

Landform development at the Ciudad Encantada, near Cuenca, Spain

Desarrollo de formas superficiales en la Ciudad Encantada (Cuenca, España)

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The Ciudad Encantada, near Cuenca, in east-central Spain, is a complex of mushroom-shaped rocks and elongate plateau remnants developed in flat-lying Cretaceous dolomite. Natural bridges are also present. The forms are attributed partly to structural factors, namely the presence of strata of contrasted resistance to weathering and erosion, but also to differential subsurface moisture attack beneath the plateau surface. Other factors contributing to the relative stability of the caprock include biotic coating, calcite concentration, and dryness at site scale.

Key words: mushroom-shaped rocks, landform development, Ciudad Encantada.

La Ciudad Encantada, cerca de la ciudad de Cuenca, es morfológicamente un conjunto de rocas fungiformes, restos de plataformas elongadas y arcos naturales modelados sobre dolomitas cretácicas de estructura subhorizontal. Su origen se atribuye a factores estructurales, presencia de estratos con diferente resistencia a la erosión, y ataque generalizado de la humedad primero subedáficamente y luego subaéreamente al pie de las formas actuales. Los factores que contribuyen a la estabilidad actual en la parte superior de estas formas, son los recubrimientos biológicos, la concentración de calcita o las variaciones locales en el régimen de humedad.

Palabras clave: rocas fungiformes, desarrollo morfológico, Ciudad Encantada.

INTRODUCTION

The Ciudad Encantada (or Enchanted City) is a group of pedestal or mushroom rocks with which are associated several natural bridges (Pl. 1). It is located in the Sierra de Valdecabras, a region of dissected plateaus (Fig. 1), some 135 Km. ESE of Madrid, and near the town of Cuenca, in La Mancha Province in east-central Spain. Developed in flat-lying Cretaceous dolomite, the landform assemblage is justifiably well-known as a tourist attraction, for the forms are spectacular. They are however by no means unique even in the region in which they occur. Similar groups of mushroom-shaped rocks are developed on the plateaus and more particularly at the margins of the uplands (Fig. 2). Such features are clearly visible high in the sidewalls of the valley of the Arroyo de Valdecabras and that of the Rio Huecar, at Cuenca. The Ciudad Encantada is well known not only because it includes especially well developed and spectacular forms, some of them isolated and hence readily discernible, but also because it is readily accessible.

GEOLOGY

The sediments in which the landforms under discussion are developed are known as the Ciudad Encantada Dolomites (MELLENDEZ, 1971). They are of later Cretaceous age (Turonian) according to VILAS *et al.* (1982) and earlier workers, Cenomanian according to GIMENEZ (1989) and other recent workers. They were deposited on a shallow continental shelf bordering the Iberian Range Basin. The sequence, which is 55-85 m. thick, was originally formed of biomicrites and biosparites (packstone, grainstone, rudstone), with oosparitic and oobiosparitic grainstone in the higher part. These have been recrystallised to form a dolomitic sequence in which cross-bedding,

bioclastic debris and some calcarenitic shoals are discernible (GIMENEZ, 1989).

Most of the Cretaceous beds of the region were folded and faulted, three compressional phases having been identified (CAPOTE, 1983). Even where the strata remain locally flat-lying of essentially so, as in many parts of the Cuenca district, Tertiary earth movements have produced shear stress and pressure dissolution that may be significant in explaining fracture patterns and their subsequent exploitation.

The major fractures dividing the outcrop at the Ciudad and adjacent areas are shown in Pl. 2. In the study area the major partings trend ENE-WSW in the north, but run closer to east-west in the south. Cutting across these regional trends (for similar patterns occur elsewhere in the district) is a band of fractures oriented WNW-SSE in the northern area but becoming essentially north-south in the centre of the Ciudad exposures (Pl. 2). Thus the country rock is commonly subdivided by fractures into blocks that are rhomboidal or rectangular in plan.

LANDFORMS

Regionally the Ciudad Encantada, which stands 1.400 m. above sea level, is part of a dissected plateau or very low angle cuesta developed in Upper Cretaceous dolomite. The valleys eroded by the Rio Jucar and its several tributaries, typically to depths of 100-140 m., are characteristically bordered by faceted slopes with structural benches and a prominent bluff high on the slope (Fig. 2). The divides take the form of domed plateaus. The residuals have resulted from the dissection of the plateau for it is on interfluvies, and especially at the margins of the divides, that the fields of pedestal rocks, for which Ciudad Encantada is well known, are best developed.

The residual blocks of the Ciudad Encantada and other similar occurrences take

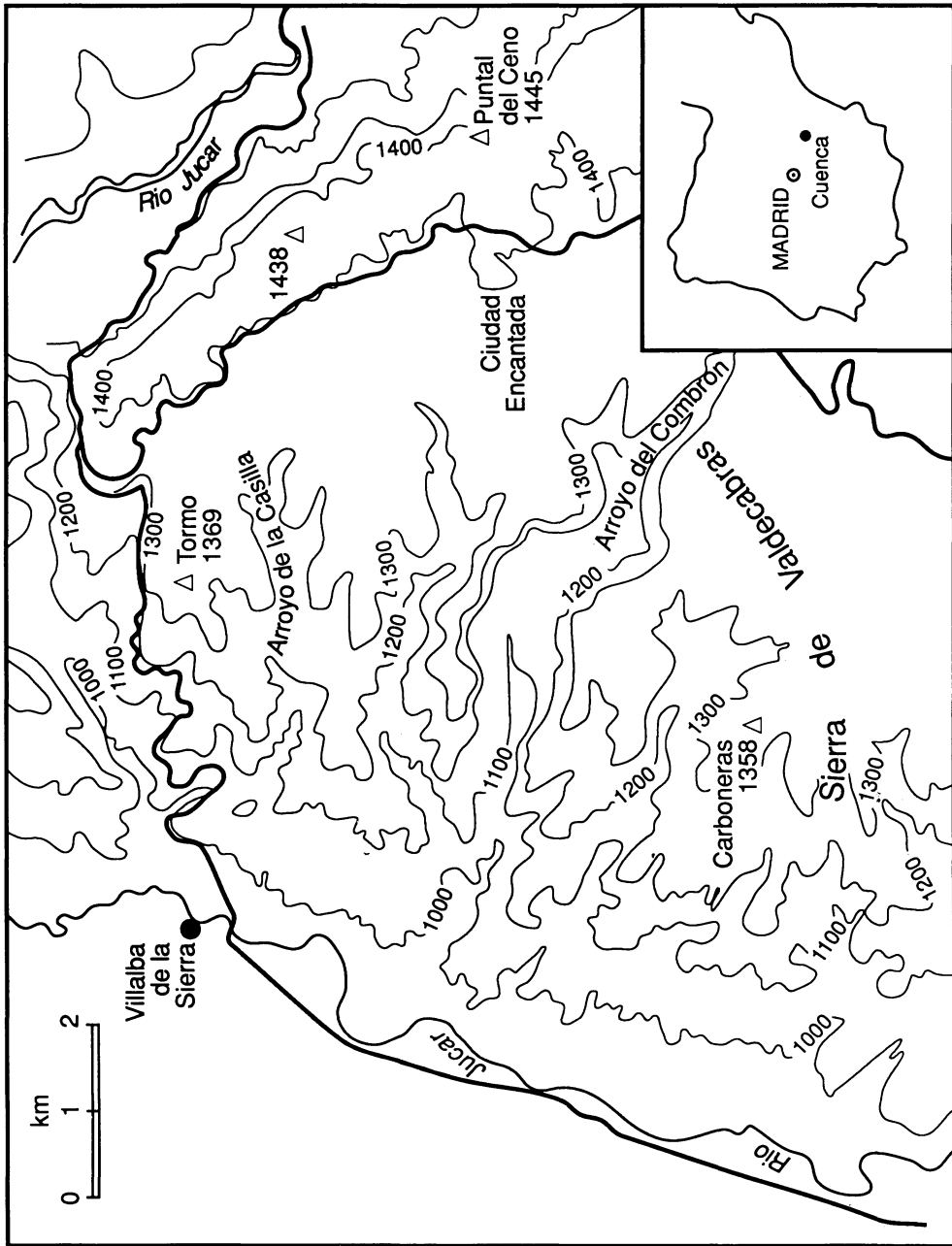


Fig. 1. Location (inset), and topography of Sierra Valdecabras.

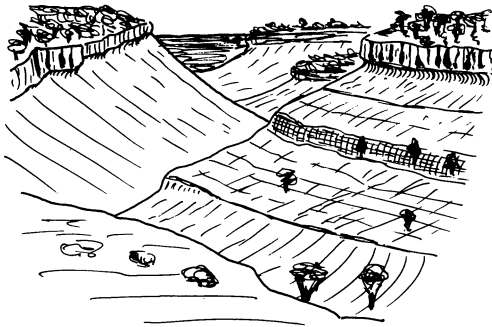


Fig. 2. Valley sidewalls; on the left, simple faceted slope, and on the right, a complex faceted slope. In both instances however flared blocks occur only on the uppermost of the bluff.

the form of pedestal or mushroom rocks, the most spectacular standing in isolation (Pl. 1), but far more commonly consisting of elongate minor flat-topped ridges and plateaus with flared sidewalls that form flat-topped ridges, elongate plateaus, or mushroom rocks (Pl. 3). They stand 6-8 m. above

the adjacent plains or corridors. The isolated mushroom rocks reflected an advanced stage of dissection of flat-lying sediments subdivided into square or rhomboidal blocks in areas where the regional sublatitudinal system of fractured in cross-cut by meridional fractures. The elongate plateaus occur where the two sets of fractures are disposed in essential parallelism, or where they cut at acute angles.

Whatever their dimensions and plan shapes however, and whatever their situation *vis à vis* adjacent forms, the residuals consists of a comparatively wide cap or table supported by a narrower stem of shaft. Each is developed of a block, the plan form of which reflects the well developed horizontal or only gently inclined bedding of the dolomite on the one hand and the vertical partings, probably the result of Tertiary shearing, on the other. In places the fractures have been greatly widened by weathering, presumably dissolution, so that the residuals based in each block are separate and

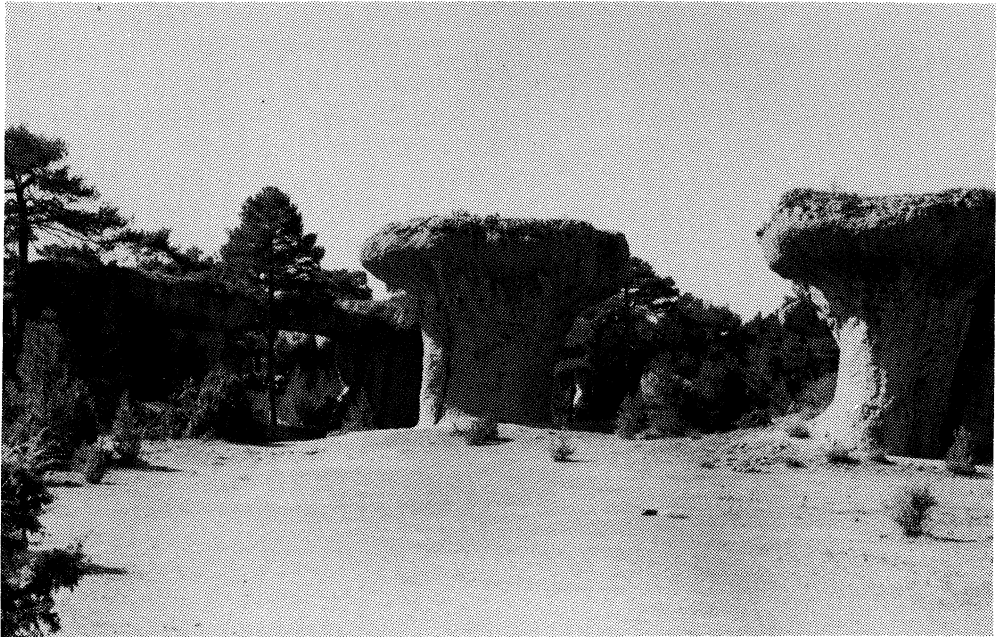


Photo 1. Isolated mushroom rock with natural bridge in background.

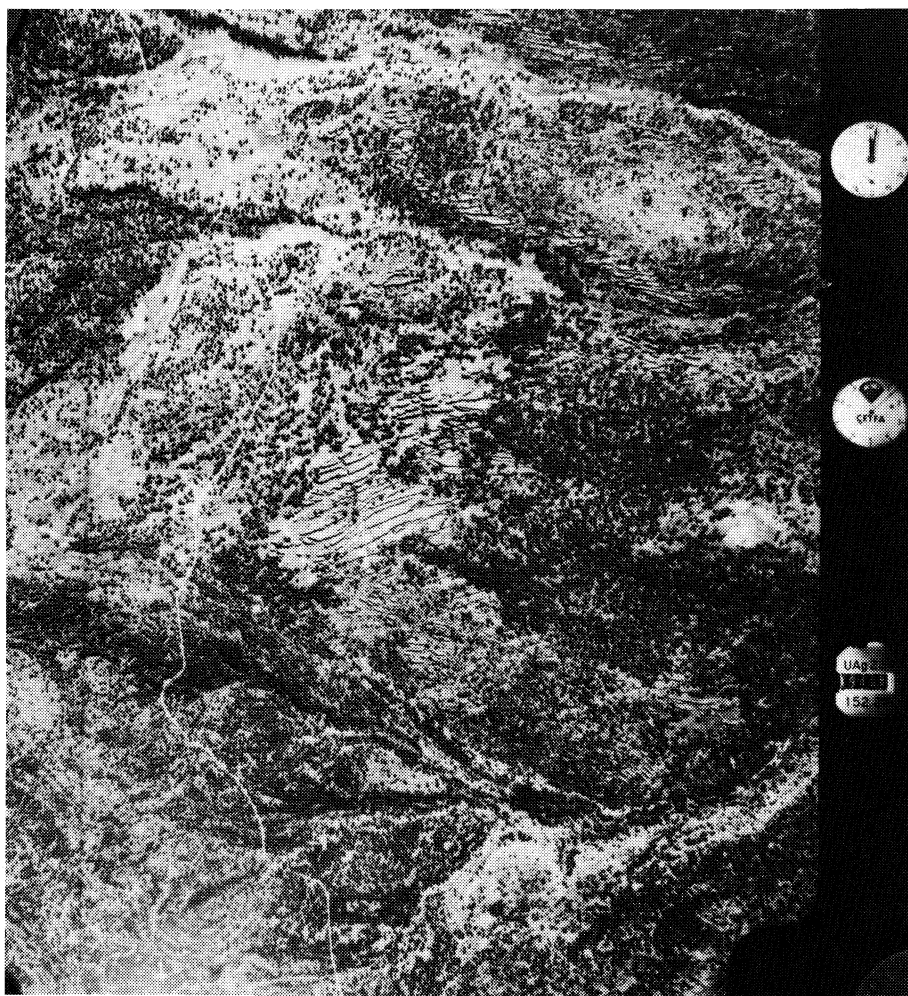


Photo 2. Air photo showing fracture pattern at Ciudad Encantada.

distinct and stand in essential isolation. Elsewhere however the partings remain narrow and merely interrupt the surface of plateaus. Whether isolated or grouped, whether minor residuals, elongate ridge forms or plateaus, the morphology of the crests and plateaus on the one hand, or the sidewalls and clefts on the other, are similar.

The cap or table that stands on the shaft or stem is the dissected representative of the plateau caprock and is thus essentially mas-

sive, though bedding planes exploited by weathering are visible in a few caps. The caprock consists of a dolomite bed between one and three metres thick. Its outer surface is grey in colour due to a coating of lichen and moss, though the rock itself is a creamy yellow-brown. The upper, flattish surface of both caps and plateaus is in detail irregular (Pl. 4), with numerous shallow flat-floored solution basins, pans or *kamenitzas*; so much so that many of them merge leaving

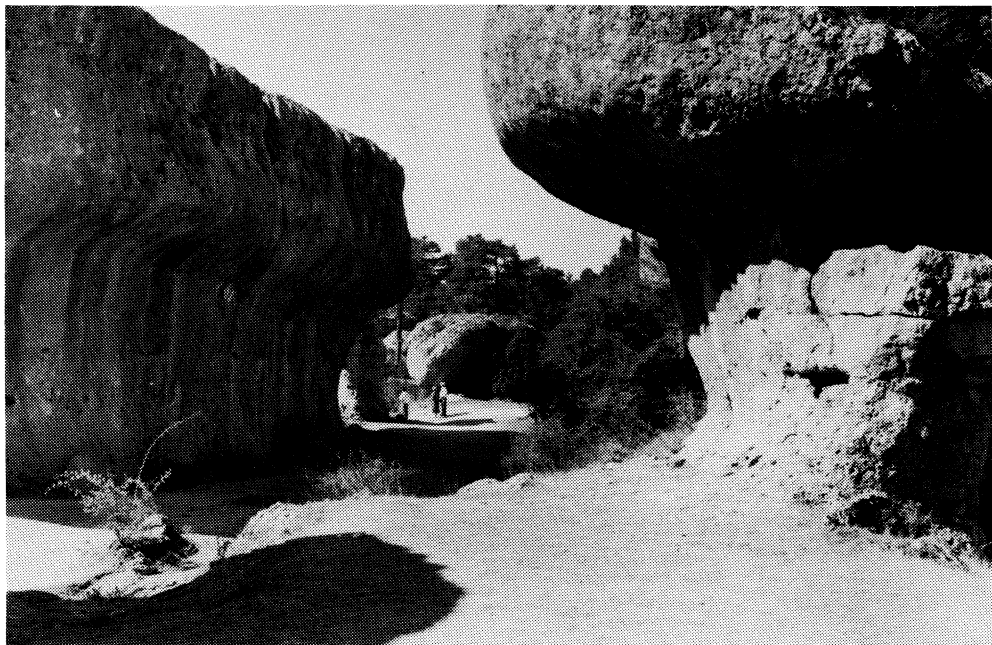


Photo 3. Elongate plateau remnants, with pedestal rock and flared sidewalls.

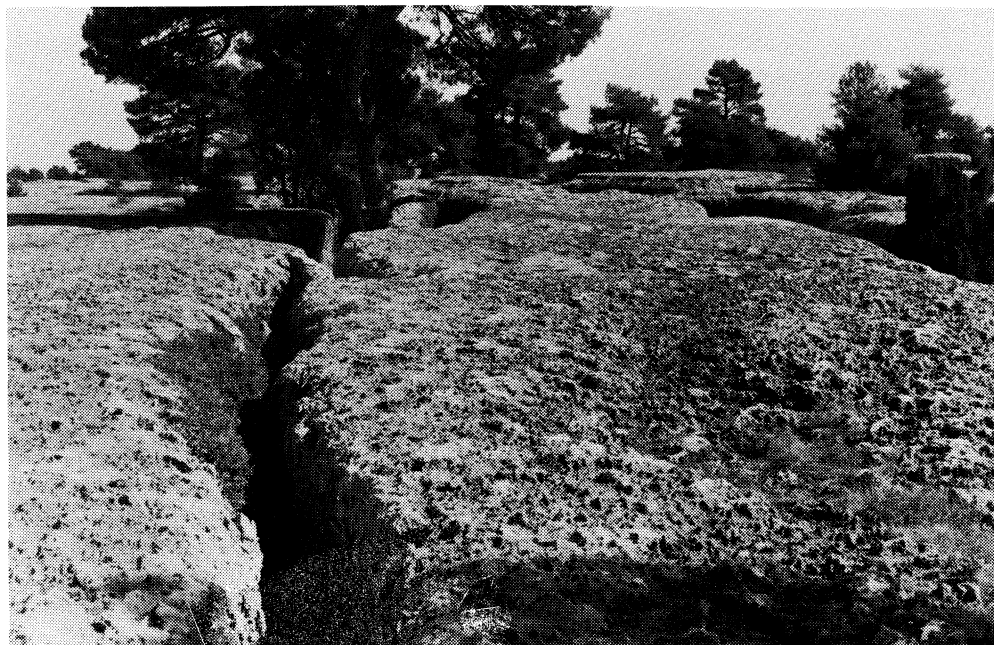


Photo 4. Detail of plateau surface.

narrow but sharply serrated rims in isolation. Most of these basins are only a few centimetres deep but some attain depths of 25-30 centimetres.

Some of the sidewalls, particularly of the ridge-plateau tabular slabs, are scored by grooves or *Rillen* (Pl. 5). The overhang of the cap varies between one and three metres. The junction between cap and stem takes the form of a bedrock curve with the more massive cap merging gradually and smoothly with the surface shaped in the weaker strata that form the stem. In several places the cap, thinner than in adjacent parts of the residual is undermined and remains, supported at each end, as a natural bridge (e.g. Pl. 5).

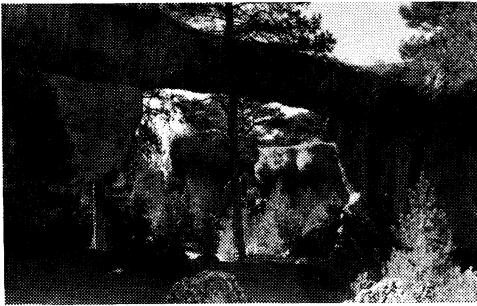


Photo 5. Natural bridge, El Puente Romano.

The stem is of course everywhere narrower than the cap but its thickness both in absolute terms and in comparison with the cap, varies from site to site. In some residuals the shaft tapers, being thinner near the ground than immediately beneath the cap (Pl. 6), though however short it is, it everywhere merges with a wide base or plinth. Most stems are essentially of hour-glass shape, the sidewalls being concave or flared in varying degrees. The dolomite exposed in the stem is essentially its natural colour for it lacks the biotic veneer that gives the cap its grey colour. Bedding and cross-bedding are discernible at some sites.

Small shelters or tafoni are formed

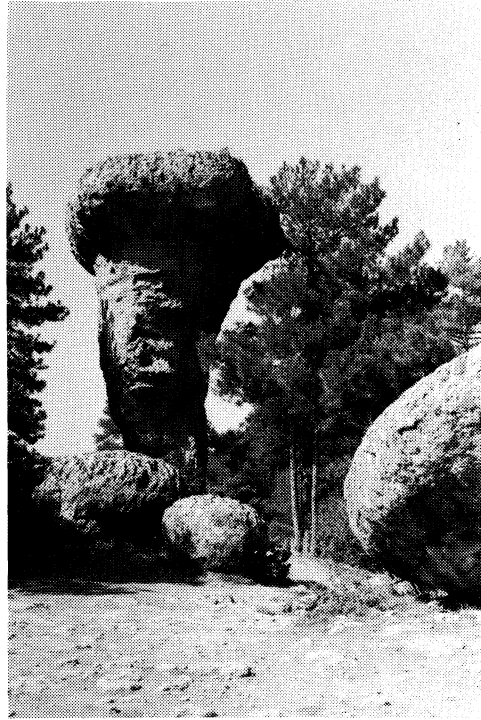


Photo 6. Mushroom rock with tapering stem.

along fractures and also near the base of the stems. Tubular weathering, consisting of interconnected tubes of variable diameter and orientation (but of the order of 2-3 cm. diameter), is developed in places (cf. TWIDALE, 1964). Flaking of scaling, i.e. the development of layers of rock of the order of 1-3 mm. thickness, is commonplace on the stems.

In broad view, then, all the residuals are similar in morphology, yet there is a marked contrast in their settings between the isolate mushroom-shaped rocks; the areas of juxtaposed elongate flat-topped ridges separated by narrow corridors (Pl. 3) or, as they occur in a «city», streets (cf. WEBER, 1980; MUELLER and TWIDALE, 1988) enclosed by concave walls; and the quite extensive wooded plateaus with rough rocky surfaces and only narrow clefts interrupting the continuity of the pavements.

ORIGIN OF THE MUSHROOM ROCKS

a) Past work

Pedestal or mushroom rocks similar to those of the Ciudad Encantada and adjacent areas, though known by a variety of local names (see TWIDALE and CAMPBELL, 1992), have been described from various parts of the world. They are developed in several lithological contexts and climatic settings. For example, though very well developed in granitic rocks, they have been reported from basic and silicic volcanics, sandstone and limestone, as well as dolomite (HUME, 1925) and from cold and hot, humid and arid, climatic regions, though they are well exposed and hence readily noticed in arid regions.

Previous theories of origin are reviewed in BRYAN (1923, 1927), PETTY (1932) and CRICKMAY (1935). Suffice it to state that because of their apparent wide development in desert many early workers attributed them to aeolian activity, sandblast erosion being effective near ground level and converting blocks and boulders to mushroom forms (e.g. BLACKWELDER, 1909; WALTHER, 1912; WOODWARD, 1914; HOBBS, 1917). Much evidence and argument can be marshalled against this theory. For example mushroom rocks are developed in various climatic settings, including humid regions (e.g. PETTY, 1932; CRICKMAY, 1935) the anvil-shaped rock noted in CENTENO and TWIDALE (1988) stands on the crest of a hill, and in the Ciudad Encantada the location of the elegantly shaped residuals near the edges of the plateau, but at high topographic levels, is inconsistent with such an origin. Moreover though arid phases did develop in the region during the Tertiary, they were brief and unimportant with no sedimentological or regolith effects; certainly there is no evidence of aridity in the later Cainozoic, no suggestion of aeolian activity even by wind funnelled within the narrow corridors.

Others (e.g. MARTEL, 1910) thought mushroom rocks were due to lateral stream undercutting. Again there are many arguments against the suggestion, and in the area under discussion the location of the residuals in divides as well as at plateau margins, weighs against it; as does the permeable and pervious nature of the country rock, and its related areic (streamless) character.

As an explanation of the stem that is the critical feature of mushroom rocks, preferential weathering and erosion near ground level has found much favour. The detailed mechanism suggested varies from author to author. Some called upon a moist microenvironment (e.g. MERRIL, 1898), others on splash effects (e.g. BRYAN, 1923, 1927). Others favoured salt weathering in desert regions as the causation (e.g. MECKELEIN, 1959; PEEL, 1966; FAIRBRIDGE, 1968), and yet others pointed to frost action (KEIT and STERRET, 1931; FAIRBRIDGE, 1968) in appropriate areas. Some, like ANDERSON (1931) on the contrary attributed the survival of the cap to case hardening, and implicitly the destruction of the stem to the absence of any such protective patina. It is fair to say, however, that with the exception of MABBUTT (1977), who cited soil moisture attack, all previous workers have endeavoured to explain the mushroom shape in terms of epigene or subaerial processes. Yet there is ample evidence that the stem is the result of preferential weathering of the still-covered part of a block or boulder by moisture in the zone a short distance (a few metres at most) beneath the ground surface (TWIDALE and CAMPBELL, 1992).

b) General Evidence

The stems of pedestal rocks vary in their detailed morphology but all are, or they strongly resemble, flared sidewalls like those that have been recorded from various parts of the world (though particularly in southern Australia) and from various litho-

logical settings (though particularly from granitic terrains). Flared slopes are demonstrably (Pl. 7) initiated in the subsurface (TWIDALE, 1962, 1982, pp. 243-258), nascent examples having now been located not only at several sites on Eyre Peninsula, South Australia and in central Spain (CENTENO, 1989), but also in California, New Mexico, Brittany, southern France, West Malaysia and southern Africa.

c) Evidence from the Ciudad Encantada

In addition to interferences based in the demonstrated subsurface origin of flared bedrock slopes in other places, the sidewalls of clefts extending below the karst plateau at Ciudad Encantada are themselves flared (Pl. 8). It is difficult to conceive of a mechanism other than weathering being operative at such sites. Moreover many of the blocks exposed in bluffs near Cuenca, in the Arroyo de Valdecabras, in the Drakensberg of southern Africa and elsewhere, are manifestly flared; again it is difficult to argue that any agency other than subsurface weathering and probably moisture held in regolithic detritus developed along fracture planes could be responsible. In terms of subsurface moisture attack the tapering or thinning of the stems toward the base is understandable as due to either duration of weathering, or, and more likely, the fluctuation of a shallow watertable. Thus it is suggested that the mushroom rocks and flared ridges of the Ciudad are merely rather more pronounced flared pillars like those described from Murphy Haystacks (Pl. 9) on northwestern Eyre Peninsula (TWIDALE and CAMPBELL, 1984) and elsewhere.

The detailed morphology of the dolomite shafts is consistent with this view for scaling (or flaking) and minor tafoni are associated with the weathering front (TWIDALE, 1986) and flared slopes respectively (TWIDALE, 1982, pp. 257-258). Tubular weathering is characteristic of shallow subsur-

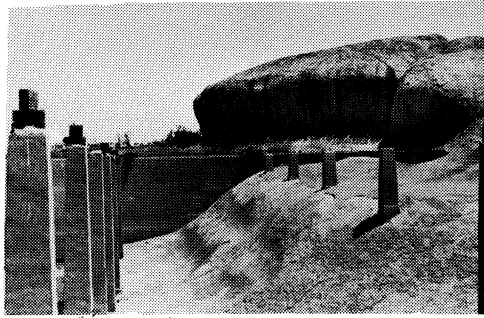


Photo 7. Flared slopes, actual and incipient, the latter exposed in a reservoir at Yarwondutta Rock, near Minnipa, northwestern Eyre Peninsula, South Australia.



Photo 8. Flared sidewall developed in cleft beneath the plateau.

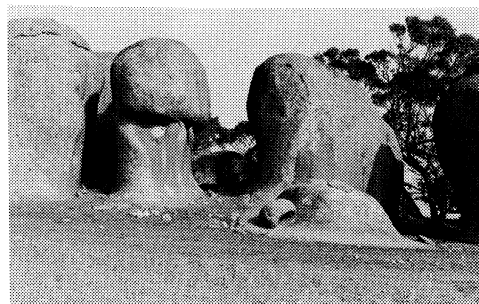


Photo 9. Flared pillards in granite, Murphy Haystacks, northwestern Eyre Peninsula, South Australia.

face solution in carbonate rocks. And multiple flared forms on the same slope merely reflect (local) shifts in baselevel and/or the water table.

It is not suggested that preferential subsurface weathering alone is responsible for the mushroom forms developed at the Ciudad Encantada. Structure is critically important also. The isolated residuals, like the ridge plateaus, were originally part of the plateau that before dissection by the Rio Jucar and its tributaries occupied the entire district.

The pronounced caprock is developed in massive dolomite. The thickness of the stratum determines the thickness of the cap or table. The caprock is harder than the rock of the shaft not only by virtue of its lithology and texture but also because of a coating of biotic remains, in particular a skin composed of lichen and moss. It also carries a patina of calcium carbonate. Such calcite rinds are not uncommon on carbonate rocks. According to MONROE (1966, 1976) they are due to solutional effects of meteoric waters penetrating into the permeable country rock, taking calcium carbonate into solution and reprecipitating it at the surface when the waters are drawn to the surface by capillary action during dry periods. In respect of dolomitic materials, however, HUME (1925, p. 148) suggested that as magnesium carbonate is more readily dissociated than the calcium carbonate, it is more rapidly removed, leaving the calcite concentrated in a surficial skin. Finally because the plateau is dissected, the caprock tends to be dry and therefore stable (cf. BARTON, 1916). This suggestion applies particularly to the edges of the upland and of clefts and valleys, partly because drainage is facilitated, partly because the sidewalls and upper surface of the table are exposed to the air and sun. Here there is a coating of lichen and moss (which require light). The underlying strata on the other hand were permanently moist and were thus weathered more quickly, for limestone under a soil cover and in contact

with moisture is dissolved several times more rapidly than that exposed to the air (see e.g. BOGLI, 1960, 1980; GAMS, 1962).

Whatever the dimensions of the flared walls of the stems, however, the morphology is due to weathering by shallow groundwaters. Quite apart from evidence from other areas, it is noticeable that in the sidewalls of canyons cut into the plateau of the Sierra de Valdecabras, for instance, flared blocks are restricted to the upper surface, near the plateau margin (Fig. 2). Some sidewalls consist of simple faceted slopes with a single bluff and debris slope but others are complex with structural benches and several bluffs. Here the blocks exposed in the bluffs retain their rectangular form and weaker strata find expression in simple partings and re-entrants. However, at the top of the slope, where, before dissection vertical partings were penetrated by meteoric waters, the bluff is basally fretted and consists of blocks separated by wide clefts, the sides of some of which are modestly flared.

Thus the mushroom forms are conceived as having developed in two stages. First, subsurface waters infiltrating into the subsurface and particularly along vertical partings, caused differential weathering. The weaker strata beneath the exposed massive dolomite, and adjacent to fractures, were especially affected. Second, as the plateau was dissected the altered rock was evacuated, and the incipient mushroom forms were exposed. Such exposure is pronounced at the edges of the dissected zones (cf. CRICKMAY, 1935), but is not restricted to them. The first stage of the mechanism can be glimpsed by an examination of the narrow vertical clefts that interrupt the plateau surface.

THE NATURAL BRIDGES

The natural bridges at Ciudad Encantada are all developed in the massive dolomi-

te, though the stratum is more or less attenuated where it forms bridges. They reflect first the elongate shape of many of the ridge plateaus (in other words the fracture pattern imposed by Tertiary tectonism) which has caused many of the individual exposures of the dolomite to be narrow in plan along one axis. Second, they are due to the preferential weathering of the weaker formation beneath the massive dolomite. Where weathering has eaten back into this formation, but the overlying stratum remains virtually untouched, the receding opposed walls of the stem eventually intersect so that the caprock becomes locally unsupported. At some sites an early stage in this process is in evidence for the stem is so thin that in places it is breached by «peepholes». That the weathering that causes the undermining of the massive stratum and the formation of the natural bridges takes place beneath, rather than at, the surface. This is implied by the suggestion that the flares are subsurface forms, but more particularly by the fact that, just as flares can be seen in vertical clefts at the Ciudad (Pl. 8) so attenuated bars of massive dolomite which are interpreted as nascent bridges, can be seen in clefts already isolated and lacking support from beneath (Pl. 10).

If this interpretation (Fig. 3) is correct then the natural bridges of the Ciudad Encantada are unusual. Examination of various general texts has led to the conclusion, admirably summarised in BATES and

JACKSON (1978), that most natural bridges are developed in three contexts. Some, like the Augusta Natural Bridge and Rainbow Bridge, in Utah, USA, are due to the undercutting and breaching from opposite sides of incised meander spurs or goosenecks: they are due to lateral corrosion by deeply incised and meandering rivers. Others, in limestone terrains, are isolated remnants of roofs of caves most of which have collapsed. Yet others are due to wave attack that has caused promontories to be undermined to form sea arches, and eventually to be breached to form sea stacks.

In addition some natural bridges are due to the formation and extension of shelters on the opposite sides of narrow residuals. Caves or shelters have formed by seepage and sapping at the base of the sedimentary outcrop; in places they have exten-

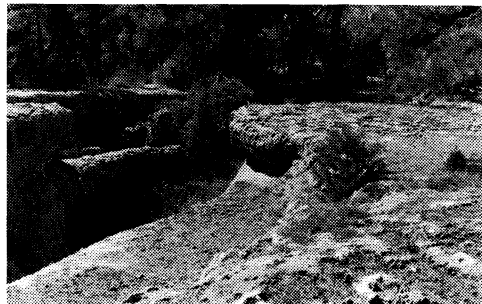


Photo 10. Attenuated bar, isolated by weathering of the underlying bedrock and exposed in a cleft in the plateau.

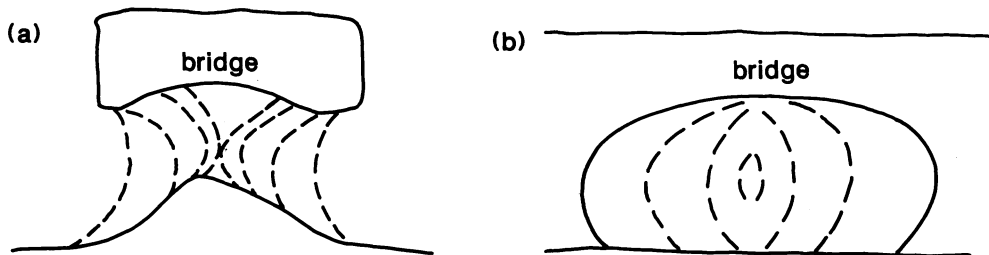


Fig. 3. Development of natural bridge through differential subsurface weathering.

ded so far into the narrow outcrop that two, developing from opposed bluffs, have merged to produce a bridge. If this interpretation is correct, however, the seepage responsible has taken place on exposed outcrops. The proposed subsurface origin of the natural bridges at Ciudad Encantada constitutes a fifth explanation for such features.

CONCLUSIONS

Evidence is adduced to show that both the flared residuals (isolated mushroom rocks, ridge plateaus) and the natural brid-

ges developed in dolomite at Ciudad Encantada are two stage forms. They were initiated by subsurface moisture attack and the stems of the mushroom-shaped residuals, formed by weathering beneath the land were then exposed as the plateaus, and particularly the plateau margins, were dissected and the weathered detritus evacuated.

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