colorado Plateau as a whole.

DISCUSSION AND CONCLUSIONS

The analysis of form and process attributes of individual types of scarp slopes (concave, convex, straight) showed that, in accordance with their inherent lithological characteristics, they respond differently to morphoclimatic changes (cf. Schmidt, 1996; Schmidt & Meitz, 1996). Thresholds separating distinct states of form–process relationships must be specially defined for the individual slope types. The specific response of the convex slope (type 2) is demonstrated in this presentation. Increasing humidity, accompanied by a denser vegetation cover, leads to slope stabilization with respect to dissection processes on erosion-controlled slopes. Dissection is also reduced on the convex slope in the more humid altitudinal belts (Fig. 5(a)). But from a more general point of view, the morphodynamic system of slope type 2 is destabilized, as the effects of mass movement activity increase when precipitation or the cold (humid) phase moisture equivalent exceed 500 mm. Once covered by large mass movement accumulations (Fig. 4), the lower slope attains a greater resistance to change. Longer relaxation times for adjustments to changing morphoclimatic conditions are the consequence. The irregular slope profile inherited from times of mass movement activity is persistent enough not to have been transformed into an erosion-controlled profile in the course of the Holocene in the central elevations of Cottonwood Canyon. Obviously landslide-controlled slopes have a greater resistance to change than erosion-controlled slopes.

Though material displacements by landsliding are morphodynamically most active in the zones of greatest humidity, dissection and fluvial sediment output are more effective at the semi-arid low altitudes with their sparse vegetation cover. Mass movements produce enormous quantities of disintegrated material, which is, however, stored within the system and not exported to the foreland tributaries and to major rivers for long periods of time ($10^5$ years, see above). On the mass movement controlled slopes with their high storage potential there is no equilibrium between material production and removal. On the other hand, the dissected slopes in the dry areas are systems in equilibrium with talus input being equal to talus output. A valuable indicator for material export from geomorphological systems is the sediment load of rivers. A comprehensive study on the relation between specific yield ($1 \text{s}^{-1} \text{km}^{-2}$) and
suspended sediment yield for gauging stations in the Upper Colorado River basin showed that there is a significant inverse correlation between these variables (Schmidt, 1985). In the dry areas material is not protected by vegetation, it is more readily available for erosion, dissection densities are higher, and the runoff regime is highly variable. Moreover, the importance of storage on slope systems decreases with decreasing humidity. These general findings are supported by the slope attributes registered in Cottonwood Canyon.

The more general results of the investigations of the individual slope types show that it is not possible to define a typical arid slope system or a typical humid slope system (cf. Schmidt, 1996; Schmidt & Meitz, 1996). The combined influence of climate and lithology must be synoptically evaluated. Rough generalizations do not consider the actual variety of control, response and feedback mechanisms in form-process relationships. Changes in humidity may induce opposing tendencies of reactions in different rock types. This applies to the characteristics of form and process variables as well as to more general considerations of morphodynamic stability or activity.

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**REFERENCES**


