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LANDSCAPE INHERITANCE AND THE PEDIMENT PROBLEM IN THE MOJAVE DESERT OF SOUTHERN CALIFORNIA

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ABSTRACT. Currently there appears to be no expansion of granitic pediments in the Mojave Desert due to stabilization of rock slopes under the existing climate. The presence of early Pliocene volcanics on the higher portions of both major and minor pediments graded to existing base levels indicates those erosional surfaces to be inherited features, formed in their entirety prior to the establishment of full desert conditions in the Mojave region. During the late Pliocene and Quaternary the Mojave pediments have been altered primarily by the stripping of a weathered mantle inherited from the preceding semiarid morphogenetic system. Fragments of this mantle are preserved under Tertiary volcanics widely distributed throughout the region. Active pedimentation in the Tertiary landscape seems to have been predicated upon "denudational equilibrium" in which hillslope erosion was in balance with regolith renewal by rapid chemical breakdown of granitic rock along the subsurface weathering front. Relationships at piedmont angles in the present stripped landscape require parallel rectilinear backwearing (rather than downwearing) of soil-covered slopes during most active landscape morphogenesis. Tertiary weathering profiles and landscape evolution in the Mojave region appear similar to those of non-desert areas in which pediments appear to be expanding at present. Pedimentation by slope retreat in a soil-covered landscape can be explained in terms of a combination of findings previously contributed by Schumm (1956, 1962, 1966), Ruxton and Berry (1961), and Emmett (1970).

INTRODUCTION

The results of recent morphometric analyses of Mojave Desert pediment landscapes (Cooke, 1970; Cooke and Reeves, 1972) are illustrative of the degree to which the most fundamental questions related to desert pediments remain unresolved. Cooke has advanced several good reasons for the unproductiveness of past research on pediments. To these I venture to add one more of a quite different nature, which this paper will attempt to substantiate: namely, that in the Mojave Desert region, at least, it is futile to attack the pediment problem through analysis of contemporary process/form associations because the classic pediment landscapes in this region developed under an altogether different morphogenetic regime than that dominant in the area at present. It appears that pediments are still expanding in crystalline rock in the southwestern United States but not in true desert landscapes and not in the manner suggested by the majority of American writers on the subject.

THE PEDIMENT PROBLEM

The "pediment problem" that has occupied the attention of so many distinguished American geomorphologists proceeds from the difficulty of accounting for the conspicuous ramp-like erosion surfaces that truncate resistant rock in the arid regions of the southwestern United States and that terminate so abruptly against steep mountain walls and relief forms of the "inselberg" type. The fact that bold relief forms are developed in bedrock that differs in no apparent way from that exposed on adjacent erosionally subdued pediments is the crux of the pediment problem. The origin of geometrically similar erosion surfaces that bevel relatively erodible materials adjacent to resistant relief-forming outcrops has seldom been regarded as an enigma. However, surfaces of the latter type, which were discussed by Gilbert in 1877 (p. 120-126) in his discussion of "planation," have also come to be known as "pediments" (for example, Denny, 1967; Twidale, 1967; Cooke and Warren, 1973) despite warnings against the tendency (Howard, 1942; Tator, 1952; Birot and Dresch, 1966). Planation surfaces bordering uplands composed of more resistant rock (*peripediment* of Howard, *glacis* of Birot and Dresch) are commonly capped by gravels derived from rocks other than those truncated, are clearly localized by outcrop pattern, and (except where peripheral to a horizontal cap rock) have never been imagined as expanding headward through time. These characteristics are all in marked contradistinction to peripheral erosion surfaces that are cut *into* the rocks of the upland itself. In the following, the term *pediment* is used exclusively in reference to the more problematical form — the ramp-like erosion surface cutting the same resistant rock that forms the adjacent upland.

THE PEDIMENT LANDSCAPE

Erosional pediments abutting on rocky inselbergs, escarpments, and mountain walls are particularly characteristic of the granitic terranes of southern Arizona and the Mojave Desert of southern California, extending also into the Sonoran Desert in Mexico. According to the most recent summary of the literature on pediments in the southwestern United States (Hadley, 1967), the preponderant opinion is that pediments truncating hard rock have originated as a concomitant of the backwearing of escarpments and serve as slopes of transportation for the fine products of weathering derived from the positive forms rising above them. Where granitic rock is involved, there is an abrupt change of slope, the "piedmont angle" (Ruxton, 1958), between the pediment, which rarely attains a slope in excess of 5 degrees, and the steeper forms rising above it at angles generally exceeding 20 degrees. The steep slopes are in most cases mantled with boulders, whereas the pediment surface is veneered with coarse sand occasionally interrupted by exposures of bedrock. Frequently granitic pediment surfaces are studded with rocky tors or are dissected by washes cut into decomposed bedrock or opened along joints in sounder material.

It has been noted by many investigators that the reduction of granitic boulders to a certain minimum size (approx 30 cm, or 1 ft, diam) is followed by their direct breakdown into grus. The conspicuous slope break between pediments and surmounting residual masses has been attributed to the resulting bimodal size distribution of granitic debris: the steep boulder slopes above pediments being regarded as the repose slopes for blocks loosened by weathering into joints (for example, Gilluly, 1937), and the pediment being the minimum slope permitting evacuation of the grus resulting from weathering in the boulder zone. Bryan (1923) and Davis (1938) pointed out that weathering of most non-granitic rocks produces fragments having a continuous gradation of sizes; as a consequence pediments developed on such rocks commonly merge with mountain front slopes by way of a smooth concavity, with no abrupt slope break evident. The association of pediments with granitic rocks has generally been stressed (Davis, 1938; Gilluly, 1937; Tuan, 1959; Birot and Dresch, 1966) and attributed to the distinctive bimodal size grading of granitic weathering products. This suggests that the presence of a well-defined piedmont angle is critical to identification of the pediment landform. A recent analytical treatment of pediment systems (Cooke and Warren, 1973, p. 188-215) contains no suggestion that existing pediment forms may not be the product of processes presently observable in desert regions.

THE PEDIMENT PROBLEM TODAY

Recent quantitative studies have cast doubt upon certain of the above assumptions. Melton (1965) established that the angles of boulder slopes are not clearly related to boulder size, refuting Bryan's concept of the "boulder controlled" slope, and morphometric analyses by Mammerickx (1964), Cooke (1970), and Cooke and Reeves (1972) have indicated that pediment slope cannot be correlated with pediment length, tributary area, rock type, or particle size, which suggests that the function of existing pediments as slopes graded for transportation is not as straightforward as some have supposed. On the basis of denudation rates, the evidence of paleosols, and current weathering tendencies the present author has attempted to show that the backwearing of slopes required to produce pediments is not occurring at present in granitic terranes in the Mojave Desert, where the major landscape features appear to be relict from pre-Quaternary non-desert morphogenetic regimes (Oberlander, 1972).

THE PROBLEM IN ITS GEOGRAPHICAL SETTING

The following interpretation of Mojave Desert pediments presents further evidence suggesting that the origin of these erosional forms is not to be sought in studies of the existing morphogenetic regime but through reconstruction of the Tertiary history of the region. The evidence is derived not only from examination of the pediments themselves but from associated landforms and surficial deposits suggestive of the environment in which the pediments were developed.

The conclusions offered here are an application of previous findings related to Tertiary weathering profiles in the Mojave Desert (Oberlander, 1972). The reader is referred to the latter for the details summarized with little substantiation in the first portion of the present paper. The work as a whole is based upon examination of granitic landforms in various portions of the Mojave Desert over a period of several years, with particular concentration upon the area extending from Victorville to Dale Lake (in the maximum rain shadow of the San Bernardino Mountains) and between Baker and Amboy in the central portion of the desert (fig. 1). The annual precipitation in these areas is generally less than 100 mm (4 in.), the majority occurring between November and April as a result

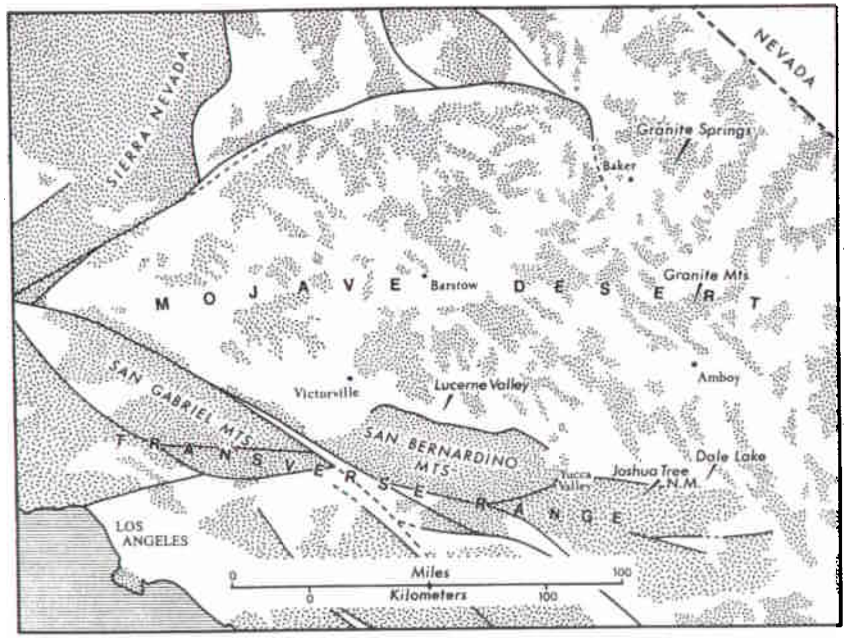


Fig. 1. Mojave Desert area and adjacent locations referenced in text. Lines indicate major faults. Patterned areas represent eroding uplands and peripheral pediments. Unpatterned areas represent Quaternary alluvium.

of frontal activity. The characteristic vegetation is creosote bush (*Larea divericata*) and *Yucca schidigera*, joined at higher elevations by *Yucca brevifolia*, with isolated pinyon pine and juniper encountered above 1100 m (3500 ft) at points of runoff concentration from bare rock slopes.

The scenery within the areas studied is diverse, the southern region being dominated by extensive pediments peripheral to large and small granitic masses, while the central desert area includes several broad, almost featureless granitic domes (such as Cima Dome) having diameters of 3 to 8 km, as well as significant granitic highland masses bordered by pediments exposing bedrock a kilometer or more beyond the mountain front. The dominant granitic rock is medium-grained equigranular quartz monzonite containing 2 to 7 percent biotite and equal proportions of plagioclase and potassic feldspar. Granite, granodiorite, gneiss, and meta-volcanic rocks are local constituents of the pediment-inselberg landscapes of the region.

GENERAL CONSIDERATIONS

Before considering the specific evidence bearing upon the origin of the Mojave pediments two facts should be noted:

1. Botanical indications (Axelrod, 1958) and stratigraphic evidence related to the time of uplift of the Transverse Ranges (Richmond, 1960) both suggest that the rain shadow accounting for the Mojave Desert was not fully developed until late Pleistocene time. Axelrod's interpretation of the palynological record has been disputed insofar as it ignores the possible existence of local pockets of aridity prior to this time — a point of great importance in the evolution of the Mojave Desert flora — but his conclusion that aridity became general over the region this recently has not been argued (Johnson, 1968). Assuming (generously) that the present arid conditions became prevalent about 6 m.y. ago and that pedimentation by slope backwearing ensued, the minimum rate of slope retreat in bedrock necessary to produce pediments as little as 1500 m (5000 ft) in length would be 254 mm (10 in.)/1000 yrs.

2. The presence of patination ("desert varnish") and case hardening over boulders and massive rock outcrops on residuals rising above pediments suggests that retreat of such surfaces is exceedingly slow at present. Relations at the sites of indurated radiometrically-dated wood rat (*Neotoma*) middens in the Lucerne Valley area and Joshua Tree National Monument indicate no obvious retreat of the quartz monzonite faces that have enclosed them over the past 10,000 yrs. Beyond the Mojave Desert proper, there has been no measurable wearing back of the granitic outcrops in the climatically and morphologically similar Alabama Hills of the Owens Valley region in approximately 50,000 yrs, since the Tahoe-age glacial outwash of Lone Pine Creek accumulated against them. North of the San Bernardino Mountains basalts having radiometric ages exceeding 8 m.y. lie within 40 m of existing low elevation piedmont angles (Oberlander, 1972). Depths of removal of quartz monzonite beneath radiometrically dated basalt in the adjacent White Mountains indicate rates of erosion ranging between 10 and 30 mm/1000 yrs over the past 10.8 m.y. (Marchand, 1971). Removal of well-decayed quartz monzonite and granodiorite from beneath basalt dated at 8.9 ± 0.9 m.y. in the Lucerne Valley area of the western Mojave Desert (Oberlander, 1972) provides a maximum erosion rate of approximately 8 mm/1000 yrs.

Adherence to the belief that the Mojave pediments are a product of backwearing of boulder-clad slopes under the existing morphogenetic regime (for example, Warnke, 1969) requires one to find some means of reconciling the denudation rate thereby required with the preceding evidence of slow contemporary modification of exposed bedrock surfaces. Unless the length of the arid period has been underestimated by an order of magnitude, it must be admitted that the Mojave pediments are not primarily a product of arid morphogenesis.

THE TERTIARY LANDSCAPE

Although Quaternary erosion clearly has produced the existing topography in terranes composed of less consolidated materials, both direct and indirect evidence suggests that the granitic pediments of the Mojave region are indeed relict forms inherited from prior non-desert landscapes. Such landscapes were still in existence in the present desert region some 8 to 10 m.y. ago. Their remnants, locally affected by both vertical and horizontal tectonic displacements, are widely distributed in the Mojave Desert and can be recognized through their distinctive weathering profiles, which are preserved under basaltic lavas having radiometric ages in excess of 8 m.y. Details relating to key sites, the nature of the ancient weathering profiles, and their significance in the development of existing boulder slopes, have been published previously (Oberlander, 1972). The picture that can be assembled from investigation of all accessible sub-volcanic exposures in the Mojave Desert west of Baker and south of Barstow is one of a strongly weathered landscape blanketed by an occasionally brick-red (5YR 4/4 to 2.5YR 3/6-4/6) argillaceous soil locally containing either dense clay pans or massive calcrete crusts (these also rubified and thus easily distinguished from Pleistocene developments).

This ancient landscape included both cut and fill surfaces of considerable extent, surmounted by steep-sided hills that appear to have maintained a soil cover. The steep phase of the soil is preserved in a few sub-volcanic exposures, and its former existence is suggested indirectly by the convexo-concave nature of certain existing boulder slopes, as well as by projection of truncated soil remnants preserved on pediments (Oberlander, 1972). Stone layers in the basal soil and local discontinuities between the soil mantle and subjacent friable rock suggest that movement of a colluvial mantle was characteristic of some hillslopes. Maintenance of a soil cover on moderate to steep slopes implies a complete cover of vegetation of non-desert composition and type and tends to support Axelrod's conclusions regarding the Miocene and Pliocene flora of the region. Parallel rectilinear slope recession appears to have been characteristic, predicated upon the existence of a mantle of saprolite overlying an active subsurface weathering front along which chemical alteration of the subsurface rock kept pace with surface erosion. Preserved sub-volcanic exposures indicate that exposed bedrock was friable and easily planed by surface wash. There are no exposures of Tertiary basalt in contact with sound granitic rock.

In the Mojave region early Pliocene hillslope weathering profiles in quartz monzonite and granodiorite varied in depth between 6 and 14 m (20 to 40 ft), with rock decay occasionally extending to depths in excess of 30 m (100 ft) in piedmont areas. The subsurface weathering front in granitic rock varied greatly in position and character as a consequence of local structural and petrographic characteristis. In many localities there is clear stratigraphic continuity between the boulders littering present day hillslopes and corestone horizons in the basal portions of weathering profiles covered by volcanics having K-Ar ages exceeding 8 m.y. Wherever datable materials and *in situ* boulders have been seen together the boulders can be shown to have been derived from an early Pliocene regolith (Oberlander, 1972, figs. 11, 12, 13). The associated landscapes are often close to existing base levels and are unusual only by the presence of a few thin basaltic remnants. Thus I believe that the existing boulder mantles characteristic of granitic hillslopes in the Mojave Desert may consist, in general, of former corestones originating within pre-Quaternary weathering profiles. These have been exposed by Quaternary stripping of the Tertiary weathered mantle. Cessation of subsurface decay and acceleration of surface erosion during the late Pliocene and Quaternary is presumed to be the consequence of the establishment of negative moisture balances and deterioration of the vegetative cover during Pliocene and Pleistocene time. These changes have been documented by Axelrod's analysis of the pollen record since Miocene time (Axelrod, 1958). The general climatic desiccation of this period seems largely attributable to tectonism producing rain shadow conditions east of the rising Western Cordillera, particularly the Sierra Nevada, and the Transverse and Peninsular ranges of southern California.

TERTIARY PEDIMENTS

Saprolite-covered pediments were an integral part of the Tertiary landscape. Certain existing pediments still carry remnants of Tertiary weathering profiles preserved under remnants of lava flows that have survived the general denudation of the past few million years. Such examples clearly indicate that existing pediments in the Mojave region were already fully developed at least 8 m.y. ago and have been modified subsequently only by removal of soil and decayed rock inherited from the Tertiary morphogenetic regime.

In this regard the nature of the somewhat misleading parallel to the well-investigated history of Australian arid landscapes should be made clear. In both the Australian and southern Californian deserts stripping of an inherited Tertiary weathered mantle followed late Quaternary climatic desiccation. The absence of strong tectonism in interior Australia indicates that the stripping process there was primarily a consequence of climatic change and its effect on the vegetative cover (Mabbutt, 1965). In the Mojave region pediments have downslope profiles exposing bedrock to a distance of a kilometer or more beyond hillfronts, with Tertiary volcanics preserved on the pediments themselves. On the contrary, the Australian pediments seem to be secondary features formed subsequent to the onset of aridity, being a consequence of Quaternary subsoil notching of structurally determined hill bases inherited from the Tertiary landscape (Mabbutt, 1965, 1966). Similar notching has likewise affected the bases of bedrock eminences in the Mojave Desert but is a very superficial feature, amounting to a few meters at most. Pedalogical and stratigraphic evidence suggests that the Mojave climate has been more arid than that of interior Australia since early Tertiary time. There was no laterite or silcrete formation in the Mojave region prior to the onset of full desert conditions, and the existing climate and vegetation continue to be of a somewhat more xeric nature than their counterparts in the Australian deserts. Thus complete parallelism in the development of the two regions should not be anticipated. However, Mabbutt's clear demonstration that the Australian interior has been stripped of an inherited mantle as a consequence of climatic change, without assistance from tectonism, is of the utmost importance to an understanding of the existing Mojave Desert landscape.

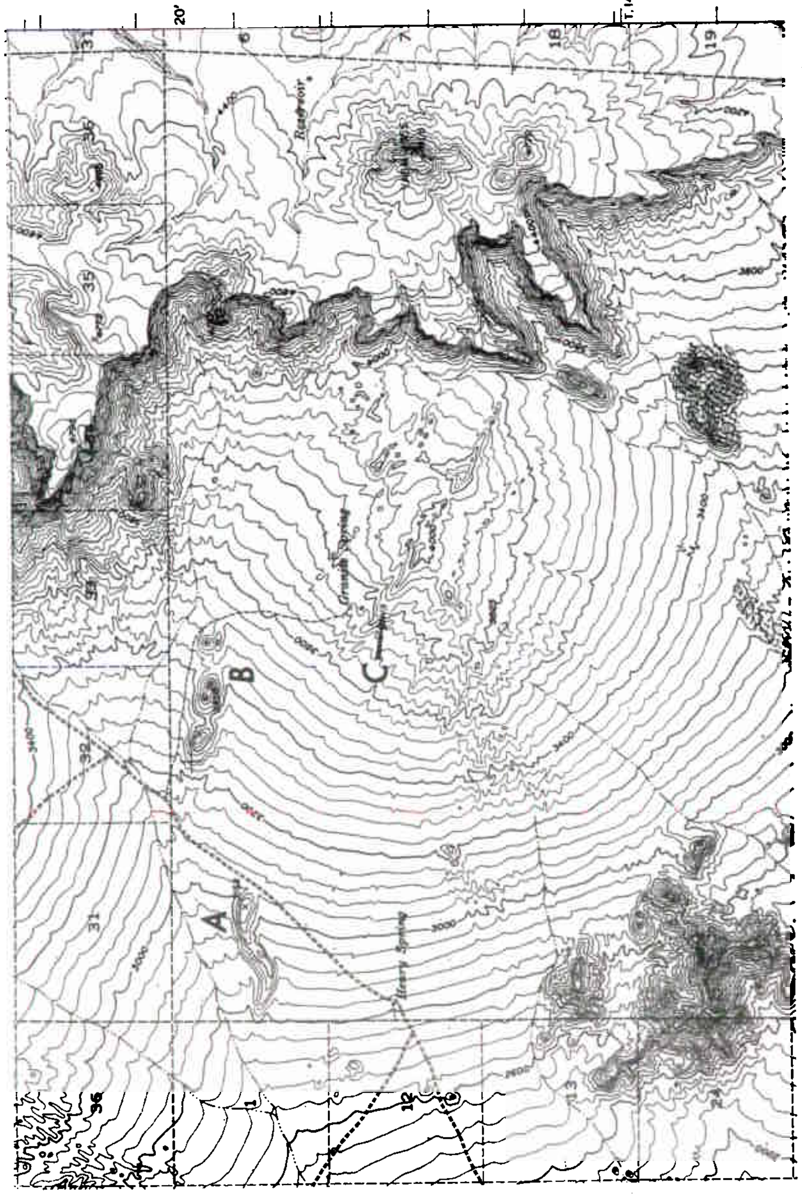


Fig. 2. Granite Springs pediment, east of Baker, Calif. (Halloran Spring 15-min quadrangle). Numbered sections cover 2.56 km² (1 sq mile). Escarpment to east is composed of flood basalts of probably Pliocene age, covering decayed quartz monzonite. At locations A, B, and C, Tertiary quartz monzonite weathering profiles are preserved under remnants of basalt dated at 9.2 m.y. Bedrock is exposed west of the pediment apex to approximately the 792 m (2600 ft) contour, a distance of some 5.6 km (3.5 miles).

An instructive example of Mojave pediment characteristics may be seen 24 km (15 miles) east of Baker at Granite Spring (Halloran Spring 15-min quadrangle). At this locality remnants of basalt having a K-Ar age of 9.2 ± 0.6 m.y. indicate that Pliocene lavas flooded westward across the higher portion of a classically-formed pediment and onto its lower slopes (fig. 2, pl. 1). Radiometric ages of basalts from the summit and base of the bedrock pediment, spanning a distance of 3.2 km (2 miles), vary by only 1 percent, suggesting that the samples were taken from remnants of a formerly continuous single sheet, as would be concluded from the field relations. Even if the remnants are from different flows, they define one subvolcanic surface. Thus the Granite Spring pediment is more than 8 m.y. old and has been modified during late Pliocene and Quaternary time only by the stripping of the Tertiary weathering profile seen beneath the remaining basaltic fragments. As could be anticipated in the case of an erosion surface produced by backwearing, weathering below the sub-volcanic Tertiary surface was significantly deeper toward the distal portions of the pediment. Subsequent erosion, stripping off the lava and underlying Tertiary saprolite, has left basalt-capped mesas standing 70 m (200 ft) above the denuded pediment at the 1040 m (3400 ft) level, whereas those near the summit, 120 to 180 m (400 to 600 ft) higher, rise much less conspicuously 30 m (100 ft) or less above the surrounding topography. The height of such mesas, excluding the thickness of the lava, approximates the local depth of weathering in the Tertiary landscape, reflecting the fact that arid Quaternary denudation has selectively affected previously decayed rock and has been ineffective in the sound rock exposed at the ancient weathering front. It is tempting to suppose that the steepening of pediment gradient resulting from erosional stripping in this instance may have been a general tendency during the transition to desert conditions at the close of the Tertiary. Such an interpretation would be based on the normal inverse relationship between surface slope and surface water discharge. In actuality, any such steepening more probably is diagnostic of the depth profile of the erodible weathered mantle inherited from the prior morphogenetic system — the latest phase of removal terminating against the more resistant surface of the former weathering front.

As the bases of 8 to 10 m.y. old lava caps in various widely separated localities in the Mojave region repeatedly stand 20 to 45 m (70 to 150 ft) above adjacent solid and continuous granitic outcrops, the average depth of pre-Quaternary weathering on the larger granitic pediments appears to have fallen within this range.

STRIPPING OF PEDIMENTS VERSUS PEDIMENT "EXHUMATION"

During the late Pliocene and Quaternary, pediments and residuals alike have been largely denuded of their former regolith mantle. The consequence in the case of hillslopes has been to leave them clad with boulders: some let down as a lag of corestones, others delineating the joint-controlled pre-Quaternary basal surface of weathering (Oberlander,

PLATE 1

Summit of Granite Springs pediment and basalt remnants viewed from north. Relief on pediment provided by resistance of northwest-trending dikes. Small intrusive neck of basalt centered in gap between basalt caps in middle distance. Behind this is the highest remnant of flow basalt (C in fig. 2).

1972). In the case of pediments, stripping, presumably as a consequence of deteriorating vegetative cover associated with climatic desiccation, has led to wholesale exposure of the Tertiary weathering front, which has been interpreted by several prior observers as "exhumation" of a rock-cut suballuvial bench (for example, Tuan, 1959; Cooke, 1970, p. 36-37). Examination of relict weathering profiles indicates that the granitic pediments of the Mojave were not cut in rock but were extended by erosion of regolith that was constantly being renewed at the weathering front, as proposed by Ruxton and Berry (1961) in their model of slope retreat based on observation of Sudanese landscapes. According to this reconstruction, the Mojave pediments were not formed as suballuvial benches in a desert environment in the manner first proposed by Lawson (1915) but developed as either wash-graded or maturely-dissected footslopes fronting escarpments retreating under semiarid conditions. Export of detritus to a few distant tectonic depressions appears to have been characteristic during pedimentation. These depressions originated by subsidence during post-Eocene tectonic dislocations, trapping fluvial and lacustrine sediments that formerly had been carried to the sea (Dibblee, 1967). The present local endoreic hydrography with rising base levels and the encroachment of alluvial embankments onto the pediments themselves seems to be a subsequent development resulting from late Pliocene and Quaternary desiccation.

The Quaternary alluvium presently veneering pediments in the Mojave Desert may consist predominantly of translocated weathering products inherited from the pre-Quaternary landscape. After the strongly oxidized and occasionally duricrusted surface horizons of the Tertiary soil were removed from pediments and associated uplands, a much greater thickness of erodible decomposed quartz monzonite was bared. Seen without the distinctive surface soil this material would not be (and has not been) recognized as the C-horizon of a formerly more extensive weathering profile. This inherited preweathered material is continuing to be eroded today, both on pediments and residual relief, and is the source of modern alluvial accumulations.

The present alluvial veneer over pediments is in contact with the bases of most sizable mountainous masses due to continuing sediment arrivals from large catchments or long slopes above, where large quantities of preweathered material persist. However, where pediments are crowned by very small residuals, the alluvial edge is well separated from the summit relief forms, which uniformly consist of naked rock which supplies far less detritus than existing transportational processes are competent to remove from the slope foot (pl. 3, p. 863). Bedrock exposures below the piedmont angle in such instances are expanding, but after a complex evolution apparently involving (1) the general stripping of the upper portion of the former weathering profile; (2) transport of debris continuing to issue from the higher residual relief, in which erosion has exploited deeply decayed partitions to vastly increase the mesorelief; and (3) stripping to solid rock at the former weathering front as a consequence of diminution of sediment deliveries from increasingly denuded tributary slopes. The processes that have resulted in the present degree of bedrock exposure cannot be envisaged as simple and uni-directional in time, as such a landscape would be a delicate indicator of the many climatic fluctuations that have affected the southwestern United States over the past several million years.

Trimming of projecting bedrock irregularities on bedrock pediment surfaces continues to occur subaerially, but such projections have themselves been exposed by stripping of preweathered material, and the total amount of backwearing produced by surficial exsudation and flushing (mostly in the form of basal undercutting) seems nowhere more than 4 or 5 m — half this amount being more characteristic. This seems essentially the full extent of erosional modification of solid granitic outcrops under the present morphogenetic system. Even this doubtless includes removal of some material preweathered along the Tertiary basal surface of rock decay.

As existing "stripped" pediments vary in configuration from planar expanses of massive rock to bouldery chaoses, it is not clear whether the Tertiary pediments were smooth surfaces — "graded" for transport of sediment arriving from the steeper relief above them — or were "born dissected" as proposed by Gilluly (1937) and Sharp (1940). If the first is true, pediment stripping may have been accelerated by erosional stagnation in the higher standing relief as a consequence of near-complete loss of its own much thinner regolith. Even if pediments are "born dissected", as seems likely, decrease in sediment arrivals from divide regions as a consequence of either diminishing relief or regolith stripping on steep slopes would trigger incision of washes, leading to eventual exposure of solid rock at the former weathering front. In either case the change would be very gradual, involving slow adjustment of pediment wash profiles to existing sediment-discharge relationships and modes of water and sediment transport.

THE PIEDMONT ANGLE

Where the slopes of pediments and inselbergs are regarded as a consequence of the bimodal size distribution of granitic weathering products, the sharpness of the piedmont angle between the pediment and surmounting residual relief is generally emphasized. The reality of this sharp slope break cannot be disputed where boulder slopes terminate downward against surfaces of sandy alluvium, as is commonly the case; it is also well defined at the base of domed inselbergs that rise abruptly above well planed crystalline rock. In the Tertiary landscape, however, sharply defined piedmont angles appear not to have been present, for all surfaces seem to have been mantled by saprolite, with no contrast in the size of particles on retreating hillslopes and expanding peripheral surfaces.

Where bedrock is exposed continuously from hillslope to piedmont in the present landscape, a sharp piedmont angle may or may not be present. Where the pediment is itself free of detritus at the piedmont angle the nature of the latter varies according to the character of the associated hillslope, which may be composed of solid rock or loose boulders. The best developed piedmont angles appear where the smaller detached boulders first exposed on hillslopes in the stripping process have disintegrated, exposing smooth dome-like forms or well-jointed steep-sided masses rising from exposed solid bedrock pediments. The associated pediments have likewise been severely denuded, as seen in the absence of boulders and tors and the continuous flat expanses of sound rock in which only the master joint sets are open (usually in one dominant direction), with the subsidiary joints being tightly compressed. The sharp piedmont angles defining granitic domes are frequently situated on open joints, but they also cut across joints perpendicularly. In such instances complete disintegration of former boulder mantles has been followed by basal weathering at the ground surface, a true desert phenomenon that girdles the inselberg, creating an abrupt piedmont angle unrelated to joint configuration. Basal undercutting amounting to 3 to 4 m in some cases creates a very sharp piedmont angle by a process having nothing to do with the original backwearing that produced the pediment itself.

Where the Tertiary weathering profiles were unusually deep as a consequence of high macro-porosity due to dense jointing, the stripping process has left slopes mantled with a residuum of loose boulders (former corestones) of relatively small size (0.5 to 1 m diam). The hills north of Yucca Valley are an accessible example. Beneath this rubble the subjacent rock is decayed to a depth of several meters. The profiles of such slopes reflect the original surface slope, which in the Tertiary landscape appears to have been smoothly concave from hillslope to pediment. The piedmont angle remains poorly developed in such settings, as the boulder slope is transitional into the pediment over a broad concavity. There is no possibility of basal weathering in such circumstances as there are no solid outcrops to be notched.

LOCALIZATION OF THE PIEDMONT ANGLE

All the foregoing is predicated upon evidence that backwearing has indeed occurred, and that the plan and position of the positive relief forms — hill fronts, escarpments, domes, and tors — are not fully predetermined by structural characteristics. Whereas backwearing of slopes in semiarid and arid regions has been accepted by most American geomorphologists (Hadley, 1967), observers of arid landscapes in some other parts of the world have stressed almost total structural control of the morphology and position of both major and minor relief elements, including the piedmont angle (for example, Twidale, 1967). According to the latter view, parallel rectilinear slope recession occurs only where a relatively resistant caprock is being undercut by the more rapid erosion of its substrate.

Well-known quantitative investigations by Schumm (1956, 1962) seem to refute this hypothesis. However, Schumm's analyses have concentrated upon manageable small scale landforms in essentially soil-free landscapes, from which extrapolation to larger forms and longer time scales may be hazardous. Likewise, Emmett's overland flow experiments (1970) seem to explain the mechanism of parallel retreat of soil-covered convexo-concave hillslopes, but his conclusions rest upon an extremely likely but as yet unproved deduction regarding the most probable balance of the hydrologic factors in overland flow. Ruxton and Berry (1961) have outlined a mechanism of slope backwearing that appears to be in complete harmony with the Mojave evidence; however, caution is advisable in any extrapolation from present Sudanese landscapes to those of the Tertiary in southern California. Thus, it does not appear that one can disregard the possibility of downwearing (as opposed to backwearing) of major relief forms, even under arid conditions.

In a landscape that is dominated by downward erosion, all piedmont angles separate areas of either unlike lithology or unlike joint density; both the position and the plan of relief forms are structurally predetermined; and existing pediments do not enlarge signficantly through time.

Opposing any such interpretation of the Mojave landforms are several facts that seem much more compatible with horizontally migrating piedmont angles between backwearing hillslopes and expanding pediments:

1. The landscape existing during the period of pediment formation in the Mojave region was veneered with a soil developed on granitic saprolite that appears to have blanketed hillslopes and pediments alike. This soil and its parent saprolite are preserved under basaltic remnants in a variety of locations and on slopes as steep as present boulder slopes in the region. Thus the eroding land surface and the joint controlled weathering front were well separated and independent of one another during the period of most active morphogenesis. Variations in effective joint density appear to have been insufficient to permit the agencies of transportation to be more effective quantitatively than those of downward rock decay even where abrupt positive relief forms are present today. Hillfronts seem to have retreated under conditions of denudational equilibrium (Ruxton and Berry, 1961; Ahnert, 1967) in which creation of erodible material by weathering below the surface is quantitatively equivalent to erosion of the surface. The Tertiary geomorphic system appears to have been "transport-limited", whereas the presently-existing system is "weathering-limited". How parallel rectilinear slope retreat can occur in a transport-limited system is considered at the conclusion of this paper.

2. A downslope transect through the weathering profile preserved under Tertiary basaltic remnants on the Granite Spring pediment (fig. 2; pl. 1) indicates that the depth of weathering was proportionate to distance from the pediment apex. This single instance is compatible with the backwearing hypothesis, since the time available for rock decay should increase outward from the apical region as the pediment extends headward at the base of a shrinking residual mass. Unfortunately, no other pediments in the Mojave region have been sufficiently engulfed by lavas to allow preservation of ancient weathering profiles over a significant distance along the pediment radius.

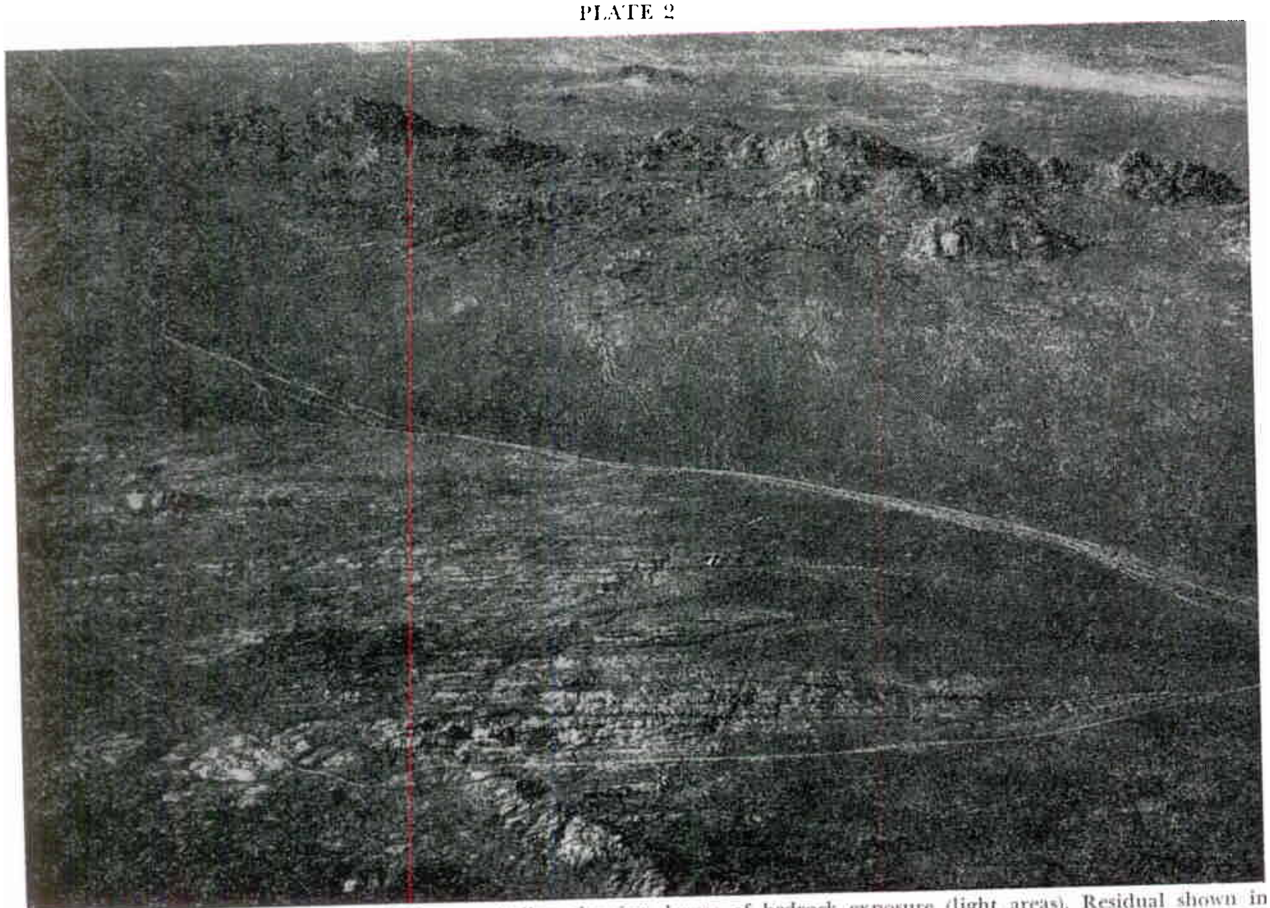
3. If downwearing under the control of joint density is altogether responsible for the epigene profiles of the desert, the ramp-like pediment form is difficult to explain. No one would suggest that the distance between joints increases regularly as the pediment rises. Thus one must assume that the pediment profile was, initially at least, a slope of transportation and not totally the consequence of structure. The downwearing hypothesis would require an enormous contrast in bedrock characteristics to allow steep-sided structurally controlled relief forms to abut against smooth slopes across which bedrock resistance has been entirely subjugated by decay and hydraulic erosion.

It is clear that in the granitic terranes of the Mojave Desert no such contrast in resistance exists between the pediment and surmounting residual masses. Indeed, this has been the essence of the pediment problem in the southwestern United States. Pediments in the Lucerne Valley district of the Mojave Desert expose sound quartz monzonite over expanses of tens to hundreds of hectares, often remaining free of either residuum or alluvium a km beyond the hillfront. Joint spacing above the piedmont angle and outward from it for hundreds of meters may be measured to the centimeter with a steel tape on the ground, and the overall pattern is clear and unambiguous in aerial view (pls. 2 and 3). In such a naked landscape one is often perplexed by the surprising *absence* of correspondence between structure and surface form. Where open vertical joints dominate the mesorelief, as in the Granite Mountains, narrow fins of rock in areas of close jointing may stand as high as thick monolithic slabs; likewise, the jointing seen on smooth pediments may extend into rough hill masses without discernible change in density or character (pl. 3). While the residual relief is compartmentalized by jointing, the piedmont angle not uncommonly runs transverse or oblique to the dominant joint set and may be localized on minor fractures whose adjacent counterparts produce little or no surface effect. Indeed, it was the anomalous relationship between visible jointing characteristics and slope plans and profiles that first suggested to the writer — independently of the direct evidence discovered later — that a blanket of residuum must have been present in some depth over the entirety of this landscape while its present relief was being established.

PEDIMENT MORPHOMETRY

Morphometric analyses of the characteristics of pediments and associated landscape elements have failed to produce evidence of the mode of origin or geomorphic function of the pediment landform (Mammerickx, 1964; Cooke, 1970; Cooke and Reeves, 1972). Cooke has adduced evidence for pediment exhumation, but the exhumation hypothesis fails to explain the origin of the erosion surface so revealed. Both Cooke and Mammerickx found that, among other enigmas, so fundamental a prop-

PLATE 2



Aerial view of pediments east of Lucerne Valley, showing degree of bedrock exposure (light areas). Residual shown in plate 3 is near center of left margin of photograph.

PLATE 3

View of residual on quartz monzonite pediment in Lucerne Valley north of San Bernardino range, showing nature of jointing on pediment and residual. Rather than localization of the residual by less dense jointing, there seems to be a higher density of visible joints in the residual, probably due to relaxation associated with off-loading.

erty as pediment slope correlates only weakly with "pediment length" (as usually defined) and shows little relation to rock type or particle size.

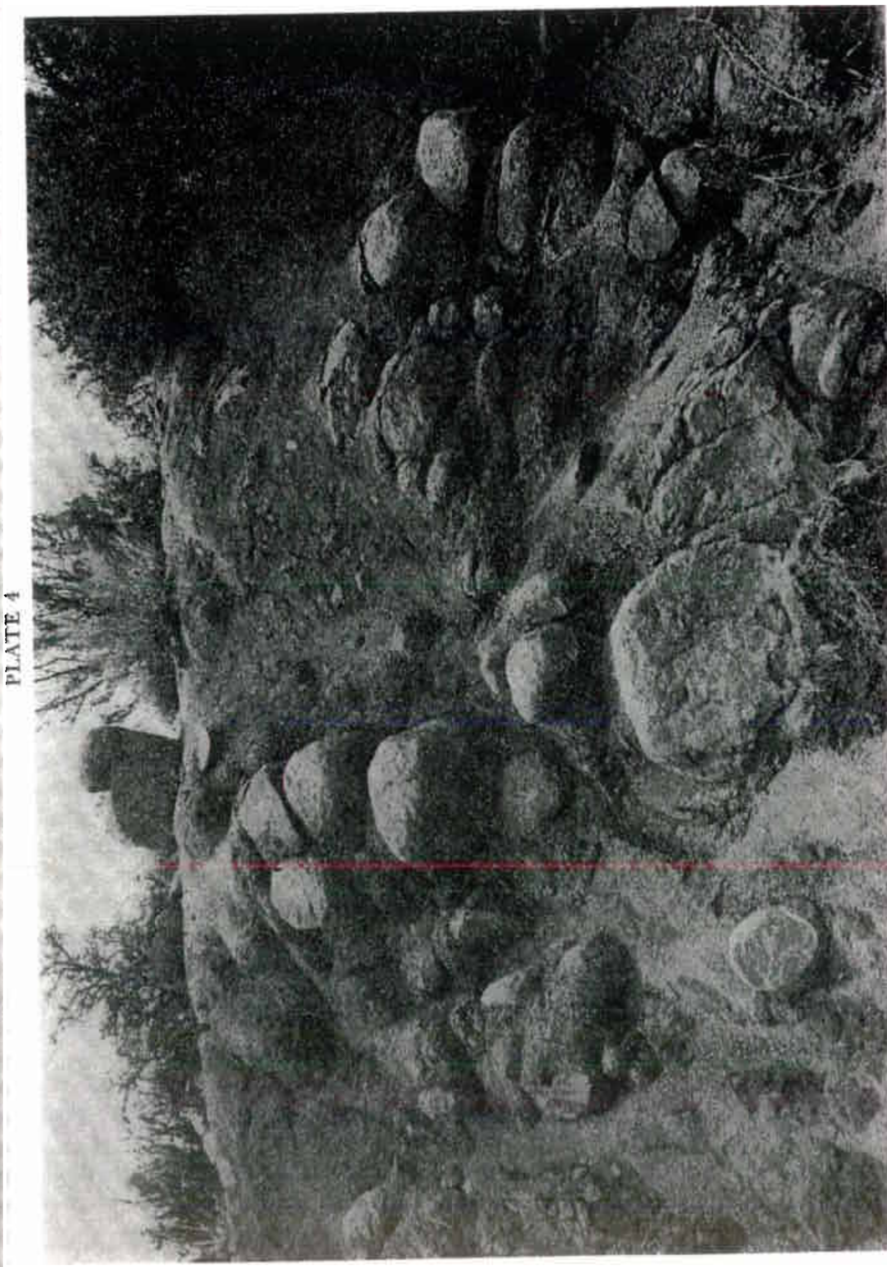
While agreeing with Cooke's criticism of past research on pediments, I feel that for two reasons morphometric analysis of the pediment landform — as it appears in the Mojave Desert — will not be able to provide more positive results than more traditional investigative approaches to the pediment problem. These reasons have to do with the nature of the information used in the morphometric analyses that have been carried out and the inapplicability of the technique to relict landscapes.

First, the fundamental property of "pediment length" has been defined as the exposure of bedrock between the upper edge of the alluvial apron and the mountain front (Tuan, 1959; Cooke, 1970); this is easily measured both in the field and on geological maps and aerial photographs but treats only the emerged portion of an iceberg-like phenomenon. The bulk of the erosion surface whose length and slope might be expected to be correlated inversely is presently hidden from view beneath the ubiquitous alluvial veneer and receives no consideration in the analysis. The stripping and/or exhumation that has exposed the pediment is a recent superficial development unrelated to the formation of the erosion surface itself. It has resulted from local imbalances between weathering and erosion perhaps contingent upon tectonism or the erosional condition of the sediment source (the upland). Recent migrations of the alluvial edge, characterized as "exhumation", bare an erosion surface produced at a different time by different processes. Thus "pediment length", defined as the recently exposed portion of a partially buried erosion surface, should have little bearing upon the pediment slope established much earlier by an altogether different mechanism.

The second disability of morphometric analysis in the Mojave Desert context proceeds from the facts presented in the present paper: the pediments of the Mojave region are relict from a prior morphogenetic system. Morphometric analysis of a landscape undergoing active pedimentation would doubtless yield positive results. But conventional morphometric analysis of a relict landscape that has been stripped to a fossil weathering front can at best reveal anomalies that indicate lack of adjustment between form and process in the landscape.

Existing bedrock pediment slopes appear to express the surface slopes in the Tertiary landscape minus the thickness of the former weathered mantle. Thus the longer pediment slopes might be significantly steepened by arid stripping owing to downslope increase in the depth of pre-Quaternary weathering, as in the Granite Spring example. As this effect would not be so marked on shorter pediments, whose mean gradients have been presumed to be relatively steep (Lawson, 1915; Cooke, 1970), pediment gradients might not differ significantly after stripping regardless of pediment length. Absence of good correlation between pediment length and pediment slope in the stripped landscape produces a geomorphic quandry and a tendency to introduce the possibility of tectonic disturbance. However, restoration of the pre-Quaternary

PLATE 4



Exposure of pedimented quartz monzonite east of Wilhoit, Ariz., showing nature of bedrock susceptible to pedimentation. Weathering to this degree prior to pedimentation is shown by boulder content of correlated alluvium.

slope gradients might well show that prior to stripping the relationship between pediment slope and pediment length actually was of the expected nature.

What morphometric analysis can do, and apparently has done in the case of pediment studies, is to indicate a lack of consistent relationships between elements of the existing landscape hitherto regarded as closely associated. Other types of evidence are then required to produce explanations for the unexpected discrepancies. In the present case we have the obverse of the nice morphometric relationships described by Denny (1967) in reference to alluvial fans and fluvial planation surfaces in several regions of the western United States, which could be interpreted as expressing steady-state development. In Denny's investigations the study of paleosols was intentionally disregarded. This seemed valid because the forms described truly appear to be products of the morphogenetic system in which they are presently seen, quite unlike the granitic pediments of the Mojave Desert.

EXISTING ANALOGUES TO TERTIARY PEDIMENTATION

The classic pediments cutting crystalline rocks in the desert Southwest of the United States continue to be treated by many geomorphologists as products of arid morphogenesis (for example, Hadley, 1967; Warnke, 1969; Cooke and Warren, 1973). However, investigators working elsewhere have identified pediments in a wide variety of climatic settings. Beyond the United States the pediment landform is widely recognized as an indicator of semiaridity rather than true desert conditions. This view appears to take cognizance of the efficiency of surface wash resulting from torrential rainfall that occurs seasonally on surfaces lacking a dense vegetative cover. So widely experienced an observer as Birot has suggested that the development of pediments on crystalline rock is most rapid in the warm and seasonally wet low-latitude thorn forests, with pediment formation in the less humid mid-latitude semiarid environment being much less effective (Birot, 1960).

Analogues to the conditions under which pedimentation seems to have occurred in the Mojave region in pre-Pliocene time appear to exist today in the southwestern United States. On the lee side of the San Gabriel and San Bernardino ranges, less than 1000 m above the nearby pediments of the western Mojave Desert, shrubland dominated by pinyon pine, oak, juniper, and chaparral species form a cover over steep slopes that maintain a veneer of granitic saprolite only occasionally interrupted by exposed corestones and tor-like outcrops. As these ranges have been elevated by Plio-Pleistocene movements, which continue today, they are bordered by alluvial fans rather than pediments, although the fans appear to cover range-front pediments in some cases. However, the upland topography includes numbers of surfaces of low relief that can easily be construed as pediments that are continuing to expand by the slow erosion of fine regolith on adjacent slopes. Similar surfaces veneered by reddish soils under a dense brush cover are conspicuous in Riverside County west of the San Jacinto Range and south of Hemet.

A clearer parallel to the Tertiary landscape of the Mojave region exists in the uplands of central Arizona. Weathering profiles and surface forms in granitic areas such as the Sierra Prieta, west of Prescott, seem to present a modern counterpart to the ancient Mojave landscape.

Throughout the Sierra Prieta, red weathering profiles derived from quartz monzonite abound with corestones in various stages of disengagement from surrounding rotted bedrock. Although these occasionally appear at the surface, the steeper slopes overlooking the western piedmont of the range, and rising from valleys within it, are essentially smooth, being cut across friable decomposed rock. A pediment borders the low western escarpment of the Sierra Prieta, exposing thoroughly decomposed quartz monzonite in a 2.5 km-wide band along the mountain front (fig. 3). Beyond this, rubified bouldery alluvium laps onto the pediment, thickening westward. A thin layer of colluvium similar in appearance to the bouldery alluvium is conspicuous on the lower slopes of several residuals that rise from the pediment just at the upper margin of the alluvial apron. Granitic bounders in both the colluvium and alluvium are strongly decayed and friable.

The western pediment of the Sierra Prieta emerges from beneath the onlapping older alluvium at an elevation of about 1500 m (5000 ft) near Wilhoit (Kirkland 15-min quadrangle), where it is easily accessible from Highway 89 (fig. 3). The transition from pediment to older alluvium is clearly evident in the texture of the surface material — coarse grus characterizing eroding pediment surfaces, in contrast to the argillaceous surface soil on the older alluvium. Exposed corestones are thinly scattered over the rolling surface of the pediment, but most slopes are smooth, being developed in saprolite veneered by a lag of coarse granules and vein fragments. The proportion of bare ground exposed on the pediment is no more than 30 to 35 percent, the present cover consisting of bunch grass, scrub oak, mountain mahogany (*Cercocarpus*), catclaw acacia (*A. gregii*), manzanita (*Arctostaphylus*), prickly pear (*Opuntia*), and other shrubby species. Appropriately, both the flora and the climatic regime of the Sierra Prieta, which receives year-around precipitation averaging well in excess of 500 mm (20 in.), closely corresponds to Axelrod's reconstruction of conditions in the western Mojave during Miocene time, when the Mojave pediments appear to have been expanding. The vegetation of the Sierra Prieta pediment and hillfront is sufficiently dense that paths must be consciously searched out, and backtracking is frequently necessary (pl. 5). Cattle trails and washes provide the best access. The composition and density of the vegetation has been affected to an unknown extent by grazing, and shrubby growth may be more characteristic at present than under former natural conditions. Open areas of bunch grass, in which no bare ground is exposed, are present on the older alluvium and may approximate the natural cover in the piedmont zone.

The overall slope of the bedrock pediment is about 4 degrees, but it is far from a plane surface. If pedimentation is indeed active here, as it seems to be, there can be no doubt that pediments in this area are "born

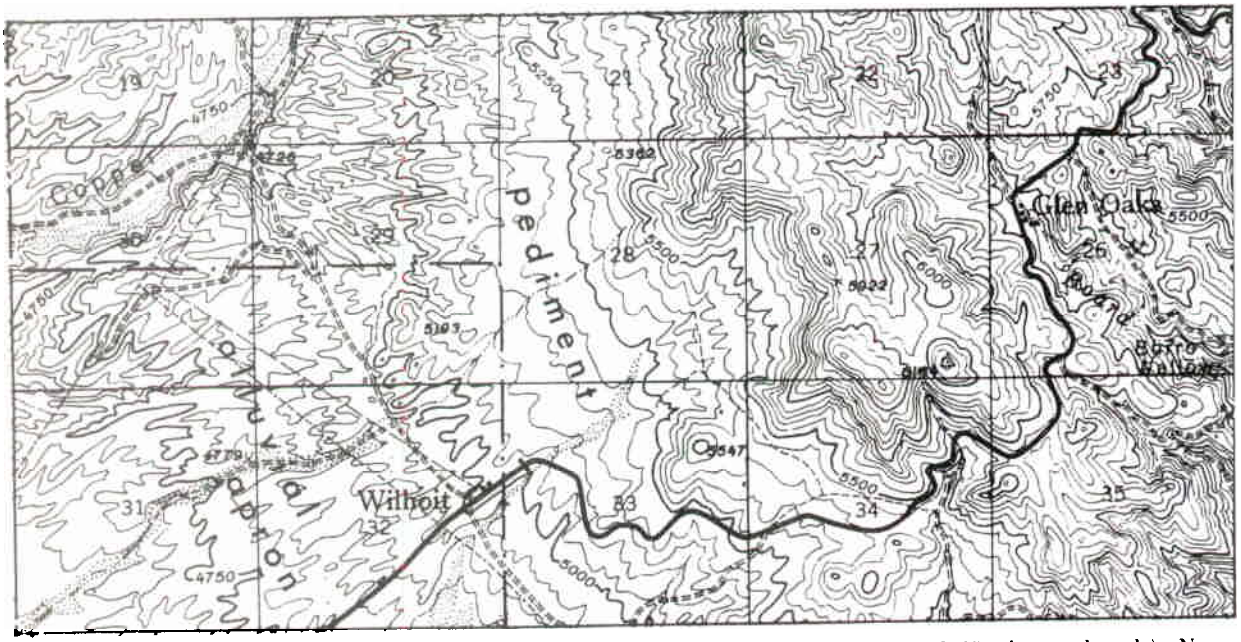
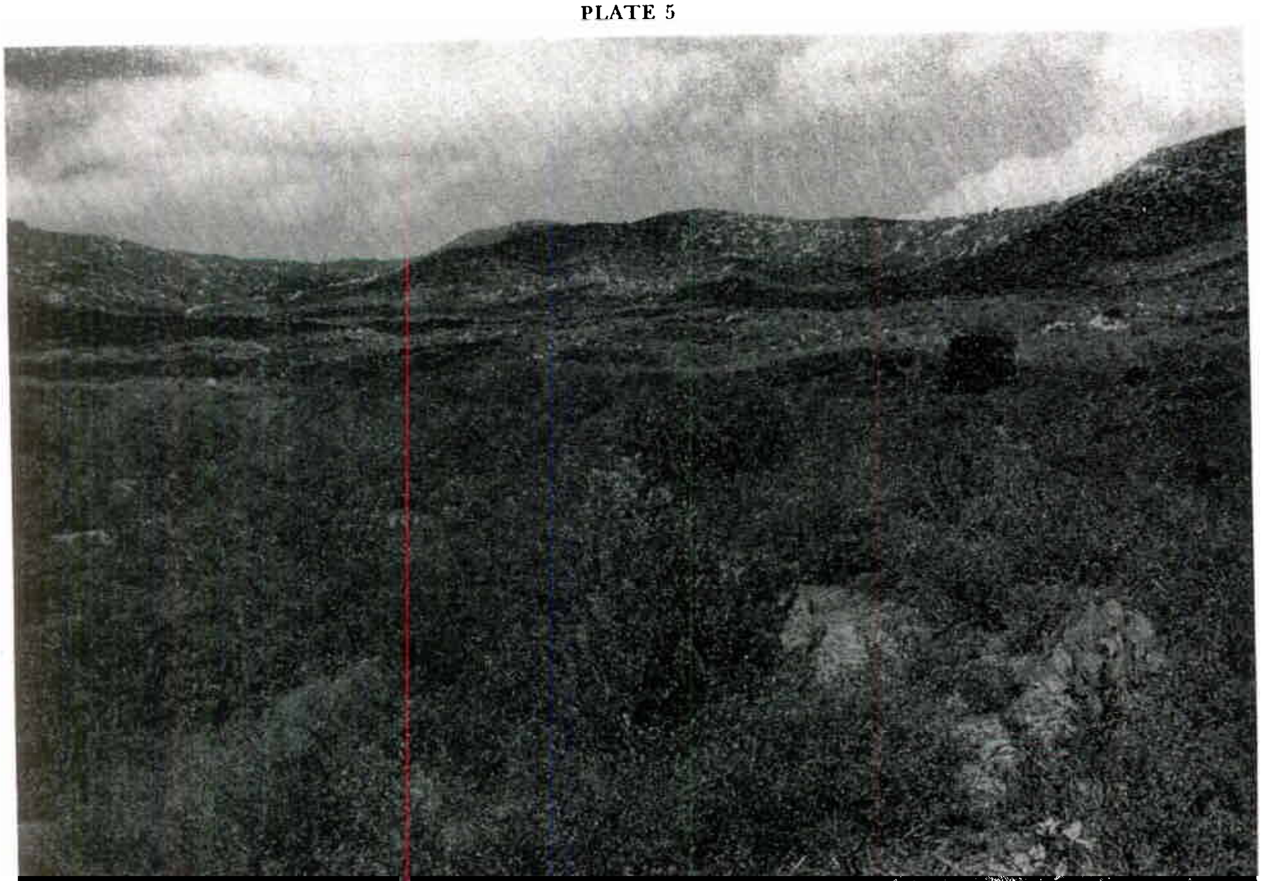


Fig. 3. Pediment along western front of Sierra Prieta, west of Prescott, Ariz. (Kirkland 15-min quadrangle). Numbered sections cover 2.56 km² (1 sq mile). Decomposed granite of the pediment is exposed continuously from the upland to Wilhoit, the upper edge of the alluvial apron to the west more or less coinciding with the 1524 m (5000 ft) contour.

PLATE 5



Sierra Prieta pediment, showing nature of relief and density of vegetative cover. Light areas on distant hillslopes are grass.

"dissected" and exemplify Ruxton and Berry's "dissected plinth", which borders actively retreating hillfronts in the dry savanna and wet semi-arid regions of the Sudan (Ruxton and Berry, 1961). The Wilhoit pediment merges with the low frontal escarpment of the Sierra Prieta by a sweeping concavity that is accurately portrayed by 50-ft (15.24 m) contours on the Kirkland 15-min quadrangle (fig. 3). As the contours indicate, dissection of the upper pediment is more severe than gullying on the frontal escarpment; nevertheless, the lines of erosion on the pediment do indent the slope of the mountain front. Here we apparently have an excellent example of a mountain front retreating, without change in declivity, in consequence of erosion of fine weathering products that are continually renewed by subsurface rock decomposition. The products of slope erosion are evacuated through a network of washes that dissect the pediment, which is a multi-convex surface that is itself lowered uniformly as the mountain front recedes. While it is tempting to imagine the eroding scarp/dissected pediment/alluvial apron association migrating relentlessly eastward without change in either form or elevation, the cross-cutting relationships between the older (rubified and dissected) and younger alluvial deposits signify breaks in the continuity of erosion and deposition in the piedmont zone. It could be expected that in an area currently receiving 500 mm of precipitation, pre-Quaternary and Pleistocene climatic fluctuations – and resultant periodic changes in vegetative cover and runoff — would have marked effects on sediment deliveries and hydraulic gradients. Detailed investigation of this locality, as of most others, would almost certainly indicate complexities in Quaternary erosional history. What the Sierra Prieta piedmont does seem to illustrate, however, is an observable case of parallel rectilinear backwearing of soil-covered slopes developed on saprolite containing detached corestones. The presence of thoroughly decayed spheroidal boulders (originally corestones) in the older alluvium of the piedmont zone clearly indicates that the deep weathering noted on eroding surfaces did not post-date pedimentation but was, in fact, critical to it.

This instance reinforces the evidence from Tertiary weathering profiles in the Mojave Desert indicating that pediment development in crystalline rock is predicated upon the existence of a saprolite that can be eroded by surface wash but at no greater rate than its renewal by subsurface weathering.

SLOPE RETREAT IN THE TERTIARY LANDSCAPE

The problem of how parallel rectilinear slope retreat can proceed in a convexo-concave soil covered landscape may not be as difficult as once supposed (for example, King, 1967, p. 157). Schumm (1962, 1966) has demonstrated that backwearing at a constant angle requires only that there be no accumulation of debris at the slope foot. His quantitative investigations in the Badlands of South Dakota indicate how this condition is achieved in the case of the miniature pediments of that area, where decrease in roughness from hillslope to pediment result in water flows on the pediment having velocities as high or higher than those on the hillslope. Schumm (1956) had previously established that the process of creep tends to anchor the slope foot, causing the slope angle to diminish with time. Schumm's field measurements thus indicated that where surface wash was the principal mode of sediment transport, slopes retreated parallel to themselves, whereas removal by gravitational transfer caused slope flattening. More recently, controlled experiments on slope development by Emmett (1970) have suggested that the normal transition from laminar to mixed to turbulent overland flow on hillslopes produces parallel retreat of soil-covered slopes that are convex at the summit, straight in the middle portion, and concave at the base. It seems significant that convexo-concave slopes are characteristic in the Sierra Prieta and in those localities within the Mojave Desert where the boulder cover is best preserved and slope profiles are least altered from their Tertiary configuration.

For continuous slope retreat in this manner, "denudational equilibrium" must prevail; that is, subsurface weathering penetration must provide erodible materials at a rate at least equal to removal by surface wash. Ruxton and Berry (1961) have presented evidence suggesting how this requirement is met in Sudanese landscapes. They place emphasis on the particularly aggressive nature of subsurface moisture on soil-covered hillslopes. As subsurface water migrates downslope it is replenished more rapidly than on level surfaces, making it more reactive with the bedrock at the weathering front. A parallel with the well-known effects of solvent motion on limestone solution seems obvious. Thus decay of subsurface rock on hillslopes is rapid — providing a continuous supply of erodible material — but is not intense (mature weathering products not having time to form prior to erosional removal). Ruxton and Berry's conclusions are based upon tangible evidence of the presence of strong subsurface flow and removal of both solid and dissolved material on both hillslopes and pediments (Ruxton, 1958; Ruxton and Berry, 1961). The same evidence, mainly in the form of lateral eluviation of fines, can be seen in many parts of the Mojave Desert where alluvium is present or a weathered mantle persists.

The possibility of parallel retreat of soil-covered slopes having been demonstrated by several types of evidence, it remains a question whether those of the Tertiary Mojave region would lend themselves to this mode of development. On the basis of facts presently available the crucial factor appears to be the relative importance of creep versus overland flow in the erosional process. This would appear to be controlled by both the surface and mass permeability of the quartz monzonite weathering profile. High surface permeability discourages overland flow and favors the creep process (Schumm, 1956). However, creep may be less active on materials of high mass permeability than on materials with a shallow permeable layer, where a sharp weathering front or discrete lubricated zone is present, or where volume changes are localized, producing a well defined horizon or zone of shear. It is an obvious temptation at this point to emphasize the high mass permeability of quartz monzonite residuum. Obvious colluvial movement in the Tertiary Mojave weathering profiles has, in fact, been discovered only in instances in which there *was* an abrupt transition to altered but coherent rock less than a meter below the surface. The vast majority of exposures of Tertiary surfaces investigated closely resemble those of the Sierra Prieta, which has almost everywhere been eroded by surface wash. In both instances, weathering profiles characteristically are gradational into solid rock through a zone of corestones in a saprolite or grus matrix overlying a highly irregular joint controlled weathering front.

CONCLUSION

The contemporary landscape in such areas as the Sierra Prieta, as well as observations by Ruxton and Berry, Schumm, and Emmett, seem to demonstrate that parallel rectilinear slope recession can and does proceed in saprolite-mantled terranes like those that characterized the Mojave region during the Tertiary. This type of development accounts for the pediment landscape of the present, which we see stripped of a former weathered mantle. This stripping presumably occurred as a consequence of Pliocene climatic change that produced greater surface exposure due to impoverishment of the vegetative cover. Stripping of hillslopes to solid rock at the former weathering front has terminated pediment expansion by arresting the retreat of slopes, which are essentially stagnant under present conditions. It seems ironic that the problem of pediment formation in the North American deserts may be, in the last analysis, the problem of slope retreat in a soil-covered landscape.

ACKNOWLEDGMENTS

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