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MORPHOGENESIS OF GRANITIC BOULDER SLOPES IN THE MOJAVE DESERT, CALIFORNIA[1]

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ABSTRACT

Examination of quartz monzonite residuals in the western Mojave Desert indicates that current weathering of exposed granitic rocks is not renewing the boulder mantles characteristic of this region. Boulder mantles are presently disintegrating to expose massive outcrops that change thereafter only by the detachment of exfoliation shells. The existing boulders were originally isolated as corestones by subsurface chemical weathering and have been exposed by the stripping of a thick weathered mantle formed during pre-Quaternary periods of greater moisture availability. North of the San Bernardino Mountains deep-weathering profiles characterized by brick red surface horizons, rubefied calcrete crusts, and the presence of corestones in a grus matrix are widely encountered beneath basaltic remnants having radiometric ages in excess of 8 m.y. Continuity between these relict weathering profiles and present boulder mantles establishes the boulders as inherited features. The gradual onset of aridity during the later Tertiary terminated subsurface weathering and accelerated surface erosion, bringing about the massive exposure of Tertiary corestones and the joint-controlled Tertiary "weathering front." Slope retreat and pedimentation occurred here in the absence of a soil cover; thus the extensive granitic pediments of the region are also relict forms inherited from the Tertiary landscape.

INTRODUCTION

Throughout the deserts of the southwestern United States, hillslopes developed in granitic rocks have a distinctive appearance proceeding from their characteristic armor of naked boulders, which, together with more massive rock slabs, ribs, and domes, give rise to landscapes unlike those associated with any other geological terrain. Since the pioneer essays of Lawson (1915) and Bryan (1923, 1925) concerning granitic landforms in the southwestern United States, American physiographers have not dissented from the view that boulders mantling granitic slopes are products of continuing near-surface weathering effects in well-jointed rock (Davis 1938; Gilluly 1946; Melton 1965*b*). Under the present float of more or less spheroidal boulders, a second crop is assumed to be in formation through a concentration of chemical weathering at joint intersections, which tends to round the apices of originally plane-faced blocks. Bryan (1925, p. 85–86) described the process as follows: "As the bedrock of the mountain slope disintegrates, and the rain washes away the finer fragments, protuberances of the bedrock are left that consist of the most compact rock between the most widely spaced joints. The protuberances are cut loose from the bedrock by the same process that formed them, and a new crop of boulders comes into existence. By these slow but continuous processes the mountain front recedes, maintaining its angle of slope according to the spacing of joints and the granular structure of the granite."

Davis (1938, p. 1360–1361) shifted the

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emphasis to the subsurface, stating that "inasmuch as a supply of subsoil boulders is always ready to be laid bare," the retreat of granitic mountain faces is at the rate of inward penetration of subsurface chemical decomposition. He noted that "the boulders which now conspicuously cover the faces of desert granitic mountains are homologus [*sic*] with the invisible boulders of similar mountains in humid regions, although these are covered with a forested soil, as I have elsewhere shown."

According to either of these views the general character of granitic inselberg surfaces in desert settings could not be expected to change through time; boulder-clad slopes are retreating, and retreating slopes remain boulder clad. Likewise, the processes currently observable are assumed to account for all the forms seen.

More recently, Melton (1965*a*, 1965*b*) has suggested that boulder production has been accelerated periodically by the mechanical effects of lowered temperature, concluding that exceptionally coarse alluvial deposits in southern Arizona, and possibly also the boulders still mantling granitic slopes, are a consequence of intensified freeze and thaw cycles during the Pleistocene. This climatic hypothesis has not been accepted without argument (Lustig 1966). Simultaneously, however, Melton (1965*b*, p. 720) supports the conclusion of Bryan that boulders are continuing to be produced by the weathering of well-jointed rock. In a remark that could easily be overlooked, Melton makes the important observation that some of the weathering he noted was probably relict from an undetermined age.

Meanwhile, investigators of certain Old World and Southern Hemisphere deserts have identified boulders, tors, and massive outcrops in these regions as relict features inherited from antecedent morphogenetic regimes. The boulders are regarded as former corestones isolated in the subsurface by chemical weathering along joint planes and exposed at the surface as a consequence of climatic desiccation and stripping of a weathered mantle formed under prior humid conditions. Examples have been identified in the central Saharan highlands (Dresch 1959), and the outstanding analyses of Australian desert landscapes by Mabbutt (1961, 1965) are predicated upon this view.

My own observations of the granitic terranes of the Mojave Desert of California likewise suggest that the present character of slopes in the latter area is not a consequence of continuous arid morphogenesis, as is ordinarily supposed (e.g., Warnke 1969). In this region, as in the central Sahara and the Australian deserts, a variety of evidence indicates recent erosional stripping of a weathered mantle, and further discloses that the ubiquitous boulder cloaks are but a transitional form in an evolutionary development triggered by regional climatic changes initiated in the late Tertiary. The familiar landform types of the present Mojave Desert are thus viewed as both new and ephemeral, bearing little resemblance to the forms of a few million years ago but predicated upon the development of those forms, and at the same time displaying a residual disequilibrium with the existing climatic regime.

Accordingly, points to be discussed include the derivation of boulders from solid outcrops and deep weathering profiles, the fossil nature of deep-weathering profiles in the Mojave Desert, and the significance of prior weathering and landscape development in the evolution of the contemporary landscape of this region.

CHARACTERISTICS OF THE STUDY AREA

The evidence for this interpretation of the geomorphic history of the Mojave Desert has been gathered in the course of studies pursued intermittently over several years in that portion of the desert marginal to the San Bernardino and Little San Bernardino Mountains between Victorville and Dale Lake (fig. 1). Within this district the areas of Lucerne and Johnson Valleys and Joshua Tree National Monument have received closest attention.

Lucerne Valley and neighboring Johnson Valley lie in the rain shadow of the 10,000-

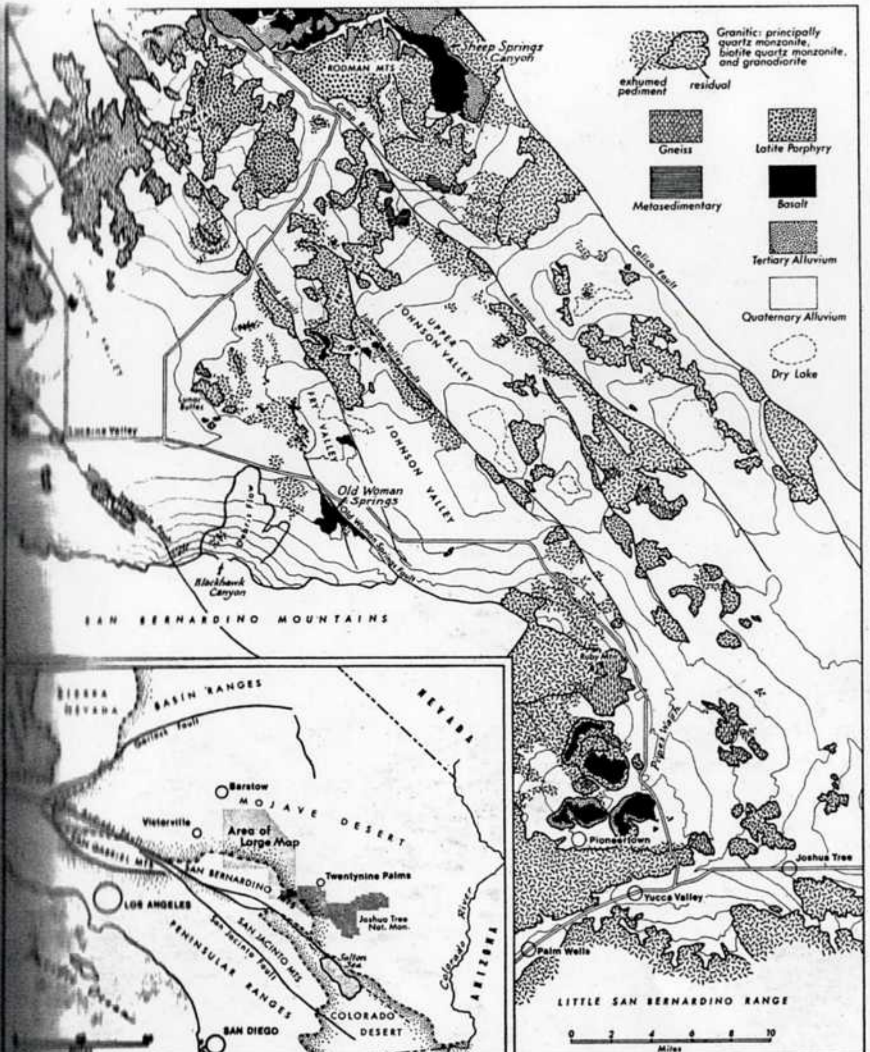

FIG. 1.—Location and general geologic map. Contours are drawn on quaternary alluvium at 200-foot intervals. Absence of bold line around outcrops indicates no topographic break.

San Bernardino Mountains, while Joshua Tree National Monument is located east of the Salton Depression and includes portions of the Little San Bernardino Mountains. Both areas receive less than four inches of precipitation annually, with a strong winter maximum. Creosote bush (*Larrea divericata*) is dominant on alluvial aprons and pediments, with *Yucca schidigera* and Joshua trees (*Y. brevifolia*) encountered above 3,000 feet. All drainage presently terminates in closed basins occupied by dry lake beds lying at elevations between 2,500 and 2,800 feet. Morphologically diverse granitic divides rise about 2,000 feet higher, with pediments and alluvial aprons accounting for more than half of the local relief in certain areas.

The majority of bedrock erosional forms are developed in quartz monzonite of Mesozoic age, which, in a variety of textures, is ubiquitous in the western half of the Mojave Desert. As described by Dibblee (1964*a*, 1964*b*, 1967*a*, 1967*b*), this rock is characteristically gray white, massive, medium grained, equigranular (average grain size usually 2–3 mm), and weakly coherent where weathered; breaks down by separation of grains; is composed of quartz, potassic feldspar (orthoclase or microcline), and plagioclase (oligoclase or andesine) in generally equal proportions; and contains 2%–7% biotite and a total of less than 2% sphene, apatite, zircon, magnetite, and hornblende—the latter being rare. Granite, granodiorite, gneiss, and metavolcanics are encountered locally.

Granitic relief features.—The positive relief forms of the region consist of short comb ridges and clusters of juxtaposed rock cones rising above extensive erosional pediments, portions of which display a diversified relief of bouldery tors, more massive rock bosses, and extensive plane surfaces scored by gullies along open joints. A few tabular granitic massifs are also present; these exhibit little erosional development in certain instances, as shown by an absence of peripheral pediments and by the wide separation between young canyons that occasionally interrupt the steep margins of the massifs.

The positive granitic relief forms in this area, as in most granitic terranes, consist of wash slopes, boulder-clad slopes, and massive outcrops. Wash slopes are encountered locally on pediments and the larger residual masses wherever the bedrock is too thoroughly decomposed to release solid boulders (fig. 2). They are smooth surfaces, veneered with coarse grus in downslope transport, and may attain angles in excess of 30°.

More commonly, the steeper slopes are a jumble of subangular to spheroidal boulders of a variety of shapes and sizes clearly derived from plane-faced blocks bounded by intersecting joints (fig. 3). The boulders may be either sound or well decayed, the latter often displaying various degrees of cavernous weathering under case-hardened veneers. Where the boulders remain in place, the joint configuration within the mass is usually apparent; however, nonorthogonal jointing frequently produces a chaos of enormous blocks, looming walls, and giant pinnacles.

By contrast, massive outcrops are normally broken by sheeting fractures, the

FIG. 2.—In the foreground, wash slopes on decomposed quartz monzonite in Joshua Tree National Monument. Typical boulder slopes in the distance. Boulders and tors of less decomposed rock are left in relief as the more thoroughly decayed material is removed by surface wash.

FIG. 3.—Characteristic boulder slope on well-jointed quartz monzonite west of Lucerne Valley. A variety of joint patterns is evident, but sheeting dominates.

details of their topography being supplied by the surfaces and edges of lenticular exfoliation slabs. Such outcrops assume the forms of domes and buttresses often surrounded and surmounted by in situ boulders (figs. 4, 5).

All exposed surfaces, including those clearly exhumed from beneath an alluvial cover, have been patinated by a varnish of insoluble iron and manganese oxides that is presently being destroyed by pitting and flaking. On long-exposed surfaces of somewhat decayed rock the impregnation is deep enough to rebind the partially disaggregated exterior material, producing a "case-hardened" rind an inch or two thick. Case hardening has affected all surfaces on the majority of inselbergs and tors, reaching even into closed joints that penetrate massive outcrops. This dark brown, almost black, weathering cortex has been in large part removed from many outcrops, its destruction being initiated by networks of cracks normal to exterior surfaces. Subcutaneous chemical action commencing along the lines of these cracks eventually leads to the detachment of plates an inch or more thick, exposing decayed rock stained buff by iron oxide. This material is being affected by granular disintegration.

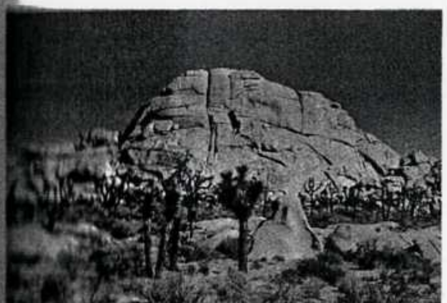

FIG. 4.—Massive outcrop, showing sheeting and major vertical joints, Joshua Tree National Monument. Height, about 100 feet.

FIG. 5.—Massive outcrops being exposed by disintegration of the boulder mantle, Joshua Tree National Monument. Two domes are present in this view, each crowned by boulders originally defined by joints that project into the domes themselves.

Massive outcrops differ from the above in that they ordinarily bear scattered remnants of a formerly more complete but purely surficial patina of iron and manganese oxides imparting a medium gray color to the rock. Most such outcrops lack the separate zone of buff ferric oxide stains always found beneath thicker weathering rinds and, despite surficial flaking, are sound enough to make a hammer bounce. By contrast, rock currently being exposed by the stripping of weathered residuum is only weakly coherent, crumbling into grus when struck even though the mafic minerals are so little altered that the rock may show little or no staining by iron oxide.

The present weathering style on exposed surfaces is a generally reliable index of rock soundness. Solid outcrops shed fine scales of fresh minerals, but granular disintegration is characteristic where there has been slight to thorough chemical alteration of the rock mass. Scaling likewise occurs on cavernous surfaces that maintain relatively humid microclimates; however, such scales consist largely of secondary minerals, unlike those shed by exposed surfaces.

RELATION OF BOULDERS TO MASSIVE OUTCROPS

Where boulder mantles and massive outcrops are found in close association, the relationships between the two make it difficult to envisage the contemporary formation of boulders by weathering into well-jointed rock.

Massive granitic outcrops in the Mojave region are generally encountered in the form of domes similar in most respects to

the domed inselbergs described in the central Sahara (Birot 1958; Dresch 1959), Brazil (Birot 1958), Australia (Twidale 1964), and Nigeria (Thomas 1965, 1966); such domes are encountered wherever granitic rocks appear in arid or semiarid settings. These forms have been attributed to local decreases in joint density or suppression of jointing along lines of tectonic compression, the boulders that frequently litter their surfaces being viewed as a product of subaerial weathering of dome surfaces (e.g., Birot 1958; Twidale 1964). Thomas has interpreted the similar bornhardts of the subtropical Nigerian savannas as "exhumed" portions of highly irregular subsurface weathering fronts, and he regards superincumbent boulders as having been isolated by chemical decomposition in the subsurface.

One cannot deny that domed inselbergs in the Mojave Desert are structurally controlled and constitute compartmented landforms conforming to local joint configurations. Whether they are also localized individually by diminished joint density is difficult to determine, since the bedrock between them is ordinarily obscured by alluvium and residual deposits. Where this bedrock is exposed, as in pediment passes just north of the Lunar Buttes of Lucerne Valley, density of jointing does not appear to differ significantly from that in higher standing areas.

The configuration of individual granitic hills suggests that the contrast between boulder mantles and massive outcrops is itself not altogether attributable to variations in joint density. The massive outcrops are frequently subjacent in position to boulder mantles and are being exposed by disintegration of the latter. Dwindling concentrations of more or less decayed blocks and boulders on the crests and flanks of many smooth domes give them the appearance of emerging hemispherical cores (fig. 5). It is clear that certain boulder mantles are derived from fragmented exfoliation shells, but others seem related to older orthogonal, rhombohedral, and less systematic joint systems that are traceable into the intact dome surfaces below. In many instances well-rounded boulders, occasionally displaying cavernous weathering, rest on expanses of granite that remain smoothly planate across the same joint partings that have defined the overlying much-reduced blocks. Thus, between the present boulder mantles and the dome surfaces beneath them, there is a notable lack of a transitional zone of blocks that are *becoming* boulders (fig. 6).

Twidale (1964) has suggested that closed joints in crystalline rocks may result from compression, as in local synclinal flexures, whereas open joints favorable to the penetration of decay effects would proceed from tensional stressing in adjacent anticlinal warps. In the present case, however, closed joints project upward into mantles of boulders rounded to various degrees, indicating quite effective weathering in these same partings to a fairly well-defined level, at which rock decay appears to have halted rather abruptly.

Even where the rock exposed on dome surfaces is decayed, as indicated by granular disintegration, invasion of cracks by iron and manganese oxides may cause their margins to project above the mass of the rock, rather than forming reentrants in its surface (fig. 7). Accordingly, jointed surfaces of relatively sound quartz monzonite do not appear to be developing a micro-

FIG. 6.—Preweathered boulders atop massive outcrop. Spheroidal boulder (center) is 6 feet high. Cavernous weathering in large block at right produces hollows adequate to shelter several humans simultaneously. Note patination to edges of partings, suggesting minimal present weathering into cracks.

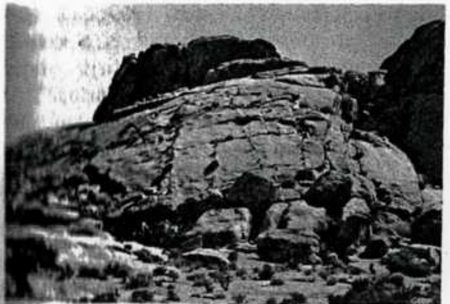

FIG. 7.—Massive outcrop broken by vertical joints. Margins of blocks project above centers because of slight case hardening. No present tendency for weathering to be concentrated in partings. Location is north of Lunar Buttes of Lucerne Valley.

relief related to present weathering at vertical cracks. This is not to say that nowhere have fractures in exfoliation shells been enlarged by weathering and erosion; however, such etching is confined to manifestly unsound rock that appears to have been preweathered in the subsurface, as will be discussed elsewhere.

One cannot dismiss the possibility that gravitational creep or relaxation following off-loading will in time cause the fragmentation of sound exfoliation plates along the lines of observable fractures, isolating separate blocks that thereafter become rounded, producing a new boulder mantle. While fragmentation of this type undoubtedly occurs, observation suggests that it is not a general phase of development. Moreover, although it could account for the absence of a transitional zone of incompletely separated blocks, mechanical fragmentation does not explain the advanced decay of many boulder covers as compared with their substrate.

The upper surfaces of granitic domes thus seem to constitute an interface separating somewhat decayed rock from subjacent sound material. Although the density of joints in many massive outcrops is probably little, if any, less than in the boulder zones marginal to them, it does not appear that continuation of the present style of development will renew the boulder crop currently in existence. Meanwhile, existing boulders, most of which are somewhat decayed throughout, continue to be reduced by granular exfoliation and cavernous weathering. It therefore appears that one must anticipate the eventual disappearance of the boulder mantles of granitic hills and their replacement by multiconvex exfoliating domes resembling the bornhardts and sugarloafs well known in the subtropical granitic landscapes of the African savannas and similar regions.

ORIGIN OF EXISTING BOULDERS

If there is little tendency for disintegrating boulders to be replaced under existing conditions, how were the boulder cloaks originally formed? The answer to this question can be seen in exposures of the subsurface in an expanding number of excavations for highways, pipelines, and even residential subdivisions in the Mojave Desert.

Wherever artificial cuts into erosional surfaces on granitic rocks are available for examination in the Mojave, one is struck by the advanced chemical alteration of the subsurface materials, which may be decomposed to depths of scores of feet even where complete boulder mantles are present (fig. 8). Weathering profiles vary considerably but commonly consist of subangular to spheroidal corestones in a grus matrix. This

FIG. 8.—Decomposed quartz monzonite beneath a boulder litter, Yucca Valley. Decayed rock easily bulldozed. Boulders represent a lag of former corestones exhumed during Plio-Pleistocene denudation.

fact has been verified by seismic inspection, which reveals that granitic pediments having discontinuous bedrock outcrops may transmit seismic waves at velocities little above those in sandy alluvium, velocities characteristic of fresh granite being detected only sporadically as large corestones are encountered. The unsound condition of subsurface granitic rocks in the drier portions of California is attested in many engineering studies (e.g., Kiersch and Treasher 1955) and in the quarrying industry, which is characterized by small operations utilizing isolated surface boulders and monolithic domes rather than large pits.

The corestones visible in excavations are of all sizes and vary widely in definition and degree of development, some being gradational into their grus matrix, while others are surrounded by discrete spalls of much-altered rock. These variations presumably derive from subtle differences in petrography and local weathering solutions. The breakdown of granitic rocks by the decay of biotite and partial hydration of plagioclase feldspars appears to proceed similarly wherever studied in the western United States, according to the descriptions by Larsen (1948), Kiersch and Treasher (1955), Wahrhaftig (1965), Eggler et al. (1969), and others.

Where exposures of the subsurface are available, the origin of surface boulders can hardly be in doubt. Wherever large boulders are strewn over wash slopes on pediments and residual masses, the subsurface rock is friable and may be resolved into a complex of more or less well-formed corestones surrounded by grus. The surface boulders are corestones exposed by erosion and reflect joint-controlled subsurface chemical weathering of surprising effectiveness for a desert environment. Although such boulders have been preweathered in the subsurface, they may appear more solid than still-entombed corestones due to case hardening of their exteriors.

Once exposed at the surface, further decay of the boulders is greatly retarded. This phenomenon has been noted in a variety of climatic settings (Dresch 1959; Thomas 1965; Wahrhaftig 1965) and is a consequence of the greater humidity, under average conditions, of the subsurface environment as contrasted with that of the surface. Thus surface boulders may persist in the landscape long after their subsurface counterparts have been totally disintegrated. Evidence to be presented indicates that the antiquity of such boulders, measured from their inception as corestones, can be established and is far greater than one might reasonably expect.

FOSSIL NATURE OF THE DEEP-WEATHERING PROFILES

Deep weathering of granitic rocks poses somewhat of a geomorphic anomaly in the face of Quaternary moisture regimes in the Mojave Desert. The latter are documented by sporadic massive carbonate crusts encountered widely in alluvium, from a few inches to 3 feet below the surface. While certain K-horizons (calcrete, caliche) appear to be a consequence of upward capillary rise from a former water table, the morphology of others indicates accretion from above as a consequence of shallow penetration of moisture (Gile et al. 1966). Whether the carbonate crusts of the Mojave region formed during Pleistocene moist phases or are a product of the contemporary climate, it seems clear that even under the most exceptional of present conditions meteoric water must not penetrate far below the levels at which the carbonate crusts occur. Studies of the relationship between precipitation quantities and leaching effectiveness (Jenny and Leonard 1939; Arkley 1963), as well as the presence of massive calcrete layers at shallow depths, suggest that under existing conditions meteoric moisture may never gain access to the subsurface "weathering front" in many areas of the Mojave Desert, where decomposed granitic rocks are commonly found at depths in excess of 100 feet. This indicates that the deep weathering observed occurred under conditions unlike those of the present. If such is the case, the weathering profiles, their included corestones, and the boulder mantles derived from them must be regarded as fossil forms.

The lack of rudimentary pedogenic developments on moderate slopes underlain by zones of rock decomposition scores of feet in depth is another anomaly that can best be explained by assuming that the weathering profiles formed under conditions that no longer prevail and are incomplete due to truncation by erosion.

PRE-QUATERNARY WEATHERING PROFILES

There is direct evidence that the decomposed granite, included corestones, and surface boulders encountered in the western Mojave Desert are decapitated remnants of ancient weathering profiles. Fortunately, pre-Quaternary lavas, erupted locally, have entombed fragments of Tertiary land surfaces, which are accessible for study today.

Volcanics of Tertiary and Quaternary age are frequently encountered north of the San Bernardino Mountains where they are associated with transcurrent faults parallel to the San Andreas system. Several such fractures extend northwestward out of the San Bernardino range, their trends clearly marked by rift topography and springs. Here and there along their traces masses of basaltic lava appear, themselves rifted apart in evidence of continued displacement along the fractures. In some areas denudation has lowered the entire land surface by 200 feet or more since the volcanic episode; elsewhere there has been just enough erosion to reveal the ancient surface onto which the volcanics were erupted.

The topographic surfaces and fragments of regolith that are preserved under lavas in the western Mojave are distinctly different from those encountered on present denudational surfaces. All are deeply weathered and attest to development under conditions unlike those of the present, this fact being expressed in distinctive reddish saprolites of varying thicknesses overlying rock decomposed to depths of several tens of feet. Grey grus similar to that encountered over contemporary denudational surfaces is found only in the basal portions of the archaic weathering profiles.

Localities in which ancient soils could be recognized are indicated in figure 10. The range of both site and soil characteristics is illustrated by four exposures on the eastern periphery of Lucerne Valley.

Sites 1 and 2 are encountered near the southern end of the Fry Mountains, where a tongue of basalt approximately 1 mile long curves westward from a vent now stranded more than 500 feet above the desert surface on a residual mass of quartz monzonite. Throughout much of its length the base of the flow stands about 200 feet above its surroundings, approaching to within 50 feet at its terminus. A K/Ar date of 8.9 ± 0.9 m.y. has been obtained from the basalt.

At site 1 on the south side of the flow the basalt covers a brick red saprolite that includes a concretelike pedogenic crust (fig. 9). The crust, which could be described as either a ferruginous calcrete or a calcareous ferricrete, is composed of two horizons, each as much as 10 inches thick, separated by 1–3 inches of silty material. The lower and thicker of these crusts rises locally to pinch out the upper layer. Microscopic examination, as well as the depth of

FIG. 9.—Indurated layers in Tertiary paleosol at site 1 east of Fry Valley. The truncated soil in colluvium is exposed at the base of basalt having a radiometric age in excess of 8 m.y. Hammer rests on top of lower calcrete horizon (upper horizon obscured by recent rockfall), which pinches out upper horizon in center of photo. At right, exhumed corestones in direct contact with basalt. Entire weathering profile, including crust, corestones, and subjacent altered rock, is brick red.

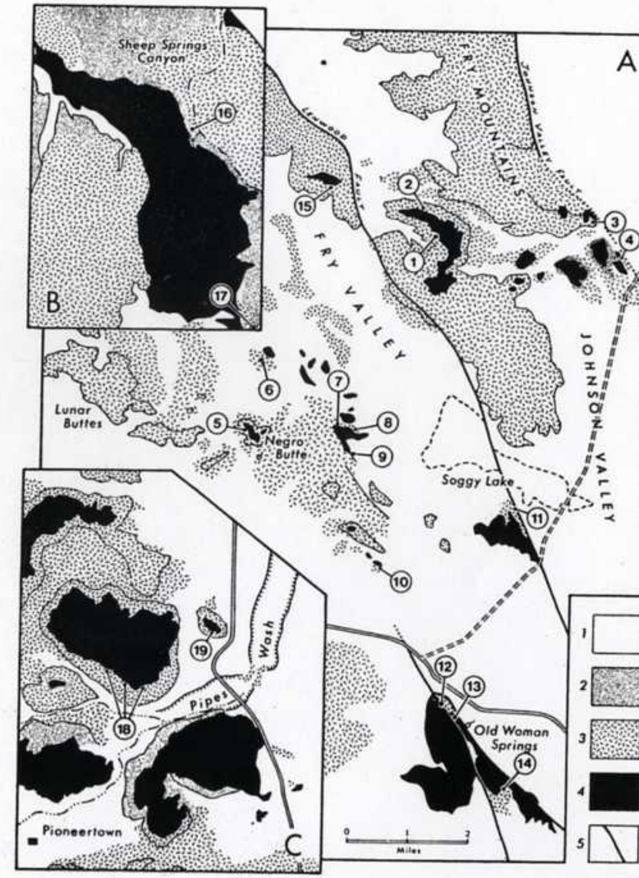

FIG. 10.—Accessible remnants of Tertiary weathering profiles north of the San Bernardino range. Gross physicial characteristics of the sites are noted in table 1. Areas shown may be located on fig. 1.

rubefaction in the weathering profile, rules out any possibility that either the color or induration is a consequence of baking by the lava. The indurated layers are developed in colluvium dominated by subangular fragments of quartz and feldspar, with common chunks of aplite, and are cemented by iron oxide and calcium carbonate in intimate association. The compound, cross-cutting character of the crust indicates that the carbonate cement was not derived from chemical decay of the overlying basalt. X-ray diffraction verifies an obvious paucity of clay minerals in the weathering crust but reveals that K-feldspars are quite fresh. Microscopic examination indicates that the iron oxide and carbonate are both authigenic, the oxides presumably being fixed in the weathering profile as a consequence of an alkaline soil solution.

The indurated layers at the top of the profile rest on a foot or two of strongly rubefied quartz monzonite saprolite that grades downward with no change in color into friable, spheroidally weathered quartz monzonite and biotite quartz monzonite. Finely ground dry samples from the indurated layers and subjacent regolith and decayed rock range from reddish brown (5 YR 4/4) to red (2.5 YR 4/6) and dark red (2.5 YR 3/6). Rubefaction gradually decreases in the zone of spheroidal weathering. Within 10–15 feet of the surface, iron oxide stains, while still highly conspicuous, take the form of separate concentric shells in individual corestones with less stained shells between. Below this zone, which is 15–20 feet thick, ferric oxide stains are absent, and a dark gray weathering patina is presently flaking away from sound quartz monzonite. This final zone, commencing 30–40 feet below the soil surface, is typical of sound rock surfaces exposed elsewhere over the desert floor.

The north side of the lava flow (site 2) covered somewhat higher ground in the prevolcanic landscape. Although reconnaissance did not locate any upslope extension of the calcrete, the zone of incoherent granitic residuum here thickens to more than 20 feet. This material is mottled in color and erodes to smooth convexities along gully walls. Undisturbed aplite veins crop out on exposed faces of the decomposed quartz monzonite and biotite quartz monzonite, establishing this unconsolidated material as bedrock rather than the immature alluvial arkoses of the area, with which it could be confused. The mottled character of the deposit is diagnostic of deep-weathering profiles on quartz monzonite and may reflect termination of the phase of rubefaction before all former corestones had acquired the color of their longer-decayed grus matrix.

A remnant of the Tertiary landscape that differs appreciably from the foregoing is seen at sites 12 and 13 one-half mile northeast of Old Woman Springs and 7 miles north of the preceding location. These exposures are associated with the Old Woman Springs Fault, which extends obliquely out of the San Bernardino range. A fault scarp [illegible] feet high at this locality is capped by basalt on which a K/Ar date of 8.2 ± 0.5 m.y. has been obtained. The basalt with a substratum of ash overlies an unconsolidated alluvial arkose deposited on decayed granodiorite.

The upper 6 feet of the arkose is strongly colored by iron oxide, and a second rubefied zone occurs near the middle of the deposit. The latter is fine grained and poorly sorted, lacks visible bedding, and includes little, if any, nongranitic debris. Accordingly, the transition to the subjacent granodiorite saprolite is inconspicuous. The granitic residuum is about 5 feet in depth and grades downward into disintegrating corestones and rooted granodiorite knobs at the base of the exposure. The residuum is buff at the top, while the corestones beneath exhibit the usual light gray hue of unpatinated surface outcrops of granitic rock in the neighborhood. No pedogenic crust or clearly demarcated textural horizon has been noted in this exposure.

A different sequence is exposed on the opposite (northeast) side of the fault (site 13) only a few yards from the preceding exposure. Here several remnants of basalt having a thin substratum of ash recur, but the ash is in direct contact with a dark red, clay-rich, residual saprolite that is veined by aplite. The red saprolite grades into unsound but coherent buff-colored granodiorite at a depth of 5–8 feet. The abrupt termination of the arkosic alluvium and the marked change in the character of the residuum at the line of the Old Woman Springs Fault appears to be a consequence of lateral displacement along the fault since eruption of the basalt.

The exposures at sites 12 and 13 flanking the Old Woman Springs Fault reveal a period of general and rather deep rubefaction of a composite cut-and-fill surface formed during the late Miocene or early Pliocene. Visible fragments of the erosional portions of this Tertiary landscape are everywhere strongly weathered, reminding one of the Tertiary landscapes of central Australia as reconstructed by Mabbutt (1965). While most exposures of this surface are vividly colored as a consequence of the decay of iron-bearing silicates in a strongly oxidizing environment, climatic conditions in the Mojave Basin were nowhere conducive to the formation of true lateritic weathering profiles of the type found in the present arid heart of Australia; and complete parallelism in the landscapes of the two regions should not be expected. Nevertheless, many of Mabbutt's conclusions regarding the evolution of Australian scenery by the stripping of a weathered mantle as a consequence of progressive desiccation seem pertinent to the development of landforms in the Mojave Desert.

General characteristics of the weathering profiles.—Figure 10 indicates the distribution of Tertiary paleosol remnants located in the study area, and table 1 summarizes the nature of the different exposures. Surface expression of the relict weathering profiles takes three forms. Uppermost, and most conspicuous where preserved, is the red saprolite (Zone I), 1–6 feet thick and occasionally including either claypans or crusts cemented by calcium carbonate and iron oxide. The range of Beckman pH values 4–6 inches below the surface in clay-rich residuum is 6.2–7.3; in claypans, 7.3–7.4, and in red calcrete layers, 6.4–7.8. The higher figure in the last reflects contamination by recent carbonate dust and white caliche veins extending into the overlying lavas. Vein fragments and angular granitic clasts are locally plentiful at the base of Zone I and identify some of the material as colluvium.

Below the saprolite is weakly coherent pink to gray granitic rock that produces smooth multiconvex surfaces where exposed (Zone II). This zone, which is as much as 40 feet deep, is thoroughly decayed, despite a relatively fresh appearance, and does not release boulders as it is worn away. It is thus the material of most wash slopes. Zone II surfaces are frequently littered with fragments of aplite and quartz that are stained dark red by iron oxide, and less strongly colored veins of these materials are visible in every Zone II exposure. The lag of more highly colored vein material has been derived from eroded portions of the weathering profile. The pH values in this zone range between 7.0 and 8.8, the latter figure being obtained from the suballuvial exposure at site 16. Below this is the boulder zone (Zone III).

Zone III exposures consist of sound boulders, knobs still rooted in the solid rock beneath, and friable former corestones that have been exposed and let down as a lag deposit as denudation has proceeded. Included in Zone III are all projections that are being etched into relief at present by erosion of preweathered material marginal to sound rock. This applies particularly to current etching in joints, which is here regarded as erosion of preweathered material within Zone III, which terminates downward at the Tertiary weathering front.

As indicated above, decomposition and rubefaction are not everywhere coextensive in these weathering profiles. In general, granitic residuum and decayed granitic rock are at least buff colored as a consequence of iron oxide staining, but, locally, as at site 12 west of the Old Woman Springs Fault, the decomposed rock is uncolored. On the other hand, very strong coloration has developed in relatively solid rock at site 1, Negro Butte (site 5), and elsewhere. At site 1, weathering Zone I overlies Zone III directly, Zone II being absent altogether; and at sites 5 and 9, only Zone III occurs.

All paleosol exposures are partially truncated as a consequence of erosion preceding the eruption of the Tertiary basalts. Tertiary alluvial arkoses and conglomerates, such as those at the Old Woman Springs locality and adjacent to site 4, occasionally interpose between the lava and the relict weathering profiles on granitic rock, and themselves bear surficial pedogenic developments similar to those on the latter. The upper portions of these alluvial deposits are strongly rubefied and include clay pans and calcrete crusts as much as 10 feet thick.

Red soils are also found on a few remnants of ancient surfaces that have not experienced volcanism and cannot be dated with assurance. Such weathering profiles are thin (6 inches to 2 feet to coherent rock) but are well developed texturally and are conspicuous because of their color. They vary in pH (6.2–7.4 at approximately 4 inches)

TABLE 1

MORPHOLOGICAL CHARACTERISTICS AT SITES OF TERTIARY WEATHERING PROFILES

Site Characteristics	Site Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Exposed beneath Tertiary basalt	x	x	x	x	x	x	x	...	x	x	x	...	...	x	x	...	...	x	x
Exposed beneath Tertiary alluvium	...	...	...	...	...	...	...	x	...	...	...	x	x	...	...	x	x	...	...
Bedrock altered to saprolite (Zone I)	x	x	x	x	...	x	x	x	...	x	x	x	x	x	x	x	x	x	x
Oxidation visible	...	...	...	...	...	...	...	...	...	...	...	x	...	...	...	x	...	...	...
Medium oxidation (buff to pink hues)	...	x	x	...	...	x	x	x	x	x	x	...	x	x	x	x	x	x	x
Advanced oxidation (red to dark red)	x	...	...	x	...	...	...	...	...	...	...	...	x	x	...	...	...	...	...
Clay pan	...	...	x	...	...	...	...	...	...	...	x	...	x	...	...	...	x	...	...
Indurated layer (red carbonate crust)	x	...	...	x	...	...	...	...	...	...	...	...	...	x	...	...	...	...	x
Bedrock altered but coherent (Zone II)	x	x	x	x	x	x	x	x	x	x	?*	x	x	x	x	x	x	x	x
No oxidation evident	...	...	...	...	...	...	...	...	...	...	...	x	...	...	...	...	...	...	...
Oxidation visible	...	...	...	...	...	...	...	...	...	x	...	...	...	...	...	x	...	...	...
Medium oxidation (buff to pink)	...	x	x	x	...	x	x	x	...	...	...	...	x	...	x	...	x	x	x
Advanced oxidation (red to dark red)	x	...	...	...	x	...	...	...	x	...	...	...	...	x	...	...	...	...	...
Bedrock altered along joints (Zone III)	x	x	x	x	x	x	x	x	x	x	?	x	x	x	...	x	x	x	x
Corestones in weathering profile	x	x	x	x	x	x	x	x	x	x	...	x	x	x	x	x	x	x	x
Surface boulders derived from weathering profile	...	...	x	x	x	x	x	...	x	x	...	...	x	...	...	...	x	x	x

* Not exposed.

and have a high content of montmorillonite or mixed-layer clay, which locally forms impermeable pans more than 10 inches thick. The most accessible example is found on the east tor-studded pediment fronting the northeast corner of the San Bernardino Range north of Ruby Mountain.

The Tertiary arkose deposits.—Recognition of the Tertiary regolith is to some degree hampered by the striking similarity in appearance of granitic residuum to the Tertiary alluvial arkoses found in scattered exposures north of the San Bernardino Range. This has produced errors on recent geological maps, which in several instances designate weathered granitic outcrops as alluvium or fail to note the base of alluvium in contact with weathered granitic surfaces. Instances noted are at sites 4, 12, and 18. Alternatively, an enormous valley fill of early Pleistocene (?) arkosic alluvium beneath the Malpais Lava (exposed in Sheep Springs Canyon, site 16) has been mapped as quartz monzonite because of its resemblance to the granitic material of the opposite canyon wall (Rodman Mountains quadrangle). Although most such errors appear to have proceeded from long-distance identifications, the two materials are hard to distinguish even upon close macroscopic examination because of the clay content; abundance of incompletely decayed mafic minerals; lack of rounding, sorting, channeling, and bedding; and paucity of nongranitic debris in many exposures of the arkose. Both have been rubefied to similar depths below the surface and in many cases have similar color, texture, and permeability.

The great depth of the Tertiary arkosic formations in the area drained by Pipe's Wash and north of Pioneertown and its extension north into Lucerne Valley reflects equiplanation on an impressive scale in the

late Miocene. A composite surface of regolith-covered granite and granitic alluvium was created, the remnants of which rise about 200 feet per mile westward into the San Bernardino Mountains. This surface was stabilized under strongly oxidizing conditions long enough to acquire a relatively uniform degree of coloration extending to depths of several feet over areas of both aggradation and erosion, and to produce ferruginous calcrete horizons in both types of settings. Rubefaction of the Tertiary alluvial deposits clearly occurred in situ, being developed from the surface downward.

The most complete description of the alluvium has been given by Shreve (1959, p. 15–18; 1968, p. 12–14), who named the formation the "Old Woman Sandstone," with lower Blackhawk Canyon designated as the type locality. Shreve recognized that the material rested in depositional contact on a surface of gneiss and quartz monzonite that is deeply weathered and has a local relief of "at least 150 feet." Local relief of the subjacent surface in fact exceeds 400 feet in the area of Pioneertown. As marble clasts are absent from the formation despite its proximity to the San Bernardino Mountains, it is thought to have originated prior to the thrust faulting that brought marbles to surface positions in the Tertiary and that presumably accounted for a major part of the elevation of that range (Richmond 1960).

Tertiary climate of the Mojave Basin.—If the Tertiary arkosic deposits predate the major uplift of the San Bernardino range, the pedogenic developments on the alluvium, as well as the relict weathering profiles on granitic rocks that are found in association with it, are explained. Assuming an atmospheric circulation pattern similar to that of the present, less than full uplift of the Transverse Ranges (San Gabriel, San Bernardino ranges, etc.) implies less than full development of the rain shadow to which the Mojave Desert owes its existence. The available paleobotanical evidence also suggests that Tertiary weathering profiles must have been developed under conditions more humid than those of today. According to Axelrod (1939, 1950), during Miocene time the Mojave Basin supported a vegetation association of thorn scrub, chapparal, and open live oak and conifer woodland interspersed with grassy plains. The estimated annual precipitation was 15–25 inches, with rainfall occurring throughout the year. By mid-Pliocene time grassland and semidesert shrubland had become dominant, the precipitation probably decreasing to 10–15 inches and tending toward a strong winter maximum. The floristic change indicating the onset of conditions similar to those of the present did not occur until the late Pliocene or early Pleistocene and is presumed to be a consequence of full development of the rain shadow proceeding from several thousand feet of additional uplift of the Transverse Ranges (Axelrod 1958, p. 476). Stratigraphic evidence suggests that the present interior drainage pattern of the western Mojave Basin likewise did not become established until this time (Hopper 1947, p. 401). Although dismemberment of preexisting oceanic drainage systems has been attributed to tectonic damming associated with the intensified orogenic activity of this period, such a tendency would clearly be facilitated by increasing climatic desiccation.

While the available botanical evidence regarding the Tertiary climates of the Mojave Basin seems consistent with the geological history of the area, the pedological evidence is itself not so conclusive. The characteristic rubefaction of the relict weathering profiles would seem to suggest a climate considerably more humid that the present. According to Van Houten (1961, p. 106, 112–113, 120), the climatic requirements for the formation of red soils are "fundamental," with the redbeds of deserts having inherited their pigment from older deposits or having formed during earlier, more humid periods. A considerable literature, cited by Van Houten, supports this view. However, more recent investigations by Walker (1967) seem to show rather convincingly that in situ rubefaction occurs in alluvium in an area of Baja California receiving about 3 inches of precipitation annually. The principal requirements for the formation of hematite pigment from iron-bearing silicates, according to Walker, are high Eh and pH of interstitial water, low water table, sparse vegetation, and time. The red soils he describes are rich in carbonate throughout the profile and have a matrix of immature clay, especially montmorillonite. Although the ancient soils observed in the Mojave Desert are similar in the first respect, certain of the calcrete (or ferricrete) exposures show a dearth of clay minerals of any description, at the same time revealing very fresh feldspar fragments.

While Walker's work dealt exclusively with alluvium in various depositional environments, there seems no reason not to apply his interpretation to weathering profiles formed on bedrock as well. The sticking point here is the depth of decomposition and rubefaction in the Mojave, where granitic bedrock is decayed 100 feet below the surface in some localities and may be vividly colored by iron oxide throughout the upper [illegible] feet, even where the rock remains coherent. Rubefaction of the mineralogically similar but far more permeable Tertiary alluvium nowhere exceeds this depth, leaving the base of the formation uncolored and facilitating recognition of its contact with subjacent oxidized residuum.

Quite possibly the usual association of ferric oxide content and climate cannot be sustained, and perhaps the depth of Tertiary weathering noted in the Mojave Desert can be explained as a consequence of time alone. Nevertheless, the existing botanical evidence, and the difficulty of decomposing rock at depths in excess of that normally penetrated by moisture under contemporary conditions, suggests that the fossil weathering profiles of the Mojave must have formed under conditions more humid than those of the present. These climates would, nonetheless, be semiarid at best, with high temperatures and moisture regimes possibly resembling those now encountered only 1,000–[illegible] feet higher on the pinyon pine–, juniper-, and chaparral-clad slopes of the adjacent San Bernardino and San Gabriel ranges. In such settings residuum continues to blanket steep slopes on granitic rocks in sufficient depth that outcrops are not conspicuous. It seems reasonable to suppose that the configuration of slopes in these ranges is similar to that prevailing in the Mojave hills of late Tertiary time.

TERTIARY WEATHERING AND THE EXISTING LANDSCAPE

Although the existence of ancient weathering profiles containing corestones can be established without difficulty, additional proof is required to demonstrate convincingly that these same weathering profiles are relevant to contemporary landscapes in the Mojave Desert. Evidence that this is the case is present in the form of several instances of continuity between datable relict weathering profiles and complete boulder mantles typical of those that dominate the present scenery in this region.

The most accessible example of the relationship between Tertiary weathering profiles and contemporary boulder mantles is found at site 13 one-half mile northwest of Old Woman Springs (fig. 11). Here a boulder-clad granodiorite hill is half ringed by a pediment some 35 yards wide, which terminates downslope against knolls of clayey red saprolite capped by basalt that has a radiometric age of 8.3 m.y. Projection of the base of the lava would bring the subjacent saprolite well above the present boulder-clad slopes of the hill, as indicated in figure 12. Such a projection suggests that between 20 and 40 feet of red saprolite and decayed granodiorite has been removed from the hillslope since emplacement of the lava. Friable granodiorite, grading downward in color from pink to white, forms the surface of the fringing pediment. Downslope projection of the layer of boulders mantling the hillslope places them subjacent to the material of the pediment. The boulders are thoroughly decayed and crumble under hammer impact. A vertical section down through the Tertiary weathering profile

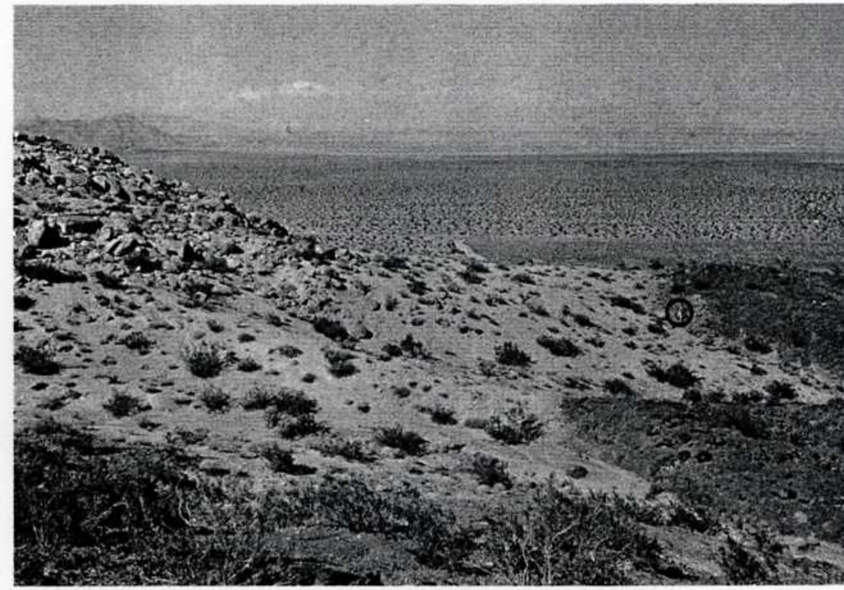

FIG. 11.—Paleosol site 13 adjacent to Old Woman Springs Fault. Six-foot figure (circle) provides scale. Boulders at left project under wash slope in center. Basalt (right) caps paleosol remnants that project above boulder slopes. Radiometric age of basalt exceeds 8 m.y.

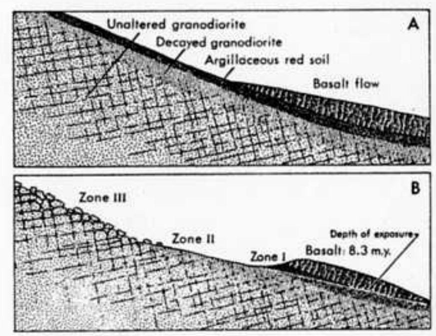

FIG. 12.—Diagrammatic representation of conditions at Old Woman Springs (site 13). *A*, Immediately after the Pliocene volcanic episode. *B*, At present, indicating characteristic morphological zones of Tertiary weathering profiles. The vertical scale is somewhat exaggerated (see fig. 11).

may thus be examined by moving horizontally from the gullied lava and subjacent residuum (Zone I), across the pediment (Zone II), and into the boulders at the base of the residual hill (Zone III).

One-and-a-half miles farther southeast along the Old Woman Springs Fault (site 14), one encounters the same horizontal sequence: basalt, clay-rich red soil, friable granitic rock, granitic boulders. Here dislocation along the fault has tilted the lava steeply so that a traverse on the ground is almost normal to the weathering profile, making its relationship to exposed boulders quite clear.

It is conceivable that these low-lying sites have been buried by alluvium from the San Bernardino range since eruption of the basalt, an explanation that would account for the surprisingly limited amount of denudation that has occurred. However, less accessible but equally clear displays of the continuity between subvolcanic Tertiary weathering profiles and surface boulder mantles are seen on the peripheries of Fry and upper Johnson Valleys, as at sites 3, 4, 9, and 10 (fig. 13). There is little possibility that these sites have not been exposed continuously since volcanism occurred, many

FIG. 13. Paleosol site 3, north of Johnson Valley. Undated basalt fragment (right) caps red paleosol, which projects under main volcanic accumulation to left. In situ boulders in foreground exposed by erosion through the paleosol.

of them being situated at high points in the landscape, with their associated lavas standing well above all younger deposits.

The boulder cover.—All ancient granitic weathering profiles in the area investigated constituted a mass of easily eroded material covering zones of spheroidal weathering in which countless numbers of corestones awaited exposure as surface boulders. Whenever denudation became more active than subsurface chemical decay, the first corestones to be uncovered would have been thoroughly decayed and friable at the surface, where their existence would be quite ephemeral. Only the development of a case-hardened rind could prevent their rapid collapse into heaps of grus. Those corestones exposed by deeper erosion would be much sounder kernels that would in time form a formidable armor where exhumed en masse. Various degrees of prior subsurface alteration, related to position in the weathering profile attacked by erosion, provide a seemingly satisfactory explanation of the conspicuous but otherwise puzzling local variations in the conditions of existing surface boulders of similar petrography. Unless this fact is appreciated, one is at a loss to account for the lack of uniformity in the boulders constituting local groups and mantles, some being highly colored, some pale, some thoroughly decayed under a case-hardened cortex, some sound enough to ring to the hammer and bearing only a film of desert varnish.

Slope profiles.—A subsurface origin for granitic boulder mantles in desert regions is consistent with the results of Melton's inquiry (1965*b*) into the geometry of boulder-clad slopes in southern Arizona. According to Bryan (1923, 1925), Dresch (1959), and others, declivities of granitic hillslopes mantled by boulders are determined by the dimensions of the boulders present at any point. As boulder size is controlled by joint density, such hillslopes are structurally controlled. Melton's detailed quantitative investigation of a typical boulder slope in Bryan's Papago Country refutes this hypothesis.

Boulder-clad granitic hills in the Mojave Desert are frequently sigmoidal in profile, with concave lower slopes passing into convex summits. The boulders covering such hills do not show any systematic changes in caliber throughout concave, convex, and straight slope segments; and there is no evident tendency for any size grouping to dominate any particular slope configuration. This is easily explained, as is Melton's conclusion, if the present boulders are recognized as corestones exposed by the stripping of a weathered mantle. The observed slope profiles reflect the character of denudational processes operating on this mantle, which was subject to sheetwash, rill erosion, and mass transfer, unlike the present boulder slopes. Where a chaos of boulders can be resolved into generally straight or concavo-convex slopes, a former soil cover over the whole landscape seems to be a necessity.

Pediment formation.—Peripheral to the boulder-clad slopes of this study are classic erosional pediments, 1–3 miles wide. The development of these surfaces is clearly linked with that of the positive relief forms that stand above them. A recent summary of the literature on desert pediments indicates that most investigators of these features in the southwestern United States have regarded them as the concomitant of the wearing back of a mountain front or escarpment (Hadley 1967). Where the latter

is boulder-clad, backwearing is assumed to progress by the slow disintegration of surface boulders that are continuously replaced from solid rock by weathering into joints (e.g., Gilluly 1946; Warnke 1969).

The present investigation suggests that inselberg surfaces have not retreated as exposed rock walls, and in the last 8 m.y. have been modified primarily by the removal of previously decomposed overburden. This has in some cases measured as little as 20–40 feet in depth; elsewhere more than 200 feet of material has been removed, including perhaps 50 feet of relatively sound rock. Assuming that parallel slope recession has indeed produced the pediments, it appears that during retreat the slopes were mantled with clay-rich residuum under a cover of vegetation, and that the pediments originated during a semiarid period within the Tertiary, rather than being a product of the present arid phase. They would therefore be fossil forms that have changed during the present arid epoch only by the removal of a formerly complete mantle of residuum. Individual pediments in the area investigated are studded with boulders, penitent rocks, and tors, exposed by the stripping of the same weathered mantle that covered the adjacent hillslopes.

As projection of the subvolcanic weathering profiles in the Mojave indicates a saprolite cover over the whole granitic landscape, no place is left for the rock faces postulated by King during the pediplanation cycle (King 1967, p. 157). In this region parallel rectilinear slope retreat and the expansion of pediments apparently proceeded in the presence of the very blanket of soil that King described as having "dire consequences upon the active evolution of the landscape as a whole" (King 1967, p. 158).

CONCLUSION

Some 8 m.y. ago the Mojave landscape seems to have been one of rolling hills covered with a soil whose characteristics were developed in response to a climate distinct from that of the present. Although subsequent loss of the upper horizon of this soil precludes any precise summary of the pedogenic processes of the time, the result was a strongly rubefied argillaceous regolith in which clay pans and calcrete (or ferricrete) horizons were developed even on sloping surfaces. These effects suggest a hot semiarid climate in which soil formation and surface denudation were more or less in balance. Such an interpretation is in agreement with the available botanical evidence, which indicates progressive deterioration of vegetation throughout the Miocene and Pliocene in both the Great Basin and Mojave Desert, the present climatic regimes of these regions becoming fully established only during the Pleistocene. In the Mojave the gradual transformation in vegetation, which probably included many fluctuations similar to those known from the Pleistocene, left increasing proportions of the surface unprotected by a plant cover and accelerated denudation of the soil, whose renewal was simultaneously retarded by the establishment of a negative moisture balance throughout the year.

Erosion triggered by deterioration of the vegetative cover over the Mojave Basin has by now stripped the mantle of fine residuum from most hillslopes, leaving them covered by a litter of spheroidal to subangular boulders. These were formerly subsurface corestones isolated by chemical weathering along joint planes. In many instances friable decomposed rock remains beneath the boulder cover. Complete armoring of slopes with residual boulders arrests the denudational process until such time as the protective boulder mantle itself disintegrates. Although the boulders have been preweathered in the subsurface, interposition of phases of patination and case hardening allows them to endure at the surface far longer than their internal condition would suggest. In certain instances weathering profiles are such that several successive mantles of corestones will be concentrated before the Tertiary weathering front is exposed.

Nonetheless, nearly all granitic areas of moderate relief show examples of near-complete removal of the boulder mantle, exposing smooth cores of undecomposed rock rising tens to hundreds of feet above upland surfaces. Such desert domes appear to be the undecayed cores of Tertiary hill forms resulting from fluvial dissection and circumdenudation, rather than residuals owing their presence to paucity of joints (fig. 14).

The further evolution of the larger monolithic masses will evidently proceed as outlined by Thomas (1965) in his discussion of the breakdown of bornhardts into kopjes. Smaller projections, including kopjelike forms, will be eliminated by microexfoliation and granular disintegration operating over all rock surfaces exposed to the atmosphere—processes whose effectiveness in removing minor irregularities is manifest wherever bare rock is exposed on desert pediments but which cannot account for the pediments themselves.

Contrary to assumptions predicated upon the continuous renewal of boulder mantles by weathering of exposed outcrops, this reconstruction indicates that granitic landscapes in the Mojave Desert have been evolving in a sequential manner since the late Tertiary. This evolution has been triggered by climatic change, and reflects the instability of a landscape determined under conditions that no longer exist. Consequent changes in morphology will cease to be diagnostic of climatic change only when all weathered residuum inherited from the Tertiary morphogenetic regime is stripped from elevated portions of the landscape and transferred to adjacent basins of sedimentation.

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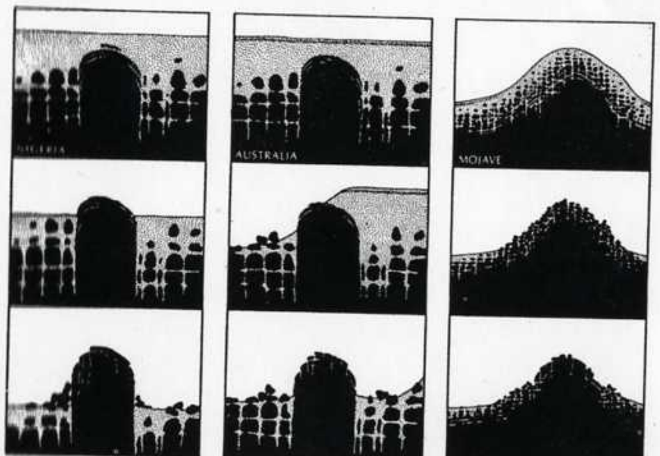

A B C

Fig. 14. Evolution of domed residuals under different geomorphic conditions. *A*, Nigerian bornhardts isolated by differential subsurface weathering and exposed by surface lowering (Thomas). Subsurface decay continues, so that the dome "grows downward." *B*, Domed inselberg of western Australia isolated by differential subsurface weathering under humid conditions and exposed by subsequent retreat of a duricrust-capped fluvial escarpment under arid conditions (Mabbutt 1961). Former weathering front stagnant as a consequence of regional desiccation. *C*, Domed inselberg of Mojave Desert, initially isolated as a soil-covered hill, subsequently stripped of soil, decayed rock, and residual boulders. Present configuration reflects jointless original hill not localized by structure. Surface of dome represents essentially the downward limit of chemical weathering in the Tertiary landscape.

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