ETL-0566

The Landforms of Granitic Rocks: An Annotated Bibliography

Judy Ehlen

May 1990

U.S. Army Corps of Engineers
Engineer Topographic Laboratories
Fort Belvoir, Virginia 22060-5546

Destroy this report when no longer needed.
Do not return it to the originator.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The citation in this report of trade names of commercially available products does not constitute official endorsement or approval of the use of such products.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1990	annotated bibliography: Jun 86 - Sep 89

4. TITLE AND SUBTITLE

The Landforms of Granitic Rocks: An Annotated Bibliography

5. FUNDING NUMBERS

6. AUTHOR(S)

Judy Ehlen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Topographic Laboratories
Fort Belvoir, Virginia .22060-5546

8. PERFORMING ORGANIZATION REPORT NUMBER

ETL-0566

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Related Reports:
A Bibliography on the Chemical Weathering of Granitic Rocks. ETL-0505, September 1988, AD A200 157.
Fractures in Rock: An Annotated Bibliography. ETL-0555, January 1990, AD A220 093.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This bibliography addresses the study of granite landforms throughout the world from a variety of different perspectives. It summarizes the content of more than 150 papers and books. The subjects addressed include theories of origin for the respective landforms, the weathering processes acting upon these landforms, and the composition, texture and structure (mainly jointing) of granitic rocks as they relate to landform development.

14. SUBJECT TERMS

granite, landforms, process, fractures, weathering

15. NUMBER OF PAGES

77

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Preface

Part of this bibliography was compiled under DA Project 4A161102B52C, Task OC, Work Unit 010, "Indicators of Terrain Conditions."

The bibliography was prepared between June 1986 and September 1989, partly under the supervision of Dr. J.N. Rinker, Team Leader, Center for Remote Sensing; and of Dr. Richard Gomez, Director, Research Institute.

Col. David F. Maune, EN, was Commander and Director, and Mr. Walter E. Boge was Technical Director of the U. S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia 22060-5546, during preparation of the report.

Introduction

This annotated bibliography presents summaries of more than 150 papers and books about landforms composed of granitic rock. The subjects addressed include theories of origin, processes of formation, weathering processes, and the geological and structural properties of granites as they affect landform development. Many different types of granite landforms, including tors, tafoni, boulders, and inselbergs, are addressed, with the exception of granite plains.

The bibliography is an outgrowth of a long-term study that attempts to identify different rock types on aerial imagery by determining their characteristic patterns. Granitic rocks were selected for study for the following reasons:

1) they are relatively common;

2) their image patterns are fairly well understood and documented;

3) they form distinctive landform assemblages that should be readily identifiable from imagery; and

4) they have equally distinctive fracture patterns that can serve as an aid to identification.

The study of the rock characteristics and fracture patterns also complements research on fluid flow in fractures and fracture flow networks as well as on the identification of fracture patterns at depth. Granitic rocks are of particular interest with respect to fractures in relation to their potential as repositories for toxic and nuclear waste. In addition, many studies of fractures in rock, whether simply for gaining an understanding of how fractures initiate and propagate or for more practical applications, are done using granitic rocks.[1] Because, as will become clear below, fractures tend to control landforms in granitic rocks, the study of granite landforms is highly relevant to many similar applications, civil and military. In addition to those mentioned above, such applications include cross-country mobility, location of ground water sources, location of engineering materials (sand, gravel, etc.) and site selection for engineering structures, such as dams.

The geologic literature on granites worldwide is huge. Granites have always attracted attention, partly because of their mode of origin and what they can tell us of processes occurring deep within the crust, but mainly because they are typically highly mineralized. Granites, or their metamorphic aureoles, are major sources of copper, tin, silver, gold, and many other valuable commodities. They are naturally highly radioactive, particularly at depth, and are thus sources of heat and geothermal energy. They have been used for centuries as building materials and in the construction of monuments, so much so that any coarse-grained rock used by the building trade is called granite regardless of its true identity.

---

[1] Bourke, P.J., Evans, G.V., Hodgkinson, D.P. and Ivanovich, M. 1982. An approach to prediction of water flow and radionuclide transport through fractured rock. In Geophysical investigations in connection with geological disposal of radioactive waste, Proceedings of a Nuclear Energy Agency Workshop (Ottawa, Canada). Paris: Organisation for Economic Co-operation and Development, pp. 189-198 is an example of practical application.

The study of granite landforms has fascinated people for over 150 years and the number of published papers on the subject is very large. Much of the early literature was observational or descriptive. MacCulloch (1814), for instance, describes the peculiar effects of weathering on some Cornish tors[2] and Ormerod (1859, 1869) is concerned with the origin of rock basins. Geomorphological interest seems to have waned in the latter part of the 19th century and first half of the 20th century, but Linton's 1955 paper on the origin of tors forced new interest and much controversy, and can perhaps be defined as the beginning of modern interest in the subject.

Three main theories of origin for granite landforms have been suggested. These are: 1) the two-stage theory, which involves deep, sub-surface, chemical weathering followed by (probably periglacial) removal of the weathered debris; (2) the theory of pediplanation (parallel retreat) followed by rejuvenation; and (3) the periglacial theory involving frost action and solifluction. The two-stage theory was proposed by Handley in 1952 with reference to tors in Tanganyika (modern Tanzania). Twidale and Mueller (1988), however, state that Hassenfratz was the first to suggest a two-stage origin for granite landforms in his 1791 paper "Sur l'arrangement de plusieurs gros blocs de differentes pierres que l'on observe dans les montagnes" published in Annales de Chimie. Regardless of when it was initially proposed, the theory was "popularised" by Linton in his 1955 paper. The pediplanation theory was first espoused by Davis in 1933 for granite domes in the Mohave Desert in California. King (1958, 1966, 1975), who has applied this theory extensively in southern Africa, is the most forceful modern proponent. The periglacial theory was published in 1930 by Albers with reference to Dartmoor in southwest England, but he attributes its first application to R.N. Worth in his 1898 paper "Some phases of Devonian detrital geology" published in the Transactions of the Plymouth Institution. Palmer and Radley (1961) have applied this theory to the granite tors of Dartmoor using their knowledge of the gritstone tors in Yorkshire in northeast England.

All three theories have received support from other workers as well. The two-stage theory is supported by, among others, Ruxton and Berry (1959), Eden and Green (1971), Jahn (1974), Twidale and Bourne (1975a), Dyke (1976) and Twidale and Mueller (1988), whereas Mabbutt (1952), Ollier and Tuddenham (1961), Rahn (1966) and Ojany (1969) support King's theory, and Palmer and Neilson (1962) support the periglacial theory. Demek (1964) supports the two-stage hypothesis for granitic landforms, but prefers the periglacial theory of Palmer and Radley (1961) for landforms composed of metamorphic rock.

There has been much controversy, some of it quite acrimonious, over these three theories. Most of the controversy was between King and Linton; much of it was initiated by King. King cannot accept the two-stage hypothesis because he sees no evidence of deep chemical weathering associated with the granite landforms with which he is familiar (1966, 1975). Since the mid-1960's, however, most workers use combinations of these theories to explain the landforms in granitic rocks. The vehemence of earlier exchanges has disappeared and cooler heads advance the concept of convergence (White, 1945) or equifinality (Bertallanffy, 1950), i.e. that different processes operating on forms of different origins can produce the same result.[3] These include Brunsden (1964), Cunningham (1965, 1968), Leigh (1970),

---

[2] "Tor" is a local name in southwest England for a prominent, usually isolated, rock outcrop. The word is derived from a Cornish word meaning tower.

[3] Bertallanffy, J. von. 1950. An outline of general systems theory. British Journal for the Philosophy of Science, vol. 1, pp. 134-165.

Thomas (1974), Selby (1977a), Brook (1978), Ollier (1978b), and Gerrard (1984).[4] The concept of a structural origin for granite landforms has also received renewed attention, particularly in the work of Twidale in Australia (1964, 1973, 1982b). He advocates a theory of compressional jointing that is not dissimilar to theories presented earlier concerning sheeting and exfoliation (Gilbert, 1904; Bain, 1923). Another interesting theory is that presented by Selby (1972) for Antarctic tors which involves salt crystallization.

As implied above, interest in granites and granite landforms exists worldwide. In Britain, where much research on this subject has been done, granite landforms have been studied by Waters (1957), Brunsden and Gerrard (1970), Gerrard (1978, 1982) and Ehlen (1989b), all of whom worked on Dartmoor in southwest England. Wagner (1913), King (1949, 1958, 1966, 1975), Mabbutt (1952), Jeje (1973, 1974), Thomas (1965), Thorp (1967a, 1967b), and Pye et al. (1984) and Pye et al. (1986) have studied various aspects of granite landforms in Africa. In Australia, Ollier (1965, 1978b), Ollier and Tuddenham (1961), and Twidale (1964, 1980, 1981, 1982a, 1982b, 1986) are the major researchers in the study of granite landforms. The Hong Kong granites were studied by Ruxton and Berry (1957, 1959) and those in Singapore by Tschang (1961). In the United States, Gilbert (1904), Davis (1933), Willis (1934), White (1944, 1945), Wahrhaftig (1965) and Cunningham (1969, 1971) have published on the subject. Demek (1964) worked in Czechoslovakia, and Jahn (1974) and Dumanowski (1964, 1968) in Poland. Granitic rocks in cold climates were studied by Oen in Greenland (1965), by Selby (1972) and Derbyshire (1972) in Antarctica, and by Dyke (1976) in the Canadian Arctic.

There is also a large body of literature on the weathering of granitic rocks, much of which relates weathering processes to landform development and evolution; such papers are therefore included here. Ollier (1984) provides good general discussions of physical and chemical weathering as well as specific information on granitic rocks. His bibliography is a good source for additional reading. A more recent survey of papers on the chemical weathering of granitic rocks is provided by Ehlen and Gerrard (1988). Early work on the physical weathering of granitic rocks was done by Blackwelder. He investigated exfoliation (1925), fire (1926) and insolation (1933) as possible weathering agents.[5] Ollier (1971) discusses a number of different hypotheses for the origin of spheroidal forms, and also addresses induced fracture as a form of physical weathering (Ollier, 1978a). Crickmay (1935) in the southern Appalachians and Blank (1951b) in Texas conclude that the main process acting on granitic rocks is granular disintegration. Granular disintegration is often cited as the major cause for tafoni as well (Dragovich, 1969; Bradley et al., 1978). Kesel (1977) cited sheeting and spalling as the major process in central Arizona. Crystal growth, usually salt or ice, is a common form of physical weathering. Palmer and Radley (1961) and Palmer and Neilson (1962) suggest freeze/thaw is largely responsible for gritstone and granite tors in England, and Kelly and Zumberge (1961) found salt weathering in conjunction with freeze/thaw was the major process forming tors in the Dry Valleys of Antarctica. King (1949, 1966, 1975), of course, strongly advocates physical processes for the origin of granite landforms in southern Africa, as does Mabbutt (1952).

A number of authors have addressed relations between the mineralogical and textural characteristics of granitic rocks and their landforms because these factors play important roles

---

[4] Gerrard, A.J.W. 1984. Multiple working hypotheses and equifinality in geomorphology: Comments on recent article by Haines-Young and Petch. Transactions of the Institute of British Geographers, vol. 9, pp. 364-366.

[5] Blackwelder, E. 1926. Fire as an agent in rock weathering. Journal of Geology, vol. 35, pp. 134-140; and Blackwelder, E. 1933. The insolation hypothesis of rock weathering. American Journal of Science, vol. 26, pp. 97-113.

in determining the resistance of rocks to weathering. Certain minerals are more resistant to weathering than others because of their compositions, thermal expansion characteristics and/-or compressibilities (Ehlen and Zen, 1986).[6] For example, mafic minerals, such as biotite, weather relatively rapidly whereas minerals with low iron and magnesium contents or with none at all, such as quartz and feldspar, are much more resistant. Mafic minerals are more mobile and the chemical bonds in these minerals are more easily broken. These types of considerations help explain why areas underlain by the more mafic granitic rocks, such as diorite or tonalite, often occur at lower elevations and have less relief than nearby areas composed of granite or granodiorite. This also helps explains why inselbergs are composed of granites and gneisses, a metamorphic rock similar in composition to granite, rather than of diorites or quartz diorites.

Lithologic or petrographic boundaries commonly coincide with landform boundaries. Such relations were found by Demek (1964) who worked in the Bohemian granites, Eggler et al. (1969) who studied the Sherman granite in the western U.S.A., Jeje (1973) in Nigeria and Ollier (1978b) who worked on granites in the Namib Desert. Hack (1966), King (1975) and Brook (1978), on the other hand, found no relation between landform and lithology. Dumanowski (1964, 1968) in Poland, Brook (1978) and Robb (1979) in South Africa and Pye et al. (1986) in Kenya have identified relations between granite landforms and the potassium feldspar content of the rocks that form them. The inselbergs tend to have high potassium feldspar contents whereas rocks in areas without inselbergs tend to be low in potassium feldspar. Ehlen's (1989b) work on Dartmoor in southwest England further substantiates these relations in that the larger, more massive tors have more potassium feldspar in the ground mass and also contain more large potassium feldspar megacrysts.

Rock texture may be important with respect to landform development as well. Gibbons (1981), Pye et al. (1984) and Ehlen (1989a; 1989b) identified significant relations between texture and resistance to weathering. They found porphyritic granites are more resistant than non-porphyritic granites. Megacrysts in granitic rocks are usually composed of potassium feldspar, so this textural evidence supports conclusions based on the lithologic data. Pye (1986) has summarized much of the data relating rock texture and landform.

The relation between joints and granite landforms is mentioned in a general way in many papers, but details are seldom provided, except with reference to sheeting joints. Joints are usually described as controlling the general outline of the landform by allowing water into the rock, thus becoming the locations for chemical weathering. Jones (1859), Bain (1923), King (1949, 1966), Linton (1955), Waters (1957), Brunsden (1964), Feininger (1969), Thomas (1974), Twidale and Bourne (1976, 1978) and Pye et al. (1984) are examples. Many workers, including Ormerod (1859, 1869), Wagner (1913), Mabbutt (1952), Thomas (n.d.), Twidale (1964, 1982b), Cunningham (1971) and Brook (1978), point out that certain landforms are defined in terms of joint spacing, e.g. domes develop only where joints are very widely spaced. Most papers referring to joint spacing, however, merely state that horizontal spacing increases with depth or give ranges in spacing values for vertical joints (Jahns, 1943; Kieslinger, 1960; Oen, 1965; Twidale, 1973; Lee et al., 1979).

Only Gerrard (1974, 1978, 1982) and Ehlen (1989a, 1989b), however, have specifically addressed the importance of jointing in the evolution of granite landforms. Gerrard (1974) showed that weathering along joints is responsible for the initial compartments or domes on

---

[6] Ehlen, J. and Zen, E. 1986. Petrographic factors affecting jointing in the Banded Series, Stillwater Complex, Montana. Journal of Geology, vol. 94, pp. 575-584.

Dartmoor in southwest England in that the drainage net is controlled by the major regional fractures. Tors develop on the domes as a result of "secondary" jointing. This jointing is caused by stress release within compartments on the domes and results from further, more localized weathering and stream incision. In a later paper (1978), he showed that tors are located where differential physical and chemical weathering can have occurred and where the weathered material could be removed. In other words, tors occur where joints are closely spaced in comparison to the rest of the dome, but not so closely spaced that everything is weathered and removed. Using mean joint spacing data, Ehlen (1989) has identified possible pathways and restrictions in the evolution and development of granite landforms defined according to topographic position.

* * *

One cannot study the landforms developed in granitic rocks as isolated individuals; each suite has a history and each individual has evolved from something and will probably evolve into something else before it disappears. An understanding of the weathering characteristics of granitic rocks is thus integral to an understanding of the shapes of landforms composed of these rocks. Likewise, there is a general consensus that joint patterns probably control landform shape, and that other factors, such as mineralogy, grain size and rock texture, also play important roles in this relationship. In addition, there is some evidence that certain combinations of characteristics lead to specific types of landforms in certain environments. Moreover, an understanding of the range in forms and their variations and possible origins provides a framework for evaluating any specific suite of granite landforms, most of which probably evolved in climates different from those of the present day. Study of such characteristics is one way to gain an understanding of landform evolution which cannot practically be observed as it occurs. This bibliography brings together the results of research done over the past 175 years on all these subjects. The papers are written by people from many parts of the world with different backgrounds and different perspectives, so each paper included provides unique insight into the puzzle that is the development of landforms in granitic rocks.

All references cited in the annotations are included in this bibliography except when the citation is given in a footnote. In addition, all papers are in English or contain a summary in English. Finally, unless other rock types are specified, all papers refer to granite. Keywords are given for each paper.

* * *

Albers, G. 1930. Notes on the tors and the clitter of Dartmoor. *Transactions of the Devonshire Association for the Advancement of Science, Literature and Art*, vol. 62, pp. 373-378.

Keywords: boulders, weathering, frost action, southwest England

Most tors exhibit pseudobedding as well as vertical fissures but the latter are far less common.[7] Most also have vertical slopes. Scree occurs at the bases of outcrops, becoming one-foot thick blocks of clitter down slope. When there are only a few blocks, they lie flat on the surface, but when there are many, they are horizontal, vertical or inclined, i.e. they dip back into the slope. Theories of clitter emplacement by ice-rafting and by sliding down snow slopes are discounted, and Worth's (1898)[8] suggestion that solifluction is in part responsible is supported. The author expands on Worth's theory by adding the concept of "pushing down by frost produced regelation" (p. 377). He cannot refute that the tors may be pre-Pleistocene, but believes they are mainly Pleistocene in origin. He believes the tors were split into slabs by frost action. Differences between granite and aureole tors are noted.

Bain, A.D.N. 1923. The formation of inselbergs. *Geological Magazine*, vol. 60, pp. 97-101.

Keywords: inselbergs, granite gneiss, theory, jointing, Nigeria

The purpose of the article is to show, from a study of Nigerian inselbergs, that the alternating wet and dry climate of the Sudan is favorable to inselberg formation. Existing theories of formation are listed. Two types of inselbergs occur: 1) dome-shaped, steep-sided, unscaleable ones formed of coarse-textured, porphyritic granite gneiss, and 2) less perfectly shaped, scaleable ones formed of other types of gneiss. Three main factors control formation: climate, jointing and the nature of the rock. Good jointing occurs only on a very large scale. Chemical weathering occurs along joints, but between joints only exfoliation occurs. Weathered debris is removed during the wet season, leaving a fresh surface to be attacked. Vegetation keeps moisture available in the dry season for further chemical weathering. This results in long, narrow valleys with steep-sided ridges between. The same procedure occurs along cross joints, eventually producing isolated inselbergs. The nature of the rock is least important, but uniformity of texture and the absence of foliation lead to more perfect inselbergs. Rock surfaces are often rough. Exfoliation is caused by diurnal temperature changes. The slabs vary between 1 and 5 feet thick. Horizontal joints also play a part.

---

[7] As stated previously, "tor" is a local name for a rock outcrop, apparently derived from a Cornish word meaning tower. Clitter refers to large detached boulders on the surface of the ground, that usually occur down slope from a tor. Pseudobedding, also a local term, refers to a form of horizontal jointing in which the joints are closely spaced and very wavy and often parallel the land surface.

[8] R.N. Worth. 1898. Some phases of Devonian detrital geology. Transactions of the Plymouth Institution, no page numbers.

Bakker, J. P. 1960. Some observations in connection with recent Dutch investigations about granite weathering and slope development in different climates and climate changes. *Zeitschrift für Geomorphologie*, Supplement 1, pp. 69-92.

Keywords: clay, weathering, climate, soils, rock basins

This article revolves around two questions: 1) How does spheroidal weathering, predetermined at some depth, proceed in different climates? and 2) What are the final clay weathering products in different climates? Chapman and Greenfield's (1949) theory of concentric exfoliation is summarized and accepted. Schermerhorn (1959)[9] found that woolsacks (rounded boulders) only occur where potassium feldspar is abundant, and generally where it forms megacrysts. He also found that woolsacks are typical forms in areas where relief is low. Three weathering periods are defined. The first is a red-yellow weathering, similar to the red-yellow U.S. podzols, where kaolinite predominates and the climate is Koppen's Cw, CFa or CXa.[10] This was probably early Pliocene. The second period probably began in late Pliocene and continued into the first interglacial. It consists of red-yellow profiles, which can occur beside bleached profiles, that are illite dominated. The climate was Mediterranean. The third period is characterized by grayish-brown and brown, illite-dominated soils in Western Europe. Thus it follows that ultimate weathering products differ and depend on climate and vegetation. Acid and alkaline weathering products from granite are different, the former having a much larger clay fraction. The author indicates that rock basins form under alkaline conditions.

Barton, D. C. 1916. Notes on the disintegration of granite in Egypt. *Journal of Geology*, vol. 24, pp. 382-393.

Keywords: Egypt, weathering, exfoliation, disintegration

Massive granular disintegration with accompanying kaolinization, which decreases with depth, is the norm in the Aswan region. The main type of present-day disintegration is exfoliation, although loosening of fragments from roughened surfaces and spalling also occur. The rock is a red, coarse, porphyritic granite. Joints are comparatively far apart; where they are close together, less exfoliation is evident. Nearby fine-grained granite is much less affected and is heavily jointed. The rate of disintegration is much slower than stated by previous workers. Disintegration is greater further north, at Luxor, Karnak and Cairo, on statues and pyramids. These suggest a rate of 1 to 0.5 cm in 5000 years. Disintegration is due to moisture.

---

[9] Schermerhorn, L.J.G. 1959. Igneous, metamorphic and ore geology of the Castro Daire-Sao Pedro do Sul-Satao region (Northern Portugal). Unpublished thesis, Amsterdam, University of Amsterdam, no page numbers.

[10] Cw is a China-type climate, characteristic of a tropical monsoon region, where summer temperatures are about the same as those of a tropical rainforest and rainfall is high. CFa and Cwa climates are characterized by hot humid summers and moderately cool winters.

Bisdom, E. B. A. 1967a. The role of micro-crack systems in the spheroidal weathering of an intrusive granite in Galicia (NW Spain). *Geologie en Mijnbouw*, vol. 46, pp. 333-340.

Keywords: Spain, granite, weathering, microcracks, flaking

Pressure release is generally accepted as the cause of large-scale sheeting and dome formation, but its relation to scaling and flaking is unknown. Chapman and Greenfield (1949) suggested dilation due to hydrolysis, oxidation and carbonation, and Schattner (1961)[11] suggested decreasing strength away from cooling centers. The granite, a coarse-grained, biotite-hornblende granite, was separated into zones ranging from unweathered rock with only structural microcracks to weathered material with released scales. Structural microcracks in zone 1 can be distinguished from weathering microcracks in zones 2 and 3 by the absence of iron oxide and by their straightness and their angular intersections. Microcracks occur in two ways: 1) directed toward the core and 2) parallel to the outer surface. The scales themselves are filled with sinuous microcracks arranged as overlapping discoids. Boulders becomes concentric because weathering is most intense on corners. The following distinction in terminology is proposed: "Spheroidal weathering thus applies to the arrangement of scales and flakes around the boulder, and concentric banding to the crack system involved" (p. 357). Concentric banding disappears toward the center of a disintegrated boulder because the cracks within the scales continue to enlarge. These results are supported neither by Schattner's theory nor, at this scale, by pressure release theories.

_____. 1967b. Micromorphology of a weathered granite near the Ria de Arosa (NW Spain). *Leidse Geologische Mededelingen*, vol. 37, pp. 33-67.

Keywords: Spain, weathering, microcracks, clay, granite

The purpose of this study is to obtain insight into weathering phenomena at the microscopic scale. The rock is a coarse-grained, biotite-hornblende granite, forms tors and is post-tectonic and late Hercynian in age. The climate is humid temperate with cool summers. Initially, weathering proceeds mainly along joints. The weathering environment in closed joints is reducing. Weathered material along joints is finer-grained. Bisdom (1967a) is summarized. Weathering stages in saprolite are described. The more coarsely grained the granite, the larger are the boulders produced. An oscillating water table chiefly affects secondary minerals along joints, not in the weathered material adjacent. Soils are described. Saprolite can be separated from colluvium in this area on the basis of heavy minerals. Gibbsite occurs only in the finest fractions whereas kaolinite is ubiquitous. Gibbsite results from weathering of the plagioclase, and kaolinite, from weathering of biotite. Feldspars weather along microcracks. The ways in which feldspar, biotite and muscovite are thought to weather are discussed. Kaolinite and metahalloysite are the most common clay minerals. The fabrics of the weathering profiles are described using Brewer's (1964) system.[12] There is more clay in weathering profiles affected by oscillating water tables. Greater thicknesses of saprolite occur in coarser-grained rocks.

---

[11] Schattner, I. 1961. Weathering phenomena in the crystalline of the Sinai in the light of current notions. Bulletin of the Research Council of Israel, vol. 10 G, pp. 247-266.

[12] Brewer, R. 1964. Fabric and Mineral Analysis of Soils. New York: John Wiley and Sons, Inc., 470 pp.

Blackwelder, E. 1925. Exfoliation as a phase of rock weathering. *Journal of Geology*, vol. 33, pp. 793-806.

Keywords: exfoliation, chemical weathering

Exfoliation is most common in granitoid igneous rocks. Existing theories are summarized. Blackwelder's observations indicate it is not a simple process. It is tensional, as indicated by the fact that the cracks are concentric around the boulder. The chief causes, traditionally, are considered to be daily or hourly temperature changes produced by insolation and heat radiation. Existing theories are discussed and most are discarded. The author concludes that exfoliation results from chemical decay in moist environments, where hydration and oxidation are favored.

Blank, H. R. 1951a. "Rock doughnuts," a product of granite weathering. *American Journal of Science*, vol. 249, pp. 822-829.

Keywords: Texas, rock basins, erosion

Rock basins or weathering pits are common and are attributed to the chemical actions of water and organic matter and wind removal of debris by most authors. Doughnuts occur on decided slopes and most are associated with joints. There is no compositional difference between the ring and the pit in the center. Doughnuts are rare in comparison to weathering pits. Possible origins are discussed and most are discarded, but he concludes that differential erosion caused by sheet floods could be the cause.

_____, 1951b. Exfoliation and weathering on granite domes in central Texas. *Texas Journal of Science*, vol. 3, pp. 376-390.

Keywords: domes, exfoliation, Texas, granular disintegration

The granite consists of pink potassium feldspar, white plagioclase, biotite and quartz. It is porphyritic, and forms domes. Domes are thought to be formed by exfoliation, commonly believed to result from pressure release upon removal of overburden. The author shows that granular disintegration is also important to dome formation. Talus is generally absent at the bases of domes. This is attributed to in situ granular disintegration; the granular debris is washed down slope and away from the domes. Exfoliation plays a major role in the formation of some weathering pits. Relative rates of exfoliation vs. granular disintegration determine the landform surface. Faster exfoliation results in imbricate sheets, such as Yosemite, whereas faster granular disintegration results in few detached boulders and a deeply pitted and dissected surface. Variations in stress in a granite body could determine which process is paramount.

Bradley, W. C., Hutton, J. T. and Twidale, C. R. 1978. Role of salts in development of granitic tafoni, South Australia. *Journal of Geology*, vol. 86, pp. 647-654.

Keywords: Australia, tafoni, salt weathering

Tafoni are enlarged inward and upward by flaking and granular disintegration. The cause is unknown, but salt weathering is "popular." The purpose of the paper is to evaluate relations between salt weathering and tafoni. The climate in the study area is semi-arid with hot summers, mild winters and 30-60 cm of rain per year. There appear to be two sets of microfractures: one unoriented, crossing, going around grains and filled with clay and iron oxide, and the other, subparallel to the ceiling or wall and cross cutting the first set, but with no filling. Flakes are no more altered than solid rock, but sulphur and chlorine are more abundant in flakes. Halite and gypsum are probably the minerals present. The authors conclude that the mechanism of salt weathering is crystal growth. Fluid inclusions in the granite are thought to be the source of the salts.

Brook, G. A. 1978. A new approach to the study of inselberg landscapes. *Zeitschrift für Geomorphologie*, Supplement 31, pp. 138-160.

Keywords: inselbergs, joint control, South Africa, theory, potassium metasomatism

An inselberg is defined as "...a residual upland in any rock type which stands in isolation above the general level of the surrounding plains" (p. 139). Bornhardts, conical hills and boulder hills may or may not be inselbergs. Bornhardts form in unjointed rock (or where joints are filled and closed) and their shape is controlled by secondary sheeting joints. Bornhardts are separated into domes, whalebacks and turtlebacks. Sheeting structures are poorly developed in conical hills, which are mantled by loose blocks and controlled by closed, steeply-dipping joints. Boulder hills have both vertical and horizontal joints, usually have massive cores, and are of two types: castle koppies or tors. Chemical weathering is concentrated at the junction between the pediment and the inselberg. There are two major theories of origin: 1) that inselbergs are residuals of pediplanation and 2) Linton's two cycle theory. Brook formulates a new theory, assuming rejeuvenation of streams, that allows both theories and their combination in different circumstances. In the Johannesburg-Pretoria dome, inselbergs are restricted to potassium metasomatized rocks; elsewhere inselbergs occur in younger, potassium-rich rocks. Inselbergs are larger and more frequent where metasomatism has sealed the joints. The bases of inselbergs do not represent lithologic contacts, but are probably boundaries in rock fissility, i.e they mark zones where fracture density changes. Fracture patterns control the regolith profile as well as inselberg form and shape.

Brunner, F. K. and Scheidegger, A. E. 1973. Exfoliation (abstract). *Rock Mechanics*, vol. 5, pp. 43-62.

Keywords: exfoliation, theory, tension fracture

Exfoliation is usually preglacial and is independent of primary structures. Plate thickness increases with depth and ordered orientation is lost at about 50 m. The stress relief theory is shown to be unsuitable. The authors present a model of tension fracture by induced tensional stress, which explains the parallelism with the surface, the increase in spacing with depth and the disappearance at depth.

Brunsden, D. 1964. The origin of decomposed granite on Dartmoor. In *Dartmoor Essays*, edited by I.G. Simmons, Exeter, Devonshire Association for the Advancement of Science, Literature and Art, pp. 97-116.

Keywords: southwest England, chemical weathering, pneumatolysis, frost action, saprolite

Three possible origins have been espoused for the origin of growan (saprolite): 1) deep chemical weathering, 2) frost shattering and solifluction, and 3) pneumatolysis. Brunsden has found evidence of all three, often in the same section, and the paper discusses how this can occur. The chemical decomposition of granite is described and weathering zones are discussed. Joint spacing varies from 1 to 20 feet. Physical weathering does not produce growan, but makes the granite more susceptible to chemical decomposition. The alteration processes are described. The growan is probably not all the same age: that associated with pneumatolysis is Late Carboniferous-Permian in age; frost-shattered deposits and head are Pleistocene; and chemically-weathered granite is probably Tertiary.

Brunsden, D. and Gerrard, J. 1970. The physical environment of Dartmoor. In *Dartmoor, A New Study*, edited by C. Gill, Newton Abbot, David and Charles, pp. 21-53.

Keywords: weathering, soils, joint spacing, southwest England, climate

Dartmoor, as well as the surrounding area, consists of bevelled erosion surfaces. There are four types of rocks: 1) contact rocks; 2) the giant granite, which forms most of the high areas; 3) the blue granite, which is visible mainly in quarries; and 4) aplite veins and dikes. Tin is found on Dartmoor, but copper is common only around the edges. Tin and copper lodes run east-west and lead lodes run north-south. Contacts between granite and country rock are usually sharp. Vertical joints are abundant and occur with all orientations. There are two main erosion surfaces, one at 1900-1700 feet and the other at 1650-1500 feet, in addition to other less important ones at lower elevations. The highest shorelines around Dartmoor are between 680 and 700 feet. Structures that control landscape evolution are 1) fault zones that control the outline of Dartmoor, 2) vertical joints that divide the rocks into blocks at 1-20 foot intervals, and 3) curved or horizontal joints that run parallel to the land surface. There are three weathering zones: 1) an upper disturbed soil zone containing mineral fragments, 2) a residual layer of pale decomposed rock, and 3) bedrock in the form of angular joint blocks. The authors state that sheeting joints form as erosion removes the upper material, allowing the rock below to fracture perpendicular to the direction of stress release. These joints control the shapes of the tors. Evidence of Pleistocene frost action consists of frost-shattered outcrops, frost-produced soil layers and small scale benched landforms. Tor formation theories are summarized. There are two types of soils: peaty and brown earths. Peaty soils form where rainfall is in excess of 80 inches per year and on slopes greater than 15 degrees. Peat is most common between 1800-1500 feet in the north and 1550-1200 feet in the south. Where peat is more than 16 inches thick, the soils are called peaty gley soils. Peaty-gleyed podzols occur on hillslopes (Hexworthy Series). Valley bogs and peaty groundwater gley soils occur where there is excess ground water, but are usually thin (Laployd Series). The brown earths comprise the Moretonhampstead Series. The soils of Dartmoor reflect the activities of man, i.e. vegetation and forest clearance. The Hexworthy Series probably developed from forest brown earths. The climate of Devon is oceanic. Average rainfall on Dartmoor is 60 inches per year, but 100 inches per year is common. Maximum rainfall occurs in January and minimum rainfall, in June. Average daily maximum and minimum temperatures for Princetown are 5.6 and 10.6

degrees, respectively, for January and 10.0 and 17.2 degrees, respectively, for July. Prevailing winds are west-southwest. Snow is common on the moor, lying 15-20 days on open moorland and 30 days on the summits. The raven is the most common bird. A general summary of bird, mammal and insect life is given. Much of the geology and geomorphology sections of this paper are repeats of parts of Brunsden (1968).

Caine, N. 1967. The tors of Ben Lomond, Tasmania. *Zeitschrift für Geomorphologie*, vol. 11, pp. 418-229.

Keywords: Tasmania, dolerite, chemical weathering, frost action

The purpose of the paper is to evaluate the Tasmanian tors in light of the two opposing theories of origin. The tors are dolerite and occur on summits, at breaks in slope, and on valley sides. Valleyside tors are most common. The area was glaciated and is affected by frost action today. Most tors are peripheral to the highland and consist of blocks 2-4 m high and 1 m across. They are usually less than 6 m high and the highest are valleyside tors. Jointing is columnar and the tors are angular. There is no evidence that periglacial processes produced tors, only that they reworked existing residuals. Caine suggests that summit and break-in-slope tors result from chemical decomposition and that valley side tors result from postglacial frost action.

Chapman, C. A. 1958. Control of jointing by topography. *Journal of Geology*, vol. 66, pp. 552-558.

Keywords: Maine, topography, joint control, sheeting joints

Joint patterns and distribution in Acadia National Park are largely controlled by surface conditions. The rock is massive, coarse, hornblende granite. Both vertical and sheeting joints are more abundant on hilltops and higher slopes than on glaciated valley sides. Joints are less common on broad, rounded hilltops than on narrow, sharp ones. There are generally two to three sets of well-formed joints and one to three sets of poorly-developed joints. The dominant joints are those favorably oriented to lateral expansion directions. The sliding down slope of sheeting layers releases pressure and allows joints parallel and perpendicular to the direction of movement to open. Joints are truncated by sheeting, indicating they opened after sheeting occurred and thus are surficial features. Joints tend to turn and parallel cliff faces. Sheeting and topography allow favorably oriented joints to open. Many other incipient joints, not properly oriented, remain closed, thus no joint study truly reflects what is really there or what the proper relations between joints are. The fact that the best-developed joints in one outcrop are less prominent elsewhere reflects local conditions. The typical joint pattern is two mutually perpendicular sets parallel and perpendicular to slope and two additional sets that cross them diagonally.

Chapman, C. A. and Rioux, R. L. 1958. Statistical study of topography, sheeting and jointing in granite, Acadia National Park, Maine. *American Journal of Science*, vol. 256, pp. 111-127.

Keywords: Maine, topography, joint control, sheeting joints

The paper attempts to interrelate jointing and sheeting with the topographic effects of stream and glacial erosion. The rock is petrographically uniform and medium grained. There are both biotite and hornblende granites; the hornblende variety is more resistant. The area is glaciated and ice movement was parallel to present valley trends. Slope measurements from maps were plotted on stereonet equivalents. Sheeting roughly conforms to present topography. It conforms least at low elevations where it is less steep than the slope. Most of the sheeting is preglacial, but some is parallel to ice-cut surfaces, indicating glacial or postglacial age. The fact that sheeting surfaces are more closely spaced on ridge tops than on ice-cut slopes favors the unloading hypothesis. When sheeting and slope diagrams are compared (the sheeting diagram representing preglacial topography), a change in valley trend of 25 degree as well as increased asymmetry are shown. The results of this study show that joints partly control topography and topography partly controls jointing. Valley walls parallel major joint sets.

Chapman, R. W. and Greenfield, M. A. 1949. Spheroidal weathering of igneous rocks. *American Journal of Science*, vol. 247, pp. 407-429.

Keywords: theory, chemical weathering, exfoliation

The purpose of the paper is to clear up confusion among exfoliation, spheroidal weathering and similar terms and processes. The first part of the paper describes the development of theories concerning spheroidal weathering. Two hypotheses are generally accepted:1) swelling and spalling caused by hydration, carbonation and oxidation, and 2) swelling and spalling caused by the intense heat of forest and brush fires. The former is more common. The second part of the paper describes the results of a microscopic study of spheroidal boulders, two of which were basalts and one, a granite. The main differences between inner, relatively unweathered granite core and weathered outer shell are 1) more feldspar and less quartz are present in the outer shell, 2) more intensely altered orthoclase occurs in the outer shell and 3) sericite increases in the outer shell. The intensity of alteration in all three samples increases outward from the center more or less regularly. The new minerals in the rocks indicate the addition of oxygen, water and possibly carbon dioxide during weathering. The new minerals are lighter, indicating an increase in volume.

Clayton, R. W. 1956. Linear depressions (Bergfussniederungen) in savannah landscapes. *Geographical Studies*, vol. 3, pp. 102-126.

Keywords: microrelief, west Africa, gneiss, chemical weathering, inselbergs

The purpose of this paper is to evaluate hypotheses for the origin of linear depressions surrounding inselbergs. The inselbergs are in garnet-hornblende gneiss and are castle koppies. The depressions have no influence on "...the rate or steepness of retreat of the mountain slopes" (p. 105). The presence of rotted rock in the depressions suggests they are areas where moisture is retained in the debris and thus zones of more thorough, nearer-surface chemical

weathering. The moisture is derived from seepage through fractures in the rock and weathered material. The rock at the inselberg foot where the depression is located is the only rotted bit; the rest of the inselberg is solid.

Conca, J. L. and Astor, A. M. 1987. Capillary moisture flow and the origin of cavernous weathering in dolerites of Bull Pass, Antarctica. *Geology*, vol. 15, pp. 151-154.

Keywords: Antarctica, dolerite, chemical weathering

The paper presents a mathematical model for the forms produced by cavernous weathering. The authors show that the actual shapes produced are controlled by spatial variations in permeability resulting from a silica coating on the rock. The variations in permeability in turn control variations in moisture flow and thus weathering and form.

Crickmay, G. W. 1935. Granite pedestal rocks in the southern Appalachian piedmont. *Journal of Geology*, vol. 43, pp. 745-758.

Keywords: Appalachians, pedestal rocks, theory

Granitic outcrops in the Appalachian Piedmont are of three types: monadnocks, flat rocks and disintegration boulders. The latter are most common and are associated with well-developed pedestal rocks. Pedestal rocks consist of a cap and a base of the same material usually of porphyritic granite. They also occur, however, in equigranular granite, granite augen gneiss and granite gneiss. All occur on upland surfaces with deep saprolite near areas of recent dissection. The caps are usually solid, fresh rock and the pedestals are friable and crumbly. In most cases, jointing has little to do with the form. Crickmay believes they result from a combination of exfoliation, which occurs mainly on the cap, and granular disintegration, which acts mainly on the pedestal.

Cunningham, F. F. 1965. Tor theories in the light of South Pennine evidence. *East Midland Geographer*, vol. 3, pp. 424-433.

Keywords: northern England, Millstone Grit, theory, chemical weathering, frost action

The purpose of the paper is to evaluate the two opposing theories of the origin of tors with respect to gritstone tors.[13] The theories are discussed with respect to landscape development, tor form, siting of tors, and the distribution and significance of the tors. Cunningham finds neither of the existing theories to be satisfactory. One area (Mother Cap Moor) is described in detail and from this, he develops a theory of origin combining aspects of the theories of Linton (1955) and Palmer and his co-workers (1961, 1962).

[13] Gritstone is a very coarse-grained quartz sandstone.

_____. 1968. The significance of Caribbean evidence in the elucidation of tors. *Caribbean Journal of Science*, vol. 8, pp. 187-196.

Keywords: Caribbean, theory, equifinality

Tors occur in three general topographic positions worldwide: on summits, along breaks in slope and in front of scarps. The chief mechanism of tor destruction appears to be penetration along horizontal joints or bedding planes. Theories of tor formation are discussed in detail, i.e. the two-cycle theory, that they are remnants of scarp retreat or that they are Tertiary but have been sub-aerial for most of their lives. The second theory involves periglacial processes. Cunningham points out that all tors do not originate in the same way.

_____. 1969. The Crow Tors, Laramie Mountains, Wyoming, USA. *Zeitschrift für Geomorphologie*, vol. 13, pp. 56-74.

Keywords: Wyoming, theory, landforms, equifinality

Four main theories of origin have been espoused for tors: 1) tors formed according to the two-cycle theory, 2) tors as unconsumed remnants of an incomplete erosion cycle involving rejuvenation, i.e. chemical weathering is not required, 3) tors as remnants of scarp retreat in periglacial conditions, and 4) tors formed in tropical conditions that are sub-aerial features throughout their existence (these have karren or lapies). Tors originate in different ways and are examples of convergence, i.e. disparate processes producing the same landform. The tors occupy two types of sites: on or near summits and on spurs. Most of the Sherman granite is unaltered. The general geology of the area is described. Medium-sized tors (up to 50 feet in height) are roughly rectangular and have a multiple woolsack form. Horizontal joints predominate and are spaced about 6 feet apart. Large tors (more than 100 feet in height) are crude domes with sheeting joints. The tops of large tors are often castellated. Cunningham proposes a theory for the origin of these tors.

_____. 1971. The Silent City of Rocks, a bornhardt landscape in the Cotterrel Range, South Idaho, USA. *Zeitschrift für Geomorphologie*, vol. 15, pp. 405-429.

Keywords: Idaho, landforms, bornhardts

The general geology and geologic history of southeast Idaho is described. The rock in the Silent City is coarse-grained hornblende granite. Many of the features in the area are bornhardts and bornhardt remnants. Bornhardts and tors are different features, the former being dome shaped with domical joints and the latter being rectangular with horizontal joints as the dominant type. The area is one of significant relief changes and there is much rotted rock; the amount of relief suggests the cause of rotting was pneumatolysis rather than deep chemical weathering. Fins occur where vertical joints are dominant. Duricrust and rock basins are common. The latter are independent of jointing and are associated with the older, thicker duricrust.

Davis, W. M. 1933. Granitic domes of the Mohave Desert, California. *Transactions of the San Diego Society of Natural History*, vol. 7, pp. 211-258.

Keywords: Mojave Desert, landforms, domes, theory, California

Lawson's (1915) theory of erosion is discussed and modified.[14] Once original slopes are worn back to the proper declivity (about 35 degrees for granite), they retreat parallel to themselves and result in an inclined rock floor covered by detritus. The final result will be a bedrock platform covered by debris with a symmetrical, low rock ridge at the crest. If the original shape is oval or round, only a pinnacle will be left. The rock floor has a hyperbolic profile, indicating the surface is merely transportational, not erosional. Once the scarp produces too little debris, sheetfloods begin to erode the detritus, eventually producing a concave surface. Desert domes are lowered most at their crests. Forms on other rocks differ from granite forms because they have less homogeneous structure and disintegrate differently. Examples of the various kinds and stages of degradation are described.

Dearman, W. R. and Baynes, F. J. 1978. A field study of the basic controls of weathering patterns in the Dartmoor granite. *Proceedings of the Ussher Society*, vol. 4, pp. 192-203.

Keywords: chemical weathering, joint spacing, frost action, engineering, southwest England

Three weathering processes have affected the Dartmoor granite: hydrothermal alteration, chemical weathering and frost shattering. The geology and geomorphology are briefly summarized and field-based grading criteria for identifying effective weathering processes are presented. The field evidence is from quarries. The probable weathering sequence is 1) the initial presence of granulated and tectonic joints, dikes and veins, 2) hydrothermal alteration including kaolinization, accompanied by de-stressing and development of sheeting joints, 3) chemical weathering following zones of previous hydrothermal alteration and closely-spaced joints, and 4) Pleistocene erosion, frost shattering and solifluction. It is relatively easy to determine the dominant process, but the precise effects of each process are much more difficult to determine.

Dearman, W.R., Baynes, F.J. and Irfan, T.Y. 1978. Engineering grading of weathered granite. *Engineering Geology*, vol. 12, pp. 345-374.

Keywords: engineering, weathering, classification

Granites are classified according to texture and grain size and there are three subdivisions: alkali granites, adamellites and granodiorites. The purpose of weathering is to achieve stability under surface conditions. Weathering processes on granite are described. The type of weathering product depends on climate. Existing weathering classification schemes are discussed. The authors present their own, highly detailed classification, based on modifications of existing schemes, but place more emphasis on engineering properties.

---

[14] Lawson, A.C. 1915. The epigene profiles of the desert. University of California Publications, Bulletin of the Department of Geology, vol. 9, pp. 23-48.

Demek, J. 1964. Castle koppies and tors in the Bohemian Highland (Czechoslovakia). *Biulteyn Peryglacjalny*, vol. 14, pp. 195-216.

Keywords: Czechoslovakia, theory, landform, weathering, composition, grain size

There are two types of castle koppies and tors: those that are formed of rock that is different from surrounding rocks and those that are composed of the same materials as surrounding rocks. They occur on summits or on the upper parts of slopes. Tors are simply smaller versions of castle koppies. Sandstone and granite forms are rounded, but in other rocks, forms are more angular. Variations in depth and degree of rotting result from differences in composition and texture as well as variations in joint spacing. Tors occur where the greatest denudation took place. Rounded forms occur in coarse-grained granite whereas forms are more angular in fine-grained granites. Different forms on the same boulder are attributed to different climates of weathering: rounded forms are attributed to hot, humid Tertiary climates and more angular forms are attributed to Pleistocene periglacial climates. He attributes granite tors to the two-stage theory and sedimentary and metamorphic tors to the one-stage theory. The latter involves unequal retreat and back-wearing of frost-riven cliffs. Tors and castle koppies are the remnants of these cliffs.

Derbyshire, E. 1972. Tors, rock weathering and climate in southern Victoria Land, Antarctica. In *Polar Geomorphology*, edited by R.J. Price and D.E. Sugden, Institute of British Geographers Special Publication No. 4, pp. 93-105.

Keywords: Antarctica, sandstone, dolerite, theory, weathering

The climate in the dry valleys is now arid periglacial. The landforms are of two types: those formed under arid periglacial conditions and those formed by periodically increased run-off. Salt weathering, frost action and thermal contraction are now the dominant weathering processes with wind as the main transport agent. The tors are sandstone and dolerite; both form angular tors. Dolerite summit tors, however, can be rounded. Chemical weathering does occur in the area, but physical weathering is the dominant process. The author suggests two theories: (1) that chemical weathering and physical weathering have alternated over time and (2) that chemical weathering is continuous, albeit slow, and occurs in drier locations, and frost weathering occurs in areas where moisture accumulates. Derbyshire believes the second theory best fits the field evidence. Neither Palmer and Neilson's (1962) nor Linton's (1955) theories fit the evidence, and Palmer and Radley's (1961) suggestion that different shapes evolve under different climates is nullified.

Dixon, J.C. and Young, R.W. 1981. Character and origin of deep arenaceous weathering mantles on the Bega Batholith, Southeastern Australia. *Catena*, vol. 8, pp. 97-109.

Keywords: Australia, physical weathering, chemical analyses, joint spacing, composition

The paper investigates the proposition that arenization, not kaolinization, is the characteristic mode of weathering for granitic rocks in humid, temperate climates. There are two landform assemblages on the batholith: rolling terrain with few outcrops except along stream valleys and higher, steeper plateaus and hills dotted with torfields. Weathering extends to at

least 13 m and the mantle tends to be continuous. Most mantles are in situ, as are the soils, which are about 0.5 m deep. Weathering does not increase or decrease as joints are approached or down slope on exposures or inward; this is evidence for disaggregation/arenization rather than for chemical weathering. They measured some joint spacings and found the means are significantly different and that spacing is wider in the torless areas than in the areas with tors. Differences in mineralogy are very important. Tor rock is much higher in quartz, and mantle parent rock is high in mafics. Also, potassium feldspar dominates in the tors, and plagioclase in the mantles. Tors are developed on granite, and the weathered mantle is developed on granodiorite. The alteration of biotite to chlorite and of plagioclase to sericite, in addition to the presence of shatter cracks, some of which are filled, indicates hydrothermal alteration occurred. Hydrothermal alteration opened pathways for weathering solutions which explains why weathering is so pervasive; it used these ubiquitous, tiny cracks for ingress. "In short, arenization on the Bega Batholith seems to be most readily promoted by a mineralogy which responds rapidly to the movement of weathering solutions through a fine network of cracks" (p. 105). Expansion of biotite is considered the most important factor leading to disintegration. Plagioclase weathering is variable. Clay, mainly kaolinite, increases toward the surface of the mantle, indicating a subaerial weathering, rather than hydrothermal, origin. The authors refute Ollier's (1965) suggestion that terrain of this type is relict and the result of deep weathering. They believe the mantles were formed during valley incision and that they are still forming today.

Douglass, P.M. and Voight, B. 1969. Anisotropy of granites: A reflection of microscopic fabric. *Geotechnique*, vol. 19, pp. 376-398.

Keywords: microcracks, structure, joint orientations

Rocks are only homogeneous in a statistical sense. Most are considered linearly-isotropic, but studies on whether they really are or not are few. The results of this study indicate anisotropy is not universal, but is very likely, and that modifications should be made for isotropic analyses. Their results also suggest microfracture orientation is non-random. Microfracture orientations are concentrated parallel to rift and grain; no other structural element is.

Dragovich, D. 1969. The origin of cavernous surfaces (tafoni) in granitic rocks of South Australia. *Zeitschrift für Geomorphologie*, vol. 13, pp. 163-181.

Keywords: Australia, tafoni, origin, weathering

The paper discusses the causes of initiation of tafoni. The rocks in the area are varied. All but porphyritic microgranites appear equally susceptible to cavernous weathering. There are two types of tafoni: basal and sidewall. The former enlarge primarily by flaking and are associated with joints and the latter enlarge by disaggregation. Tafoni can be initiated under two conditions: 1) when weathering does not act uniformly, or 2) when there are significant inequalities in the rock. Most tafoni are at or near ground level. They are initiated at points of mineralogical weakness where moisture can concentrate. They are formed by ground level weathering.

Dumanowski, B. 1964. Problem of the development of slopes in granitoids. *Zeitschrift für Geomorphologie*, Supplement 5, pp. 30-40.

Keywords: slopes, joint spacing, chemical weathering, landform, composition

Granite slopes in a number of areas are described. General joint spacing figures are given. Chemical weathering is enhanced by unequal grain size and closely-spaced joints. The quantitative proportions of specific minerals is also important; for instance, the more potassium feldspar there is, the more resistant the rock. Straight-line and concave slopes are most common in dry regions, whereas convex-concave slopes dominate in humid regions. Local conditions produce the details. Steps are common in all climates, but the effect of structure decreases with increasing humidity.

_____, 1968. Influence of petrographical differentiation in granitoids on landforms. *Geographica Polonica*, vol. 14, pp. 93-98.

Keywords: composition, fractures, geologic structure

The thesis of this paper is that structure, not climate, controls landforms. According to most people, influences on the development of regolith and landform in decreasing order of importance are: fractures, grain size, composition. Dumanowski discusses these influences with respect to specific areas, and concludes that this order of importance is not true in all areas. Rocks with high plagioclase content weather more rapidly.

Dyke, A.S. 1976. Tors and associated weathering phenomena, Somerset Island, District of Franklin. *Geological Survey of Canada*, Paper 76-1B, pp. 209-216.

Keywords: Arctic, gneiss, theory, weathering

The purpose of the paper is to provide initial information on distribution, characteristics and formation of tors in the central Arctic. Tors occur on all bedrock types — gneiss, gabbro, granite, quartzite, chert, and carbonates — and on summits and valley sides. They are not randomly distributed. Tors on gneiss often occur in linear associations, parallel to foliation and jointing. Tors on carbonates and sandstones are only briefly discussed. The tors are thought to result from subaerial physical and chemical weathering combined with periglacial mass movement.

Dzulynski, St. and Kotarba, A. 1979. Solution pans and their bearing on the development of pediments and tors in granites. *Zeitschrift für Geomorphologie*, vol. 23, pp. 172-191.

Keywords: rock basins, Mongolia, landform development, chemical weathering

The rock exposures are formed of slabs ranging from several tens of centimeters to one meter thick separated by sheeting joints; vertical joints are rare and widely spaced. The tors are all surrounded by sloping, bare rock pediments and are not randomly distributed. Pan

depth is controlled by sheet thickness. The pans are related to dissolution in standing water. The formation of pans may be the most effective factor in degradation of rock surfaces. The pan-forming processes also shape tors; armchairs, for instance, continually eat away at the sides while pans eat down from the top. Because pans develop on, at most, gentle slopes, steep slopes can be left standing. Pediments can be formed by the down-wearing of pans.

Eden, M.J. 1971. Some aspects of weathering and landforms in Guyana (formerly British Guiana). *Zeitschrift für Geomorphologie*, vol. 15, pp. 181-198.

Keywords: Guyana, chemical weathering, etch planation, theory

The landscape of Guyana is described and the author concludes it is the product of deep weathering rather than parallel retreat. The surfaces upon which the landforms are developed are considered stripped rather than rock cut. The process described is called etch planation.

Eden, M.J. and Green, C.P. 1971. Some aspects of granite weathering and tor formation on Dartmoor, England. *Geografiska Annaler*, vol. 53, pp. 92-99.

Keywords: chemical weathering, theory, tors, saprolite, southwest England

The origin of the growan or saprolite is crucial to the understanding of the origin of tors as suggested by Linton (1955) and Palmer and Neilson (1962). Both theories regard tors as relict; Linton considers them relicts of Tertiary chemical weathering and later stripping, and Palmer and Neilson consider them relicts of Pleistocene frost shattering and solifluction. Growan samples, soil material above in situ growan and china clay samples were analyzed. The high feldspar content and persisting rock texture suggest limited chemical weathering of growan. The study does support a weathering origin for the growan, but not deep, tropical weathering. Seismic and other data suggest localization of deep weathering near river valleys, as the principle determinant of tor formation and distribution.

Eggler, D.H. and Larson, E.E. 1967. Relationship of topography to bedrock type: Example of the use of geophysical and petrographic methods in geomorphology. *Geological Society of America Abstracts with Program*, p. 54.

Keywords: composition, chemical weathering, Colorado, Wyoming, saprolite

One facies of the Sherman Granite, a coarse, red granite, shows development of deep grus (saprolite), while another facies, quartz monzonite, forms tors. The red coloring is hematite, and petrography and clay mineral analyses suggest the grus formed by shattering as expanding clays developed in biotite that was previously expanded by the growth of hematite.

Eggler, D.H., Larson, E.E., and Bradley, W.C. 1969. Granites, grusses and the Sherman Erosion Surface, southern Laramie Range, Colorado-Wyoming. *American Journal of Science*, vol. 267, pp. 510-522.

Keywords: Colorado, Wyoming, composition, chemical weathering, saprolite

Topography in the Laramie Range is closely related to bedrock type. The authors conclude that the Sherman surface in its type area is associated almost exclusively with one granite (Trail Creek), because this granite disintegrates rapidly and totally to grus (saprolite) under the expanding effects of altering biotite. High temperature alteration prepared the granite for later exploitation. The grus is up to 200 feet thick and is, for the most part, in situ. The other granite, the Cap Rock quartz monzonite, forms a park land topography with tor clusters. Grain size in the Trail Creek granite varies widely and shows a relation to mineralogy. Study of the clays shows three weathering stages. The initial Precambrian alteration was caused by oxidation.

Ehlen, J. 1989a. Significant geomorphic and petrographic relations with joint spacing in the Dartmoor granite, southwest England. *Abstracts of Papers and Posters, Second International Conference on Geomorphology (Frankfurt/Main, FRG)*, Mainstrasse, FRG, Geooeko-Verlag, p. 83.

Keywords: landform, joint spacing, southwest England, rock texture

Statistically significant relations were identified between rock texture, grain size, relative relief, landform type and joint spacing. The most important significant relations identified are that mean joint spacing is different in different landforms, increases with increasing numbers of megacrysts and is generally wider in porphyritic rocks, generally decreases with increasing relative relief, and increases from valleyside to spur to summit landforms. In addition, summit landforms tend to have the greatest number of megacrysts. These relations suggest that valleyside landforms cannot evolve into summit or spur landforms as one might think they would.

_____. 1989b. *Geomorphic, Petrographic and Structural Relationships in the Dartmoor Granite, Southwest England.* Unpublished Ph.D. thesis, Birmingham, England, University of Birmingham, 2 volumes, 408 pp.

Keywords: landform, joint spacing, southwest England, rock texture, grain size, composition

The purpose of this study was to evaluate geomorphic, petrographic and structural characteristics of the Dartmoor granites. Data obtained in the field from 58 sample sites was compared to that obtained using air photo interpretation procedures using statistical and numerical procedures. Study of joint and lineation orientations indicated that it highly likely that the same joint sets are visible at both ground and image scales, but that different individuals are seen at each, suggesting that the joint sets are regional in nature and tectonic in origin.

Multivariate analysis allowed the 58 sample sites to be separated into five groups with distinctive combinations of characteristics in terms of landform, composition, rock texture, joint spacing and grain size. The five groups are also spatially distinct. Analysis of the joint spacing frequency distributions for each group showed that most of the groups were significantly different from each other with respect to joint spacing. The results of the multivariate analysis were also compared to the air photo analysis; individual clusters tend to occur predominantly in the same landform category on each photo mosaic. A new landform classification, defining landforms with respect to grain size, topographic position, rock texture composition and joint spacing was derived.

Ehlen, J. and Gerrard, A.J.W. 1988. *A bibliography of the chemical weathering of granitic rocks*. Fort Belvoir, Virginia: U.S. Army Engineer Topographic Laboratories, ETL-0505, 25 p.

Keywords: chemical weathering

This bibliography lists many of the papers in the international published geological, geomorphological and soils literature that discuss the chemical weathering of rocks considered "non-soluble." Emphasis is placed on granitic rocks.

Exley, C.S. 1961. A note on greisening in the Bodmin Moor granite. *Geological Magazine*, vol. 98, pp. 427-430.

Keywords: southwest England, alteration, greisenization

Many tors have ridged or corrugated surfaces, some of which are due to differential erosion of aplites and/or tourmaline veins. Others are caused by tiny veins of micaceous material in association with extensively altered feldspar, i.e. incompletely greisened granite. The greisen is resistant to chemical weathering and thus forms ridges. Greisenization occurred while the granite was still hot.

_____. 1976. Observations on the formation of kaolinite in the St. Austell granite, Cornwall. *Clay Minerals*, vol. 11, pp. 51-63.

Keywords: southwest England, hydrothermal alteration, clay

The paper investigates suggestions that secondary mica is an intermediate product between feldspar and clay and that plagioclase rather than potassium feldspar is the major source. The rocks used are fluorite granites, late lithionite granites and early lithionite granites. The latter are highly altered. Slices were taken of each rock at intervals away from the vein. Feldspar crystals, or their pseudomorphs, were used for analysis. X-ray was used to analyze crushed mineral fractions, but there were problems with too strong reflections for some feldspar peaks and with background reflections (the grains were cemented to glass plates). The results are thus considered to be more qualitative than quantitative. Whole rock analyses were done by flame photometry and atomic absorption. Potassium oxide tends to decrease with increasing alteration for all three rock types and sodium oxide tends to decrease

in two. Calcium oxide increases slightly, then remains constant in the fluorite granites and in late lithionite granites. In potassium feldspar, as feldspar decreases, mica increases and then appears to level off with increasing kaolinite. There is no montmorillinite. In plagioclase, montmorillinite and kaolinite increase in a general way as feldspar and mica decrease. Exley assumes mica replaces plagioclase and is in turn replaced by clay. He later describes the results as trends. His results indicate that clays form from secondary alteration products of potassium feldspars, as well as directly from plagioclase. Using the reaction curves of Hemley and Jones (1964),[15] a temperature of 325 degrees with 1 kb pressure is hypothesized. Alteration occurs with a decrease in temperature and in the ratio of activities of the potassium and hydrogen ions.

Fairbridge, R.W. 1977. Note on bornhardt formation — The King-Twidale exchange. *Zeitschrift für Geomorphologie*, vol. 21, p. 368.

Keywords: theory, landform, chemical weathering

This is a one-page note discussing the King-Twidale arguments. Fairbridge suggests that chemical weathering is continuous and that because clays from weathering of feldspar are carried away, silica becomes concentrated. This eventually produces a series of low rises and saucer-shaped depressions. Base level is lowered and bornhardts result in association with silcrete.

Farmin, R. 1937. Hypogene exfoliation in rock masses. *Journal of Geology*, vol. 45, pp. 625-635.

Keywords: exfoliation, theory, unloading

The accepted interpretation for exfoliation is that it "...is caused by volume changes resulting from chemical attack on the rock by moisture during weathering" (p. 625). Exfoliation is generally considered the product of mechanical weathering; spheroidal weathering, on the other hand, is considered the result of chemical weathering. Farmin treats the feature as structural, regardless of process. Various theories — insolation, chemical weathering, concentric weathering around solidification nuclei, and dilation resulting from unloading — are discussed. He accepts the last theory because it is the only one that could be operative in all cases.

Feininger, T. 1969. Pseudokarst on quartz diorite, Colombia. *Zeitschrift für Geomorphologie*, vol. 13, pp. 287-296.

Keywords: quartz diorite, Colombia, pseudokarst, piping

---

[15] Hemley, J.J. and Jones, W.R. 1964. Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism. Economic Geology, vol. 59, pp 538-569.

A karst-like topography occurs on quartz diorite. Neither solution nor collapse are dominant processes, however. The rock is uniform, medium grained and equigranular. Pseudokarst only occurs where local relief is 50 m or less. Slopes range from 20-35 degrees and the climate is humid tropical. The rock is highly weathered with thick saprolite. Weathering occurs by the action of ground water along joints, and the size of residual boulders depends on joint spacing. Boulder size and abundance increase with depth. Weathering of surrounding metamorphic rocks results in few boulders because weathering proceeds along foliation planes as well as along joints. Erosion is by landsliding, creep and slope wash; the slope wash is least effective and the effect of the other two is proportional to local relief. The axes of the pseudokarst depressions form a dendritic pattern, similar to drainage, and there is a hole in the bottom of each depression. The depressions are related to piping; the pipes capture the drainage in valley bottoms and pseudokarst develops.

Ford, T.D. 1962. The dolomite tors of Derbyshire. *East Midland Geographer*, vol. 3, pp. 148-153.

Keywords: dolomite, north-central England, landform

The tors occur between the elevations of 900 and 1100 feet and are not confined to horizontal beds; dip is up to 15 degrees. They vary from isolated pinnacles up to 50 feet tall to castellated escarpments 200 feet high and 0.5 miles long. The tors consist of large blocks separated by open joints. Talus occurs at the bases and breakdown/decalcification only occurs on the lower, damper parts of the tors. They are angular with only very slight rounding. The tors are postglacial.

Fritz, S.J. 1988. A comparative study of gabbro and granite weathering. *Chemical Geology*, vol. 68, pp. 275-290.

Keywords: gabbro, North Carolina, chemical weathering

The chemical weathering characteristics of granite and gabbro are compared to assess the stability of common minerals. The author studied weathering rinds. Granite rinds range from 10-70 cm thick. Solution channels connect centers of alteration (biotite and plagioclase); the channels parallel the fresh rock contact. Coalescing channels produce individual rindlets. There is no plagioclase in the outer rindlets. The best indicators of granite weathering are weight percent water and the amount of clay; both increase with increasing weathering (kaolinization). The gabbro is characterized by many thin rindlets, usually about 1 cm thick. These rindlets are low in clay. There is little depletion or enrichment of major oxides; plagioclase is relatively stable. The gabbro weathers to goethite rather than to kaolinite; the process is limonitization rather than kaolinization. The more calcic plagioclase of the gabbro should be more susceptible than the granite plagioclase. This is not the case, however, because the gabbro biotite is so much more susceptible than the granite biotite, i.e. the order of stability is different. Fritz suggests the ratio FeO/Fe_2O_3 is a better indicator of chemical weathering than sodium or calcium depletions. Rinds develop as microcracks become solution channels. Microcracks cease to propagate when they touch a void. Weathered granite has more void space than weathered gabbro so there are fewer channels and thus thicker rinds.

Gerrard, A.J.W. 1969. Mystery of the Dartmoor tors. *Geographical Magazine*, pp. 606-609.

Keywords: joint spacing, chemical weathering, theory, frost action, southwest England

The Dartmoor granite is usually cut by two vertical joint sets and one horizontal joint set. The appearance of the rock is thus controlled by joint spacing; lamellar tors have few vertical joints and closely-spaced horizontal joints, whereas massive ones have well-developed vertical joints and fewer horizontal joints. The two-stage and periglacial theories of tor formation are summarized. Joint spacing controls the effectiveness of chemical weathering. The effect of frost action depends particularly on joint intensity; where joints are parallel to the steepest slope, large faces develop. Tors located on summits may result primarily from chemical weathering, whereas those on valley sides may result primarily from frost action.

_____. 1974. The geomorphological importance of jointing in the Dartmoor granite. In *Progress in Geomorphology*, edited by E.H. Brown and R.S. Waters, Institute of British Geographers Special Publication No. 7, pp. 39-50.

Keywords: joint type, southwest England, joint orientation, landform classification, theory

The paper begins with a general description of joints in granite, and Dartmoor granites in particular. There are two types of horizontal joints: 1) primary, "normal," stress-release joints corresponding to Cloos' L joints, which are often mineralized and 2) secondary, dilation (compressional) joints caused by removal of overburden in association with developing topography. The second type are the pseudobeds. Orientation work on vertical joints by previous workers is summarized. Gerrard shows north-south and east-west as the preferred directions, which are considered to be primary. Primary joints would control landform development, particularly drainage patterns. Details of the groups of tors are controlled by the joint-controlled drainage blocks with compressional domes between. There are three types of tors: summit, valley side/spur and emergent. Summit tors occur where relative relief is more than 100 m within a horizontal distance of 800 m. Average slope angle is probably important as well. Joints must be open to be exploited by weathering; the opening of the joints as the landscape developed could result from downcutting into the domes by rejuvenated streams. This would allow the most intense jointing in summit areas, which is the case, and joints would tend to open parallel or perpendicular to the contours. Generally, the predominant joint directions in non-summit tors follow this pattern.

_____. 1978. Tors and granite landforms of Dartmoor and eastern Bodmin Moor. *Proceedings of the Ussher Society*, vol. 4, pp. 204-210.

Keywords: southwest England, landform classification, joint spacing

This paper is concerned with the detailed relations between individual tors. Statistically, emergent tors are smaller, have gentler slopes at their bases, and are different from valley side/spur and summit tors. The height difference between valley side/spur and summit tors is not statistically significant. Differences in maximum slope between valley side/spur tors and the other types is significant, but not between summit and emergent tors. The intensity of horizontal jointing differs between the three landform types. Vertical joints are more widely

spaced on emergent tors than on summit or valley side/spur tors; the difference is significant. Weathering along variably-spaced vertical joints would produce a variable weathering front and thus different tor shapes. The weathering front is nearer the surface on summits and deeper near slope bases. Valley side/spur and summit tors occur where the joints are closer, the weathering front more variable and where surface processes are sufficiently intense to remove weathered material. Emergent tors may be chance exposures.

_____. 1982. Granite structures and landforms. In *Papers in Earth Studies, Lovatt Lectures - Worcester*, edited by B.A. Adlam, C.R. Fenn and L. Morris, Norwich, Geo Abstracts Ltd., pp. 69-105.

Keywords: structure, joint spacing, southwest England, rock strength

The purpose of the paper is to view characteristics of granite with respect to their physico-chemical and mechanical nature. Granite structures, including sheeting joints, A-tents, laminae, vertical joints, headings, microfractures, microcracks and rift and grain are discussed briefly. Unloading as the cause of sheeting joints is difficult to test because the same arguments can be used for unloading and for primary structures. Most people accept unloading, but the corollary is that many vertical joints would then have to be secondary. Vertical joints are usually tension fractures. Microfractures are feather joints. Irfan and Dearman (1978)[16] define seven types of microcracks. Rift is the easiest splitting direction; grain is at right angles to rift and is the second easiest splitting direction. Both are independent of flow lines and sheeting, and are parallel to fluid inclusions and microfracture concentrations. Various aspects of granite jointing, including orientation, spacing, joint surfaces, aperture thickness, infill material, water and continuity are discussed. Fracture spacing is probably the most important factor defining granite landscapes. Rocks with discontinuous fractures are stronger than ones with continuous fractures. Landforms reflect the interaction between rock strength and geomorphic processes. Relations between the physical properties of jointed rock and the characteristics of joints can be analyzed three ways: the finite element method of mathematical modeling, the construction of physical models, and observations of behavior in the field. Strength of joint surfaces can be addressed in terms of unit stiffness across and along the joint and shear stress along the joint. In eastern Bodmin Moor, the tors form a rectilinear pattern; the east-west alignment of tors is favored by narrower joint spacing in this direction. The three types of tors represent a continuum in evolution. Landscape and tor evolution is discussed, as described in Gerrard (1974).

Gibbons, C.L.M.H. 1981. Tors in Swaziland. *Geographical Journal*, vol. 147, pp. 72-78.

Keywords: Swaziland, grain size, landform

The purpose of the paper is to describe the distribution, nature and origin of the 2171 tors in the area. Air photos, topographic maps and Landsat imagery were used to map the tors. The highest density is on the youngest, coarsest granite; density is low on fine-grained granites. Spheroidal forms are most common on medium-grained rock and large, rectangular

---

[16] Iran, T.Y. and Dearman, W.R. 1978. Engineering petrography of a weathered granite in Cornwall, England. Quarterly Journal of Engineering Geology, vol. 11, pp. 233-244.

tors are most common on the coarse-grained granites. Tors are smaller where the rocks are well jointed. There is a strong correlation between joint and tor alignments, and the densest tor concentrations are found in heavily faulted and jointed areas. The distribution and morphology of the tors does not appear to be related to topographic factors (relief, valley incision or slope retreat). The most important factors are large scale geologic structures and rock texture.

Gilbert, G.K. 1904. Domes and dome structure of the High Sierra. *Geological Society of America Bulletin*, vol. 15, pp. 29-36.

Keywords: landform, sheeting joints, theory, California

There are two general theories for the origin of sheeting structures: 1) that they are original (primary) structures or 2) that the structures are subsequent to form and are caused by some reaction with the surface. Sheeting appears to be limited to a shallow depth, not more than 100 feet. This, in addition to the facts that 1) sheeting conforms to surface expression, 2) the structure of one mass is independent of others, and 3) the sheeting planes do not cross joints, indicating they are younger than the joints, indicates theory 2 is probably the correct one. Sheeting only develops in massive rock. There is no relation between vertical joint planes and topography. The author appears to be saying that joints and sheeting tend to occur separately and that domes survive because there are few to no vertical joints providing access for weathering and eventual destruction. Three theories of origin are discussed; insolation, the expansive forces of weathering, and dilation due to unloading. Gilbert concludes that there is not enough evidence to make a choice between the different theories. Rounding, however, is caused by flaking along partings.

Hack, J.T. 1966. Circular patterns and exfoliation in crystalline terrane, Grandfather Mountain area, North Carolina. *Geological Society of America Bulletin*, vol. 77, pp. 975-986.

Keywords: North Carolina, circular pattern, sheeting joints, joint spacing, gneiss

The circular forms were first observed on air photos and are believed to be erosional, usually resulting from sheeting or exfoliation. The patterns are defined by arcuate drainage and vegetation lines, domical features and basin-shaped hollows. They average 2500 feet in diameter. The features cross lithologic boundaries. The rocks are mainly gneissic, but some granitic rocks occur. Several circular features are described in detail. The radii of curvature in particular areas are similar. The features are classed as domes, basins, and rings or partial rings. There is no relation between rings and original structural features. Size, density and form vary with rock type. Study of other areas suggests circular features such as these are characteristic of crystalline rock and are uncommon on steeply-dipping sediments; circular patterns on sediments with other attitudes are unlike these features. These features are probably controlled by secondary structural features such as joints, and exfoliation is the most likely cause for the fractures that lead to their formation. In this area, joint patterns cannot be related to landform. Sheeting generally parallels slope, but also cannot be related to particular topographic characteristics. Sheeting dips less than slope and local slope strikes and sheeting strikes are discordant; any relation between slope and sheeting is confined to the shallowest sheeting, although dip directions generally correspond. Hack discusses the open/

closed joint situation and concludes that the manner in which tectonic joints open is probably dependent on sheeting. Rings and basins probably result from large spalls and domes are related to sheeting.

Handley, J.R.F. 1952. The geomorphology of the Nzega area of Tanganyika with special reference to the formation of granite tors. *19th International Geological Congress (Algiers)*, vol. 21, pp. 201-210.

Keywords: Tanzania, landform, theory

The characteristics of the granite in comparison with those of more fissile and bedded rocks plus factors governing erosion are the dominant influences on tor formation. Tors are associated with three erosion surfaces. On the African Surface (the oldest), tors occur only on summits and drainage divides. On the younger surfaces, tors occur in valley bottoms and on valley sides and consist of low, rounded whaleback ridges or rounded boulders. Tor slopes are steep, never less than 30 degrees. Pinnacles and needles occur. Boulder tors are associated with joints. Tafoni and rock basins are present and there is little talus or debris. Granite is the most suitable rock for tors because of the wide joint spacing and its resistance to mechanical weathering. Weathering occurs along joints. An explanation for spheroidal forms is given. The author believes tors form as a result of streams cutting their channels in the surrounding grus, removing it, and leaving the tors upstanding. Handley is thus espousing the two-cycle theory several years before Linton published his work.

Harriss, R.C. and Adams, J.A.S. 1966. Geochemical and mineralogical studies on the weathering of granitic rocks. *American Journal of Science*, vol. 264, pp. 146-173.

Keywords: chemical weathering, soil, clay, southeast United States, granodiorite

This paper addresses the geochemistry and mineralogy of granite weathering profiles emphasizing cation movement, soil-water equilibrium and the biogeochemical implications. The five soil profiles were located in Georgia and Oklahoma. The petrography of the two granites and the granodiorite is described. Only kaolinite occurs in the Georgia profile whereas kaolinite, illite and montmorillinite occur in Oklahoma. The relative mobilities and distributions of the various elements are described. Study of soil-water equilibrium shows the Georgia granodiorite soil is in equilibrium and is a mature soil whereas the Oklahoma granite soils are not in equilibrium and thus are immature.

Hitchcock, H.D. 1967-68. The origins of the surface relief in the area of Carnmenellis, Cornwall. *Transactions of the Royal Geological Society of Cornwall*, vol. 20, pp. 152-162.

Keywords: southwest England, joint orientations, erosion surfaces, pseudobedding

The study attempts to determine the extent of denudational surfaces on the Carnmenellis pluton and their altitudes. Surfaces are defined as those with less than two-degree slopes. One-quarter of the area was classed as erosion surface with two main heights: 600 and

700 feet. Hitchcock suggests the dome is symmetrical and was not much higher than the present summit. The highest point is not in the center of the dome, but central to the river heads. As it is likely that only one type of granite (with variants) comprises the pluton, it is unlikely that compositional variations could have controlled development of the drainage pattern. Major joint directions are south-southwest/north-northeast, which are related to mineral lodes, and west-northwest/east-southeast, which are related to flow structures and megacryst alignments. Valleys do not follow the zones of most frequent joints. Joints ease access for weathering agents to the granite, but do not affect river flow directions. Pseudobeds are not horizontal, but parallel to slope.

Holman, W.R. 1976. *The origin of sheeting joints: A hypothesis.* Unpublished Ph.D. thesis, University of California at Los Angeles, 75 pp.

Keywords: sheeting joints, theory, microcracks

This thesis focuses on the influence of topography on sheeting. Topography is more amenable to analysis than other possible influencing factors. Holman models various load conditions and finds that "...only a large near surface expansion with fractures according to the maximum-principal-strain criterion, which is not generally accepted, produces the observed pattern of sheeting" (p. 5). Tension fractures originate only near convex ridge crests whereas those due to compression occur first beneath valleys; sheeting commonly originates on dome flanks. The release of grain-scale residual strain by microcracking is suggested as the mechanism. Sheet thickness is unrelated to topographic slope.

Huber, N.K. 1987. "The Role of Joints." In *The Geologic Story of Yosemite National Park*, Reston, Virginia, U.S. Geological Survey Bulletin 1595, pp. 30-35.

Keywords: sheeting, landform, California, joint spacing

This is a simple explanation of the role of joints in shaping the landscape of Yosemite National Park written for the layman. Huber describes joints as the most important structures in forming the landscape. The joint patterns and different types of joints are described at regional and outcrop scales. Composition, grain size and rock texture are portrayed as having an important influence on joint spacing. These effects are illustrated with specific examples. Sheeting joints and unloading are discussed and examples are given.

Hurault, J. 1967. *L'Erosion regressive dans les regions tropicales humides et la genese des inselberg granitiques* (summary in English). Institut Geographique National, Etudes de Photo-interpretation No. 3, 68 p.

Keywords: Africa, air photos, climate, sheeting joints

In the same climate, different processes work simultaneously depending on the nature of the rock. This study addresses granitic rocks in the humid tropics. Subsurface weathering probably plays a role in shaping domes. Hurault defines fractures as regional and continuous

and joints as local and discontinuous. Curved joints are considered secondary and have no relation to the true distribution of joints. Where joint and fracture directions do not coincide, drainage follows fractures and inselbergs follow the joints. Four morphologic systems are identified. Sheeting joints are considered secondary effects associated with arid climates. Inselbergs never occur where there are three joint directions in the tropics; this is not true in arid regions, suggesting the latter are not of the same origin.

Jahn, A. 1974. Granite tors in the Sudetan Mountains. In *Progress in Geomorphology*, edited by E.H. Brown and R.S. Waters, Institute of British Geographers Special Publication No. 7, pp. 53-61.

Keywords: Poland, landform, theory

Tors occur all over the Sudetan massif, but characteristically occur on convex landforms (ridges), often rising from convex breaks in slope. There are three tor forms — table-hills; towers; and rounded, loose blocks — which occur in different areas, and there are two types of granite — equigranular and porphyritic. The weathering product is comparable to Dartmoor growan (saprolite). Tor shape is associated with fracture pattern. Tors occur in the harder granite, i.e. shape correlates with local structure. Jahn accepts Linton's (1955) two-cycle theory for the formation of these tors. The author believes deep weathering occurred in late Tertiary and that stripping was periglacial. Absence of a vegetative cover assisted stripping. Tors increase in age upslope. The number of tors increases with increasing valley network density. Tors are not considered residual hills, but forms developed on residual hills.

Jahns, R.H. 1943. Sheet structure in granites: Its origin and use as a measure of glacial erosion in New England. *Journal of Geology*, vol. 51, pp. 71-98.

Keywords: New England, sheeting joints, glacial erosion, gneiss, quartz monzonite

Sheeting tends to conform to the granite surface, except on slopes, particularly south slopes, where slope is greater than sheeting dip. This is due to the oversteepening of these slopes by glacial plucking. The characteristics of sheet structure are closely related to the amount of glacial erosion. The rocks include granite, granite gneiss and quartz monzonite. Sheeting is similar in all three, as well as in anorthosites, paragneisses and all other intrusive rocks of intermediate and acid composition. As depth increases, sheeting becomes progressively thicker, more horizontal and less irregular. Sheeting is best developed on the most massive rocks and the least jointed granites are the most thinly and regularly sheeted. The quaquaversal dips of sheet structure are independent of primary structures. Sheeting does not conform to the original shape of the intrusion. Sheet structure not only parallels the surfaces of hills, but also hollows and valleys. Sheeting extends at least to depths of 320 feet. Sheeting fractures are flat to undulatory. Theories of origin are discussed and Jahns concludes that the most probably cause is dilation upon release of primary confining pressure. Sheeting is preglacial, but "secondary," post-glacial sheets parallel to the new land surface also exist; these are of minor importance. "...Sheeting broadly controls topography when denudation is relatively slow and long continued but is reoriented when strongly concentrated erosion by water or ice creates relatively rapid topographic changes" (p. 84). The greatest amount of granite is removed by glacial plucking and abrasion where the rocks are intricately jointed. There appears to be a quantitative consistency between thickness of sheets and depth. Sheeting varies with mineralogy and texture.

Jeje, L.K. 1973. Inselbergs' evolution in a humid tropical environment: The example of South Western Nigeria. *Zeitschrift für Geomorphologie*, vol. 17, pp. 194-225.

Keywords: Nigeria, composition, joint spacing, landform, chemical weathering

Most authors working in semi-arid and subtropical areas believe inselbergs are formed by pediplanation and exfoliation or pediplanation and parallel slope retreat whereas workers in the humid tropics espouse differential weathering and multicyclic erosion. This paper addresses the effects of structural variation on inselberg development in the humid tropics. Air photos were used. Granite or gneiss forms 85% of the inselbergs. The granites are coarse grained, porphyritic and poorly jointed. Granite inselbergs are usually elongate and symmetrical, and are larger and higher than gneiss ones. Castle koppies occur only in granite. Although granite occupies only 15% of the area, more inselbergs are composed granite than of other rock types. Inselbergs occur where structural conditions permit rather than where pedimentation would favor their existence. Granite inselbergs mark petrographic boundaries. The structural control is provided by spatial variation in joint distribution. The contiguity of different landforms can only be explained as the result of deep chemical weathering. Jeje concludes the inselbergs were formed by differential weathering and erosion and that they are pre-Tertiary in age. Inselberg destruction is related to the opening of tight joints, unloading and exfoliation, and to the development of gullies. Rock basins form on weaker intrusions or where joints converge. Basal sapping is common on all inselbergs. Surface run-off and gulleying are more important to inselberg destruction than weathering. Rates of destruction are slow.

_____. 1974. Effects of rock composition and structure on landform development: The example of the Idanre Hills of western Nigeria. *Journal of Tropical Geography*, vol. 39, pp. 43-53.

Keywords: Nigeria, joint spacing, joint control, chemical weathering, gneiss

This paper illustrates the influences of rock composition and structure on landform and drainage characteristics. Air photos were used. Joint patterns and orientations are described. Different patterns occur in different areas and are associated with different types of landforms. Drainage is joint controlled and stream density and frequency correspond to joint density and frequency; this is a statistical correlation. Gneisses are highly susceptible to chemical weathering because of foliation, steepness of dip and compositional variations. Granites are less so and depth of weathering corresponds to joint density and pattern; the weathering front would thus be highly irregular. Diorites weather more easily than granites because of their composition.

Jones, T.R. 1859. Sketches from Note-Books: No. 1 — Notes on some granite tors. *The Geologist*, vol. 2, pp 301-312.

Keywords: southwest England, weathering, rock basins, landform classification

Jones identifies three landform types in the Dartmoor granites: 1) tors - irregularly prominent masses of rudely-heaped rock fragments, 2) cheesewrings - regularly piled heaps or pillars, and 3) logan stones.[17] The joint patterns in quarries near Haytor on the eastern side of Dartmoor are described as they relate to future landforms of the above descriptions. Weathering occurs along joints, forming distinct rounded blocks. Ormerod (1859) is quoted extensively on the origin of rock basins. Jones says rock basins rarely occur where vertical joints are well developed.

Kamineni, D.C. and Dugal, J.J.B. 1982. A study of rock alteration in the Eye-Dashwa Lakes Pluton, Atikokan, Northwestern Ontario. *Chemical Geology*, vol. 36, pp. 35-57.

Keywords: Canada, hydrothermal alteration, drill cores

The authors looked at degree of alteration, grain size, mineralogy and fracture fill in drill cores from a granite pluton that also contains leucogranite-granodiorite and syenodiorite. Color change to pink is related to degree of alteration; deep pink means much alteration and intense fracturing, whereas grey rock is relatively unfractured and unaltered. Least altered rocks are high in CaO and the most altered are high in magnesia. Calcium is removed from plagioclase and iron from biotite. The later migrates to fractures to produce the pink color. The alteration is hydrothermal; a model is presented. The minerals produced by alteration may retard radionuclide migration because they have lower porosity and permeability and higher sorption capacity. Also, if the heat produced by stored waste causes similar alteration, then the stored waste could provide its own barrier.

Kelly, W.C. and Zumberge, J.H. 1961. Weathering of a quartz diorite at Marble Point, McMurdo Sound, Antarctica. *Journal of Geology*, vol. 69, pp. 433-466.

Keywords: quartz diorite, Antarctica, physical weathering, salt weathering

Samples of a fine-grained quartz diorite, ranging from fresh to the crumbled weathered fraction, were collected to evaluate the efficacy of chemical weathering. Because the rock is bare, surface temperatures are higher than air temperatures. As a result, freeze/thaw cycles determined from air temperature data do not necessarily apply to rock surfaces. The rock is hydrothermally altered. Bulk composition remains relatively constant throughout the weathering cycle and no clay is formed, hence there is a lack of chemical weathering. Salt has been added to the more weathered samples by sea spray. Chemical analyses are provided. Disintegration must therefore be physical, and they suggest freeze/thaw accompanied by salt crystallization is the cause.

---

[17] A logan stone is a balanced rock that moves.

Kesel, R.H. 1977. Some aspects of the geomorphology of inselbergs in central Arizona, USA. *Zeitschrift für Geomorphologie*, vol. 21, pp. 119-146.

Keywords: Arizona, inselbergs, morphology, schist, weathering

This paper addresses the morphology of inselbergs and attempts to determine the processes that give rise to them. Of the nine inselbergs studied, seven are granite and two are schist. The term "inselberg" is restricted to erosional remnants resulting from subaerial processes. Air photos were used in the analysis. Slope profiles on granite consist of segments separated by breaks in slope whereas schist profiles are smoother. Granite slopes are also much steeper and may be stepped (joint controlled). The piedmont angle is much sharper on granite (11.7 degrees vs. 3 degrees). Granite pediments are also slightly steeper than schist ones, and are longer. Particle size analysis was conducted on the surficial debris. Plagioclase, and to a lesser extent, biotite, are lost in the breakdown of the granite; the plagioclase loss results from chemical weathering. Uplift followed by quiescence or slowed stream cutting appear to be essential to inselberg formation. Physical weathering is dominant and is primarily by sheeting and spalling. Although slopes are less steep, material is moved down slope more rapidly on schists, probably because particle size is smaller; surface roughness is also lower on schist. Kesel shows lateral planation is not the cause of pedimentation.

Kieslinger, A. 1960. Residual stress and relaxation in rocks. *Proceedings of the 21st International Geological Congress (Norden)*, part 18, pp. 270-276.

Keywords: sheeting joints, stress release

All rocks have been compressed some time in their history and when the stress is released, the rocks "relax" very slowly, so that residual stress remains. Sheeting is parallel to the surface, independent of petrofabrics, extends to depths of 40-50 m and cannot occur in jointed rock. The surface that sheeting parallels is not necessarily the present one. Rift, grain, hardway, etc., (quarrymen's terms), extend only to 40-50 m depth as well; they also result from relaxation of residual stress.

King, L. C. 1949. A theory of bornhardts. *Geographical Journal*, vol. 112, pp. 83-87.

Keywords: inselbergs, theory, Africa, pediplanation

All existing theories of inselberg formation were evaluated in the field and found wanting. King thus states that

> Briefly, no single thing, structure or process is responsible for the development of bornhardts. Bornhardts are due to the twin processes of pediplanation (scarp retreat and pedimentation) acting upon suitable rock types, following a geological history which involves stream rejuvenation. (p. 83)

All forms from tors to domes are classed as bornhardts. Bornhardts occur only in plutonic igneous or metamorphic rock, usually of acid composition. The rocks must be moderately

resistant to chemical weathering. Margins are erosional, not petrographic boundaries. Although curved joints are not essential to formation, they exercise considerable influence on external form. The normal, subrectangular joint systems of these rocks exert considerable influence on nature and distribution. Bornhardts are found only where there is evidence of two cycles of erosion. Pediments occur at the bases of almost all African bornhardts. Profiles are concave and water action is the dominant process. The bornhardt cycle is a pediplanation cycle consisting of three stages: 1) In youth, stream incision, followed by pedimentation and scarp retreat, produces a jumble of bornhardts and castle koppies. 2) By maturity, many bornhardts have disappeared, leaving a wide pediplain, but those that remain are imposing. Where jointing exerts powerful control, castle koppies occur. 3) In old age, an extensive pediplain occurs, with rubbly boulder piles.

_____. 1958. Correspondence on the problem of tors. *Geographical Journal*, vol. 124, pp. 289-291.

Keywords: theory, southwest England

King's response to Linton: There are two kinds of tors: skyline and subskyline. Linton's basal platforms could not be such because they are too smooth. Joint spacing is not adequate for differential subsurface weathering. Subsoil development and subsequent exhumation are therefore unnecessary. Skyline tors are residuals on old age surfaces. Subskyline tors are the result of later erosion cycles. They do not have pediments and occur as the result of deep chemical weathering and exhumation resulting from redissection of the land surface. King postulates that the present skyline tors throughout Britain are residuals on a "master" erosion surface. The skyline tors are probably early Tertiary, and the subskyline tors are probably Late Tertiary at the earliest. This suggests Pleistocene activity was minor.

Linton's reply to King: Linton differentiates ridge and valley side tors, but believes they have the same origin, differing only in age, degree of exhumation and later modification. Skyline tors are older and have been more affected by periglacial processes. He sees no evidence in Britain that they are formed by the action of surface water. He completely discounts King's master erosion surface.

_____. 1966. The origin of bornhardts. *Zeitschrift für Geomorphologie*, vol. 10, pp. 97-98.

Keywords: inselbergs, theory, scarp retreat, rejuvenation

King accepts a theory of origin for the bornhardts that consists of two erosion cycles, but does not believe that deep weathering is either necessary or likely. Stream incision along joints is the cause of many bornhardts in Central Africa and Brazil. The 1000-1500 foot height of bornhardts greatly surpasses the known depth of weathering. In addition, joints are usually closed at depths greater than 300 feet and cores show no weathering. Bornhardts are formed by scarp retreat in rejuvenated landscapes. Boundaries disregard structure. Once created, shape is a function of the rock material. Destruction occurs by granular disintegration and gulleying. Pre-weathering followed by rejuvenation may explain minor subskyline tors where relief is small, but it cannot explain large fields.

_____. 1975. Bornhardt landforms and what they teach. *Zeitschrift für Geomorphologie*, vol. 19, pp. 299-318.

Keywords: inselbergs, Africa, theory, pedimentation

Not all inselbergs are bornhardts; the former are residual hills on an old age plain of denudation and the latter occur below the level of the erosion surface. Boundaries are erosional, not petrographic, and bornhardts are independent of climate. They are virtually impenetrable by water, so do not decompose readily to regolith. Wasting is by scaling and spalling and grus is not common. Bare, domed crests and smooth rock faces are characteristic. The quality of the rock governs the appearance of bornhardts, whereas the waste mantle provides control for ordinary hills. Igneous granites seldom form true bornhardts as these granites are too weak. Joint distribution and occurrence are important to the bornhardt shape. King discounts the Linton theory for these reasons: 1) known depth of weathering and regolith thickness are too little to account for bornhardt type, 2) bornhardts do not show the effects of chemical alteration, 3) vertical downwearing is required to remove regolith, but this theory has been supplanted by that of scarp retreat and pedimentation, 4) bornhardts are not attacked from below by chemical weathering, 5) weathering is supposed to occur along joints, but bornhardts owe their existence to the absence of extensive joint networks, and are characterized by curved joints that develop as the bornhardt develops in the open air (older joint systems are sealed); true bornhardts are different in origin from tors and castle koppies, which can develop where rocks are well jointed, and 6) rock mechanics teaches that bornhardts cannot be formed of discrete blocks. Bornhardts differ from ordinary hills in the precipitous nature of their bare rock surfaces, the absence of waste mantle, and the contrast between their steep slopes and the gentle slopes of surrounding plains. They develop by stream incision and valley side slope evolution in tough, unweathered rock after uplift. Further evolution is dominated by scarp retreat and progressive widening of pediments. Three factors thus govern the appearance of bornhardts: 1) suitable bedrock and structure, 2) sufficient relief, and 3) the stage of the current erosion cycle. Once established, bornhardts evolve by parallel retreat. King does allow that rock basins, tafoni, and other similar fractures are formed by chemical weathering, but only at a late stage.

Kranz, R.L. 1979. Crack growth and development during creep of Barre Granite. *International Journal of Rock Mechanics and Mining Science and Geomechanics Abstracts*, vol. 16, pp. 23-35.

Keywords: microcracks, fractures, experimental, propagation

The purpose of the paper is to understand how cracks grow and interact in a rock under constant stress as a function of time and to relate this to the common creep curve. Kranz defines his terms, then describes the experimental procedure. The cracks were produced in the rock and analyzed using scanning electron microscopy (SEM). There were distinct differences between cracks in stressed and unstressed rock. Micas and minerals next to micas were most cracked for both. Almost all cracks were tensile. The crack aspect ratio distribution shifts to lower values with increasing stress and time. Cracks appear to close down to an equilibrium value once stress is removed. Stress and time tend to increase crack length. Loading induces new cracks and makes old cracks grow. The number of cracks increases with stress until creep begins when they appear to decrease in number. Crack orientation tends to change over time, moving to + 45 degrees to stress direction. Creep theories are discussed.

New cracks do develop under constant stress. Under constant strain, growth is limited by the rate of stress applied, but under creep, the controlling factor is the rate at which corrosion can decrease crack tip strength. The presence of cleavage planes can change everything.

Lee, F.T., Miller, D.R. and Nichols, T.C., Jr. 1979. The relation of stresses in granite and gneiss near Mount Waldo, Maine, to structure, topography, and rockbursts. *20th U.S. Symposium on Rock Mechanics (Austin, Texas)*, pp. 663-669.

Keywords: sheeting joints, Maine, stress, joint spacing

The purpose of this paper was to identify rock properties that promote rockbursts. The granite plutons intrude eugeosynclinal metasedimentary rocks. Sheeting is well developed and vertical joints are rare. Sheets are 3-20 cm thick, increasing to 3 m and greater at depths of 7-15 m. Subhorizontal shear zones are associated with upper levels of sheeting. Sheeting is considered to result from unloading because it cuts the youngest igneous rocks in the area (dikes) and affects glaciated and unglaciated terrains equally. Horizontal stresses are greater than can be explained by rock load and magnitude differences occur between sheets; the greater the block size, the greater the stress. Stresses in the mountain site are much greater than in the valley site, which surprised the authors because this is contrary to conventional analyses. The bedrock adjusted to erosional loading changes by strain relief, which decreases inward. They state

> The tendency for these rocks to relax was restrained by an interlocking fabric of anisotropic mineral grains, cohesion between grains, shear stresses along fractures, and stiffness variations among different rock types...Sheeting is a consequence of the slow upward expansion (decompression) brought about by erosional unloading (p. 666).

The depth at which sheeting occurs varies and is controlled by in situ stress magnitudes, stress concentrations due to topography, rock strength and deformation properties (including jointing and foliation) and the effects of ground water. The latter can explain why stress is less in the confined valley site, because rock properties including tensile and compressive strength, hardness and crystallographic control of fractures can be affected by small amounts of water. Water can extend sheeting fractures.

Leese, C.E. 1932. The rock basins on the tors of Cheesewring and Roughtor. *118th Annual Report of the Royal Geological Society of Cornwall*, pp. 219-226.

Keywords: southwest England, rock basins, weathering, vegetation

Rock basins on Cheesewring and at Roughtor on Bodmin Moor are described. Leese attributes them to the action of vegetation, water and wind. Lichens pit the surface first, then temperature changes, attrition by wind- and water-borne particles and the chemical action of water enlarge the pits to form basins, and mosses move in. The lichens break down the feldspars by producing carbon dioxide.

Leigh, C.H. 1970. Tors of subsurface origin. *The Australian Geographer*, vol. 11, pp. 288-290.

Keywords: Australia, joint spacing, chemical weathering, theory

Not all tors are of the same origin. These tors occur in areas of intermediate joint spacing (4-20 feet). Where spacing is less than 4 feet, corestones develop and where it is more than 20 feet, domes and whalebacks occur. Tor size corresponds to the zone of "correct" spacing and block size to the intensity of jointing. Tor height is restricted by the depth of weathering. Subsurface extent of exposure and degree of weathering are also important. Two tor groups are described. Stripping of weathered mantle is by stream incision and slope retreat. Tors occur on valley sides and summits. Destruction is slow and occurs by collapse and granular disintegration and spheroidal weathering.

Leonard, R.J. 1929. Polygonal cracking in granite. *American Journal of Science*, vol. 18, pp. 487-492.

Keywords: Arizona, polygonal cracking, weathering

Polygonal jointing is normally attributed to cooling, but recently has been shown to result from weathering as well. The granite outcrops are castellated, typical of arid regions. There is some rounding, but the aspect is generally blocky. Faces of large blocks and outcrops show polygonal cracking. The rock is varnished and/or case hardened. Cracks average 1-2 inches in width and depth. The cracks have rough surfaces. As weathering proceeds, the less resistant material behind the polygons disintegrates and polygonal slabs fall away. The important factors in induration probably are 1) infiltration of silica from solutions circulating along joints and local granulation and 2) solution and recrystallization of quartz on joint surfaces. The cracks are probably primary and have been opened and widened by weathering.

Linton, D.L. 1952. The significance of tors in glaciated lands. *International Geographical Union Proceedings, 8th General Assembly (Lisbon), 17th International Congress*, pp. 143-147.

Keywords: theory, glaciation

The tors in southwest England are described and "nominated" as the type for tors in general. Tors are being destroyed and modified by present day atmospheric weathering. "The true tor is an upstanding rock feature which is firmly anchored in bedrock at the base" (p. 144). Exhumation of tors is due largely to the activity of rejuvenated streams. Exhumed tors in glaciated areas could not have been overridden by ice.

_____. 1955. The problems of tors. *The Geographical Journal*, vol. 121, pp. 470-487.

Keywords: southwest England, theory, joint spacing, chemical weathering

Atmospheric weathering is in the process of destroying tors and there is no evidence it had a hand in forming them. The tors are in situ and their shape is controlled by the joint pattern. The most likely origin is subsurface rock rotting by acidulated ground water along

joints. Because parts of tors are shaped like corestones, the process could be the same. This is a two-stage process: 1) rotting, and 2) exhumation by stripping. Chemical weathering works mainly downward, but to a limited extent, it works upward from pseudobeds as well. Many tors look as if they are formed by this process, but there is direct evidence of such origin in Two Bridges quarry on Dartmoor in addition to that in other areas. Topographic and structural factors control tor location. They occur in four positions: 1) on summits, 2) on gentle slopes leading to summits, 3) on breaks in slope along valley sides, and 4) on spurs. They all rise from flat or gently sloping surfaces. All occur in positions where movement of groundwater is deficient, but joint spacing is probably the main factor. The areas of closely-spaced jointing are the norm where complete rotting takes place; some clitter would necessarily be the corestones from these areas. Pseudobedding probably does not act as the surface of the basal platform, except possibly locally, and the regional surface is probably controlled by the water table. The surface may be irregular where joints were closely spaced, but would be smooth where widely-spaced joints occur. Tor height is determined by the difference between the original surface and the water table. This explains why the highest tors are in spur end positions. Definitions are given. As list of tors on other rock types and in other areas is given. The most common rock types are granite, gritstone and arkose. The latest possible date for rock rotting is the latest inter-glacial, but it could have been much earlier, i.e. late Tertiary when the climate was warmer. The last glacial episode is the probable time of exhumation, although exhumation is probably ongoing for valley side tors. The distribution of tors is controlled by the distribution of suitably massively jointed rocks.

_____. 1964. The origin of the Pennine tors - An essay in analysis. *Zeitschrift für Geomorphologie*, vol. 8, pp. 5-24.

Keywords: northeast England, sandstone, theory, weathering

The paper is a critique of Palmer and Radley's (1961) paper on the Pennine tors in Yorkshire in which they denounce Linton's two-cycle theory. Palmer and Radley's (1961) paper and ideas are summarized. Their arguments are considered under five headings: geographical distribution, time relationships, relationships to slope phenomena, forms, and analogies with cold climate forms. Linton seems to be saying that because tors occur in areas not glaciated during the Pleistocene, Palmer and Radley's requirements for permafrost and periglacial conditions cannot be met. With respect to time, he agrees that the tors were formed in late Quaternary, but he does not accept that any tors survived actual glacial overriding. Just because tors are associated with periglacial features does not mean they were formed by periglacial processes. He completely rejects Palmer and Radley's thesis that tors are formed by frost action and that rounding is subsequent and results from atmospheric weathering; the characteristics of the open joints are those of chemical weathering, not frost action. The forms of the Pennine tors are not at all like those being formed today by frost action. He sums up: argument 1 is undecided in the Pennines, but against them elsewhere; argument 2 is based on unproven assertions; arguments 3 and 4 are misinterpretations of field evidence; and argument 5 does not even bear scrutiny. This leaves their point that there is no deep weathering in the Pennines, which Linton also demolishes. He concludes that his two-cycle theory is the best explanation for the Pennine tors. He shows how scarp edge tors can form using his theory.

Lister, L.A. 1973. The microgeomorphology of granite hills in northeastern Rhodesia. In *Symposium on Granites, Gneisses and Related Rocks*, edited by L.A. Lister, Geological Society of South Africa Special Publication No. 3, pp. 157-161.

Keywords: southern Africa, micromorphology, inselbergs

The study addresses three inselbergs. The joints are secondary and have been filled. Joints are uncommon in the dome centers and become more common toward the margins. The surfaces are covered with pans and gullies. Many pans have raised rings on their edges, as do some of the gullies (levees). There is no difference in composition between levee/ring and feature. It is suggested erosion was retarded in these areas due to lichen cover. "Mudcrack" granite also occurs - joint blocks about 1 m across with raised edges and depressions in the centers. Pans occur on the higher, relatively unjointed bits and the "mudcracks" on lower, jointed flanks. Gullies occur mainly on upper slopes, dying out on the steep lower slopes. They are mainly on south-facing slopes. Drainage channel morphology is described. Channels usually do not follow joints.

Mabbutt, J.A. 1952. A study of granite relief from South-West Africa. *Geological Magazine*, vol. 89, pp. 87-96.

Keywords: Namibia, inselbergs, joint control, sheeting joints, domes

Mabbutt's conclusions are in line with King's (1949). Climate is semi-arid. The rock is a grey, porphyritic biotite granite that is homogeneous. Aplites follow primary jointing. The inselbergs are actively developing at the present time and are in the youthful stage. Primary structures do not affect individual hills, except that they control the general layout of the inselberg groups. Hill profiles are controlled by sheeting and sub-rectangular jointing. The appearance of sheets, which may be lens-shaped, supports the dilation theory. Sheets do not occur where vertical jointing is close. Domes develop where sheeting occurs; tors, where vertical jointing is prominent. Most domes exhibit "...several differently centered plating systems..." (p. 91). Dome destruction is by plating followed by granular disintegration as a result of chemical weathering. Vertical joints tend to develop on steep whaleback shoulders. Whalebacks are peripheral to domes and flat domes peripheral to whalebacks. Tors develop where plates are widely spaced and vertical joints develop and coincide with steeper faces. Plates may have concave lower surfaces. Talus fringes most domes and tors. A granite dome cycle of development is presented.

MacCulloch, J. 1814. On the granite tors of Cornwall. *Transactions of the Geological Society*, vol. 2, pp. 66-78.

Keywords: landform, chemical weathering, southwest England

Several tors in Devon and Cornwall — the Logging Stone, Cheesewring and Vixen Tor — are described. The rounding of tor blocks is caused by the chemical action of air and water. The spheroidal forms result from primary shape imparted around cooling centers (assuming the granite is igneous).

Moeyersons, J. 1977. Joint patterns and their influence on the form of granitic residuals in NE Nigeria. *Zeitschrift für Geomorphologie*, vol. 21, pp. 14-25.

Keywords: Nigeria, joint distribution, weathering

There are two types of residual granite hills in the area: 1) saprolite covered hills and 2) bare rock domes, castle koppies and tors with deep weathering pockets. The joint pattern is cuboidal. One set of curved joints flattens with increasing depth and a second flattens upward. The second set is less curved than the first. These joints are not caused by pressure release because they link up with the other joint sets and are not related to topography. This indicates structural control of the hills. Saprolite is separated from solid rock by joint planes as are weathering zones. Horizontal joints are virtually absent from the deep weathering pockets. With reference to cuboidal joints, weathering penetrates most rapidly to where horizontal joints cross each other. Where horizontal joints are convex, weathering penetrates more slowly because density is higher on top of the hills. The curved joints will guide water away.

Nossin, J.J. and Levelt, T.W.M. 1967. Igneous rock weathering on Singapore Island. *Zeitschrift für Geomorphologie*, vol. 11, pp. 14-35.

Keywords: Singapore, chemical weathering, gabbro, clay, soil

The rocks in question are gabbro and granodiorite. Chemical weathering is deep and rapid and the regolith is 10-20 m thick. The purpose of the paper is to compare weathering processes on the two rock types. The granodiorite is heavily jointed. Weathering on horizontal joints is both upward and downward. Clay content, resulting from the decay of feldspar, increases away from fresh rock and corestones as does the heavy mineral content. The clays are kaolinite and gibbsite; as the later decreases downward from corestones, secondary formation of kaolinite from gibbsite is assumed. Gibbsite occurs throughout the profile. The gabbro is peripheral to the granodiorite and varies in composition from gabbro to norite. It has been metamorphosed. Clay content increases upward from the weathering front. Grain size of all minerals decreases away from fresh rock. The dominant clay is kaolinite; gibbsite is absent except very close to fresh rock and corestones. The sandiness of the regolith depends on the amount of quartz in the rock.

Nur, A. and Simmons, G. 1970. The origin of small cracks in igneous rocks. *International Journal of Rock Mechanics and Mining Science*, vol. 7, pp. 307-314.

Keywords: microcracks, fractures, quartz

The paper attempts to determine the origin of microcracks and to see if they can be induced by drilling. The authors define microcracks as equal to or shorter than characteristic grain dimensions and state that microcracks are associated with grain boundaries. Mathematical models are used to show that differential thermal expansion and differential compressibility are a possible source for microcracks and that such cracks should be expected in the presence of quartz because of its properties. With respect to induced cracks, they determine that cracks only occur close to the stress at which discing occurs.

Oberlander, T.D. 1972. Morphogenesis of granitic boulder slopes in the Mojave Desert, California: *Journal of Geology*, vol. 80, pp. 1-20.

Keywords: California, theory, boulder-clad slopes, quartz monzonite

Granite landscapes in the southwestern United States are unlike landscapes on other materials. According to previous workers, boulder-clad slopes do not change through time; as these slopes retreat, new boulders are uncovered and the process continues ad infinitum until there is nothing left. Oberlander, however, believes there is evidence of recent stripping and that boulder-clad slopes are transitional, resulting from changes begun in the Late Tertiary. The rock is an even-grained, equigranular quartz monzonite (average grain size 2-3 mm). Although jointing is well developed, boulders predominate; sheeting, however, dominates in large, massive outcrops. Desert varnish is ubiquitous and case hardening, which even penetrates closed joints, is common, although it is being removed under the present climatic conditions. Massive outcrops have only remnants of case hardening. Scaling occurs on fresh rock; granular disintegration, on chemically weathered surfaces. Joint density does not appear different on pediments and massive outcrops. There does not appear to be a transition between boulders and blocks becoming boulders. Oberlander believes boulder-clad slopes evolve to multiconvex exfoliating domes. "The surface boulders are corestones exposed by erosion and reflect joint-controlled subsurface chemical weathering..." (p. 8). Once the boulders are exposed, further decay is greatly retarded, which explains why there is no transition between surface and subsurface forms. Studies show subsurface weathering is not occurring to depths where decomposed granitic rocks exist, indicating a change in climate. Weathering profiles are described and discussed. Differences in degree of weathering in boulders is indicative of where they came from in the weathered mantle; fresh boulders come from greater depths. Erosion/stripping began in the late Tertiary and was initiated by deterioration of the vegetative cover due to changing climate (becoming dryer). Domes are undecayed Tertiary hills, not residuals due to wider joint spacing.

Oen, I.S. 1965. Sheeting and exfoliation in the granites of Sermersoq, South Greenland. *Meddelelser om Gronland, Kommissionen for Videnskabelige Undersogelser I. Gronland*, vol. 179, pp. 8-36.

Keywords: Greenland, sheeting joints, theory, glaciation

The geomorphological history of the area is summarized. The differences between large-scale sheeting and small-scale exfoliation are discussed. Oen considers sheeting secondary and recognizes the existence of similar primary structures, but does not give them a name. The characteristics of sheeting in the study area are: 1) it is dependent on glacial geomorphological forms, 2) it extends to depths beyond which weathering and insolation are effective, 3) it is unrelated to primary granite structures, 4) there are no displacements or sills along the sheets, 5) well-developed sheeting exists only in rocks "...poor in pre-existing open joints..." (p. 12) and 6) thickness increases from a few decimeters to 2 meters with depth. Sheeting is parallel to glaciated valley walls and also parallels the surface in the bottoms of broad valleys and cirques; in general, it parallels the land surface. It is best developed where there is high relief. Because not all such areas have sheeting, it must have developed after glacial sculpture was completed. "The only discernable relation between sheeting and other jointing in the granite seems to be that they tend to exclude each other" (p. 18). In areas without pronounced relief, sheeting and vertical joints occur together, but neither is well

developed. Because sheeting occurs in many rock types, it cannot be attributed to textural or compositional characteristics of the rocks. Sheeting only seems to occur in other rocks, however, near granite massifs, usually post-tectonic. Oen suggests such sheeted granites as these represent an early stage in disintegration. This implies the later opening of vertical joints and the rounding of joint blocks by weathering. The cause is probably dilation, which operates hand in hand with weathering. Hypotheses of origin are discussed and discarded. The author suggests a new theory, i.e. that the mass deficiency of granites due to their lower density results in gravitational forces that cause the granite to rise, which in turn generates vertical compression. As uplift slows or ceases, decompression occurs and sheeting results. This theory allows sheeting to develop only once unless the uplift occurs again in a similar manner, i.e. uplift cannot be a continuous process. Small-scale exfoliation, such as the development of sheeting in quarries, would result from release of small residual stresses. Such stresses are greater than what would result from unloading. If erosion is sufficiently rapid, decompression could occur slowly and sheeting would never develop. Stoping is a likely method of emplacement for granites that develop sheeting in this manner, because they would remain free of open joints.

Ojany, F.F. 1969. The inselbergs of eastern Kenya with special reference to the Ukambani area. *Zeitschrift für Geomorphologie*, vol. 13, pp. 196-206.

Keywords: Kenya, inselbergs, theory, pediplanation

The paper describes inselbergs in Kenya. In East Africa, inselbergs occur mainly in arid and semi-arid areas. They are all below 6000 feet in elevation and occur on all rock types. Because they occur on all erosion surfaces except Gondwana, it is assumed that they are formed by current processes; *lateral planation is the mechanism.* Downwearing is slow. Deep chemical weathering (more than 25 feet) is active at the bases of all inselbergs and occurs in the wet season. Ojany accepts King's proposed theory of origin (i.e. scarp retreat and pediplanation) and proposes an inselberg cycle: 1) initial stage: uplift; 2) youth: river incision is dominant, inselbergs are large with flat tops; 3) maturity: pediplanation is dominant, individual inselbergs are being broken up into parts, and bare rock faces develop on granitic inselbergs; and 4) old age: pediments are dominant in the landscape, relief is low, tors develop as residuals in granitic rock, and weathering is mechanical.

Ollier, C.D., 1965, Some features of granite weathering in Australia. *Zeitschrift für Geomorphologie*, vol. 9, pp. 285-304.

Keywords: Australia, weathering

The paper describes features of Australian granites and attempts to ascribe them to the type of weathering that formed them. Bore holes indicate that more than 400 feet of weathered material can be present over fresh rock. Weathering is most intense near the surface and decreases with depth. Where joints are closely spaced, weathering is uniform, but where joint spacing is wide, spheroidal weathering is most common. A field classification for degree of weathering is proposed. The different degrees of weathering do not always occur in regular order, i.e. fresh corestones can be found in fully weathered regolith. Transitional fringes between degrees of weathering, however, are usually absent. Sheeting occurs in the more mas-

sive exposures, is due to unloading and is a mechanical process. Exfoliation occurs below the ground surface and flaking occurs above; the two processes can be distinguished by the presence of exfoliation on the bottoms of corestones where flaking cannot occur. Granular disintegration always occurs in association with case hardening. There are two types of granite landscapes: 1) an abundance of outcrops, pavements and tors and 2) rounded hills and vales of low relief with only occasional outcrops. The former occurs in areas of fresh rock and the latter in areas of deep regolith. Surface weathering is not as significant to landscape evolution as erosion of the regolith. Not all altered granite can necessarily be attributed to deep weathering, particularly as depth increases (900 feet of rotten granite is reported for the Snowey Mountains).

> Many variations of granite scenery appear to reflect the type and intensity of former deep weathering and the degree of removal or preservation of the regolith, and are largely independent of present climate (p. 301-302).

_____. 1967. Spheroidal weathering, exfoliation and constant volume alteration. *Zeitschrift für Geomorphologie*, vol. 11, pp. 103-108.

Keywords: exfoliation, theory, spheroidal weathering

Exfoliation and spheroidal weathering are different. Exfoliation occurs on two scales: massive, where it is called sheeting and is presumably caused by unloading, and small scale, where it is called flaking and is due to expansion during weathering. Expansion is possibly caused by temperature change, foreign substances (frost, salt, rootlets) and/or chemical changes. Flaking only affects exposed boulders and does not continue below ground level. Spheroidal weathering produces completely concentric shells. It is most common on hard rocks with good jointing, especially granite and basalt. Shells are millimeters or centimeters thick and are usually uniform in one area. The evidence, particularly undeformed joint patterns, suggests there is no volume alteration with spheroidal weathering. Ollier suggests spheroidal weathering is caused by hydrolysis in the saturated zone below the water table. Alteration occurs rhythmically, producing concentric shells. Hydrolysis produces lower density, greater volume minerals, so to maintain constant volume, the "excess" must be removed in solution. The author discuses work by others that suggests volume change as the cause of spheroidal weathering, and concludes it does not constitute proof. Flaking could occur all around small boulders. Boulders produced at depth by spheroidal weathering probably would change process once exhumed and lead to confusion.

_____. 1971. Causes of spheroidal weathering. *Earth-Science Reviews*, vol. 7, pp. 127-141.

Keywords: spheroidal weathering, theory

Exfoliation includes flaking, spalling and spheroidal weathering. Definitions of the three types are given in Ollier (1965, 1967). Flaking and spalling are surface phenomena. Inner shells on spheroidally weathered boulders are more nearly spherical than outer ones. Possible causes include: expansion, unloading, constant volume alteration, Liesegang processes, microcracks and miscellaneous special cases. Each hypothesis is discussed. The Liesegang

hypothesis involves: "...periodic precipitation zones obtained from diffusion of soluble substances that form a slightly soluble precipitate" (p. 136). The microcrack theory is that described by Bisdom (1967). The author comes to no conclusion with respect to causes.

_____. 1978a. Induced fracture and granite landforms. *Zeitschrift für Geomorphologie*, vol. 22, pp. 249-257.

Keywords: induced failure, corestones, pedestal rocks

Corestones are produced by weathering along joints, especially at intersections. Corestones occasionally rest on boulders with fresh, straight cracks that are not joints. The stress is comparable to uniaxial compression and the strength of an exposed corestone is less than that of embedded rock. Induced fracture occurs in the supporting rock/corestone in pedestal rocks. Highest stress occurs where the two corestones are in contact, and pestle-shaped boulders can result. Possible mechanisms of induced failure include stress fatigue and stress corrosion (weathering occurs more rapidly when the material is under stress).

_____. 1978b. Inselbergs of the Namib Desert, processes and history. *Zeitschrift für Geomorphologie*, Supplement 31, pp. 161-176.

Keywords: inselbergs, Namibia, equifinality, mantle planation

The paper describes weathering processes on the stony desert north of the Kuiseb River and outlines the geomorphic history of the region. Processes in evidence include unloading, flaking, granular disintegration and dirt cracking. Solution and wind erosion are minor. Neither salt weathering nor spheroidal weathering are in evidence. There is no evidence of deep chemical weathering. Weathering occurs only on protruding bits and the desert is virtually a plain cut across fresh rock. Inselbergs develop best on resistant rock with low fissility where topographic and geologic boundaries coincide. Neither scarp retreat nor stripping appear to be the cause of the inselbergs (the former because geologic and topographic boundaries coincide and the latter because there is no evidence of chemical weathering). Ollier suggests Mabutt's (1966) theory of mantle planation[18] as a third cause of inselberg formation, supporting Selby's (1977) concept of convergent landforms (equifinality). The geologic and geomorphic histories of the area are summarized. The author is attempting to prove that the stony desert is an old, exhumed plain and not the product of present-day processes. The latter are merely removing upstanding features and making the plain flatter.

_____. 1983. Weathering or hydrothermal alteration? *Catena*, vol. 10, pp. 57-59.

Keywords: hydrothermal alteration, chemical weathering, Australia

This paper is a comment on an earlier paper by Dixon and Young (1981). Ollier states Dixon and Young chose a hydrothermal origin for alteration of the Bega Batholith, whereas

---

[18] Mabutt, J.A. 1966. Mantle-controlled planation of pediments. American Journal of Science, vol. 264, pp. 78-91.

he believes it is due to chemical weathering. Weathering depends on mineralogy, not temperature, and the most weatherable mineral is the weak link. Differences in terrain are thus dependent on the amount of the weakest mineral in the rock. He refutes their evidence as equally likely under weathering. Hydrothermal alteration should be evidenced by geochemical indicators, including increase in the economic metals, as well as in sulphur, chlorine, and fluorine content, among other similar elements and should be accompanied by mineralization. Neither of these conditions apply to the Bega Batholith. Hydrothermal alteration is rare and chemical weathering is common, so the latter should be accepted unless the former is proved.

_____. 1984. *Weathering, 2nd edition.* London: Longman, 270 p.

Keywords: weathering

This is a general book covering all aspects of weathering. There are, however, extensive discussions of the weathering of granitic rocks, and granites are used as examples in many chapters.

Ollier, C.D. and Tuddenham, W.G. 1961. Inselbergs of central Australia. *Zeitschrift für Geomorphologie*, vol. 5, pp. 257-276.

Keywords: inselbergs, Australia, sedimentary rocks, parallel retreat

There are only three inselbergs in the central Australian area — Ayers Rock, Mount Olga and Mount Conner. The paper describes them and attempts to deduce origin. Ayers Rock and Mount Olga consist of uniform, but different, rock and Mount Conner, of horizontal sediments of different hardness. Mount Conner has a quartzite cap and consists of interbedded sandstone and siltstone. It has two sets of widely-spaced vertical joints. The dominant weathering process is bouldery disintegration. Insolation cleaving also occurs. Talus is present. Ayers Rock is formed of coarse, arkose grit with rare conglomerate bands. It is massive with no joints. The dominant weathering process is spalling of flakes averaging 1 inch by 1 foot. Some unloading occurs as well as caving. There is no talus. Mount Olga consists of massive conglomerate formed of pebbles of resistant rock 9-15 inches across. The massif is separated into joint-controlled blocks. Joints are mainly vertical and are present only in valleys. The dominant process is unloading. There is a thin veneer of debris. All three inselbergs evolved by parallel retreat and are remnants on an old erosion surface. Chemical weathering occurs on Ayers Rock whereas thermal expansion and contraction are prominent on Mounts Olga and Conner. Weathering is responsible for Ayers Rock and Mount Olga, whereas on Mount Conner, erosion and slope development are responsible for the shape. There is no evidence of deep chemical weathering. The authors accept King's (1948) theory of bornhardt development in principle, but with restrictions.

Onodero, T.F., Yoshinaka, R. and Oda, M. 1974. Weathering and its relation to mechanical properties of granite. *Advances in Rock Mechanics, Proceedings of the Third International Conference, International Society for Rock Mechanics*, vol. 2, pp. 71-78.

Keywords: Japan, weathering, microcracks, engineering

The paper evaluates the effects of physical and chemical weathering on the mechanical/engineering properties of the rock. The authors conclude that, even in saprolite, chemical weathering is minor. The only useful chemical parameter they identified was the ferrous/ferric ratio in biotite; as the ratio increases so does porosity. With respect to physical weathering, they show that increases in porosity are related to increasing microcrack density and suggest this is due to decreased bonding between minerals. They also show: Shore hardness decreases with increasing microcrack density; the static and dynamic Young's moduli decrease with increasing porosity; the residual strain ratio increases with increasing porosity and microcrack density; apparent cohesion decreases rapidly with increasing porosity; and that the value of 3-4% porosity appears to be crucial.

Ormerod, G.W. 1859. On the rock basins in the granite of the Dartmoor district, Devonshire. *Quarterly Journal of the Geological Society of London*, vol. 15, pp. 16-29.

Keywords: rock basins, southwest England, chemical weathering

The paper is a study of rock basins on Dartmoor. The basins occur in a central belt between the east-west-trending part of the Dart Valley and the headwaters of the Rivers Tavy and Teign, an area that includes about 1/3 of the moor. The locations of a number of basins are described as well as details of some basins. Details are given in tables. Possible origins are discussed. Ormerod ascribes the origin to enlargement of cavities or hollows by water percolating through the rock. Rock basins tend to occur where the rocks are slabby and where vertical jointing is poorly developed.

_____. 1869. On some of the results arising from the bedding, joints and spheroidal structure of the granite on the eastern side of Dartmoor, Devonshire. *Quarterly Journal of the Geological Society of London*, vol. 25, pp. 273-280.

Keywords: southwest England, landforms, structure

This paper presents the author's observations on horizontal and vertical joints and spheroidal structures on Dartmoor. General joint trends, dips and patterns are discussed. Tor shape is joint-controlled. Individual tors were probably one mass of granite at one time. The granite in the northern part of the moor is described as being harder and more crystalline than elsewhere and spheroidal masses appear to be best developed in the northeastern part of the moor.

Pain, C.F. and Ollier, C.D. 1981. Geomorphology of a Pliocene granite in Papua New Guinea. *Zeitschrift für Geomorphologie*, vol. 25, pp. 249-258.

Keywords: New Guinea, landform, chemical weathering

The paper addresses landscape evolution on young granites. The area consists of steep-sided, V-shaped valleys with narrow ridge crests. The main drainage pattern is dendritic with joint-controlled tributaries. There are few outcrops; most are on valley bottoms. The presence of kaolinite, halloysite and gibbsite in soils on side slopes and crests indicates chemical weathering. Most typical granite landforms are absent. The slopes are weathering controlled and the key process is stream downcutting in bedrock. This suggests the possibility of a steady-state landscape that is time-independent. As the erosion rate just about equals the uplift rate, this situation should continue for some time.

Palmer, J. and Neilson, R.A. 1962. The origin of granite tors on Dartmoor, Devonshire. *Proceedings of the Yorkshire Geological Society*, vol. 33, pp. 315-340.

Keywords: southwest England, theory, joint spacing, frost action, solifluction

The purpose of the paper is to explain the tors of Dartmoor. Previous work is summarized. Albers (1930) was the first to suggest periglacial origin. Both types of decay, physical and chemical, are generally recognized as occurring. Growan (saprolite) cannot be due to chemical weathering because it contains no clay, and the authors consider it to be solifluction deposits. The incoherent granite results from pneumatolysis. Bore hole data show the granite consists of layers of normal granite and decomposed or kaolinized granite to a depth of 140 feet. This sequence and depth cannot be explained by percolating ground water because the water table has always been high under valley floors. Tors occupy the most resistant parts of the granite and where kaolinized granite occurs, there are no tors. Rotten granite occurs mainly in valleys. Decomposition is associated with mineralization and is thus probably late Carboniferous or Permian whereas valley formation cannot be earlier than Tertiary. Rotten granite was probably never present near existing tors. Core stones do exist, but not near tors, so there is probably no association between rotten granite and tors. Clitter is too angular, and often too large, to result from chemical weathering. It occurs on slopes of more than 5 degrees where soil creep is not possible, and the movement of blocks is thus probably due to solifluction. Stone and vegetation scallops and stone stripes are evidence of solifluction as are antiplanation terraces and boulder fans. Tor shapes and the joint patterns that control them are described. Rounding of tor blocks is due to post-glacial atmospheric weathering, chiefly chemical weathering. Lamellar tors are more rounded than massive tors because of their closely spaced pseudobedding planes. Because core stones are lacking and because atmospheric weathering can account for rounding, they believe the tors have a periglacial origin. There are three stages in the process: 1) loss of soil from hilltops and the tops of hillsides by solifluction, 2) frost action on the granite acting primarily on joints and partings, and 3) down slope movement of blocks. Tors are best developed on intermediate slopes. The effects of frost action and the down slope movement of blocks depend particularly on the intensity of jointing. Avenues probably result from removal of more closely jointed but not decayed granite, and small gaps are probably caused by frost action resulting from nivation assisted by solifluction.[19] The three-stage process has not gone to completion; if it had, there would be

[19] Avenue is a local term for a wide gap on the crest of a hill between two elongate outcrops.

no tors. Tors are particularly scarce west of Widecombe and south of the Dart; this is due to variations within the granite. The blue granite, for instance, does not give rise to tors. Palmer and Neilsen believe the basal surface is the downward limit of frost action and periglacial processes, not the downward limit of chemical weathering. The position of tors around hilltops would ensure early Pleistocene exhumation. Deep weathering profiles may have existed, but there is no evidence for them. This theory allows development of fresh tors through successive glaciations until slopes reached the point where solifluction was difficult. There is, however, no known evidence for this.

Palmer, J. and Radley, J. 1961. Gritstone tors of the English Pennines. *Zeitschrift für Geomorphologie*, vol. 5, pp. 37-52.

Keywords: northern England, sandstone, theory, landform

Tors are indicators and products of climatic change. Composition and joint patterns in the Millstone Grit in the English Pennines are comparable to those of granite. The beds are gently dipping and are 15-100 feet thick. There are large shale interbeds. Tors occur mainly on the Lower Grit, especially the Kinderscout Grit. These units are well jointed, massive, have calcite cement and show current bedding. Tors occur on summits and near free faces at breaks in slope and their shapes are controlled by current bedding, joints and the resistance of the cement. They never stand alone on level areas, but are either surrounded by peat or rise from bare rock platforms. Problems with Linton's (1955) theory with respect to these tors are that: 1) there is no evidence of deep chemical weathering in the Pennines, 2) the tors are not related to any exhumation process and are not corestones, and 3) the tors are similar to cold weather forms in other parts of the world. The authors believe the tors are chiseled out of free faces. Because the tors fringe known glaciated areas and because they could not survive glaciation, a periglacial origin is implied. In addition, because the tors are being destroyed today and many are surrounded by peat, they must date between the last glacial maximum and the present. "The open joints exhibited in every free-face are usually clean and unweathered and are the product of frost splitting" (p. 47). Vertical joints are more important than horizontal joints. Tors were isolated from the free faces along joint planes, most of which have been rounded and fretted by subsequent atmospheric denudation.

Peng, S. and Johnson, A.M. 1972. Crack growth and faulting in cylindrical specimens of Chelmsford granite. *International Journal of Rock Mechanics and Mining Science*, vol. 9, pp. 37-86.

Keywords: fractures, microcracks, experimental work, Massachusetts

The paper begins with a brief, clear discussion of fracture theory in which the authors show that neither the Coulomb nor Griffith theories can predict fracture orientation. Theory does correctly predict that growth occurs near (but not at) the ends of pre-existing cracks and is not in the plane of the pre-existing crack. The process of fracture is studied by a combination of experimental and laboratory work. A very detailed and precise fabric study of the granite, which included identifying different types of microcracks, measuring them, and evaluating them with reference to rift, grain and hardway, is presented. The planes are also identified petrographically. Different types of stress are studied on the samples. A lengthy

discussion of the methodology/technique developed for measuring stress follows, as well as the experimental results. The results indicate that no matter what kind of stress is placed on the specimen, crack growth occurs parallel to rift. Crack patterns and densities are identified in the stressed specimens, but are not related to initial crack patterns or distributions. A theory of faulting called beam buckling is then proposed and derived mathematically. This theory fits the experimental results better than either the Coulomb or Griffith theories.

Pullan, R.A. 1959. Tors. *The Scottish Geological Magazine*, vol. 75, pp. 51-55.

Keywords: landform, northeast England, weathering, theory

The term buttress is defined. Three types of tors are described: 1) large massive tors rising from flat summits or low hills attributed to deep chemical weathering, 2) small, residual tors rising from flat benches attributed to periglacial frost shattering and removal of debris by snow melt or solifluction, and 3) tors of variable size rising from hillsides with slopes of 10 degrees or more attributed to buttress isolation by retreat of slopes on all sides under periglacial conditions. Type 1 is Linton's (1955) type of tor, type 3 is Palmer's (1961) type and type 2 is probably a variant of Palmer's. Pullan does not accept Linton's genetic definition and believes that any type of differential weathering is all that is required for tor formation. He believes weathering is usually composite. Removal of debris is by mass movement and is controlled by slope inclination. He does not accept a two-stage origin for valleyside tors. Because tors are destroyed by backwashing, valleyside tors are short lived whereas summit tors can be very old.

Purves, W.D. 1973. Engineering implications of granite weathering. In *Symposium on Granites, Gneisses and Related Rocks*, edited by L.A. Lister, Geological Society of South Africa Special Publication No. 3, pp. 163-166.

Keywords: southern Africa, engineering, chemical weathering, joint fill

Stability problems are rare when building on granite, but leakage along joints is often encountered. The purpose of this paper is to investigate the material that fills these joints — its origin, permeability and significance to dam building. The study area is along the Lesape River south/southwest of Rusape in Rhodesia. Observation of the material in the joints indicates that it probably formed as a result of percolating water. Material was removed and analyzed microscopically. Weathering begins with the development of microcracks and proceeds in the order biotite and plagioclase, more microcracking, more biotite weathering accompanied by decomposition of plagioclase, and finally, slight alteration of potassium feldspar. Quartz was not weathered, and was merely reduced in size by fracturing. Chemical examination indicated leaching would occur more rapidly in vertical joints. The clay fraction was also examined and was found to consist mainly of kaolinite (also in the fine sand fraction) and some gibbsite. Permeability measurements of these materials indicate serious leakage would occur through these filled joints and that the joints must be sealed prior to construction.

Pye, K. 1986. Mineralogical a· 1 textural controls on the weathering of granitoid rock. *Catena*, vol. 13, pp. 47-57.

Keywords: southern Africa, composition, texture, fractures, weathering

This paper reviews the effects of petrographic characteristics on weathering, mainly with reference to Africa. Pye shows that rocks high in quartz and potassium feldspar tend to be more resistant than rocks richer in plagioclase and biotite. The more resistant rocks form highs in areas of greater relief. Some chemical analyses are presented. The effect of texture is evaluated and found wanting with respect to granites. Theoretically, fine-grained rocks should weather more readily than coarse-grained ones because there are more grain boundary cracks, but openness is apparently more important than number. The degree of grain interlocking may also be important; granite grains are only moderately interlocking, however. Microcracks are very important in that they in·rease permeability (i.e., they allow greater ingress) and thus allow more chemical reaction at exposed mineral surfaces.

Pye, K., Goudie, A.S. and Thomas, D.S.G. 1984. A test of petrological control in the development of bornhardts and koppies on the Matopos Batholith, Zimbabwe. *Earth Surface Processes and Landforms*, vol. 9, pp. 455-467.

Keywords: Zimbabwe, inselbergs, composition, grain size, chemistry, rock texture

The paper tests the hypothesis that there are significant petrologic differences between bornhardts and castle koppies by analysis of grain size, mineralogy and chemistry. The Matopos granite is medium to coarse grained and sometimes porphyritic. There were no significant differences in average grain size, chemistry or mineralogy between the two landforms. There is a significant difference in the numb r of phenocrysts more than 1 cm long, however; bornhardts contain the larger phenocrysts. The authors do not believe this could account for the greater resistance to weathering in bornhardts, but that "porphyriticness" is frequently associated with weathering resistance for other reasons. Joint spacing exerts control on individual landforms. The bornhardts are metasomatized, and they believe this is why they are so resistant.

Pye, K., Goudie, A.S. and Watson, A. 1986. Petrological influence on differential weathering and inselberg development in the Kora area of central Kenya. *Earth Surface Processes and Landforms*, vol. 11, pp. 41-52.

Keywords: petrology, Kenya, landform, migmatite, metasomatism, gneiss

The purpose of this paper is to further examine the hypothesis that a relationship exists between potassium content, feldspar composition, weathering resistance and inselberg development. The rock is mainly granitoid gneiss, but other rock types occur as well. Inselbergs are preferentially located on the granitoid migmatites. Rock hardness is not significantly different between rock types. Migmatite, quartz-feldspar gneiss and granoblastites have higher silica and K_2O. There are significant differences in chemical composition with the inselberg-forming rocks which are classified as adamellites or granite whereas other rock types are more mafic. The same is true when classification is based on normative plagioclase to ortho-

clase. The authors identify statistically significant relations between differences in K_2O and normative orthoclase for migmatites vs. quartz-feldspar gneiss samples, as well as between mean normative orthoclase contents for inselberg-forming and inter-inselberg migmatites. The results thus support the idea of preferential inselberg development in potassium-rich rocks. They suggest finally that jointing may play a part as well, in that metasomatism was more active in the migmatites and joints were filled, making these rocks stronger.

Raeside, J.D. 1949. The origin of the schist tors in central Otago. *New Zealand Geographer*, vol. 5, pp. 72-76.

Keywords: New Zealand, schist, theory

Climatic differences had no part in tor formation in central Otago, New Zealand, although climate controls weathering. The tors are features of a fossil plain and were overlain by sedimentary rocks subsequently eroded. The rounded shape of tors is attributed to wind erosion.

Rahn, P.H. 1966. Inselbergs and nickpoints in Southwestern Arizona. *Zeitschrift für Geomorphologie*, vol. 10, pp. 217-225.

Keywords: inselbergs, Arizona, lateral planation

This paper discusses the cause(s) of nickpoints at the bases of inselbergs. Nineteen theories have been put forward. Rahn notes that nickpoints appear to be caused by lateral planation and that there seems to be a relation between size of detritus and the magnitude of the break in slope, i.e. nickpoints are associated with large debris. Basalt and granite are the most common rocks in the area. Granite debris is bimodal. Mode rather than mean is used. Erosion could not be measured, so lateral planation is addressed in terms of the presence or absence of streams. Results show the break in slope is greater when a stream is present and that breaks in slope are maintained by large debris after the stream has migrated away.

Rice, C.M. 1973. Chemical weathering of the Carnmenellis granite. *Mineralogical Magazine*, vol. 39, pp. 429-447.

Keywords: southwest England, chemical weathering, soil, geochemistry

The soil profile evaluated is in a quarry in the Carnmenellis pluton where the granite is relatively fresh. The purpose of the paper is to study weathering from a geochemical perspective. Most of the elements were determined using wet chemistry,[20] but x-ray and spectrography were also used. Three horizons and one sub-horizon identified in the field are also distinct chemically. Generally, however, there is very little chemical change in the soil relative to fresh rock, indicating the soil is juvenile. There is also little mineralogical change, except that there is considerable redistribution within horizons. Gibbsite is present in a D sub-

[20] Elemental distributions determined by this procedure may be suspect (Zen, oral communication, 1988).

horizon and kaolinite is present throughout (and in the fresh rock). The fine fraction is also analyzed. There is little change as grain size decreases except that biotite is replaced by chlorite and that gibbsite occurs throughout the C horizon as well as the D horizon. The clays are probably pseudomorphs after feldspar. Kaolinite is the main clay in all but the D horizon where gibbsite predominates. All elements show significant changes with grain size. Trace element concentrations are high in the weathered material because they normally reside in the least stable minerals. The evidence suggests the clays result from weathering, and that they are now the stable phases. The profile is in a sense inverted, because the D horizon is more weathered than it should be relative to those above it. It is either the remnant of an earlier, truncated profile or the result of more reactive fluids and primarily lateral movement through the soil.

Robb, L.J. 1979. *The distribution of granitophile elements in Archean granites of the Eastern Transvaal, and their bearing on geomorphological and geological features of the area.* Johannesburg, South Africa, University of the Witwatersrand, Economic Geology Research Unit Information Circular 129, 14 p.

Keywords: composition, feldspar, topography, trend surface analysis, South Africa

The purpose of the paper is to show a relationship between composition and topography using contour maps and trend surface analysis. The latter supports previous work on fractional crystallization. There are six different granitic rock types, the major portion of which is potassic. The granophile elements are K_2O, Na_2O, boron, rubidium and strontium. In discussing relations between grain size/texture and rate of weathering, Robb indicates that the contradictory evidence available suggests these factors are not decisive. There are two types of topography, each of which corresponds to a specific rock type: 1) high relief and undulating terrain with porphyritic granite and 2) flat, low-lying terrain with tonalite. High K_2O content corresponds to the higher, rougher topography, indicating potassic rocks are more resistant to weathering than sodic ones. Rubidium is like K_2O, but this is probably because rubidium associates with K_2O rather than with other elements. Boron is highly variable in the granite, but has a smooth distribution in the tonalite and Na_2O exhibits an inverse relation, but not as good as K_2O, with topography. The presence of a high, finer-grained, more porous, less potassic granodiorite in the area shows that composition is dominant only if porosity is an independent variable. Trend surface analysis supports previous work showing that the granite formed by fractional crystallization inward with respect to potassium, rubidium and Boron; plagioclase and strontium are relatively uniform throughout.

Roth, E.S. 1965. Temperature and water content as factors in desert weathering. *Journal of Geology*, vol. 73, pp. 454-468.

Keywords: deserts, weathering, thermal changes, moisture, California, quartz monzonite

The purpose of the paper is to evaluate the effects of thermal changes and moisture content on desert weathering in the field. A quartz monzonite boulder was used. Temperature measurements, both surface and internal, were taken for six months at monthly intervals at hourly intervals for 24 hours. The maximum temperature difference was 24 degrees. The thermal gradient in the outer 1 foot of rock varied from 15 degrees in October to 4 degrees

in December. The calculated maximum thermal expansion at the surface was 0.02%; at a depth of 1 foot, it was 0.008%. Moisture content was determined by destroying the boulder and weighing samples before and after slow oven drying. This study confirms previous results concerning temperature, i.e. that thermal changes in themselves cannot cause weathering, and shows that moisture is present, increasing with depth, even in arid environments.

Ruxton, B.P. and Berry, L. 1957. Weathering of granite and associated erosional features in Hong Kong. *Geological Society of America Bulletin*, vol. 68, pp. 1263-1292.

Keywords: Hong Kong, chemical weathering

The paper presents the results of a field study of local granite weathering and erosional features. Most of the granite is weathered to depths in excess of 30 m. A and B soil horizons are only superficially present. The most striking feature of the profiles is the mixture of solid rock and residual debris throughout. The profiles are separated into four zones according to the percentage of solid rock: zone 1, 0%; zone 2, more than 50%; zone 3, 50-90%; and zone 4, more than 90%. Biotite is the first mineral to decompose, followed by plagioclase, then orthoclase. At that point the rock breaks down to platy fragments forming grus (saprolite). Plagioclase completes decomposition first, followed by orthoclase, when the grus becomes silty sand. Mica flakes can outlast orthoclase. Quartz remains virtually unaltered. Spheroidal weathering stages are defined. The four weathering zones can be further defined by addition of the spheroidal weathering stages. The fresh rock is a medium-grained (1-5 mm), light grey, biotite granite with variations in texture. Two sets of vertical joints are universally present with joint spacing ranging from 0.5-12 m. Sheeting joints also occur. The weathering zones and the development of profiles are described. The sequence from least to most resistant is coarse *porphyritic granite*, *coarse-grained granite*, *medium-grained granite*, *fine-grained granite*, granite porphyry dikes. Joint spacing generally increases with coarseness, as does porosity. "Subsurface water containing, or in association with, atmospheric gases is then the prime cause of chemical weathering" (p. 1274). Weathering thus works inward from the surface and decreases with depth. Weathering is most active in the vadose zone and the lowest level of the water table acts as a base level for weathering. There are three explanations for weathered material occurring below the lowest water table: 1) initial irregularities before an integrated water circulation was established, 2) the presence of fractures and shatter belts, and 3) a change in the level of the water table. Four field areas are described. Conditions in the Pleistocene and earlier were probably conducive to deep weathering. The authors accept a two-stage process to explain the weathering profiles: a period of deep chemical weathering followed by erosion initiated by deforestation. Erosional characteristics and processes are described.

_____ and _____. 1959. The basal rock surface on weathered granitic rocks. *Proceedings of the Geologist's Association*, vol. 70, pp. 285-290.

Keywords: basal surface, joint type

The purpose of the paper is to redefine Linton's term "basal platform" to "basal surface." Basal surfaces are not necessarily restricted by the water table. Where sheeting joints are prominent, are confined to or are open near the surface, the dip of the sheets controls

water movement and the sheets become the basal surface. With blocky jointing, the water table is likely to coincide with the basal surface and in shatter zones, the control is the limits of an adequate mixture of air and gas. Basal surfaces can be exhumed; the presence of abundant, in situ corestones is the proof. In Hong Kong, the basal surface is up to 300 feet deep. Some pediments may be basal surfaces.

_____ and _____. 1961a. Weathering profiles and geomorphic position on granite in two tropical regions. *Revue de Geomorphologie Dynamique*, vol. 12, pp. 16-31.

Keywords: landform, theory, Africa, Hong Kong

Angular breaks between straight segments characterize slopes in arid regions whereas those in humid regions have curved inflexions between smooth, flowing segments. Contrasts are greatest on granites. Vegetation density, weathering depth and the role of mass movement in denudation differ as well. The humid tropical weathering profiles of Hong Kong are described (as in Ruxton and Berry, 1957). The purpose of the paper appears to be the comparison of landform development and weathering in the two types of areas, but this is rather unclear. Climate is considered largely responsible for the difference in emphasis of the various agents of denudation, "...the most significant of which is believed to be the relative importance of lateral mechanical eluviation at the foot of hillslopes on granite in semi-arid and savannah regions" (p. 23). "Chemical weathering is most rapid on the hillslope where the subsurface water flows strongest and is most frequently replenished and most intense on the foot slopes where the water lingers longest" (p. 24). Back-wearing is dominant where the drainage net is widely spaced, i.e. in arid regions. The greater the rainfall, the more relief is required. Parallel retreat is inherent to tropical climates. Subsurface climate changes continually through the geomorphic cycle.

_____ and _____. 1961b. Notes on faceted slopes, rockfans and domes in the east-central Sudan. *American Journal of Science*, vol. 259, pp. 194-206.

Keywords: Sudan, slopes, gneiss, landform, unloading

This paper attempts to describe certain minor landform features, as well as sheeting. Two batholiths were studied, one gneissic with granite and the other granite. Domes are dominant on the gneiss and rock ribs and buttresses are dominant on the granite. Slopes are faceted. Angular breaks between facets are greatest on the gneiss. Sheeting appears to be independent of rock structure and sheets terminate against steeply dipping joints that parallel contours. Rock fans are described; they do not appear to be formed by lateral cutting as suggested by others. As a residual hill is stripped, the dome form appears to extend downward, i.e. the dome form results as debris is removed and not replaced. In the core of a compartment, unloading produces domes, but on the margins, unloading produces rock fans. "Unloading and mass wasting are dominant in the dome-like portion, weathering and erosion are dominant between the buttress and plinth angle, and water transport is dominant on the clay plain" (p. 204). These landforms are better developed on gneiss. The effective depth of water penetration in granite is often limited to the depth of unloading.

Seeburger, D.A. and Zoback, M.D. 1982. The distribution of natural fractures and joints at depth in crystalline rock. *Journal of Geophysical Research*, vol. 87, pp. 5517-5534.

Keywords: fractures, boreholes, joint spacing, orientation, quartz monzonite, sandstone, granodiorite, California, South Carolina

The study analyzes various characteristics of fractures in boreholes. These are: whether statistically significant orientations can be identified, whether the number of joints and/or orientations vary with depth, whether frequency and orientation vary locally, and what relationship, if any, exists between observed fractures and regional stress and geologic history of the area. Fractures in boreholes tend to occur in clusters. The technique used is based on the smoothness of the borehole wall; dark patterns appear where planar features occur. There are two disadvantages to the technique: 1) only a small portion of a fracture is observed and orientation may thus be highly inaccurate and 2) because the borehole is vertical, vertical fractures are excluded. Data from wells drilled in the Mohave Desert in California show sandstone is much less densely fractured than quartz monzonite, that fracture density may be decreasing with depth (150-200 m) and that fracture density does not increase toward the San Andreas fault. There is no decrease in fracture density with depth in the South Carolina wells, each about 1/4 km deep, but horizontal joints tended to occur in the upper 300 m. The rocks are granodiorite. Orientations showed little consistency and surface measurements by Secor (1980)[21] support this. The third area is also in California near the San Andreas fault; it is in quartz monzonite. The holes are only about 220 m deep. Again, there is no tendency for fracture density to decrease with depth and there is also no increase toward the San Andreas. With respect to the latter, the authors state that the closest wells in the two California areas are 2 km from the fault, but also that there is no tendency for fractures to be aligned parallel to the fault. Overall, there was only a slight tendency for density to decrease with depth; most fractures were steeply dipping, not horizontal; fracture orientation was consistent throughout the holes, but varied considerably from hole to hole, indicating little/no relation with regional stress; and that surface fracture patterns "...are probably a good indication of fractures in the upper kilometer of the crust" (p. 5533).

Segall, P., and Pollard, D.D. 1983a. From joints and faults to photo lineaments. In *Proceedings of the 4th International Conference on Basement Tectonics (Norway)*, edited by I. Ramberg and R.H. Gabrielson, Denver, Colorado, Basement Tectonics Committee Inc., pp. 11-20.

Keywords: fractures, air photos, California, lineaments

The paper addresses, micro- and macroscopically, fractures and air photo lineaments in the Sierra Nevada. The purpose is to determine the nature and origin of ground fractures, to illustrate the relations between ground data and air photo lineaments and to determine if ground displacements between lineaments are apparent with respect to lineaments. They use the air photo lineaments of Lockwood and Lydon (1975).[22] There are three fracture domains, generally unrelated to lithology. All joints are dilational in origin. The fractures are

---

[21] Secor, D.T. 1980. Geological studies in an area of induced seismicity at Monticello Reservoir, South Carolina. First Technical Report, Contract 14-08-0001-19124, U.S. Geological Survey, Reston, Virginia.

[22] Lockwood, J.P. and Lydon, P.A. 1975. Geologic Map of the Mount Abbot Quadrangle, Central Sierra Nevada, California, scale 1:62,500. Reston, Virginia: U.S. Geological Survey, Geological Quadrangle Map GQ-1155.

mainly joints in one area and mainly faults in the other, although sheared filling that is compositionally the same in both areas indicates the small faults began life as joints. By measuring displacement of aplite dikes across the gullies that form the lineaments, the authors determined that the same relations occur at air photo scale. Lineaments and fractures are parallel. They suggest, because the air photo patterns of the two types of fractures are virtually identical, that interpretation of type of fracture should be made on the basis of field work as it cannot always be done from photos.

_____ and _____. 1983b. Joint formation in granitic rocks of the Sierra Nevada. *Geological Society of America Bulletin*, vol. 94, pp. 563-575.

Keywords: fractures, California, granodiorite, stress

One purpose of the paper is to provide data on joints in granitic rocks. The second is to show that by measuring displacement across a joint, direct information on strain is obtained and that combined with density measurement, this allows constraints to be put on the initial stress environment. The data is at outcrop scale and the rock is granodiorite. The joints were formed as dilational fractures. Some were filled with epidote and chlorite and some underwent minor shear later. To determine strain, joint aperture was measured perpendicular to the joints along traverse. Joint spacing is variable. Small, filled hairline cracks were not measured. The strain/stress calculations give results comparable to those from experimental data. The authors show that long joints restrain the growth of short joints such that short joints cease propagating when less than half as long as the long one. As long joints grow, they interact with other long joints further and further away. This produces large numbers of short joints and few long ones. They also suggest that the reason joint spacing is not uniform in granitic rocks is because there is no mechanical constraint, such as bedding planes, on them.

Selby, M.J. 1972. Antarctic tors. *Zeitschrift für Geomorphologie*, Supplement 13, pp. 73-86.

Keywords: Antarctic, theory, joint spacing, salt weathering, dolerite, quartz monzonite

The purpose of the paper is to describe Antarctic tors and to show that they are actively being formed by differential mechanical weathering (salt crystallization). McMurdo Oasis is composed of metamorphic rocks intruded by acid plutonic rocks. Chemical weathering does occur in the soils, although physical weathering is dominant. The outlines of the tors are controlled by joints, but detailed sculpture results from weathering. Tors in dolerite, granite and quartz monzonite were studied. "The key to tor formation is the more vigorous weathering of the inter-tor zone than the joint blocks of the tors" (p. 82). Inter-tor zones are more closely jointed. Weathering is responsible for the tors. The major effect of chemical weathering is to produce desert varnish which protects the tors. Freeze-thaw is unlikely as a cause, as is climatic change, leaving salt crystallization, for which there is evidence, as the most likely origin.

_____. 1977a. Bornhardts of the Namib Desert. *Zeitschrift für Geomorphologie*, vol. 21, pp. 1-13.

Keywords: Namibia, inselbergs, theory

The thesis of this paper is that the Namib bornhardts are produced according to King's (1949, 1966) hypothesis of lateral planation/pedimentation/parallel scarp retreat and that at least two processes can produce bornhardts. The other process is differential weathering. The rocks are porphyritic biotite granites. The bornhardts are typical and jointing is the dominant control on their form. There is no chemically weathered regolith. The climate of the area has probably been stable since the Miocene; there are indications of higher rainfall during late Cenozoic, but this climate would have been semi-arid at its wettest. Selby's argument for equifinality appears to be based more on the absence of chemical weathering than on anything else.

_____. 1977b. On the origin of sheeting and laminae in granitic rocks: The evidence from Antarctica, the Namib Desert and the Central Sahara. *Madoqua*, vol. 10, pp. 171-179.

Keywords: sheeting joints, laminae, Antarctica, Africa, theory

In general, sheeting transgresses other joints and dikes. Joint spacing becomes greater with depth and averages 0.3-8 m. Sheets are nearly parallel. There are two theories of origin: primary and secondary. On Dartmoor in southwest England, topography on the edges of the moor is Quaternary and the sheets are Cenozoic, so the unloading hypothesis is unacceptable. Sheeting in Quaternary glaciated valleys, however, does result from unloading. It appears more likely that sheeting is caused by initial compressive stress. "Laminae are scale, flake, flaggy or plate-like skins or shells of rock which are formed closely parallel to the surface of an outcrop" (p. 174). They are commonly 1-5 cm thick. They appear to develop in conformity to the surface. They occur in many rock types and climates and thus probably result from a variety of processes. Because laminae are thinner at their edges, they produce concavities. A secondary origin for sheeting is probable for both areas studied. Lamination is physical, not chemical, but the precise cause(s) could not be identified. Chemical weathering may reduce the effectiveness of the laminae-forming processes and the ubiquitousness of laminae suggests it could be due to inherent properties in the rock, such as in-built stress.

Shaler, N.S. 1869. Notes on the concentric structure of granitic rocks. *Proceedings of the Boston Society of Natural History*, vol. 12, pp. 289-293.

Keywords: sheeting joints, insolation, concentric structure

Concentric structures occur where vertical joints are uncommon, and the concentric structures provide access for weathering agents. The essential feature of sheeting joints is their curvature. Concentric structure is surficial, confined to the upper 4 or 5 feet. Insolation is the most likely cause; both seasonal and diurnal temperature changes. It is also possible that the separations result from chemical decay, but this is unlikely because chemical decay is not evident and the scales formed by such action are only 1-2 inches thick whereas the sheets are 1-3 feet thick. Dome-like forms are the result of this concentric structure.

Sugden, D.E. 1968. The selective glacial erosion in the Cairngorm Mountains, Scotland. *Transactions of the Institute of British Geographers*, vol. 45, pp. 79-92.

Keywords: glacial erosion, Scotland, joint spacing

This paper explains how obviously glaciated features, such as U-shaped valleys, can exist side by side, with equally obviously unglaciated features such as tors. Sugden's thesis is that the Cairngorm Mountains were covered by an ice sheet, not eroded by valley glaciers, and that differential ice movement within the glacier caused the existing landform pattern, i.e. that in some areas the ice moved, producing valleys, and in others, it was stationary, leaving pre-glacial tors undamaged.

Sugden, D.E. and Watts, S.H. 1977. Tors, felsenmeer, and glaciation in northern Cumberland Peninsula, Baffin Island. *Canadian Journal of Earth Sciences*, vol. 14, pp. 2817-2823.

Keywords: Canada, glaciation, landform, Arctic

The purpose of the paper is to test two hypotheses of glacial landscape development on Baffin Island. The theories are: 1) that cold-based ice protects highs, whereas warm-based ice in valleys erodes — this is called selective linear erosion, and 2) that there are three vertically distributed weathering zones indicative of glaciated valleys and unglaciated highs. The presence of erratics and the shapes of the tors (they are like roche moutinees and are oriented) suggest glaciation on highlands. Sugden and Watts see a progression in tor shape from glacially modified at lower elevations to unmodified on uplands. This suggests tors are not necessarily indications of the absence of glaciation. The authors see no reason why tors could not survive if the ice was cold based.

Tardy, Y., Bocquier, G., Paquet, H., and Millot, G. 1973. Formation of clay from granite and its distribution in relation to climate and topography. *Geoderma*, vol. 10, pp. 271-284.

Keywords: clay, weathering, climate, topography

The paper presents the view that "...in regions where the relief is not pronounced, the climatic influence could be characterized by a chain of geochemical phenomena, more or less temporary in character, but different in extent" (p. 272). This is done by looking at the distribution of secondary minerals, the weathering of primary minerals and the geochemistry of ions in solution. The topographic sequence from humid tropical to arid tropical is gibbsite, kaolinite, montmorillinite. The sequence proceeds in a down slope direction, i.e. in wettest tropics both uplands and lowlands have gibbsite; with alternating seasons, kaolinite occurs upslope, montmorillinite down slope, etc. The weathering sequences for both feldspars and biotite are given. The order of appearance of secondary minerals in these sequences is the same regardless of climate; however, the particular clay mineral derived from the particular primary mineral and its retention varies with climate. Secondary minerals within primary minerals are at different stages than those in fissures and the stages will be staggered from mineral to mineral and rock to rock. Because the minerals are not the same throughout a given rock, it is assumed that the composition of solutions also differs. Secondary minerals in primary minerals are more siliceous. High relief slows the secondary progression because solutions go through more rapidly.

Ternan, J.L. and Williams, A.G. 1979. Hydrological pathways and granite weathering on Dartmoor. In *Geographical Approaches to Fluvial Processes*, edited by A.F. Pitty, Norwich, Geo Abstracts Ltd, pp. 5-30.

Keywords: hydrology, southwest England, weathering, water chemistry

The purpose of the study is to measure water quality in a spatial sequence in a small, western Dartmoor catchment in southwest England to establish rates of decomposition and to identify controlling factors. General geology, relief, climate, vegetation, soils and hydrogeology are summarized. Probably the most significant weathering process on Dartmoor is hydrolysis of feldspars which are converted to kaolinite. Water samples were collected along transects in grassland, bracken and forest and from springs. Throughfall and stemflow were also measured. Silicon content, as a measure of chemical weathering, was determined for all samples. Most of the water on Dartmoor comes from intermittent springs and seepages. The results indicate chemical weathering is presently occurring on Dartmoor. Kaolinite is produced by slow circulating, deep springs and gibbsite from shallower, freely-draining springs.

Thomas, M.F. n.d. Granite relief, a review with examples from Australia and New Zealand. Paper given at British Geomorphological Research Group meeting, 15 p.

Keywords: New Zealand, Australia, landform, theory

The paper attempts to describe "universal" characteristics of granite terrain. Models of landform development are based on the following premises: 1) that patterns reflect compartmentization, 2) that positive and negative relief forms reflect fracture patterns and perhaps joint frequencies and mineralogical differences in the rock, and 3) that structural imprint is a function of deep differential weathering followed by stripping. It is also generally assumed that weathering is more rapid below ground than above. Both study areas are of the "basin and tor" type with fresh granite forming basin floors and tors at all elevations. Deeply weathered regolith occurs in both areas and both are assumed to result from the two-stage process. Thomas concludes that 1) except in arid and cold climates, deep weathering should be considered continuous, not periodic, 2) some form of crisis, not necessarily just tectonic, is probably required for extensive stripping, 3) where extensive stripping has occurred, it should not be viewed as "final," 4) tors are poor indications of past history, 5) fracture patterns commonly exert control, but joint frequency may have only limited influence, 6) widely-spaced joints give rise to "dome and cleft" topography, 7) basin and tor patterns may be indicative of deep weathering and an undulating weathering front, 8) highly irregular weathering fronts, on the other hand, may produce moderate to high relief and stepped topography, 9) "continuous denudation over well-jointed granites under conditions of moderate relief (less than 80 m) and a humid climate is likely to produce a multi-convex terrain with deeply weathered interfluves and occasional tors" (p. 11) and 10) the significance of tors depends on their distribution and setting.

_____. 1965. Some aspects of the geomorphology of domes and tors in Nigeria. *Zeitschrift für Geomorphologie*, vol. 9, pp. 63-81.

Keywords: Nigeria, inselbergs, theory, landforms

Definitions of the various landforms are presented. Tors and castle koppies are differentiated on the basis of whether or not they result from subaerial collapse (koppies). The purpose of the paper is to consider the evolution and formation of inselberg domes. Thomas assumes the weathering pattern gives rise to the dome form with exfoliation being subsequent and sympathetic. "...The development of rock domes in humid tropical climates can be regarded as a result of the operation of chemical and mechanical processes on a basically cuboidal form, under conditions where the speed of ground water weathering is greater than the rate of denudation of the land surface" (p. 65). This process requires the governance of a primary joint system. The fact that unsheeted domes exist indicates sheeting is secondary to form. Also the fact that domes and tors coexist indicates they result from the same process. Large domes could be produced by a prolonged period of uplift with multiple alternating periods of deep weathering and stripping, whereas small domes could result from one deep weathering period and one stripping period. Thomas does not believe exfoliation/sheeting is the primary process responsible for dome destruction and suggests that destruction results from collapse caused by the opening of previously closed vertical joints as the dome is lowered. The dome slowly becomes surrounded by talus and turns into a castle koppie which soon decays. Domes are thus more common than castle koppies because they last longer. The pattern and density of vertical joints thus controls destruction. Because few domes are mantled by waste, he accepts basal sapping only as a minor, short-term process in dome formation/destruction. An ideal cycle of bornhardt evolution is presented and related landforms are discussed. Ruwares can be either pre-domes (emergent) or destroyed dome remnants. Tors are viewed as ephemeral, appearing and disappearing as parts of the ideal cycle and dependent on the rate of stripping; they require rapid stripping. This implies that boulders on rounded surfaces could be tor bits rather than exhumed corestones let down vertically or rounded sheet remnants. Dome distribution is structurally controlled.

_____. 1974. Granite landforms: A review of some recurrent problems in interpretation. In *Progress in Geomorphology*, edited by E.H. Brown and R.S. Waters, Institute of British Geographers Special Publication No. 7, pp. 13-35.

Keywords: theory, landform development

The paper is more or less a synthesis of previous concepts concerning granite landscapes, development and evolution. Widely accepted premises in the study of granite landforms include: 1) spatial arrangement and relief development are controlled by structure (composition, texture and fractures); the resulting pattern is ellipsoidal with rectilinear compartments, 2) fractures can result from initial emplacement and crystallization, later as diastrophism and/or relief development, 3) granites are under stress, 4) sheeting results from stress relaxation, 5) variations in joint frequency, together with composition and texture, produce distinctive landforms, 6) susceptibility to chemical decay provides the key to understanding granite relief patterns, 7) regoliths are deep and irregular and result from response to structural weakness, 8) tors and domes result from regolith stripping, 9) differential weathering favors landform persistence and accentuation, 10) the two-stage hypothesis, i.e. long

weathering periods interrupted by short stripping episodes, is considered to result from climate changes, and 11) the depth and character of regoliths are affected by climate and time as well as rock properties. These points are discussed in terms of: the nature and influence of structural controls; the distribution, character and interpretation of granite regoliths; periodicity in weathering and regolith removal; the occurrence of basin forms; the development of spheroidal and domical forms; and the identification and interpretation of granite landform systems. The simple two-stage hypothesis cannot account for all granite landscapes. Thomas adds three additional premises to the above on the basis of the analysis in this paper: 1) weathering penetration should be regarded as continuous and probably depends more on rates of surface denudation than on variations in rock decay, 2) exposure of tors and corestones may occur under constant conditions as a function of differential erosion, and 3) granite landscapes are in a continual state of evolution.

_____. 1976. Criteria for the recognition of climatically induced variations in granite landforms. In *Geomorphology and Climate*, edited by E. Derbyshire, London, John Wiley and Sons, pp. 411-445.

Keywords: climate, jointing, landform

The paper attempts to "...substantiate claims for the recognition of climatogenic forms and deposits within areas of granitoid rocks" (p. 412). The author begins with a general discussion of granites and their characteristics, including jointing. He separates horizontal joints from sheeting and states that in some cases sheeting is not independent of climate. Depth of alteration may have nothing to do with climate, and depth and degree are not always related. A prolonged period of tropical or near-tropical conditions is required to produce highly kaolinized residues, longer than that available in interglacial periods. Penetration of weathering is much slower than surface denudation. He concludes this part by stating that granite weathering should be regarded as continuous through geologic time. Granite landforms are commonly exhumed from beneath regolith and should be described in terms of the degree of removal. The abrupt transition from waste-covered slopes to bare rock may be related to stability within denudation systems. Excellent definitions of tors, domes and koppies are given. Landforms can be structural or the product of convergent processes. Six possible origins for tors are listed as well as criteria that need to be addressed in determining the "correct" origin. Minor surface landforms are discussed. Thomas lists three types of granite landform systems: 1) multiconvex (dome), 2) multi-concave (basin-form), and 3) planate surfaces containing residuals (inselberg landscapes). The origins of individual mesoscale features (tors, domes) may be different from those of the total landscape. He concludes that "... few granite landforms can be unambiguously associated with closely-defined climatic environments" (p. 440). The reasons are: 1) structural and mineralogical characteristics give rise to similar features wherever granites occur, 2) few geomorphological processes can be climatically proscribed and 3) different processes produce similar forms.

_____. 1978. The study of inselbergs. *Zeitschrift für Geomorphologie*, Supplement 31, pp. 1-41.

Keywords: inselbergs, theory

There are two opposing models of inselberg development: 1) "...the reduction of the land surface and formation of inselbergs by differential weathering and erosion..." (p. 4) and 2) "...denudation brought about by lateral planation with the formation of inselbergs as erosional residuals" (p. 4). The paper attempts to show that these theories are not necessarily mutually exclusive and that there are additional hypotheses as well. Definitions of inselbergs are discussed. Inselbergs appear in all climates. The mineralogic effect on inselberg development has not been adequately tested, and neither has the effect of joint frequency. Bornhardts may be more common in the deeper parts of the more ancient intrusions. Too little attention has been paid to inselbergs as part of a landscape; most studies are of individuals or small groups. Deep weathering (30-60 m) is often associated with inselberg landscapes. Bornhardts appear to be limited to a certain range of petrographic and structural environments. Field evidence for the development of low domes (less than 50 m tall) within an in situ regolith is overwhelming. What appears to be most important, however, "...is a difference in weathering stage between the nascent dome and its matrix" (p. 22). Thomas believes that repeated or continuous weathering of foot slopes is adequate to explain the very large bornhardts and that pediplanation need not be invoked. He lists a number of ways deep weathering can affect inselberg development. The greater the lithologic and structural controls, the more likely it is that similar forms will occur in any/all environment(s). As these controls lessen, climate may become highly influential. If this is true, large bornhardts would be independent of climate, but smaller tors might not be.

Thorp, M.B. 1967a. Joint patterns and the evolution of landforms in the Jarawa granite massif, northern Nigeria. In *Liverpool Essays in Geography*, edited by R.W. Steel and R. Lawton, London, Longman, pp. 65-83.

Keywords: Nigeria, air photos, rock texture, joint spacing, landforms

The relation between joints and landform evolution and deep weathering and regolith stripping are shown in the Jarawa Hills, Nigeria. Scarps usually coincide with geological contacts. The rocks are hornblende-biotite granite and biotite granite. Three types of landform assemblage are described: 1) the relation between the relief hierarchy and joint dimension, 2) the relation between enclosed basins and joints, and 3) landforms resulting from removal of deeply weathered regolith. Joints are of two types, master and minor, and there is much more variation in the latter. "Often the joint frequency is related to rock texture, the smaller the crystals the closer the joint network" (p. 70). Because joints are virtually the only means of ingress for water into granite, they are the most intensely weathered bits, giving rise to differential denudation. Master joints form areas of positive and negative relief. Three relief/joint hierarchies are identified: 1) the smallest scale in which topography and joint patterns are discordant, 2) medium scale controlled by master joints (positive/negative relief), and 3) large scale "microrelief" controlled by minor joints. The suggested origin for the enclosed basins is that they were nodes of deep weathering at master joint junctions where the regolith was subsequently removed; they do not result from differential weathering and erosion on different rock types.

_____. 1967b. Closed basins in Younger Granite Massifs, northern Nigeria. *Zeitschrift für Geomorphologie*, vol. 11, pp. 459-480.

Keywords: Nigeria, joint control, landform, rock texture, petrography

The general geology of the area is described. Thorp attributes lower resistance to erosion in the older rocks, which are igneous and metamorphic, to texture and mineralogy. The purpose of the paper is to describe closed basins, which result from differential weathering and erosion. The basins occur in three situations: 1) on the older rocks which are less resistant, 2) on less resistant granites within the Younger Granites, and 3) where fracture patterns are favorable.

Thorpe, R. 1979. *Characterization of discontinuities in the Stripa Granite — Time-scale heater experiment.* Lawrence Berkeley Laboratory (LBL) for the U.S. Department of Energy, LBL-7083, University of California, Berkeley, 107 p.

Keywords: Sweden, boreholes, fractures, statistics

The paper is one of a pair describing related experiments at different scales. The experiments are concerned with discontinuities in granite as part of a larger study about nuclear waste disposal. The study area is an abandoned mine and the work is cooperative between Sweden and LBL. The experiment "...is designed to simulate the interactive thermal effects of an array of waste canisters over a period of 12 years" (p. 5). The overall objective is to evaluate far-field effects of heating on rock to improve modelling capabilities. Vertical displacement, temperature, stress-strain and in situ fluid pressure were measured in bore holes. Fractures were mapped at 20:1 scale on the drift floor and from core. Thorpe determined the data sets were comparable by comparing frequencies. He also determined that the frequencies were 2-3 times less than actual frequencies, because only fractures longer than 0.3 m and open fractures were measured. Average frequency was six per meter and maximum frequency was fourteen per meter. Four major, through-going fractures were identified. All data were combined and analyzed statistically. Four joint sets were identified. Orientation, size, spacing (lognormal) and infilling were studied. Past stress environment and on-going deformation are discussed. The author concludes that the methodology is adequate and sound, but that more, perhaps more detailed, work, is required to improve the statistical analysis.

Tschang, Hsi-Lin. 1961. The pseudokarren and exfoliation forms of granite on Pulau Ubin, Singapore. *Zeitschrift für Geomorphologie*, vol. 5, pp. 302-312.

Keywords: Singapore, microrelief, exfoliation, pseudokarren

Pseudokarren occur at all altitudes and in all types of climates as long as it is wet. On Pulau Ubin they tend to occur on slopes greater than 60 degrees and never on slopes less than 28 degrees; this suggests they are formed by rainwash. Deep, narrow pseudokarren are associated with rough, angular ribs and shallow, wide pseudokarren with smooth, rounded ribs. They usually occur on surfaces devoid of joints. Exfoliation, on the other hand, occurs on slopes less than 40 degrees. Exfoliation forms are usually interrupted by joints and normally do not coexist with pseudokarren. Exfoliation is probably caused by chemical weathering. Exfoliation forms, like pseudokarren, usually do not occur in association with joints.

Twidale, C.R. 1964. A contribution to the general theory of domed inselbergs, conclusions, derived from observations in South Australia. *Transactions and Papers of the Institute of British Geographers*, vol. 34, pp. 91-113.

Keywords: Australia, inselbergs, systematic joints, sheeting joints, weathering

The nature of the joint pattern determines the type of landform. Although joints strike in many directions, only some orientations are significant with respect to landform. Twidale appears to be saying that only joints that occur in obvious sets can be significant; oriented crystals are also important. The orientation of joints is tectonic. An example of greater weathering and closer spacing in a valley is contrasted to that of surrounding hills. Breaks in slope are for the most part due to differential weathering. Slope steepness is related to joint planes which guide weathering. Inselbergs are structural features. In South Australia, mechanical weathering is more important than chemical. The greater resistance of inselbergs can only rarely be attributed to mineralogy or texture. Sheeting is discussed; the degree of curvature decreases with depth. Twidale says sheeting is not primary and that it usually transgresses the subrectangular joint pattern. The origin of sheeting is discussed at length; he prefers the radial compression theory. Coarse grain size is related to rapid disintegration of joint blocks.

_____. 1973. On the origin of sheet jointing. *Rock Mechanics*, vol. 5, pp. 163-187.

Keywords: sheeting joints, theory

The purpose of the paper is to look at suggested origins for sheeting because of discrepancies that exist in the literature; e.g. inselbergs are compressional landforms yet sheeting joints, which are characteristics of inselbergs, are attributed to decompression. Sheeting is characteristic of massive rock — not necessarily unjointed, but without open joints — and usually parallels the land surface. Generally, sheet thickness increases with depth and sheeting cuts across other structures, i.e. sheets post-date consolidation. There are two general theories of origin: 1) sheeting is primary and controls the land surface or 2) sheeting is secondary and forms in response to surface conditions. The latter is the prevailing view. Twidale describes and discusses the various theories under these two headings and concludes that particular theories may well apply in different areas, but "...the best general explanation is that involving lateral compression, induced either through metasomatism, faulting, or horizontal stresses, either relict or modern" (p. 183).

_____. 1980. The origin of bornhardts. *Journal of the Geological Society of Australia*, vol. 27, pp. 195-208.

Keywords: inselbergs, theory

Twidale describes variations in the bornhardt form and defines them as "...bald, domical, steep-sided hills.... Most...are developed in granites or gneisses...." (p. 195). The boundaries of bornhardts are usually not geological in nature. There are two major theories of origin: scarp retreat and the two-stage model. He discusses the two theories in terms of the following: distribution (relationship to drainage, fracture-controlled margins, and occurrence in

multicyclic landscapes), weathering and minor landforms (weathered granite beneath plains, incipient domes, subsurface initiation of minor forms and scarpfoot depressions), stepped bornhardts, age, and bornhardts in sedimentary settings. All the evidence discussed tends to support the two-stage model rather than scarp retreat. Scarp retreat could explain more if the definition were less restrictive, i.e. if some structural control were allowed.

_____. 1981. Granitic inselbergs: domed, block-strewn and castellated. *Geographical Journal*, vol. 147, pp. 54-71.

Keywords: inselbergs, theory, domes, castle koppies, nubbins

There are three types of inselbergs: 1) bornhardts - steep-sided, bald, domical hills, 2) nubbins - roughly conical hills consisting of a jumble of large boulders with steep slopes and 3) castle koppies, otherwise known as tors, which are hills bounded by essentially vertical cliffs comprised of large blocks in situ that are typically angular and unweathered. The paper discusses whether these are separate forms or if they are genetically related. The origin of bornhardts is discussed, as in Twidale (1980), but slightly expanded with reference to his compressional theory. Nubbins are considered domes whose outer shells have been broken down by radial fractures. They appear to be particularly common in warm, wet, seasonally humid regions, are being destroyed in arid regions and are formed by subsurface weathering. Castle koppies are the least common of the three types. Many are located on the crests of large-radius domes. Domes are viewed as the penultimate stage of weathering. Castle koppies and nubbins develop earlier; the former occurring on what will be large domes, and the latter on what will be small ones. In addition, koppies tend to develop either while exposed or in the shallow subsurface, whereas nubbins develop in the deep subsurface. Nubbins have weathered over their entire surfaces whereas koppies have come mainly under marginal attack.

_____. 1982a. The evolution of bornhardts. *American Scientist*, vol. 70, pp. 268-276.

Keywords: inselbergs, theory

This article is written for the layman. Alternative theories of bornhardt evolution are discussed. The paper is a highly polished, well-reasoned exposition of the author's ideas as discussed in earlier, more scientific publications.

_____. 1982b. *Granite Landforms*. New York, Elsevier, 372 p.

Keywords: landform, microrelief, weathering

The book presents most of what Twidale has published in his papers over the years. In the first part, the characteristics and weathering of granite are described. Major landforms are discussed in depth in part 2 (boulders, inselbergs, all-slopes topography) and minor landforms, in part 3. The latter include rock basins, pedestals, doughnuts, runnels, flared slopes, platforms, scarp foot depressions, grooves, tafoni, cracks and displaced slabs. The book is well illustrated with photos and drawings.

_____. 1986. Granite landform evolution: Factors and implications. *Geologische Rundschau*, vol. 75, pp. 769-779.

Keywords: chemical weathering, equifinality, azonal, landform

The purpose of the paper is to show that granite landforms are azonal. They are etch forms that are developed within the regolith at the weathering front by percolating ground waters. They are later exposed (or exposure can occur at the same time as formation) and can then be modified by surficial processes. Twidale also states that similar landforms occur on other rocks including basalts. The climate that controls formation (in association with structure) is the climate within the regolith.

Twidale, C.R. and Bourne, J.A. 1975a. The subsurface initiation of some minor granite landforms. *Journal of the Geological Society of Australia*, vol. 22, pp. 477-484.

Keywords: microrelief, weathering, Australia

Most workers believe most minor granite landforms are formed by epigene weathering processes, but these forms may be initiated subsurface. Part of the evidence for this is the association between these minor landforms and others that are "known" to originate subsurface, such as flared slopes and platforms/benches. Rillen, gutters and grooves are virtually the same thing, but occur on decreasing slopes, i.e. rillen occur on very steep slopes and grooves, on very gentle slopes. The paper consists mainly of examples where incipient gnammas, rillen and tafoni have been found on buried granite surfaces thought, because of the pitting, to have been the weathering front. The regolith on these surfaces was excavated for construction purposes.

_____ **and** _____. 1975b. Episodic exposure of inselbergs. *Geological Society of America Bulletin*, vol. 86, pp. 1473-1481.

Keywords: inselbergs, Australia, microrelief

King has questioned the two-stage hypothesis on the basis of normal depth of weathering vs. height of inselberg, i.e. he believes too much weathered material would have to be produced and removed to account for inselberg size. The purpose of this paper is to present evidence of episodic exposure that would solve this problem. Evidence cited for episodic exposure includes flared slopes, stepped side slopes (benches/platforms) and tafoni. These forms can develop under other conditions, "but where the forms discussed occur in linear, vertically restricted, horizontal or near-horizontal bands, they possibly reflect former zones of intense weathering at or near old hill-plain junctions" (p. 1475). A chronology for exposure based on inselberg proximity to erosion surfaces is presented. The authors do not believe that vertical structural variations (joint density or petrography) could be the cause(s) of the platforms.

_____ **and** _____ 1976. The shaping and interpretation of large residual granite boulders. *Journal of the Geological Society of Australia*, vol. 23, pp. 371-381.

Keywords: microrelief, boulders, Australia, origin

Granite boulders were corestones and their size and shape varies with the original joint pattern and spacing. This is the only structural control on boulder shape and size. The same minor features develop on boulders as develop on inselbergs. Platforms/benches are not related to horizontal or near-horizontal joints. Many minor landforms, whether on boulders or inselbergs, are etch forms initiated below ground level at the weathering front during more than one geomorphic phase. They may, of course, be altered by epigene processes after exposure.

_____ **and** _____. 1978. Bornhardts. *Zeitschrift für Geomorphologie*, Supplement 31, pp. 111-137.

Keywords: inselbergs, structure, joint control

Most investigators accept bornhardts as structural forms, but questions still exist with reference to morphology, climatic significance and age. Structure is discussed under the following headings: tectonic setting, petrology, jointing and faulting. Although inselberg boundaries are broadly joint controlled, the steep side slopes are not. Orthogonal joint patterns are dominant in castle koppies and sheeting joints in domes. Climate is discussed with reference to distribution and scarp retreat. The authors conclude that structure is most important with climate and time/age becoming important only when structure allows.

Twidale, C.R. and Mueller, J.E. 1988. Etching as a process of landform development. *Professional Geographer*, **vol. 40, pp. 379-391.**

Keywords: landform, process, chemical weathering

The authors cite earlier work supporting the concept of a two-stage theory of landform development. Hassenfratz in 1791 is credited with initially proposing the theory with respect to the southern Massif of central France. Such forms—etch forms—are azonal and occur in many types of rock. They are more common in stable shield lands than in areas that are tectonically active. The purpose of the paper is to correct the lack of recognition of etch forms in North America. The two-stage process is described and is determined to be doubly azonal, i.e. with respect to both climate and lithology. Recognition of etch forms requires preservation of patches of regolith nearby. Some forms can be traced from surface exposure to subsurface. The authors recommend a conservative approach to identification. The distribution of major and minor etch forms throughout the world is described. Major forms include bornhardts and plains; minor forms include corestones and flared slopes.

Twidale, C.R. and Sved, G. 1978. Minor granite landforms associated with the release of compressive stress. *Australian Geographical Studies*, vol. 16, pp. 161-174.

Keywords: microrelief, Australia, origin

Most minor granite landforms are formed by weathering; some, such as A-tents, however, are caused by release of compressive stress. There are two types, angular and arched. The slabs of the latter are slightly curved convex upward. Angular A-tents tend to occur midslope whereas arched A-tents occur on hillcrests as well. Possible origins are discussed and the conclusion is that release of compressive stress is the only logical explanation.

van der Merwe, C.R. and Weber, H.W. 1963. The clay minerals of South African soils developed from granite under different climatic conditions. *South African Journal of Agricultural Science*, vol. 6, pp. 411-454.

Keywords: South Africa, soil, weathering, clay

The purpose of the paper was to 1) identify the clay minerals in soils developed on granite under different climatic conditions, 2) study the weathering of clay minerals in the soil-forming processes and 3) evaluate the effect of temperature on clay mineral formation during the rainy season. The soils of six different regions were analyzed, with multiple profiles in each region. The profiles are described in some detail, in tabular form as well as textually. The authors conclude that the profiles, although from a common parent, vary considerably. Illite dominates at the hot, dry end and kaolinite dominates at the wetter end of the spectrum.

> The mature soils, derived from granite under a rainfall of less than 500 mm in the summer rainfall region of South Africa, have illite as principal clay mineral. Under a precipitation of approximately 500 mm soil kaolin replaces illite as dominant clay mineral. In soils, developed from granite under a summer rainfall of 500 to 800 mm, illite and its associates occur as remnants in their clays and at about 900 mm are entirely absent in mature soils. (p. 450)

With reference to summer vs. winter rainfall, the authors conclude that chemical weathering and leaching are more intense under low winter rainfall than under low summer rainfall. The summer rainfall soil contains only kaolinite and the winter one contains soil kaolin and kaolinite as well as other clays.

Wagner, P.A. 1913. Negative spheroidal weathering and jointing in a granite of Southern Rhodesia. *Transactions and Proceedings of the Geological Society of South Africa*, vol. 15, pp. 155-163.

Keywords: Zimbabwe, landform, jointing

The Greystone Hills comprise a small stock within a large area of older gneissose, foliated granite. Petrography and texture are described; both are uniform. There is, however, much variation in landform type, and Wagner attributes this to jointing. There are three types

of joints: sheeting, orthogonal and spheroidal. Landforms are classified by joint type: 1) those in which sheeting joints are dominant, with or without spheroidal joints, 2) those in which orthogonal joints are equal in dominance to sheeting joints, and 3) those in which the three joint types are equally dominant. With respect to type 1, slope and relative relief appear to control whether bare, tall knobs/domes or lower, boulder-strewn hills result from weathering. Where there are orthogonal joints, one tends to find huge, regularly-shaped boulders piled in a confused manner on the periphery so that the surface is irregular and rugged. Pockets of sandy soil develop and support trees and shrubs. The second part of the paper addresses negative spheroidal weathering or, in other words, the development of tafoni. Wagner discounts wind erosion, weathering of basic xenoliths, and weathering of orbicular patches and decides flaking is the cause. The flaking is associated with joint type 3. Cavity shape and size depend on the shape of the original curvilinear fracture, joint spacing, and the presence or absence of well-defined joints.

Wahrhaftig, C. 1965. Stepped topography of the southern Sierra Nevada, California. *Geological Society of America Bulletin*, vol. 76, pp. 1165-1189.

Keywords: California, landform, chemical weathering, lithology, sheeting joints

Stepped topography in the Sierra Nevada occurs only in association with granite. The steps are thought to be individual joint blocks and are caused by differential weathering and erosion. Previous work and the general geology of the area are summarized. Although orthogonal joints exist (spaced 2-10 feet apart), sheeting joints are dominant. They parallel the land surface. The metamorphic rocks in the area are more resistant than the granites and generally rise above them. Most of the area of stepped topography was never glaciated. The treads and risers are described. Buried granite weathers much more rapidly than exposed granite, so once granite is exposed, a step is likely to form. This explains why the pattern of steps is random; it results from chance exposure. Gruss is formed primarily by the weathering of biotite, not plagioclase. Wahrhaftig discusses alternate hypotheses, including fault control, lithologic control, and parallel retreat, but discards them all.

Waters, R.S. 1952. Pseudo-bedding in the Dartmoor granite. *Transactions of the Royal Society of Cornwall*, vol. 18, pp. 456-462.

Keywords: pseudobedding, southwest England, theory

One of the most striking features of Dartmoor in southwest England is the coincidence of the slope of the land surface and the dip of the pseudobedding. Worth (1930) believed pseudobeds are primary structures near the roof, i.e. they reflect undulations in the overlying country rock, which implies little denudation, but the work of Brammall and Groves indicates too much denudation has occurred for this to be true.[28] In addition, Worth's (1930) explanation would require all valleys to be structural and to have been so throughout geologic time. Waters suggests pseudobeds are due to load release resulting from Tertiary fluvial erosion and valley development, in accordance with Farmin (1937) and Jahn (1947).

---

[28] Brammall, A. 1927. Notes on fissure-phenomena and lode-trend in the Dartmoor Granite. Transactions of the Royal Geological Society of Cornwall, vol. 16, pp. 15-27; and Groves, A.W. 1931. The unroofing of the Dartmoor Granite and the distribution of its detritus in the sediments of Southern England. Quarterly Journal of the Geological Society of London, vol. 87, pp. 62-96.

_____. 1957. Differential weathering and erosion on oldlands. *Geographical Journal*, vol. 123, pp. 503-513.

Keywords: southwest England, joint spacing, theory, joint orientation, chemical weathering

Differential weathering and erosion are processes by which the surface adapts to structure. Differential weathering at intermediate levels, i.e. in terms of landscape evolution and landscape modification, has been overlooked. Basins and tors are ubiquitous on Dartmoor in southwest England. Valleys tend to be series of basins. Particularly in the north, the topography tends to be a series of positive ridges and negative valleys, i.e. upstanding or depressed lineaments, trending north-northeast or north-northwest. Where positive lineaments meet, there are tors, and basins occur where negatives ones meet. The joints are the controlling structures and joint spacing is the significant factor. Basins should therefore have more closely spaced joints. Circumstantial evidence is given. Joint orientations in tors are highly varied and do not correspond to the above orientations, however. The basins could not have been formed by fluvial erosion, and may possibly be due to periglacial processes. Chemical weathering "prepared" the granite for easy removal by other processes.

Whitaker, C.R. 1974. Split boulder. *The Australian Geographer*, vol. 12, pp. 562-563.

Keywords: boulders, microrelief, Australia

Boulders can be split as a result of chemical weathering and the removal of overburden. They can also be split by dousing in water after being heated to high temperatures (fire) or by lightning. Two examples of split porphyritic granite boulders in Australia are given.

White, W.A. 1944. Geomorphic effects of indurated veneers on granites in the southeastern states. *Journal of Geology*, vol. 52, pp. 333-339.

Keywords: southeast United States, case hardening, microrelief

Case hardening has not been noted previously in humid regions. It appears to be the same as that in dryer regions. The veneers

> ...appear as dark, hardened layers on the surfaces of unjointed granite exposures that are undergoing granular disintegration; and both seem to result from the deposition of iron oxide in the interstices between the partially disaggregated mineral grains. (p. 333)

It is thought that water containing insoluble hematite is drawn by capillary rise to the dryer outer surface of the rock. It evaporates and the hematite seals cracks in the surface, forming a hardened veneer. White believes that weather pits (pans) are caused by the breeching of the veneer by lichens and mosses. Pedestal rocks are also attributed to breeched veneers.

_____. 1945. Origin of granite domes in the southeastern Piedmont. *Journal of Geology*, vol. 53, pp. 276-282.

Keywords: southeast United States, domes, theory, sheeting joints, soil

White does not believe the domes of the southeast piedmont result from exfoliation, but that they are formed by granular disintegration brought about by chemical weathering. He finds little evidence for exfoliation in the area; and some of the evidence he presents is, however, questionable. He attributes the evidence he finds to quarrying. White shows that soils formed over unjointed granites (i.e. dome-forming granites) are different from those over jointed granites. His evidence for granular disintegration, other than the presence of sandy, grussy soils, is poor, but his conclusion is most interesting: he believes granite domes should be regarded "...as the expected form wherever nonjointed homogeneous rocks are subjected to the attack of any non-directional agency of denudation" (p. 282). The agency would depend upon climate, but the resultant dome form would be the same (equifinality).

Whitlow, R. and Shakesby, R.A. 1988. Bornhardt micro-geomorphology: form and origin of micro-valleys and rimmed gutters, Domboshava, Zimbabwe. *Zeitschrift für Geomorphologie*, vol. 32, pp. 179-194.

Keywords: Zimbabwe, microrelief, landform, chemical weathering, lichen

The paper presents the results of a quantitative study of small valleys and the gutters that feed them on a granite dome. The results are based mainly on cross section measurements. The morphology suggests that the micro-valleys result from subsurface weathering followed by exhumation rather than by subaerial processes as previously proposed. The authors suggest even relatively shallow burial (no more than 1 m) would be adequate if the depressions retained moisture. The gutters, on the other hand, are considered recent and of subaerial origin. They form through active chemical weathering in non-joint controlled linear depressions caused by seepage flow in association with biological weathering caused by lichens. The rims result from silica deposition and are best developed on gutters draining vegetated micro-valleys. The authors state that the silica comes from silica-rich rain water, but apparently did not analyze the rain water.

Williams, A.G., Ternan, L. and Kent, M. 1986. Some observations on the chemical weathering of the Dartmoor granite. *Earth Surface Processes and Landforms*, vol. 11, pp. 557-574.

Keywords: southwest England, chemical weathering

The paper presents observations from different approaches to chemical weathering. The authors develop a geochemical budget, study mineralogy to identify pertinent reactions and use chemical data to determine the stable phases. They studied the upper part of the Narator Basin in the southwest part of Dartmoor in southwest England. There are two soil types: stagnopodzols on the plateau with a continuous iron pan at about 35 cm and brown podzols on hillslopes, often showing a fragipan at 70-90 cm. Samples were collected weekly for a year. The authors show active chemical weathering in an intense leaching environment. Relative ion mobility is calcium > sodium > magnesium > silica > potassium. Low potassium

mobility is due to production of kaolinite or adsorption onto clay colloids. Plagioclase and orthoclase are the two dominant minerals being weathered and kaolinite is the stable phase in the regolith. There are spatial and temporal variations, however, with gibbsite becoming stable under extremely wet flushing conditions. Clay content is very low in the soils (4.5% average) and only the A horizon has more than 70% sand. There is greater weathering near the surface. The clay minerals are kaolinite and illite; chlorite is only present in the surface horizons. Plagioclase accounts for 74% of the weathering, orthoclase for 16% and biotite for 10%. This is also the sequence for speed of weathering. Overall chemical denudation rates are about 5 mm/1000 yrs. In the Narrator basin, the total is about 6.5 mm, so chemical weathering is about three times greater than mechanical. Hydrolysis is the most significant process. The extremes invoked by Linton (1955) and others to produce the Dartmoor tors are thus not necessary; only minor variations in present conditions are needed because chemical weathering is active and continuing.

Willis, B. 1934. Inselbergs. *Annals of the Association of American Geographers*, vol. 24, pp. 123-129.

Keywords: inselbergs, lithology

Willis describes inselbergs in general and the type called bornhardt in particular. Bornhardt slopes are joint- or schistosity-controlled and summits are controlled by spalling. Bornhardts are restricted to granite, granite-gneiss, or metamorphic rocks intruded by granites and have little to no talus. Inselbergs survive because they are so resistant to erosion. Conditions that favor inselberg development are: 1) rock type as above, 2) vertical jointing or schistosity to facilitate decomposition, 3) a warm, humid climate and 4) notable uplift. Most inselbergs survive repeated geomorphic cycles, which in fact may be necessary to their development. The African ones described by Bornhardt are pre-Jurassic, and all may be very old.

Wolff, R.G. 1967. Weathering of Woodstock granite, near Baltimore, Maryland. *American Journal of Science*, vol. 265, pp. 106-117.

Keywords: Maryland, weathering, quartz monzonite, water chemistry

The paper attempts to "...document and correlate the water chemistry and mineralogic changes occurring under natural weathering conditions in a quartz monzonite..." (p. 106). Chemical and modal analyses are presented. The former show little alteration in the sample sequence. Halloysite was the major clay mineral in the saprolite. Wolff found enrichment in K_2O and water. The former results from the stability of potassium feldspar and the latter from hydration of biotite.

Worth, R.H. 1930. Address of the President: The physical geography of Dartmoor. *Transactions of the Devonshire Association for the Advancement of Science, Literature and Art*, vol. 62, pp. 49-115.

Keywords: southwest England, tors, joint orientation

A physical description of Dartmoor in southwest England is provided, and vegetation, peat, hills and valleys, china clay, tinners' influence, tors, border hills, streams and rivers, climate and geology are discussed briefly. The contours of Dartmoor are those of the upper surface of the original pluton. Valleys represent eroded synclines in the country rock. Evidence for this includes 1) coincidence of pseudobedding with hillside slopes (vertical joints and pseudobeds are primary and result from cooling); 2) inclusions, of two types, one a fine-grained granite and the other fragments of country rock; 3) patches of country rock overlying the granite; and 4) the presence of a chilled, red felsite. China clay forms only very near the surface of the granite, and Worth implies the origin is pneumatolytic. Tors owe their existence to their resistance to weathering and to the pseudobeds. Usually two sets of vertical joints, perpendicular to each other, are present. Worth appears to support the idea of snow-rafting as the origin of the clitter fields, and freeze-thaw is described as the cause of rock basins. All rock basins are in coarsely-porphyritic granite. Slopes on the metamorphic rocks of the aureole are steeper than slopes on granites. The author considers the joints to be of local origin and so highly varied in orientation that statistical analysis is impractical.