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Rock Characteristics and Susceptibility to Weathering: A Study in the Metamorphic Terrain of Ayodhya Hill, West Bengal

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Abstract: *Characteristics of a particular rock type play an important role in determining its susceptibility to weathering provided other factors affecting weathering remain more or less stable. In the present article an attempt has been made to evaluate the impact of different lithological characteristics like spacing and opening of joints and fractures, nature of the infill material, degree of foliation, texture and mineralogy of the rock, rock-strength and permeability, on the nature and extent of weathering in the metamorphic terrain of Ayodhya hill, West Bengal. Depth of weathered substratum below the ground level has been taken as the indicator of susceptibility to weathering. Because of infrastructural constraints, rock strength, permeability and depth of weathered substratum have not been measured directly, but sourced from available literature. All other parameters have been measured in field or in the laboratory. A statistical relationship has also been established between the lithological properties and depth of weathering. The study has revealed that degree of foliation, rock strength, joint spacing and rock texture are the most important predictors of the depth of weathering (R= >0.98). Based on the degree of variation in these three variables, a rating scheme has been designed to estimate the susceptibility of all the major rock types exposed in the Ayodhya hill to weathering. It has been concluded that quartz-biotite schist is most susceptible to weathering and massive amphibolite is the least susceptible. The rating scheme has the potential for application to any similar metamorphic terrain, and the principle may be tested to develop other area-specific weathering susceptibility of rocks.*

Introduction

Weathering is one of the fundamental geomorphic processes that exert control on topographic expressions and landscape evolution. Numerous factors can affect the nature and intensity of weathering (both physical and chemical), of which the variables of rock factor are very significant. Not only weathering processes can effectively alter the physical and chemical state of the rocks, but being the material itself, rocks also affect the nature, extent and effectiveness of the weathering processes. Despite this, a quantitative relationship between the two is still very difficult to establish, especially due to lack of proper instrumentation and other infrastructural facilities to measure all the parameters, as well as the very slow nature of the weathering process. In the absence of ideal weathering front, one has to look for specific drilling data, but such data are also few and location-specific. Under the circumstance, one possible solution is to design a scheme through which a few easily measurable (primary) and readily available (secondary) data can be interpreted to infer the degree of susceptibility of individual rock types to the processes of weathering. The present study has attempted to develop such a scheme for quantification of weathering susceptibility of rock types in Ayodhya hill which is located in the southwestern part of Puruliya district, West Bengal, and is a metamorphic terrain of Pre-Cambrian antiquity (Fig. 1).

Objectives

The objectives of the present study are (1) to establish a quantitative relationship between properties of a rock and its susceptibility to weathering as manifested in the Ayodhya hill area and, (2) depending on the relative importance of the rock properties, to formulate a scheme by means of which the extent up to which a particular rock is prone to weathering can be ascertained, provided the other factors affecting weathering remain more or less stable.

Materials and methods

Background information on the geological

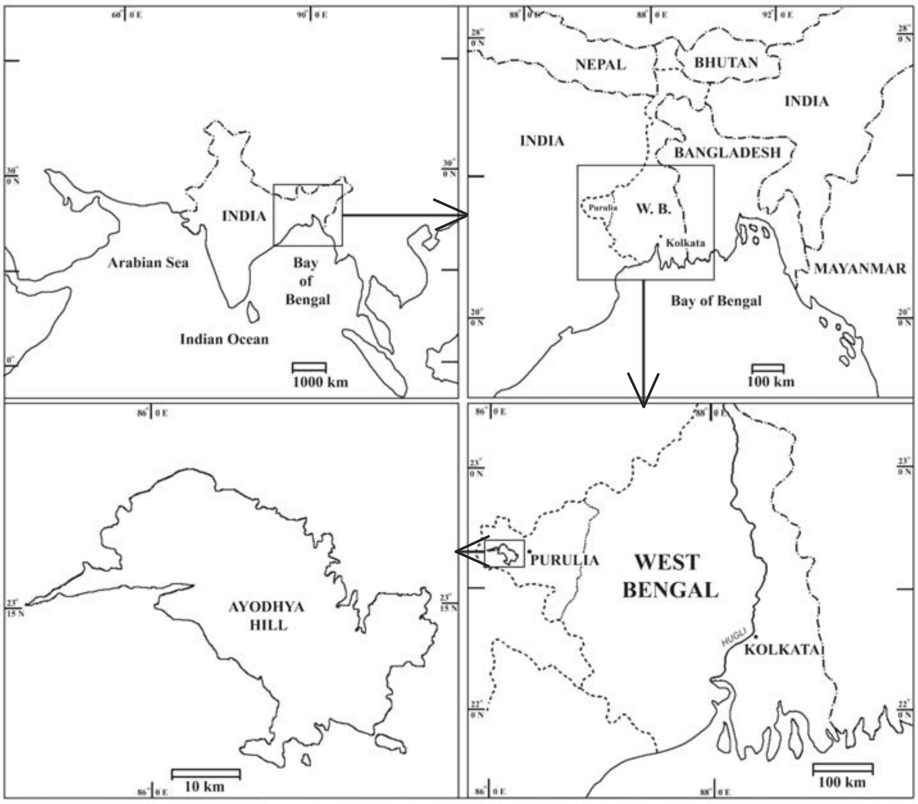

Figure 1. Location of Ayodhya hill

Table 1. Stratigraphic succession, phases of deformation, associated metamorphism and resulting structures, Ayodhya hill. (Prepared on the basis of information presented in Baidya and Chakraborty, 1988; Baidya, 1984)

Age	Lithological succession	Metamorphism	Phases of deformation	Predominant force	Resulting structure		
					Fold	Foliation	Lineation
RECENT	Alluvium	Not affected	Not affected	Not applicable	Not applicable	Not applicable	NNE-SSW Trending
PRECAMBRIAN	Dolerite	Not affected	Not affected	Not applicable	Not applicable	Not applicable	Not applicable
	Pegmatite & Quartz vein	Contact or metasomatic metamorphism	Third phase	E-W compressive	gentle of open	Shear plane type	ENE-WSW Trending lineaments
	Massive leucogranite						
	Porphyritic Biotite granite						
	Quartzo felds-pathic Gneiss		Second phase	N-S to NE-SW compressive	open fold	Crenulation type	NW-SW Trending lineaments
	Biotite-gneiss						
	Quartz-biotite gneiss						
	Banded biotite gneiss						
	Banded quartz biotite gneiss						
	Amphibolites (massive)		First phase	N-S compressive	Tight isoclinal	Bedding Parallel	
	Amphibolites (massive)	Regional metamorphism					
	Quartz-biotite Schist						
	Biotite-schist						

set-up, structural characteristics and tectonic history of the area was collected from available literature (Bose, 1957; Gangyopadhyay, 1959; Baidya, 1981, 1984; Baidya and Chakraborty, 1988; Acharya, 1990; Bhattacharya and Ghosal, 1992; Bose, 1992). For a concise map of the different rock types in the area, some important literature was consulted.

For quantification of rock properties that

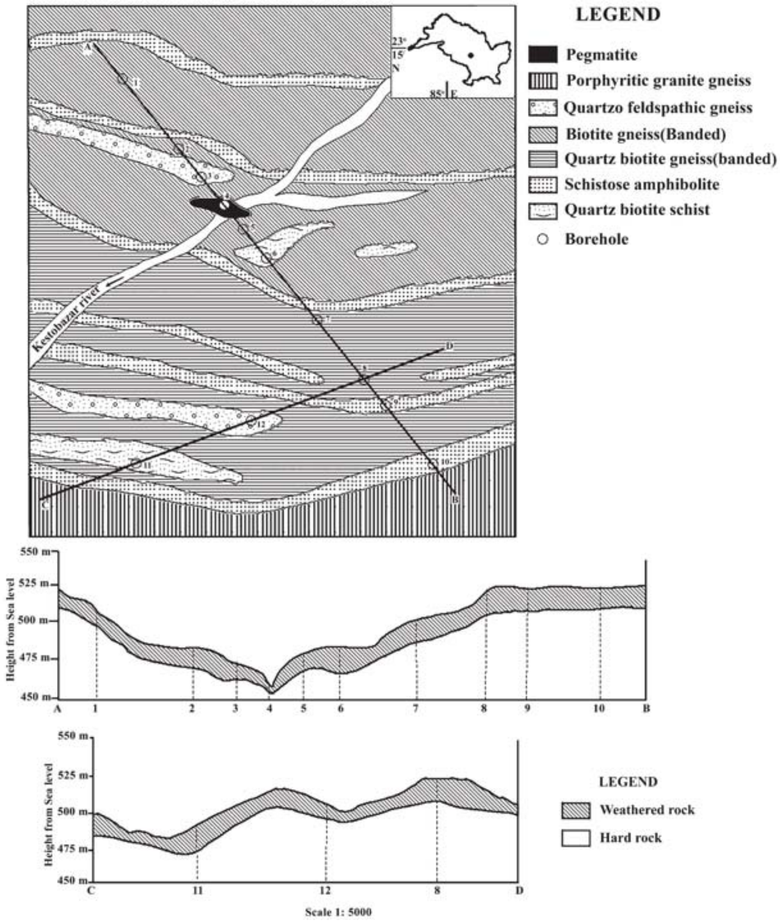

Figure 2a. Cross section showing the pattern and depth for weathering in the upper part of the Kestobazar basin, Ayodhya hill
Data Source: West Bengal State Electricity Board (1990)

control the extent of weathering, the following parameters have been considered: structural characteristics of the rocks (including spacing of the joints and fractures, opening or aperture of the same, their continuity, nature of infill material, nature of schistosity and degree of foliation), rock texture, permeability and porosity, mineralogical composition and rock strength. To estimate the susceptibility of a rock type to weathering, the depth of weathered stratum from the ground level has been considered since "weathering is deepest where the materials are most susceptible to weathering" (Cooke and Doornkamp, 1990).

Parameters like joint spacing, aperture, nature of infill material, nature of schistosity, degree of foliation, etc., have been recorded directly in the field, both quantitatively and qualitatively, using standard techniques (detail in relevant sections). Besides, a large number of rock samples (both weathered and non-weathered varieties) have been collected in the field and analysed in the laboratory, from which thin sections have also been prepared to study the textural and mineralogical composition of the rocks. Parameters like rock

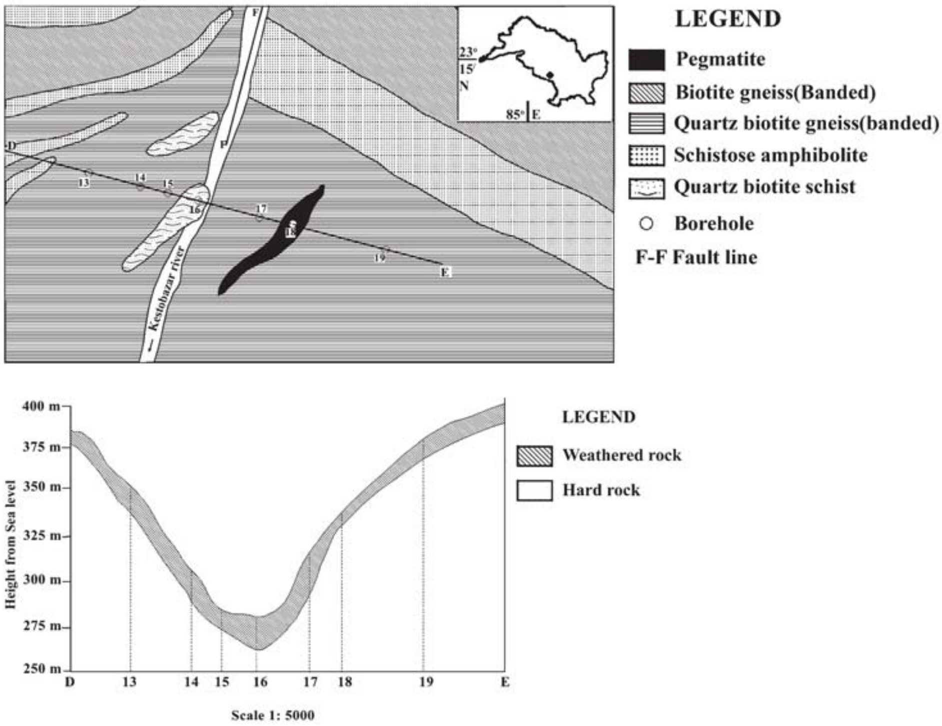

Figure 2b. Cross section showing the pattern and depth for weathering in the lower part of the Kestobazar basin, Ayodhya hill
Data Source: West Bengal State Electricity Board (1990)

strength, permeability, porosity, depth of weathering, etc., could not be measured directly in the field. These have been collected from unpublished drilling reports consisting of the litho-logs of some forty boreholes drilled in the south-central part of the Ayodhya hill and relevant engineering test results prepared by a number of consultancy agencies on behalf of the West Bengal State Electricity Board (1990, 1992).

Attempt has been made first to establish a quantitative relationship between the depth of weathering (dependent variable) and variables of rock factor (independent variables), using the data of forty drilling stations for which both the sets of data are available. Multivariate and associated statistical analyses have been carried out to establish the relationship, using the software 'Statistica' (Statsoft Inc.). Based on the relationship, a weathering susceptibility rating scheme for different rock types in the area has been formulated (procedure is described in the relevant section).

Morphological characteristics of the Ayodhya hill

The Ayodhya hill is basically a plateau (300 m – 665 m) of 401.4 km^2 area. On the basis of morphological characteristics, three distinct geomorphic sub units have been identified in this plateau area – a) the almost flat plateau top with isolated peaks and hillocks, b) the break-of-slope zone which is basically a steep, escarpment like transitional unit connecting the plateau top above and the foot hill area below and c) the piedmont zone at the foot hill. Standing about 300 m above

Table 2. Joint-spacing status of the rocks of the Ayodhya hill

Rock Type	Range of joint spacing	Mean joint spacing	Description (after Deer, 1968)
Pegmatite	6–87 cm	30.81 cm	Close to moderately close (blocky to seamy)
Quartz vein	2–35 cm	10.2 cm	Close (fractured)
Massive granite	20–50 cm	35 cm	Close to moderately close
Quartzo-feldspathic gneiss	12–80 cm	34.12 cm	Close to moderately close (blocky to seamy)
Quartz biotite gneiss	11–60 cm	31.23 cm	Close to moderately close(fractured to blocky)
Biotite gneiss	3–50 cm	21.5 cm	Very close to moderately close (fractured)
Banded quartz biotite gneiss	11–30 cm	20.25 cm	Close (fractured)
Banded biotite gneiss	10–50-cm	28.75 cm	Close to moderately close (fractured)
Massive amphibolites	Mostly non jointed, massive to solid		
Schistose amphibolites	15–23 cm	19.33 cm	Close (fractured)
Biotite schist	5–50 cm	26.66 cm	Close to moderately close (fractured)
Quartz biotite schist	25–36 cm	32 cm	Close to moderately close (blocky to seamy)

the surrounding undulating plain, the Ayodhya hill acts as the watershed between the Kangsabati system in the north and northeast and the Subarnarekha system in the southwest. This detached remnant of the 'Chhotanagpur Gneissic Complex' (CGC) represents one of the oldest exposed terrains of West Bengal. It is predominantly composed of gneissic rocks and, being located in the sub-humid tropical climate, is exposed to both physical and chemical processes of rock breakdown. Among the processes of mechanical disintegration, joint block separation is very common. The process is predominant along the highly fractured south-facing escarpment slopes. Exfoliation is also active on the dome shaped hillocks around Matha and Jhalda. The chemical processes of rock decomposition are operating mainly on comparatively gentle slopes and flat areas. The profile of weathering, as noted in the Ayodhya hill, consists basically of four layers. These are – a) the uppermost layer of sand and soil (1 m-6 m thick), b) the transitional layer of highly weathered rock fragments or boulders held in thick soil matrix (1 m-5 m thick), c) the zone of partially weathered rock (3 m-7 m thick) and d) the lower most layer of fresh rock. The depth of weathered stratum varies from 1.7 m to 23 m and it is closely related to the properties of rock (Fig. 2a and 2b). In Ayodhya hill, the end product of weathering contains kaolinitic clay and insoluble silica forming a matrix within which boulders and pebbles of rocks are embedded. But the percentage of clay content in the weathered residuum is not very high; it is only 15% to 22%. Hard indurated layer is noted only in the south central part of the hill over a limited area. The absence of hard duricrust layer suggests that weathering has not reached the advanced stage here. If weathering had attained a matured stage, hydrated aluminum oxide would have been formed by further alteration of kaolinite and silica would be removed from the system as silicic acid resulting into high silica content in the river water (10 – 25 ppm). But in the water samples of the rivers of Ayodhya hill, the average silica content varies from 5-7 ppm only.

Geological set up and lithological units

The Ayodhya hill is basically composed of gneissic rocks equivalent to the Chhotanagpur gneiss. The geological map (Fig. 3) shows that different types of granite gneiss characterise the southeastern, southern and southwestern parts, while migmatite and composite gneiss are predominant over the northeastern and northern parts. Besides, there are some scattered enclaves of mica-schist, amphibolites and intruded bodies of porphyritic granite, massive granite, pegmatite and quartz vein. Being an integral part of the Pre-Cambrian tract of Chhotanagpur Gneissic Complex (CGC), which was tectonically active for more than 1.6 billion years (Bhattacharya, 1990), the Ayodhya hill has witnessed a complex evolutionary history, marked by poly-phase tectonic movements, magmatic activities and metamorphism (Table 1). The imprints of all these events are manifest on the rock characteristics of the area.

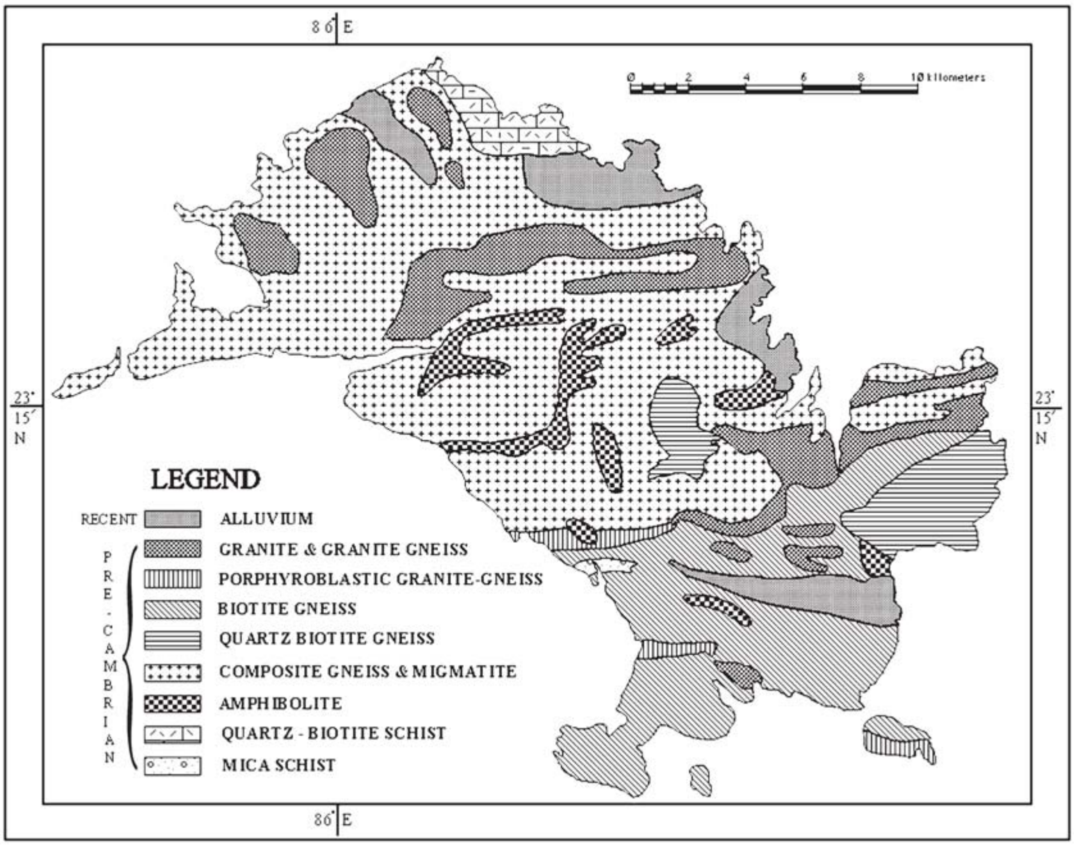

Figure 3. Geological set-up of the Ayodhya hill and its surroundings.
Source: Photogeology and Remote sensing Division of GSI, Eastern Region, Calcutta.

Rock structure

The resistance of a rock to weathering depends to a large degree on the weakness conferred upon it by its structural discontinuities (Terzaghi, 1962). Hencher, (1987) has listed ten major types of structural discontinuities that may be present in any rock mass. Of these the joints, fractures and foliation planes–marked by Hencher as typical of metamorphic rocks, are well exhibited by the gneissic terrain of the Ayodhya hill.

Joints and fractures

The Ayodhya hill is basically a well jointed terrain. Four major and some minor sets of joints and fractures, all showing northerly dip, have been identified in this area and being conspicuous structural weakness, such joints and fractures allow water to penetrate deep into the rock, causing preferential chemical weathering and also promote mechanical disintegration. Apart from these, the rocks also possess numerous micro-fissures and micro-cracks, resulting mainly from crystallisation, along which also penetrates weathering processes. But these micro cracks and fissures are very difficult to measure in the field and hence, have not been considered in this study. The joint properties of considerable importance to weathering are discussed next.

JOINT SPACING: The importance of joint spacing in the context of weathering has widely been recognised (Thomas, 1974; Selby, 1982a; Ollier, 1984; Parsons, 1988). The rocks with closely spaced joints are more susceptible to weathering, since such joints expose a large internal surface, allowing weathering to proceed rapidly to considerable depth (Chorley, 1979). In order to determine the average joint spacing characteristics in the Ayodhya hill, about 100 sets of joints have been selected in the field randomly from different rock types and their average distance have been measured along perpendicular traverse lines. The data obtained have then been grouped and classified following the scheme of Deere (1968) and Selby (1980). It has been found that spacing of more than 60% of joints varies from 5 to 30 cm, which may be designated as ‘closely spaced’. About 25% of the total observed sets have an average spacing of 30-100 cm (moderately close joints). 0nly 10% of the observed joints have a spacing of <5 cm (very closely spaced), and 1% is ‘widely spaced’(spacing >1 m). When rock wise data is considered, it appears that banded quartz biotite gneiss and schistose amphibolite are the most intensely fractured rocks, while massive variety of amphibolites is mostly non-jointed (Table 2). Even when joints are found in such rock, the average spacing is more than 1 m. Joints found in other rocks are closely to moderately closely spaced.

JOINT OPENING OR APERTURE: The extent of opening of the joints largely controls the flow of water along them and the rate of weathering of the wall rocks (Selby, 1980). Ideally the width of joints needs to be measured at a depth of 10 cm or more in the outcrops, since the observed width of the joints exposed at the ground may have been enlarged by weathering and erosion. Unfortunately, we lack proper instrument to measure the joints at depth. Aperture or opening of the joints have, therefore, been measured at the surface in the field, and at the same 100 sites as mentioned in previous section. The data has then been classified after Selby (1980). The average opening mostly varies from 1 mm to 5 cm. More than 5 cm opening has been recorded rarely. There is no

Table 3. Nature of joint aperture of the rocks of the Ayodhya hill

Rock type	Aperture/opening of the discontinuities
Pegmatite	2–5 mm
Quartz vein	1–2 mm
Massive granite	1–3 mm
Quartzo-feldspathic gneiss	2–50 mm
Quartz biotite gneiss	1–20 mm
Biotite gneiss	1–20 mm
Banded quartz biotite gneiss	2–20 mm
Banded biotite gneiss	2–20 mm
Massive amphibolites	mostly non-jointed
Schistose amphibolites	2–20 mm
Biotite schist	40–50 mm
Quartz biotite schist	40–50 mm

Source: Field measurements

remarkable rock wise variation in joint opening or aperture (Table 3).

JOINT INFILL MATERIAL: Joint infill material can have a decisive effect on rock strength especially in case of widely open joints and thereby on its resistance to weathering. Three different types of infill material have been noted in the rocks of Ayodhya Hill. These are (i) fine sand and dust (loose), (ii) clay and kaoline (soft), (iii) veins of quartz and feldspar (hard). Clay and kaoline are the most common types and are formed in situ by weathering of the feldspar present in the rocks. Sand and dust filler, characteristic of the joints of very small aperture, are washed down from the surface either by water or by wind. To determine the impact of these infilling materials on the strength of the rocks of Ayodhya hill, both field test and laboratory experiments have been conducted by different drilling agencies for the WBSEB (1990). The studies reveal that vein filling causes the rock to be more resistant to weathering, while soft infilling tends to produce lower strength. The strength of soft material-filled jointed rocks may be as low as that of the filler, but it can never be lower than the strength of the filler. The fine dust or sand has no perceptible impact on the resistance of the rocks to weathering.

No major difference in the nature of the joint infill materials has been found among the different types of rocks of Ayodhya hill. Apart from massive amphibolite, which being mostly non-jointed is devoid of such infill materials, the other rocks are characterised by all the three types of infill materials, showing a clear dominance of clay and kaoline.

JOINT CONTINUITY: Reducing the cohesive strength of the rock, providing zones of shear and permitting greater circulation of water, continuous joints usually create extensive zones of weakness. The jointed rocks of Ayodhya hill appear to be both continuous and discontinuous, but quantitative measurement of the joint continuity is difficult.

Presence of cleavage and schistosity make metamorphic rocks of the Ayodhya hill susceptible to both chemical and physical weathering. The schistose rocks are marked by preferred orientation of minerals along which planes of weakness are developed, while across the foliation planes the rocks are comparatively stronger. The amount of inclination of the foliation planes varies widely from 20º to 70º in all rock types, but the direction of inclination remains consistently towards north. It is not possible to quantify the degree of foliation; however, a qualitative gradation can be made (Table 4). It has been found that metasedimentaries and some metabasics (schistose amphibolites) are more intensely foliated than the gneissic rocks. Such a variation may be attributed to the fact that the metasediments and the earlier members of the metabasics were subjected to

Table 4. Degree of foliation of the different rock types of the Ayodhya hill

Rock types	Degree of foliation[1]	Amount of inclination of the foliation planes[2]	Direction
Pegmatite	Non-foliated	—	—
Quartz vein	Non-foliated	—	—
Massive granite	Crudely foliated	N.A	—
Quartzo-feldspathic gneiss	Moderately foliated	20º–35º	Towards N and NE
Quartz biotite gneiss	Moderately foliated	20º–35º	
Biotite gneiss	Moderately foliated	20º–60º	
Banded quartz biotite gneiss	Highly foliated	20º–70º	
Banded biotite gneiss	Highly foliated	20º–60º	
Massive amphibolites	Non-foliated	—	
Schistose amphibolites	Very highly foliated	20º–70º	
Biotite schist	Very highly foliated	20º–35º	
Quartz biotite schist	Very highly foliated	20º–55º	

1. Determined qualitatively on the basis of visual interpretation
2. Recorded in the field as well as derived from secondary sources (Sengupta, 1991; WBSEB, 1990)

higher grade regional metamorphism of amphibolite-granulite facies, while the gneissic rocks were affected by much lower grade contact or metasomatic type of metamorphism.

Rock texture

Usually coarse-grained rocks weather more rapidly than the fine-textured rocks of the same mineralogical composition. In coarse-grained rocks decay of one mineral has greater impact on loosening of the whole fabric of the rock than that of the same constituent in a fine textured species. In addition to that, often the inter-locking structure of the crystals of fine-grained rocks retards the rate of weathering. But contradictory observations are also available. Actually, the influence of mineralogical composition is so great and so closely linked with texture, that isolation of texture as a factor in the weathering of crystalline rock is very difficult (Thomas, 1974). A generalised textural gradation of the rocks of the Ayodhya hill has been made on the basis of thin section interpretations (Table 5).

Permeability and porosity

Since percolating rain water is the major reactant in chemical decomposition, the susceptibility of a rock to such decomposition process is very much controlled by the accessibility of water. One measure of accessibility of water is permeability i.e., the ease with which the water passes through the rock (Gerrard, 1988) and the other is porosity i.e. the measure of void spaces within the rock. Depending upon the frequency of discontinuities, openness of the fractures, and the degree of interconnection among them, rocks display a wide range of permeability values. The permeability values of the rocks

Table 5. Textural characteristics of the different rock types of the Ayodhya hill

Rock types	Texture[1]
Pegmatite	Very coarse
Quartz vein	Very coarse
Massive granite	Medium
Quartzo-feldspathic gneiss	Medium
Quartz biotite gneiss	Medium
Biotite gneiss	Medium
Banded quartz biotite gneiss	Medium
Banded biotite gneiss	Medium
Massive amphibolites	Fine
Schistose amphibolites	Coarse
Biotite schist	Coarse
Quartz biotite schist	Coarse

1. Determined qualitatively on the basis of microscopic study of thin sections.

of the Ayodhya hill recorded at various depths by water injection or packer test method (WBSEB, 1990) show a general downward decreasing trend (Table 6). Maximum permeability values are recorded between 13 and 17 m below ground level (bgl) in case of most of the rocks. It is observed that massive granite (less than 1 lugeon) and massive amphibolite (about 4.6 lugeon) are characterised by lower values of permeability, while all the remaining rocks have moderate permeability (mostly from 2 to 10 lugeon and above).

Porosity provides a rough guide to the surface area within a rock over which chemical activity can take place (Rice, 1988). In rocks with high porosity value, every mineral grain is exposed to weathering while less porous rocks are weathered at the surface and only along the few widely spaced joints (Ollier, 1984). In spite of such importance of porosity, its impact in this particular area cannot be assessed quantitatively due to lack of data. The average porosity value of only three rocks (fresh samples) is available (WBSEB, 1990) like pegmatite 0.92), biotite-gneiss (0.99 to 1.1) and biotite-schist (1.11 to 2.12). A general trend of decreasing porosity with increasing grade of metamorphism has been observed, but no definite conclusion can be made in this regard without more detailed study.

Mineralogical composition

"Presence of minerals particularly susceptible to alteration increase the rate of weathering penetration and may promote early disaggregation of rocks" (Thomas, 1974). The susceptibility of a mineral to be weathered depends upon the environment of the mineral as well as its structure and composition (Ollier, 1984). Hence, the ranking of minerals in a series, according to

Table 6. Permeability values of the different rock types in Ayodhya hill

Rock types	Permeability (in lugeon)
Pegmatite	1.8–9.5
Quartz vein	—
Massive granite	< 1
Quartzo-feldspathic gneiss	6.6–7.0
Quartz biotite gneiss	5.0–6.0
Biotite gneiss	2.0–7.9
Banded quartz biotite gneiss	6.6–20.5
Banded biotite gneiss	3.3–10.0
Massive amphibolites	4.6–5.0
Schistose amphibolites	6.0–10.7
Biotite schist	6.0–6.5
Quartz biotite schist	6.5–8.0

Source: WBSEB (1990)

Table 7. Ranking of the primary and secondary minerals according to their susceptibility to weathering

Primary Minerals [1]		Secondary Minerals [2]	
Name of the minerals	Weathering Susceptibility Rank[3]	Name of the minerals	Weathering Susceptibility Rank[3]
Quartz	1	Zircon	1
Muscovite	2	Apatite	2
Microcline	3	Magnetite	3
Orthoclase	4	Epidote	4
Biotite	5	Sphene	5
Plagioclase	6	Zoisite	6
Hornblende	7	Diopside	7
Pyroxene	8		
Olivine	9		

1. After Thiel (1940), Goldich (1938), Ollier (1984), Gerrard (1988)
2. After Ollier (1984)
3. Ranking has been done in an increasing order with increasing susceptibility to weathering for the ease of subsequent calculation and analyses.

the ease of weathering is not a very easy task. However, various attempts have been made in this respect (Freise, 1931; Thiel; 1940; Goldich, 1938; Ollier, 1984; Gerrard, 1988). Considering all these schemes, a generalised sequence of susceptibility to weathering of both primary and secondary minerals, characterising the rocks of Ayodhya hill, has been suggested (Table 7). Quartz comes at the top of the table being resistant to both physical and chemical processes of weathering. Hence, quartz is often considered as a standard against which weathering of the grains can be measured. On the contrary, hornblende, pyroxene and olivine are the most susceptible minerals. The average mineralogical composition of the major rock types of the Ayodhya hill are shown in Table 8. The results of modal analysis of about 45 non-weathered samples of different rock types have been consulted for this purpose. The highest percentage of weathering-susceptible minerals (e.g. hornblende) is present in both the varieties of amphibolite, whereas quartz-biotite-schist samples account for the maximum percentage occurrence of weathering-resistant minerals like quartz and microcline. The other rocks are lying in between the two extremes.

Rock strength

An index of strength which is an expression of the combined effect of factors like proportion of soft minerals, nature of schistosity and foliation, grain size and porosity (Gerrard, 1988) is very useful in assessing a rock's resistance to the natural processes like weathering. Rock strength may be determined in different ways. The particular index of rock strength used here is uniaxial compressive strength (Table 9) which has been calculated by dividing the maximum load carried by the specimen during the test by its average original cross sectional area (WBSEB, 1990). Young's modulus, i.e. the measurement of the amount of stress required

Table 8. Mineralogical composition of the rocks found in the Ayodhya hill and their weathering susceptibility

Rock type	Per cent of primary minerals									Per cent of secondary minerals						
	Least susceptible<===========>most susceptible									*Least susceptible<====>most susceptible*						
	Quartz	Muscovite	Microcline	Orthoclase	Biotite	Plagioclase	Hornblende	Pyroxene	Olivine	Zircon	Apatite	Magnetite	Epidote	Sphene	Zoisite	Diopside
Pegmatite (10)	25	12	0	50	0	13	0	0	0	0	0	0	0	0	0	0
Massive granite (5)	24.74	0.75	5.81	0	0.97	12.79	0	0	0	0	0	0	0	0	0	0
Quartzo -feldspathic gneiss (6)	24.69	0	37.65	0	4.36	31.58	0.2	0	0	0	0.28	0.1	0.6	0.09	0	0
Quartz-biotite gneiss and banded Quartz-biotite gneiss (10)	28.19	0	3.73	0	18.81	44.78	1.83	0	0	0	0.34	0	0.7	0.6	0	0
Biotite gneiss and banded biotite gneiss (7)	13.87	0.7	40.28	0	7.8	29.7	4.28	0	0	0	1.13	2.1	0.8	0.13	0	0
Massive amphibolite(18)	2.21	0	0	0	10.3	23.28	48.03	0	0	0	3.15	0	0	3.87	0	11.66
Schistose amphibolites(12)	2.08	0.96	0	0	1.9	28.72	60.98	0	0	0	0.5	0	0.82	1.45	0	2.13
Quartz-biotite schists (5)	51.6	29.1	0	0	11.6	0.6	0	0	0	0	0.4	0	0		0	0

Note: The numbers of samples studied are mentioned within the parentheses.

to produce a specified amount of strain (Gerrard, 1988), is another good indicator of rock strength. But since values of Young's modulus are not available for all rock types, it has not been considered here as the parameter for further classification and analysis. However, where both Young's modulus and uniaxial compressive strength are available, these are well conformable to each other. On the basis of uniaxial compressive strength, the rocks of the Ayodhya hill has been classified following Bieniawski's scheme (1973) into four groups (Table 10).

Relationship among the variables and their contribution in weathering

All the above parameters of rock factor are very much inter-connected and at the same time are instrumental in determining the degree of susceptibility of a rock to weathering. To establish a quantitative relationship among these variables and to assess their relative contribution in relation to weathering, a multivariate analysis has been carried out. The eight variables of rock factor (i.e. joint spacing, joint aperture, nature of joint infill material, degree of foliation, rock texture, permeability, mineralogical composition and rock strength) are considered as the independent variables, while 'depth of weathering' is taken as the dependent factor. For this analysis the drilling locations have been taken as the sample sites, since data regarding all the concerned parameters are available for those sites only (some recorded directly in the field and some obtained from secondary sources) and apart from rock factors, the variables of other factors affecting

Table 9. Strength parameters of the rocks of the Ayodhya hill

Rock types	Young's modulus (in 10 kg cm^{-2})	Uniaxial compressive strength (in kg cm^{-2})
Pegmatite	4.17	650 -940
Massive granite	N.A	N.A
Quartzo-feldspathic gneiss	N.A	740 - 868
Quartz biotite gneiss	N.A	620–638
Biotite gneiss	2.74–2.76	608–900
Banded quartz biotite gneiss	2.11	258–301
Banded biotite gneiss	2.70–2.73	320–350
Massive amphibolites	8.42	1190–1700
Schistose amphibolites	3.06–3.28	1080
Biotite schist	0.97–1.5	200–250
Quartz biotite schist	2.72–2.74	420–426

Source: WBSEB, 1990

weathering remain more or less uniform there.

The data on joint spacing, joint opening, permeability, rock strength and depth of weathering for these sample sites have been obtained directly in the numerical form. The remaining variables, like nature of joint infill material, degree of foliation, rock texture and mineralogical composition, have been recorded qualitatively, and need to be converted into quantitative terms for proper analysis. For quantification of the first three parameters of this group, a five point scale has been used where the subtypes of each parameter that contributes most to weathering are assigned with a value of 5, while those subtypes, whose contributions are least, are assigned a value of 1. To convert the factor of mineralogical composition in a usable quantitative form, the percentage of each of the constituent minerals of each of the rocks have been multiplied by the respective rank value of that minerals (Table 7). The products are then added to obtain a number for each rock, ranging from 100 (the minimum possible value) to 900 (the maximum possible value), which indicates the mineralogical composition value of that particular rock. The secondary minerals may be taken into account following the same method, but because of their very much insignificant proportion, the contribution of these minerals is totally ignored.

The data of all the nine parameters of the selected sites have then been analysed statistically. The correlation matrix, multiple regression results, analysis of variance, probability level of error and some other necessary output have been generated. The very high multiple regression value (R=0.99999455) suggests that, the independent variables taken in this study explain almost the total variation of the dependent variable; nothing is left to be explained. The very low residual (0.00102) also suggests this. The equation is highly significant also. The analysis of the relationships among the eight independent variables reveal the following findings:

(i) The highly foliated rocks are characterised by closely spaced joints (r = -0.77;

Table 10. Classification of the rocks of the Ayodhya Hill on the basis of uniaxial compressive strength

Strength classes (after Beniawski, 1973)	**Very strong**	**Strong**	**Moderately strong**	**Moderately weak**	**Weak**
Values of uniaxial Compressive strength (in kg cm^{-2})	Above 1000	500–1000	250–500	100–250	Less than 100
Rock types	Massive amphibolite	Schistose amphibolites, massive granite, quartzo-feldspathic gneiss, biotite gneiss	Quartz-biotite gneiss, banded quartz-biotite gneiss, banded biotite gneiss, biotite schist	Quartz-biotite schist	

p<0.009).

(ii) Rocks with closely spaced joints are highly permeable (r=-0.73; p<0.17).

(iii) Highly foliated rocks are of less strength (r=- 0.72, p<.018).

(iv) Highly foliated rocks are highly permeable (r=0.56, p<0.090).

(v) Rocks characterised by widely spaced joints are more strong (r=0.50, p<0.143).

(vi) More the opening of the joints, less is their strength (r=-0.71, p<0.22).

(vii) Fine textured rocks are characterised by more continuous joints with infilling materials (r=-0.80, p<0.005).

(viii) Highly foliated rocks are characterised by continuous joints with clay and vein filling (r=0.68, p<0.29).

(ix) Rocks with continuous joints having infilling materials are of lesser strength (r=-0.63, p<0.052).

(x) The closely spaced joints are more continuous with infilling materials (r=¬0.63, p<0.051).

Correlation of the dependent variable with the independent variables shows that ‘depth of weathering’ is directly or positively related to the factors like degree of foliation, joint aperture, joint condition and rock permeability, while negative relationships are noted with the remaining independent variables. Among all these relationships, the correlation coefficient values are higher for the factors of foliation (r=0.98), rock strength (r=-0.81) and joint spacing (r= -0.79). The probability of error of these relationships are also very insignificant, being <0.009, <0.007 and <0.004, respectively. Beta weights, i.e. the standardised regression weights, have also been calculated for a comparison of the relative contribution of each of the independent variables. It is found that variables like degree of foliation, rock strength, joint spacing and rock texture are the most important predictors of the depth of weathering and the first three factors are statistically significant. Thus, on the basis of all these statistical analyses, three variables of rock factor can be identified as significant in relation to weathering. These are degree of foliation, rock strength and joint spacing arranged in a descending order of importance. These three factors can explain about 98.44

Table 11. Weathering susceptibility rating scheme prepared for Ayodhya hill

Rock property	Classification and rating					
Foliation	Class	Very highly foliated	Highly foliated	Moderately foliated	Crudely foliated	Non foliated
	Rating	68	62	48	33	17
Rock strength	Class	Less than 100 kg cm^{-2}	100–250 kg cm^{-2}	250–500 kg cm^{-2}	500–1000 kg cm^{-2}	Above 1000 kg cm^{-2}
	Rating	22	18	12	9	6
Joint spacing	Class	Less than 5 cm	5–30 cm	30–100 cm	100–300 cm	Above 300 cm
	Rating	10	9	7	5	2
Total	Class	Very highly susceptible	highly susceptible	moderately susceptible	Slightly susceptible	Least susceptible
	Rating	90–100	68–89	48–67	26–47	25 and less

per cent of regression in combination.

Formulation of a rating scheme for determination of susceptibility to weathering

The data of forty boreholes, located mainly in the southcentral part of the Ayodhya hill, have been used for the multivariate analysis. But we have no direct information regarding weathering susceptibility of the remaining part of the hill. Therefore, depending upon the degree of variation of the three significant variables, a rating scheme has been designed, by means of which we can indirectly have some idea regarding the proneness of the exposed individual rock types to weathering. The scheme has been designed basically following the guidelines proposed by Selby (1980) and Bieniawski (1973). Since all the three significant factors, i.e., the degree of foliation, rock strength and joint spacing, are not of equal importance in causing weathering, it appears more logical to assign different weightage values to these three different variables according to their respective contributions. Considering the respective correlation coefficient values (r) of these three factors and their level of significance, 68 per cent weightage has been given to the factor of degree of foliation, 22 per cent to rock strength and 10 per cent to the factor of joint spacing. Each of these factors have then been classified into five subdivisions, designated as class I, II, III, IV and V, and arranged in a descending order of importance in relation to susceptibility to weathering. Class I of each factor plays the most positive role in causing the rock to be weathered. For this reason, class I of each factor is assigned with the total percentage allotted to that particular factor. The value decreases with increasing rank of the class (Table 11). In this way, separate weightage values can be obtained for each of these factors of each particular rock type. The sum

Table 12. Susceptibility rating values of the different rock types in Ayodhya hill

Rock types	Degree of foliation	Rock strength	Joint spacing	Total
Pegmatite	17	9	8.28	34.28
Massive granite	33	9	8.5	50.5
Quartzo-feldspathic gneiss	33	9	8.5	50.5
Quartz biotite gneiss	48	9	8.38	65.38
Biotite gneiss	48	9	8.37	65.37
Banded quartz biotite gneiss	62	12	9	83
Banded biotite gneiss	62	12	8.56	82.56
Massive amphibolites	17	6	2	25
Schistose amphibolites	68	6	9	83
Biotite schist	68	12	8.58	88.58
Quartz biotite schist	68	18	7.5	93.5

total of these values, which varies from less than 25 to 100, indicates the degree of susceptibility of that rock to weathering. The rating values are distributed in such a way that, greater total value indicates higher susceptibility of the rock to weathering and vice versa.

Discussion

The above rating scheme has been applied to the major rock types (Table 12) exposed in the Ayodhya hill area, considering the average condition of the three significant variables of these rocks (Tables 2, 4 and 10.). It has been found that of all the rock types exposed in the Ayodhya hill area, quartz-biotite schist is most susceptible to weathering, having a rating value of 93.5, and massive amphibolite is the least susceptible (Table 13). Banded varieties of gneiss and schist are also highly prone to weathering, while non-banded gneissic rocks and massive granite are moderately susceptible to weathering. Pegmatite is slightly susceptible. When these findings are compared with the geological map of the area, it can be inferred that the northern half of the hill area, being dominated by quartz-biotite schist and composite gneiss i.e., banded varieties of gneiss, is more susceptible to weathering as compared to its southern

Table 13. Susceptibility classification of the rocks of the Ayodhya hill

Susceptibility class (%)	Rock type
Very highly susceptible: 90–100	Quartz biotite schist
highly susceptible: 68–89	Banded quartz biotite gneiss , banded biotite gneiss biotite schist, schistose amphibolites
Moderately susceptible: 48–67	Massive granite, quartzo-feldspathic gneiss, quartz biotite gneiss, biotite gneiss
Slightly susceptible: 26–47	Pegmatite
Least susceptible: < 25	Massive amphibolites

Table A1. Correlation matrix of multivariate analysis

Variables	1	2	3	4	5	6	7	8	9
1	1	–0.16	–0.63	–0.77	0.55	–0.73	0.4	0.5	–0.79
2		1	0.36	0.35	0.18	0.07	–0.91	–0.71	0.41
3			1	0.68	–0.80	0.4	–0.04	–0.63	0.64
4				1	–0.53	0.56	–0.27	–0.72	0.98
5					1	–0.22	–0.48	0.22	–0.43
6						1	–0.03	–0.39	0.64
7							1	0.59	–0.35
8								1	–0.81
9									1

Variables: 1: joint spacing, 2: joint opening, 3: joint condition, 4: degree of foliation, 5: rock texture, 6: rock permeability, 7: mineralogical composition, 8: rock strength, 9: depth of weathered stratum

Table A2. Multiple regression results

(a) Regression value

Multiple R	0.99999455
R^2	0.9999891
Adjusted R^2	0.99990194
Standard error of estimate	0.031950046

(b) Analysis of variance

	Sum of squares	df	Mean square	F	P level
Regression	93.69187	8	11.71148	11472.79	0.00722
Residual	0.00102	1	0.00102		
Total	93.69289				

Table A3. Probability level of error of the correlation coefficients

Variables	1	2	3	4	5	6	7	8	9
1	0	<0.065	<0.051	<0.009	<0.102	<0.017	<0.923	<0.143	<0.007
2		0	<0.304	<0.321	<0.620	<0.849	<0.000	<0.022	<0.234
3			0	<0.029	<0.005	<0.248	<0.903	<0.052	<0.044
4				0	<0.111	<0.090	<0.458	<0.018	<0.000
5					0	<0.548	<0.158	<0.534	<0.220
6						0	<0.942	<0.261	<0.048
7							0	<0.075	<0.323
8								0	<0.004
9									0

Variables: 1: joint spacing, 2: joint opening, 3: joint condition, 4: degree of foliation, 5: rock texture, 6: rock permeability, 7: mineralogical composition, 8: rock strength, 9: depth of weathered stratum.

Table A4. Regression weight of the correlation of variables, their significance and probability of error

Variables	B (Beta) (Standard-ised Regression weight)	Standard error of B	t	P-level
1	–0.1324[1]	0.007457	–17.755	0.035817
2	–0.0845	0.017774	–4.7532	0.13201
3	–0.0239	0.016974	–1.4095	0.392828
4	0.756791	0.013596	55.661	0.011436
5	0.13776	0.027337	5.0392	0.124713
6	0.03866	0.009316	4.1494	0.150555
7	0.0266	0.02753	0.9661	0.510992
8	–0.3079[1]	0.007259	–42.4128	0.015007

[1]indicates significant B

Variables: 1: joint spacing, 2: joint opening, 3: joint condition, 4: degree of foliation, 5: rock texture, 6: rock permeability, 7: mineralogical composition, 8: rock strength, 9: depth of weathered stratum

Table A5. Partial correlation of the independent variables (variable 1 to 8) with the dependent variable (variable 9)

Variables	**Partial correlation**
1	-0.998418
2	-0.978578
3	-0.815588
4	0.999839
5	0.980873
6	0.972166
7	0.694793
8	0.999722

Variables: 1: joint spacing, 2: joint opening, 3: joint condition, 4: degree of foliation, 5: rock texture, 6: rock permeability, 7: mineralogical composition, 8: rock strength, 9: depth of weathered stratum.

Table A6. Contribution of the significant independent variables (variables 4, 8 and 1) in combination, in explaining the variation of the dependent variable (variable 9)

Variables	Regression	Percentage explained
4	89.21733	95.233
4, 8	91.56734	97.731
4, 8, 1	92.23306	98.441

Variables: 1: joint spacing, 2: joint opening, 3: joint condition, 4: degree of foliation, 5: rock texture, 6: rock permeability, 7: mineralogical composition, 8: rock strength, 9: depth of weathered stratum.

counterpart where the predominant rock types are mostly non-banded.

Conclusion

The present work has attempted to establish in a quantitative manner that the susceptibility of the gneissic terrain of Ayodhya hill to weathering depends more on the structural properties of the rocks and rock strength than the textural and mineralogical characteristics, provided the factors other than rock properties remain constant. The suggested rating scheme may be applied to other similar areas dominated by similar rock types. Alternately, it may encourage the development of area-specific rating schemes for other environments, following a similar methodology. In the later case sufficient data on depth of weathering is required, at least for some selected sites.

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