9-1986

Cliff-height and slope-angle relationships in a chronosequence of Quaternary marine terraces, San Clemente Island, California

Russell Crittenden

Daniel R. Muhs

Z. Geomorph. N. F.	30	3	291–301	Berlin · Stuttgart	September 1986

Cliff-height and slope-angle relationships in a chronosequence of Quaternary marine terraces, San Clemente Island, California

by

RUSSELL CRITTENDEN, Madison and DANIEL R. MUHS, Denver

with 7 figures, 1 photo and 1 table

Zusammenfassung. Eine Abfolge quartärer Strandterrassen auf San Clemente Island, Kalifornien, liefert einen Rahmen für die quantitative Analyse der Änderungen an vom Meer verlassenen Küstenkliffen als Funktion der Zeit. Es wurde eine Abschätzung der Anwendbarkeit von BUCKNAM & ANDERSON (1979) log-linearer Beziehung zwischen Wandhöhe und Hangwinkel durchgeführt, indem Brandungskliffhöhe und maximale Hangwinkel verwendet wurden. Die Ergebnisse zeigen eine regelhafte Zunahme des Hangwinkels mit dem Logarithmus der Kliffhöhe, und Kliffe einer bestimmten Höhe zeigen mit der Zeit eine Abnahme des maximalen Hangwinkels. Im ganzen waren die Relationen schwächer als für Flußterrassen und Bruchstufen in unverfestigten Materialen, aber die Methode kann wahrscheinlich verwendet werden, um frühe, mittlere und junge quartäre Bruchstufen und Küstenkliffe in verfestigtem Material erfolgreich zu unterscheiden.

Summary. A flight of Quaternary marine terraces on San Clemente Island, California, provides a framework for quantitative analysis of abandoned sea cliff modification as a function of time. An assessment was made of the applicability of BUCKNAM & ANDERSON's (1979) log-linear relationship between scarp height and slope angle using sea cliff height and maximum slope angle. Results indicate a regular increase in slope angle with the logarithm of the cliff height and cliffs of a given height show a decline in maximum slope angle with time. Overall, the relationships are weaker than for stream terraces and fault scarps in unconsolidated materials, but the method can probably be used successfully to distinguish early, middle and late Quaternary fault scarps or sea cliffs in consolidated materials.

Résumé. Une série de terrasses marines quaternaires sur l'île de San Clemente (Californie) fournit un cadre pour l'analyse quantitative de l'évolution de falaises marines mortes. Une hypothèse a été avancée concernant l'application de la relation log-normale de BUCKNAM & ANDERSON (1979) entre la hauteur de l'escarpement et l'angle de la pente appliquée ici à la hauteur de la falaise marine et l'angle maximum de la pente. Les résultats indiquent un accroissement régulier de la pente avec le logarithme de la hauteur de la falaise et les falaises d'une hauteur déterminée montrent un abaissement de l'angle de pente maximum en fonction du temps. Partout, les relations sont moins bonnes que pour les terrasses de rivières et des escarpements de failles dans des matériaux meubles. Toutefois, la méthode peut probablerment être utilisée avec succès pour donner un âge quaternaire récent moyen ou ancien aux escarpements de failles ou aux falaises marines dans des matériaux consolidés.

0372-8854/86/0030-0291 $ 2.75

Introduction

The rate of alteration of slopes, particularly those derived from fault scarps, has received increasing attention in recent years because of the need for accurate assessment of potential fault hazards (WALLACE 1977; BUCKNAM & ANDERSON, 1979; NASH 1980a, 1980b, 1984; MACHETTE 1982; COLMAN 1983; COLMAN & WATSON 1983; HANKS et al. 1984; MAYER 1984; STERR 1985). Often there is a need for age determination of a fault scarp, but little or no material available for radiometric dates. Hence, many investigators have utilized morphometric parameters in order to establish relative and in some cases absolute ages. BUCKNAM & ANDERSON (1979) were perhaps the first to quantify changes in fault scarp slope angles through time. They examined the relationship between scarp height and slope angle in Quaternary deposits in the Great Basin of western Utah and quantified earlier observations of WALLACE (1977). Their results indicated that for small scarps less than 10 m high, slope angle increases with the logarithm of scarp height and decreases through time for a scarp of a given height. This relationship has been confirmed for fault scarps in other locations in the southwestern U. S. A. (MACHETTE 1982; MAYER 1984; HANKS et al. 1984) and has been extended to other landforms such as stream terrace scarps (COLMAN 1983) and lake cliffs (NASH 1980b). Several studies have gone beyond the relative dating method proposed by BUCKNAM & ANDERSON (1979) and models for determination of absolute age have been generated (NASH 1980b, 1984; COLMAN & WATSON 1983; HANKS et al. 1984; HANKS & WALLACE 1985; STERR 1985). MAYER (1984) recently discussed the complicating effects of measurement error, lithology, particle size, and composite scarps.

Most of these studies have examined changes in scarp slope angle in unconsolidated materials. To our knowledge, the only study which has examined changes in slope angle in consolidated materials is the work by HANKS et al. (1984). These investigators examined a single shore-normal profile of marine terrace sea cliffs cut into the Pliocene Santa Cruz Mudstone. They used terrace ages based on a uniform rate of uplift in order to derive estimates of the "mass diffusivity" (which is part of the diffusion equation model of slope evolution) for each terrace; their estimates of this parameter for two high terraces agreed with their calculated value for a better-dated low terrace. The conclusion of this study was that ages derived from the constant uplift rate assumption were reasonable. However, no study that we are aware of has tested the slope-angle-scarp-height log-linear relationship of BUCKNAM & ANDERSON (1979) on dated slopes of Quaternary age in consolidated materials. Such a test is important, however, because: (1) Quaternary faults sometimes displace consolidated materials and (2) verification of the BUCKNAM & ANDERSON (1979) relationship would add to general models of slope evolution.

In this paper we test the BUCKNAM & ANDERSON (1979) relationship by examining a chronosequence of marine terraces cut into Miocene andesite on San Clemente Island, California. Certain of the terraces have been dated by amino acid and uranium-series methods and thus provide a chronologic framework for our test. We consider marine terrace cliffs to be reasonable analogs to fault scarps in the most important respects. A fault scarp is produced by one or perhaps several rapid events. On a slowly tectonically-rising land mass which is experiencing a high stand of the

Photo 1. Oblique aerial photograph of marine terraces on the west side of San Clemente Island. Lowest terrace in the foreground here is the 127,000 yr old terrace. Photograph courtesy of JOHN S. SHELTON.

sea, a sea cliff is undercut as the shore platform extends inland and is abandoned during a succeeding glacial period when the sea retreats below the platform. Not all points along a cliff erode at once and some parts of a given cliff are probably older than others (for a good review of processes of sea cliff genesis, see EMERY & KUHN 1982). However, these age differences are probably small compared to the time elapsed since the cliff was abandoned; hence, little error is introduced by considering all points along a sea cliff to be of the same age. After displacement (in the case of fault scarps) or sea-level lowering (in the case of sea cliffs), both slopes are subjected to mass movement and slopewash processes that alter the initial slope through time.

Study area

San Clemente Island, located off the California coast (fig. 1), is an uplifted structural block composed mainly of Miocene andesite with lesser amounts of dacite, rhyolite and marine sedimentary rocks (OLMSTED 1958). Quaternary deposits overlie bedrock over much of the island and include dune sand, eolianite, alluvial fan deposits and marine terrace deposits (MUHS 1983). Marine terrace deposits are almost always less than 2 m thick and are often less than 0.5 m thick. LAWSON (1893) counted as

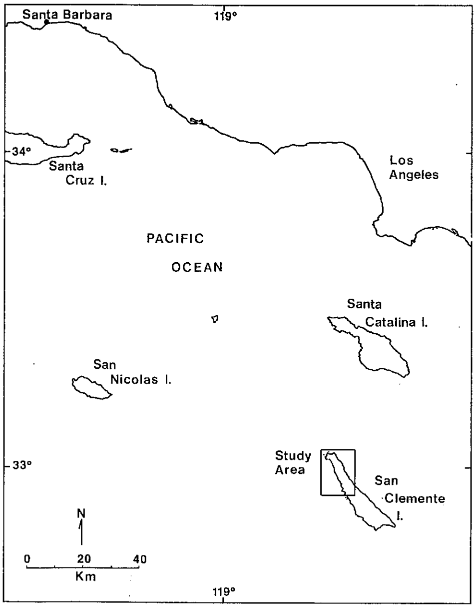

Fig. 1. Location of study area.

many as 22 marine terraces on the western side of the island; MUHS (1983) mapped these features on the northern part of the island and this where the present study was conducted (figs. 1 and 2). Marine terraces are extremely well expressed geomorphically on San Clemente Island (photo 1) as they lack the extensive, thick continental deposits which typically cover these landforms on the California mainland. On San Clemente Island, alluvial fan deposits are found only near canyon mouths on the lower terraces and dune sands and eolianites are found mainly in the extreme northern part of the island (MUHS 1983).

Three of the terraces have age estimates derived from uranium-series and amino acid methods. The second terrace, informally named the Eel Point terrace, has a U-series date on coral of 127,000 ± 7,000 yr (MUHS & SZABO 1982). The first and fifth terraces have amino acid age estimates on fossil mollusks of about 80,000–105,000 and 500,000 yr, respectively (MUHS 1983). MUHS & SZABO (1982) estimated ages for other terraces using the age and elevation of the second terrace and an assumption of uniform uplift rate. We assume that higher terraces are older, based on amino acid ratios, which are higher in fossil mollusks from higher terraces, and degree of soil development, which is greater on higher terraces (MUHS 1982).

Methods

Our methods for measuring maximum slope angle and cliff height follow those of BUCKNAM & ANDERSON (1979) and are summarized in fig. 3. Measurements were

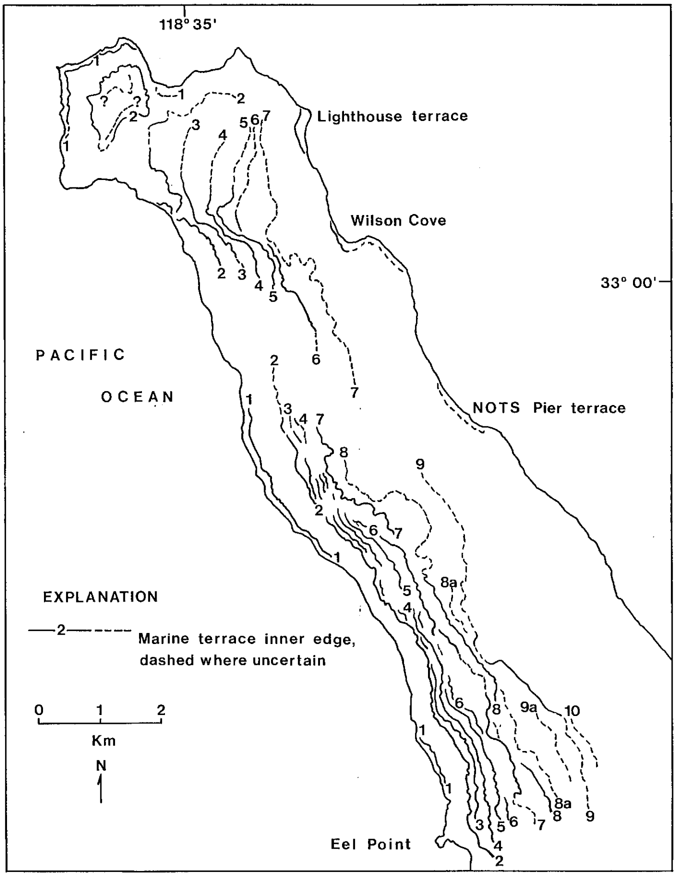

Fig. 2. Location of marine terrace inner edges on nothern San Clemente Island. Terrace locations taken from MUHS (1983).

taken from topographic profiles normal to the shore constructed from 1:4000 U.S. Navy topographic maps with a contour interval of 3.1 m (10 feet). Even with detailed topographic maps such as these, there are limits to the precision of the data collected. We estimated that a point could be placed within 0.05 cm (equivalent to 2 m on the ground) of its true position on the map when reading the intersection of a contour line with the rule used in the measurements. This error, which does not include generalization errors in the cartography, contributed to uncertainty about the true slope angle of the cliffs. The error increases for steeper slopes (when the contour lines are closer together) and decreases for longer slopes (when more contours are included), as shown in table 1. All data points for which the uncertainty in the slope determination was greater than 4 degrees were discarded. In addition, the

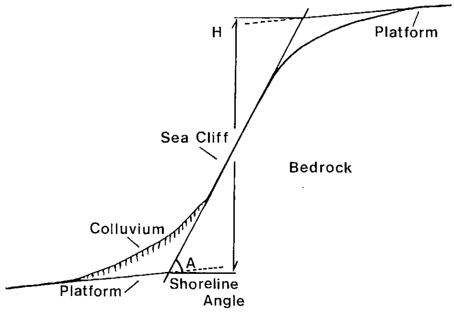

Fig. 3. Sea cliff parameters used in the study, modified for sea cliffs from BUCKNAM & ANDERSON (1979). H = height; A = maximum slope angle of sea cliff.

3.1 m contour interval contributes to a large error in the determination of the height of short cliffs; as a result, cliffs less than 9 m high were not included.

Other limitations on the number of data points were related to the distribution of Quaternary deposits or the nature of the geomorphology. Areas mapped by OLMSTED (1958) or MUHS (1983) as dune sand, eolianite or alluvial fan deposits or near faults were avoided. Areas of extensive fluvial dissection were also avoided. All cliffs that showed evidence of multiple platform-cutting episodes were avoided. Such cliffs typically have two or more long segments separated by a narrow shelf (fig. 4). In low uplift rate areas such as the southern California Channel Islands, renewed platform cutting and sea cliff retreat is common, resulting in "missing" terraces such as MUHS (1985) has recently documented for San Nicolas Island. All cliffs 30 m or more in height displayed the form showed in fig. 4 and were not included in our measurements.

Ancient shore platform gradients on bedrock in central California are commonly 1–2 degrees for inshore segments and 0.5–1 degrees for offshore segments (BRADLEY & GRIGGS 1976). On San Clemente Island, where only inshore segments were measured, slopes increase from about 2 degrees on the lowest terraces to about 5 degrees on the tenth terrace. These gradients are based on surface measurements, however, and not the bedrock shore platforms because field exposures of these features are rare. Thus, our measurements of "platform" gradient are really mea-

Table 1 Error estimates for slope determination.

Distance between contours			Range in slope angle (in degrees) by height of slope segment	
on map (mm)	on ground (m)	Slope angle (degrees)	3.1 m (10 ft)	12.4 m (40 ft)
10	40	4.4	4.7– 4.2	4.5– 4.4
5	20	8.8	9.8– 8.0	9.0– 8.6
3	12	14.5	17.2–12.5	15.1–13.9
2	8	21.2	27.3–17.2	22.4–20.0
1	4	37.8	57.2–27.3	41.5–34.6
0.5	2	57.2	90.0–37.8	64.2–51.1

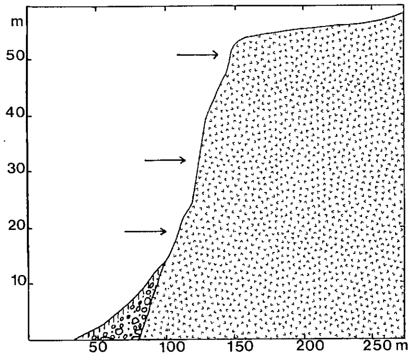

Fig. 4. Example of a cliff backing the fifth terrace that has experienced multiple undercutting episodes. Arrows point to three places on the profile where "maximum slope angle" could be measured.

surements of the slope of marine and terrestrial deposits and soil covering the platform. Through time, the shoreline angle (the junction of the sea cliff and the shore platform) is covered with colluvium and develops a broad concavity that is much steeper than the platform. Cliff retreat during subsequent high sea stands has eliminated much of the width of some terraces, leaving only the concave footslope, and as a result the method of defining cliff height used here underestimates this parameter by putting the intersection of the tangent lines (fig. 3) at a higher elevation. The same effect is achieved if the terrace above the cliff has an exaggerated gradient. No attempt was made to correct this by substituting "realistic" platform gradient values because no particular point of origin for the corrected slope could be identified as correct. In addition, the differences in cliff height between uncorrected and corrected determinations were found by experiment to be insignificant after logarithmic transformation.

Results and discussion

Four terraces on San Clemente Island yielded a sufficient number of data points after our selection criteria described above were applied. Of these, the second, fourth, and eighth terraces showed significant log-linear relationships between maximum slope angle and cliff height as predicted by the Bucknam & Anderson (1979) relationship (fig. 5). The correlation coefficients for the second and eighth terraces are good but we found only a 50% explanation for the fourth terrace, although the correlation is significant at the 0.03 level. Thus, it appears that cliff height exerts a control on maximum slope angle in consolidated rock similar to that observed in unconsolidated sediments. We have no explanation for the lack of a clear relationship between these two variables for the fifth terrace (fig. 5). The terrace is well expressed geomorphically, there are no lithological differences and the data plotted passed all our screening tests as described above. We also note that although our correlation coefficients are significant for the other three terrraces, the degree of explanation is less than that observed by some other workers for unconsolidated materials (e.g., Bucknam & Anderson 1979; Machette 1982).

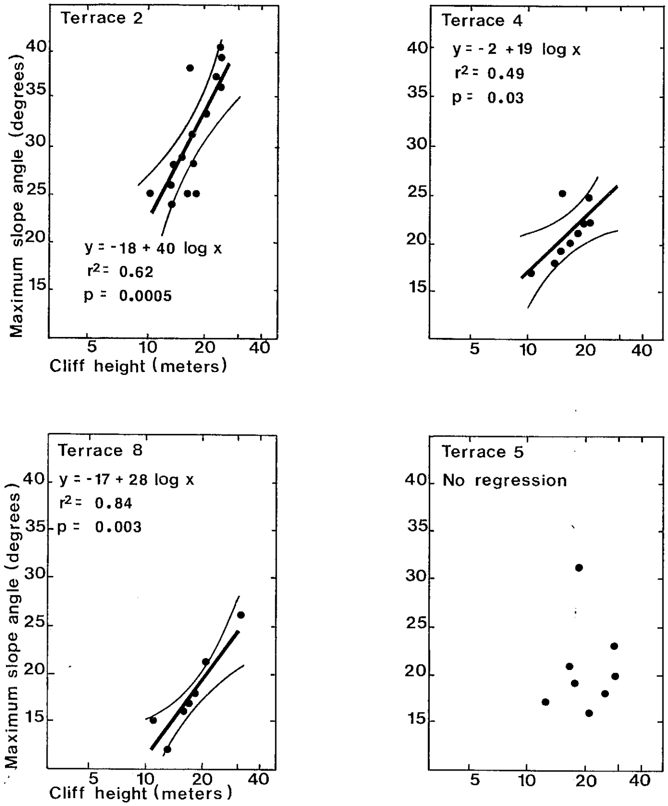

Fig. 5. Plots of maximum slope angle vs. cliff height for four terraces of differing age on San Clemente Island. Thin lines define 95% confidence interrvals.

When the three terraces with significant relationships are plotted together, it can be seen that the time-dependent nature of the slope-angle-scarp-height relationship of BUCKNAM & ANDERSON (1979) is also found in consolidated rock (fig. 6). The age estimates given in this plot are those derived from uranium-series dating of coral (for the second terrace) and extrapolated uplift rate estimates and correlations with the deep-sea record for the fourth and eighth terraces (MUHS & SZABO 1982). With increasing age, the slope-angle-cliff-height isochron slopes decrease. The three lines are plotted with their 95% confidence intervals; BUCKNAM & ANDERSON (1979) thought that resolution of two different-aged fault scarps could be made when their 95% confidence intervals did not overlap. By this criterion, we can clearly distinguish between the 127 ka second terrace and the two older terraces, but resolution of the fourth and eighth terraces is not possible. We suspect that if more measurements could be made for the fourth terrace, a higher correlation coefficient might be obtained and resolution of these two terraces might be possible.

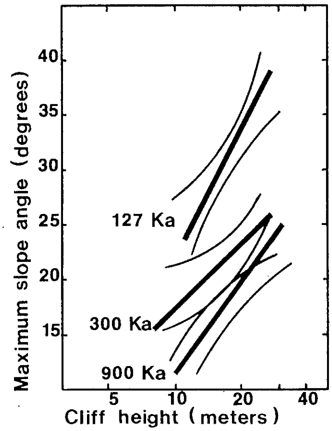

Fig. 6. Change of slope-angle-cliff-height regression line slopes as a function of terrace age given in ka (= 1000 yr). Thin lines define 95% confidence intervals.

Based on a diffusion model of slope evolution, NASH (1980a: 356) predicted that the rate of slope angle decrease would diminish through time for a scarp of a given height. We tested this prediction for consolidated rock by plotting maximum slope angles as a function of age for cliffs of three different heights using the regression equations on Figure 5 and the age estimates of the terraces provided by MUHS & SZABO (1982). The results indicate a trend similir to what NASH (1980a) predicted for unconsolidated materials (fig. 7), but since we have only three points in time and a weak relationship for the fourth terrace, we are not tempted to press the argument too far. NASH (1980a) also provided an equation for calculating the age of an undated scarp assuming that it formed under conditions similar to those of a dated scarp and that the initial angles of the two scarps were similar. The time of failure of the undated scarp (t_u) can be computed as

(1) $$t_u = t_d \, (H_u/H_d)^2$$

where t_d is the age of the dated scarp, H_u is the height of the undated scarp with some slope angle Θ, and H_d is the height of the dated scarp at slope angle Θ. Using our regression equations and the uranium-series date of 127 ka for the second terrace, we made independent calculations of the ages of the fourth and eighth terraces with equation (1). The calculated age for the fourth terrace is approximately 625 ka and the age for the eighth terrace is about 900 ka. Agreement between the Nash method of age estimate and the uplift rate age estimate for the eighth terrace is good, but the Nash method predicts an age more than twice as old as the uplift rate method for the fourth terrace. Again, the weaker realtionship between slope angle and cliff height for the fourth terrace may explain the poor agreement between the two methods; clearly, more data are needed to test the Nash model further. In addition, we recognize that the Nash height-ratio method of age determination is derived from the diffusion equation model and strictly speaking, is applicable only to "transport-limited" slopes. Since our cliffs are cut into bedrock, they may be "weathering-limited" slopes; thus our age estimates derived from equation (1) are considered to be an empirical test only.

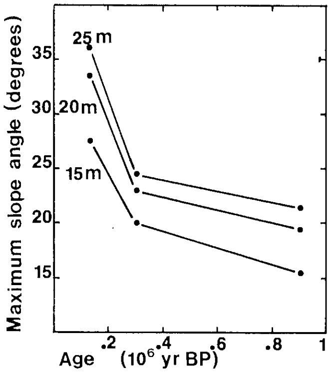

Fig. 7. Change in maximum slope angle as a function of time for three cliffs of different heights.

Conclusions

We conclude that sea cliffs cut into consolidated materials show a slope-angle-cliff-height relationship similar to that found by BUCKNAM & ANDERSON (1979) and subsequent investigators for scarps and cliffs cut into unconsolidated materials. In general the relationship is weaker and may be related to the longer timescale involved. Change of the slope angle vs. cliff height regression line with time also shows similarities to changes observed with unconsolidated materials, and this suggests that the relationship may potentially be useful as a relative-age indicator. However, for older terraces, confidence intervals overlap and thus the method may only be useful on a longer timescale, i. e., differentiating late Quaternary terraces from middle-to-early Quaternary terraces. This is not particularly useful for geomorphologists or Quaternary stratigraphers, because other techniques such as amino acid dating, soil development and even landform elevation are likely to be more sensitive geochronological tools. However, the distinction may be useful in arid environments where Quaternary faults displace volcanic rocks or other consolidated materials and the only age control available may be the maximum-limiting date derived from the age of the displaced rock unit. For example, slope-angle-scarp-height relationships may distinguish late vs. middle Quaternary faults which displace rocks in the Basin and Range province of the western U. S. A.

Acknowledgements

We thank STEVEN M. COLMAN (U.S. Geological Survey) for helpful comments on an earlier draft of this paper.

References

BRADLEY, W. C. & G. B. GRIGGS (1976): Form, genesis, and deformation of central California wave-cut platforms. – Geol. Soc. Am. Bull. **87:** 433–449.

BUCKNAM, R. C. & R. E. ANDERSON (1979): Estimation of fault-scarp ages from a scarp-height-slope-angle relationship. – Geology **7:** 11–14.

COLMAN, S. M. (1983): Progressive changes in the morphology of fluvial terraces and scarps along the Rappahannock River, Virginia. – Earth Surface Processes and Landforms **8:** 201–212.

COLMAN, S. M. & K. WATSON (1983): Ages estimated from a diffusion equation model for scarp degradation. – Science **221:** 263–265.

EMERY, K. O. & G. G. KUHN (1982): Sea cliffs: Their processes, profiles, and classification. – Geol. Soc. Am. Bull. **93:** 644–654.

HANKS, T. C., R. C. BUCKNAM, K. R. LAJOIE & R. E. WALLACE (1984): Modification of wave-cut and faulting-controlled landforms. – J. Geophys. Res. **89:** 5771–5790.

HANKS, T. C., & R. E. WALLACE (1985): Morphological analysis of the Lake Lahontan Shoreline and Beachfront fault scarps, Pershing Country, Nevada. – Bull. Seismological Soc. Am. **75:** 835–846.

LAWSON, A. C. (1893): The post-Pliocene diastrophism of the coast of southern California. – Univ. Calif., Dept. Geol. Sci. Bull. **1:** 115–160.

MACHETTE, M. N. (1982): Quaternary and Pliocene faults in the La Jencia and southern part of the Albuquerque-Belen basins, New Mexico: Evidence of fault history from fault-scarp morphology and Quaternary geology. – New Mex. Geol. Soc. Guidebook, 33rd Field Conf.: 161–169.

MAYER, L. (1984): Dating Quaternary fault scarps formed in alluvium using morphologic parameters. – Quat. Res. **22:** 300–313.

MUHS, D. R. (1982): A soil chronosequence on Quaternary marine terraces, San Clemente Island, California. – Geoderma **28:** 257–283.

– (1983): Quaternary sea-level events on northern San Clemente Island, California. – Quat. Res. **20:** 322–341.

– (1985): Amino acid age estimates of marine terraces and sea levels on San Nicolas Island, California. – Geology **13:** 58–61.

MUHS, D. R. & B. J. SZABO (1982): Uranium-series age of the Eel Point terrace, San Clemente Island, California. – Geology **10:** 23–26.

NASH, D. B. (1980a): Morphologic dating of degraded normal fault scarps. – J. Geol. **88:** 353–360.

– (1980b): Forms of bluffs degraded for different lengths of time in Emmet County, Michigan, USA. – Earth Surface Process. **5:** 331–345.

– (1984): Morphologic dating of fluvial terrace scarps and fault scarps near West Yellowstone, Montana. – Geol. Soc. Am. Bull. **95:** 1413–1424.

OLMSTED, F. H. (1958): Geologic reconnaissance of San Clemente Island, California. U. S. Geol. Surv. Bull. 1071-B.

STERR, H. (1985): Rates of change and degradation of hillslopes formed in unconsolidated materials: A morphometric approach to date Quaternary fault scarps in western Utah; USA. – Z. Geomorph. N.F. **29:** 315–333.

WALLACE, R. E. (1977): Profiles and ages of young fault scarps, north-central Nevada. – Geol. Soc. Am. Bull. **88:** 1267–1281.

Addresses of the authors: R. CRITTENDEN, Department of Geography, Science Hall, University of Wisconsin, Madison, Wisconsin 53706 USA; DANIEL R. MUHS, U.S. Geological Survey, M.S. 424, Box 25046, Federal Center, Denver, Colorado 80225 USA.