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Subaerial Exposure Environment

Mateu Esteban
Colin F. Klappa

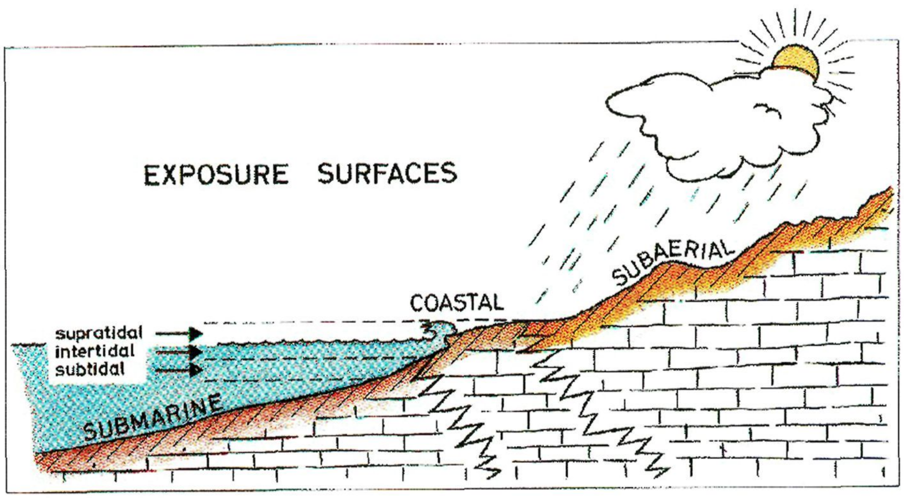

Figure 1—Classification of exposure surfaces.

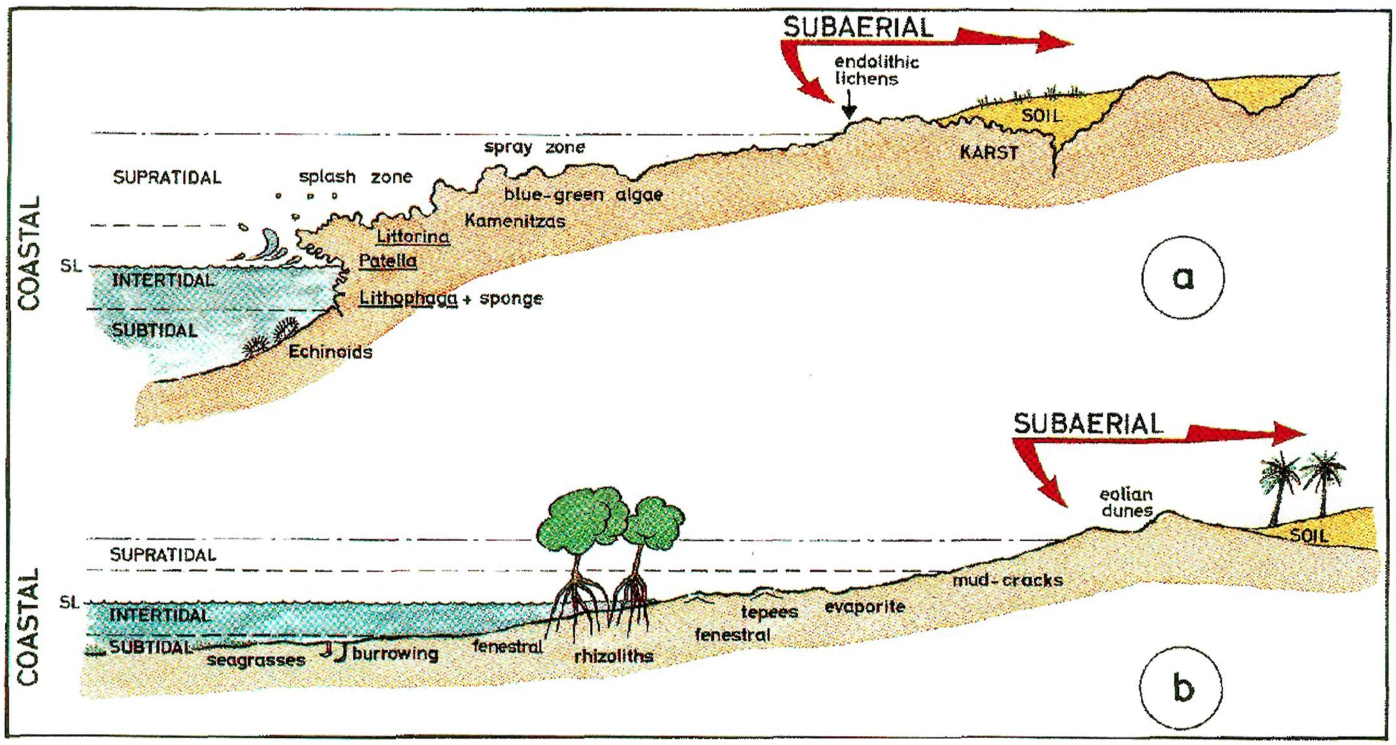

Figure 2—Schematic cross-sections of coastal exposure surfaces. (**a**) Common zonation across present-day rocky shores. (**b**) Main features across present-day sediment shores.

Exposure surfaces occur on land and under the sea, but in this chapter we are concerned only with subaerial exposure surfaces. More specifically we are concerned with the effects of subaerial exposure on carbonate sequences. Subaerial exposure surfaces are areas where upper bounding surfaces of sediment or rock show the effects of being exposed at the Earth's surface. In order to recognize fossil subaerial exposure surfaces they need to be exposed long enough to allow subaerial diagenetic processes to modify or obliterate pre-existing fabrics. This will be recorded as a break in the sedimentary sequence. This usually means that significant periods of time have passed before exposed surfaces are buried by new deposits. What we mean by significant periods of time is a relative concept dependent on our limits of resolution and powers of observation. When considering absolutes of time we will offer only abstracts; our intention here is not to quantify absolutes of timing, duration or intensity of processes acting upon exposure surfaces, nor to examine critically the processes themselves. Rather we will document common and characteristic products of subaerial exposure, list criteria which aid in recognition of fossil subaerial exposure surfaces, and point out the significance and economic importance of subaerial exposure surfaces in ancient carbonate sequences.

Adhering to this outlined conceptual framework we can define a

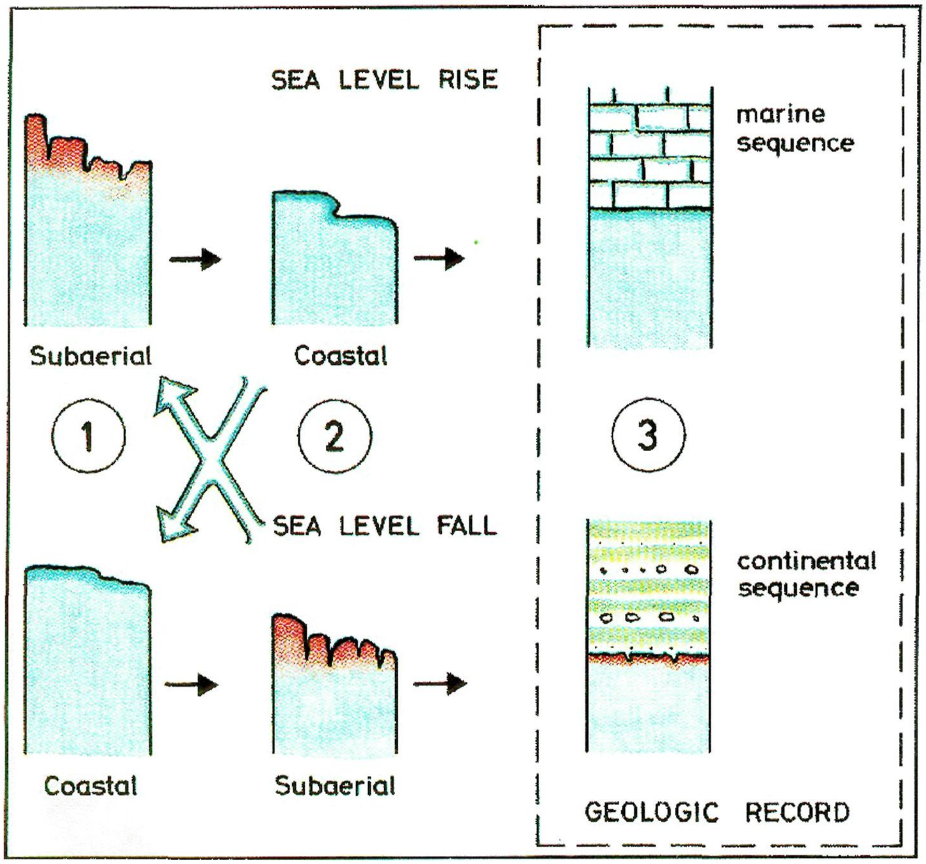

Figure 3—Major pathways of evolution of exposure surfaces.

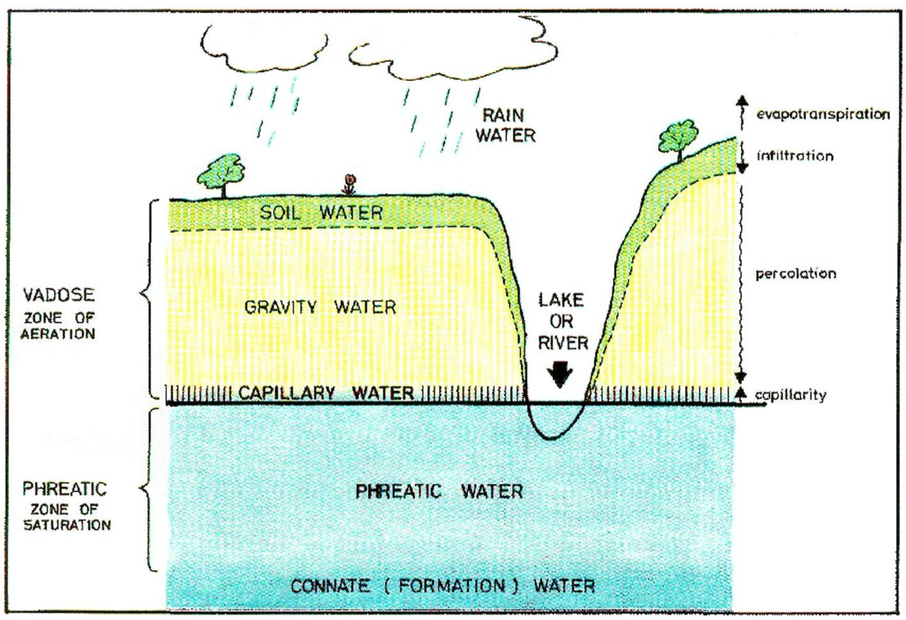

Figure 4—Schematic representation of meteoric hydrologic zones (not to scale).

subaerial exposure surface as a distinct surface on land which indicates: (1) non-deposition and commonly erosion; and (2) a break in the sedimentary sequence. Regardless of cause or length, a subaerial exposure surface is a record of interruption in sedimentation. Other terms sometimes used to describe this condition include hiatus, diastem, break, disconformity, unconformity, hardground or discontinuity surface. Even though all these terms refer to exposure surfaces, they may be submarine, subaerial, or both submarine and subaerial in origin. A

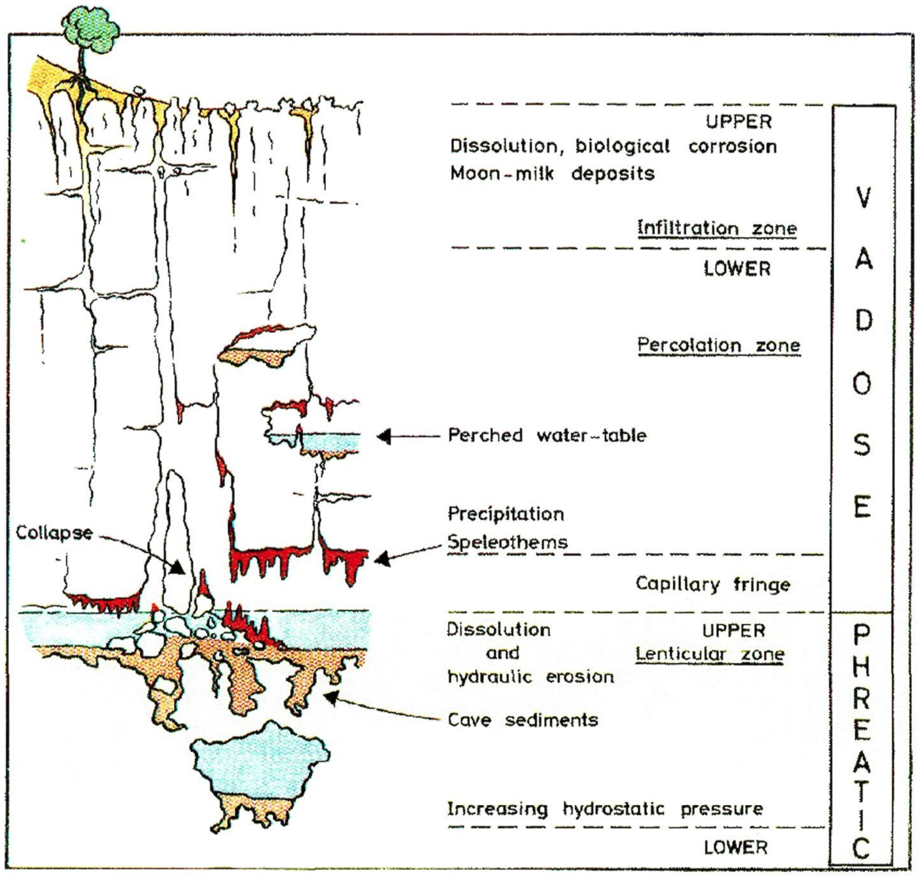

Figure 5—Idealized authigenic karst profile (not to scale).

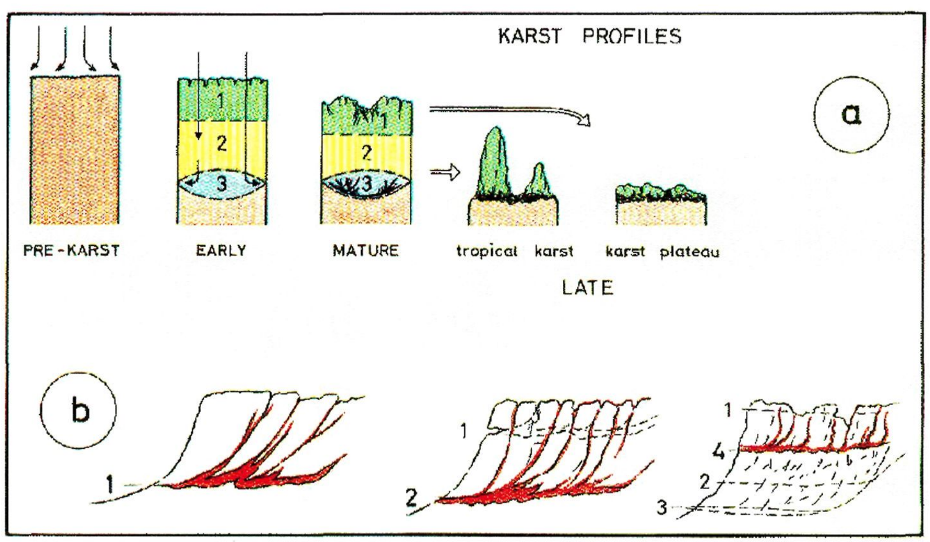

Figure 6—Evolution of karst profiles. (**a**) Successive stages of evolution in authigenic karst with stable base level. (**b**) Karst profile with repeated changes in position of water table.

subaerial exposure surface is, by definition, an emersion or a land surface.

Alteration Zone Associated with Subaerial Exposure

Below the subaerial surface itself there is an alteration or weathering zone whose thickness (ranging from a few millimeters to hundreds of meters; fractions of an inch to hundreds of feet) is controlled by a number of variables. The most important variables are climate, intensity and duration of subaerial diagenetic processes, position of the water table and its underlying freshwater phreatic lens, and the petrofabric attributes of the attacked host sediment or rock. Because of these variables, a wide variety of features may develop within this alteration zone. Because these features help us identify, and are related genetically to, subaerial exposure surfaces themselves, they are discussed in detail in later sections of

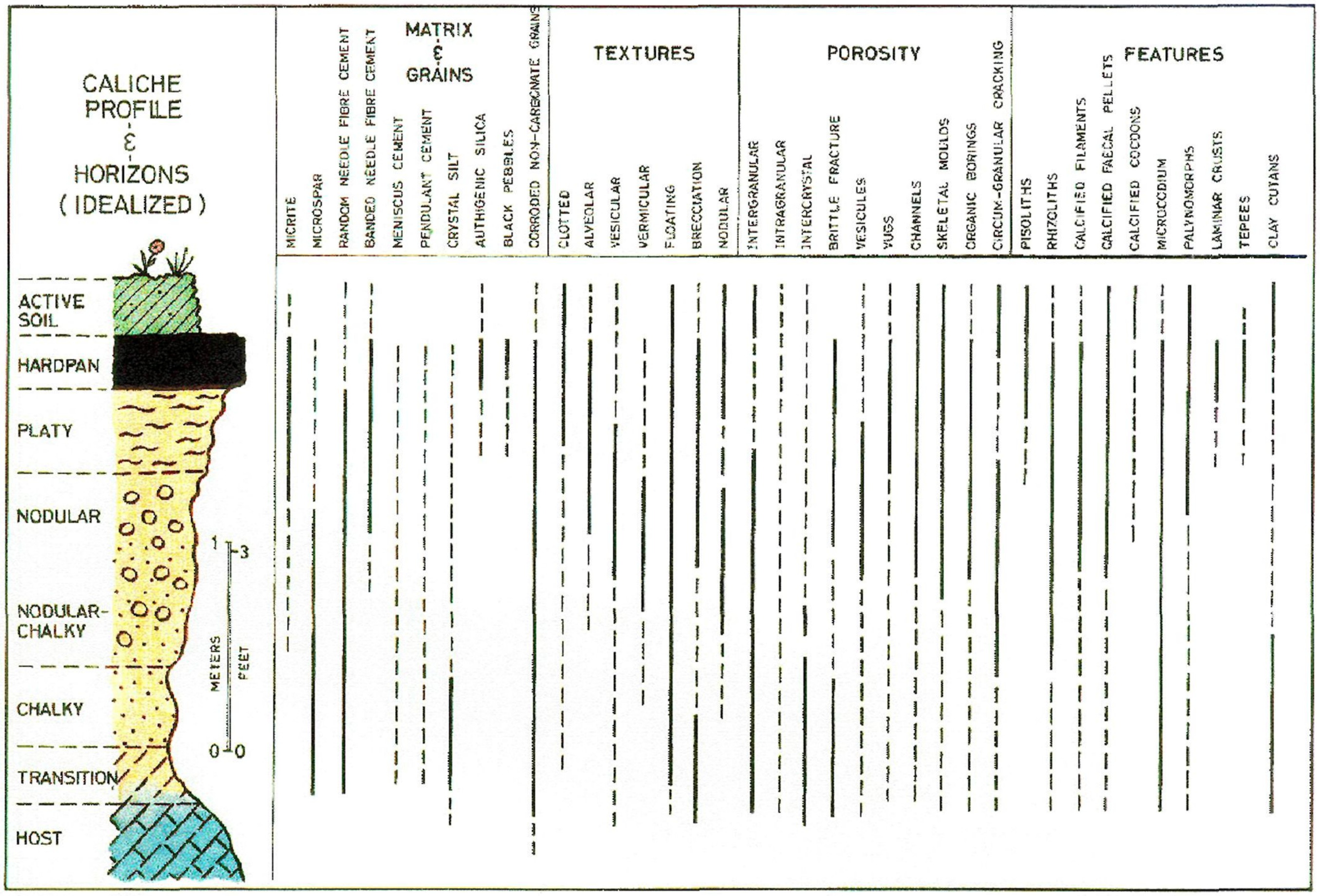

Figure 7—Idealized caliche profile and distribution of major characteristics within the profile.

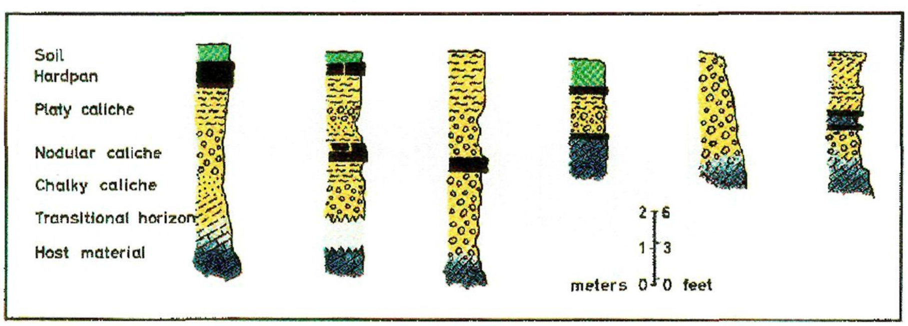

Figure 8—Some common variations of caliche profiles based on known examples.

this chapter.

End-member Products of Subaerial Exposure

Basically, two end-member diagenetic carbonate facies, the karst facies and the edaphic or soil facies, are born as a result of subaerial exposure. But because of the whims of preservation the soil facies is rarely preserved intact before the onset of subsequent erosion or sedimentation which will respectively remove the soil or incorporate, mix or dilute soil products with any new sediment influx. However, an important exception to this rule is the caliche or calcrete facies, whereby soil products become lithified prior to erosion or renewed sedimentation. Lithification of soil products by calcium carbonate forms indurated caliche facies which, like the karst facies, have a reasonable chance of being preserved in the rock record.

Fundamentals and Variations on a Theme

A subaerial exposure surface differs fundamentally from all other carbonate environments in one major aspect — it represents solely a diagenetic environment rather than a depositional one. All marine carbonate sediments are similar in one major aspect — once emergent, all

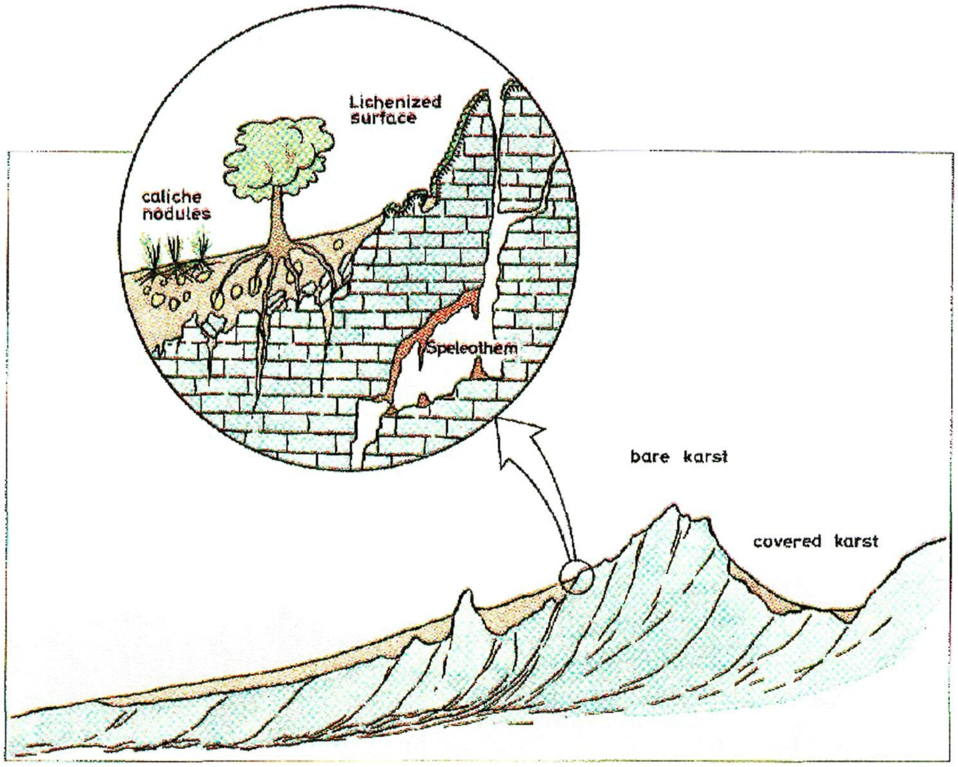

Figure 9—Co-existence of karst and caliche facies.

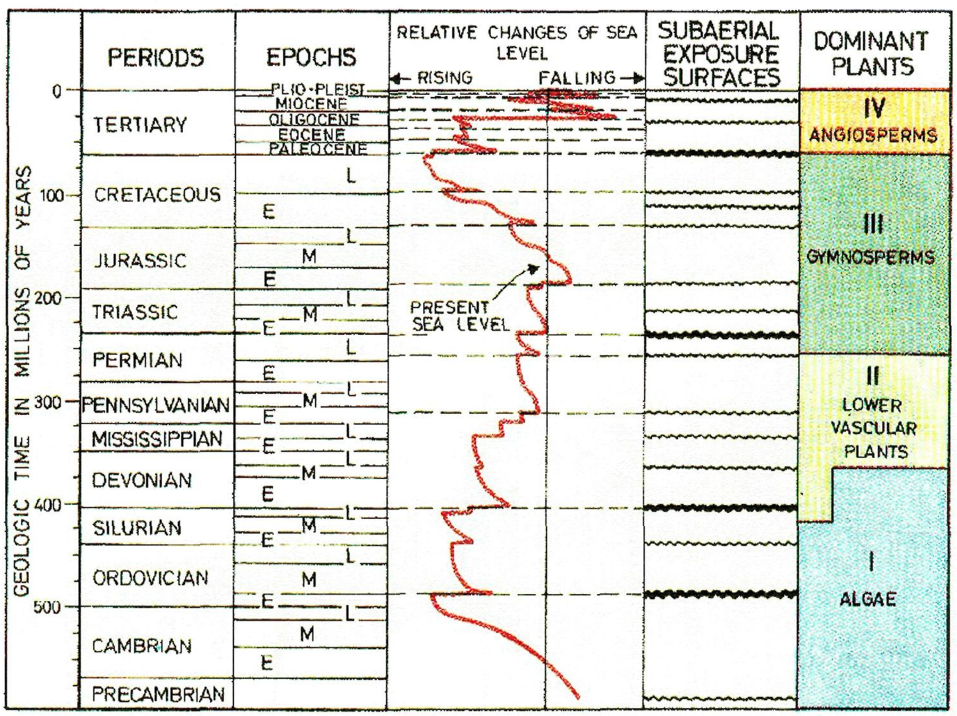

Figure 10—Relative global sea level changes, major known subaerial exposure surfaces and dominant plant groups during Phanerozoic time. (Adapted from Vail et al, 1977).

are subjected to identical subaerial diagenetic processes at their resulting exposed surfaces.

Given sufficient relative lowering of sea level, subaerial exposure surfaces may exist within shallow-water or deep-water marine carbonate sequences although their frequency should be greater in the former, assuming equal chances of preservation in the rock record. Eolian and lacustrine carbonates are but slight variations on the same theme. Once eolian carbonate sands are stabilized and lacustrine carbonates have dried out, the subaerial diagenetic processes which operate on these terrestrial carbonates will be the same as the processes which operate on subaerially exposed marine carbonate sequences. In other words, subaerial exposure surfaces obey no rules with respect to environment of formation of the subjected host carbonate. As long as

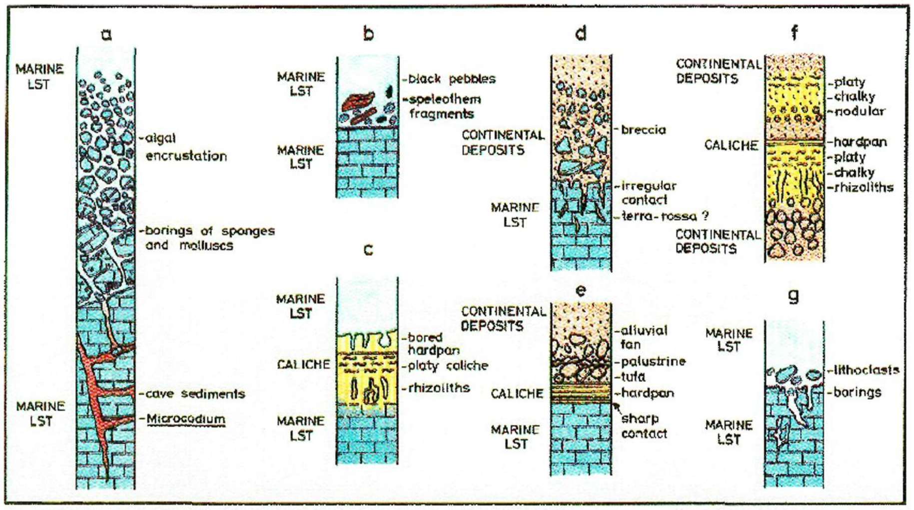

Figure 11—Generalized sequences containing exposure surfaces based on known examples. (**a**) Karstified Mesozoic limestone reworked in Miocene coastal environment. Most of the karst profile is preserved, with clear evidence of proximity of soil cover, Barcelona, Spain. (**b**) Same exposure surface as in (**a**) but karst profile is not preserved; sequence is diagnostic of close proximity of karst and soil. (**c**) Caliche profile in Tertiary marine limestone reworked in Plio-Pleistocene coastal environments, Yucatan, Mexico. (**d**) Sequence probably contains subaerial exposure but no diagnostic evidence is found, except for relics of possible terra-rossa in deep joints. Same exposure surface as (**a**) and (**b**). (**e**) Mesozoic limestone, intensively calichified, followed by Paleocene palustrine sediments and alluvial fans, Barcelona, Spain. (**f**) Calichified overbank deposits of Triassic alluvial fan complex, Barcelona, Spain. (**g**) Same exposure surface as (**a**), (**b**) and (**d**), but without traces of subaerial exposure facies. Only coastal exposure facies are recorded.

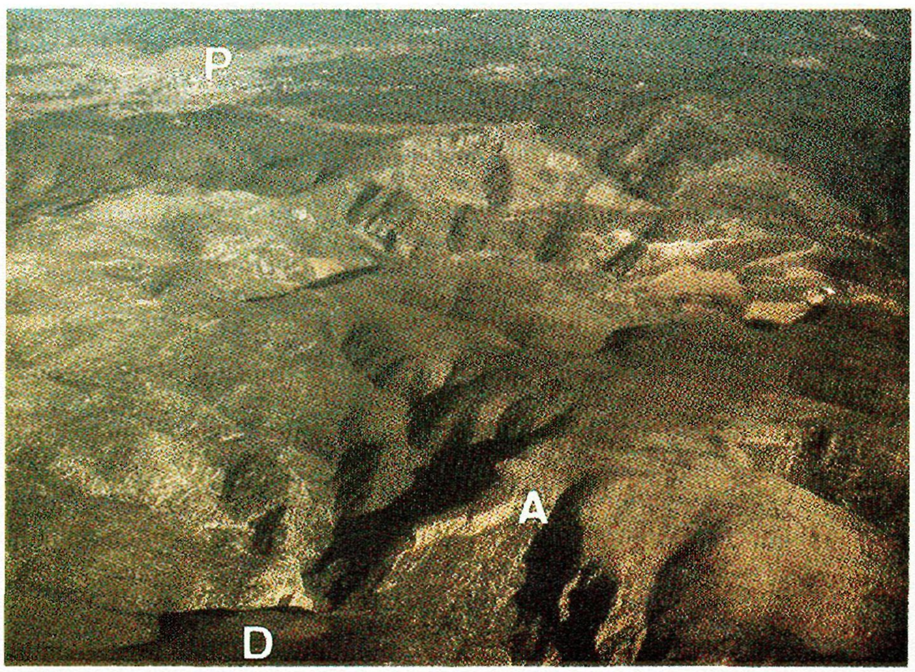

Figure 12—Karst surface landforms. Dolinas (**D**), polje (**P**) on a relic karst plateau. Relic alteration zone (**A**) outcrops as cliff on steeply dipping unaltered substrate. We believe that some of these relic karst features developed in earlier tropical climates. Present-day Mediterranean type of karst processes only produce slight modifications on the relic forms. Karst development from ?Lower Miocene (perhaps Lower Eocene?) to present on Cretaceous carbonates, Garraf Mountains, Barcelona, Spain.

there are: (1) subaerial conditions; (2) stabilization and non-deposition of sediment; and (3) sufficient time available for subaerial diagenetic processes to affect the exposed host carbonate, then a subaerial exposure surface and its underlying alteration zone will develop. Whether or not the original subaerial exposure surface and its underlying alteration zone will be preserved in the rock record depends largely on the presence or absence of any subsequent erosional phase.

Importance of Subaerial Exposure

As geologists, interested primarily in rocks, why should we concern ourselves with surfaces which represent missing pages in our story book of the Earth's history? There are at least three good reasons.

Firstly, subaerial exposure surfaces provide important information when faced with the task of trying to decipher the geologic history of a region. In many instances, it is just as important to know what is missing from a sedimentary sequence as it is to know what has been preserved. For example, when subaerial exposure surfaces can be identified within marine carbonates, important deductions can be made regarding periods of regression or upbuilding of sediment packages above sea level. Secondly, subaerial exposure surfaces can be extremely useful horizon markers for outcrop or core correlations. Thirdly, and perhaps of greatest economic importance, subaerial exposure surfaces are sites where valuable natural resources can be concentrated, including: (1) oil, gas or water traps in which the sealing unit overlies the reservoir rock below the subaerial surface; and (2)

Figure 13—Tropical karst landforms. Tower and conical karst developed since the Pleistocene on Cretaceous carbonates. North side of Mayan Mountains, Belize.

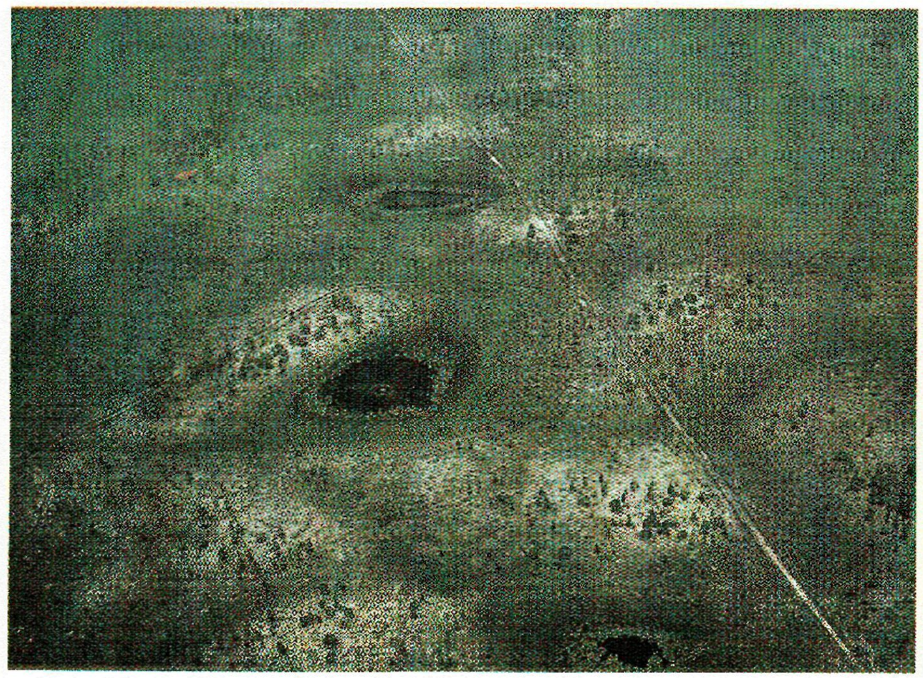

Figure 14—Dolinas. Aerial view of lowland plain with water-filled dolinas developed on Tertiary carbonates. These dolinas are believed to have formed in pre-Holocene temperate climates (Purdy, 1974). Location about 60 km (37 mi) north of Belize.

various accumulations and deposits of certain metals (lead, zinc, uranium, bauxite) related to soil processes or precipitation in karst cavities.

SETTING

Relationship to Lateral Facies

Subaerial exposure surfaces grade laterally seaward into coastal and submarine exposure surfaces (Fig. 1). Exposure surfaces in general may be highly irregular, or smooth and planar. Thus, exposure surfaces are characterized by their topography and relative position to sea level. They may be developed on sediment or rock (Fig. 2).

Submarine exposure surfaces — Carbonate sediments or rocks are exposed on the sea floor below the lower limit of noticeable wave action. This category includes submarine hardgrounds with or without their manganese, phosphatic or glauconite crusts and will not be considered further in this chapter.

Coastal exposure surfaces — Sediments or rocks are exposed in the peritidal environment above the lower limit of wave action and below the highest limit of the marine vadose salt spray zone. Some of the most com-

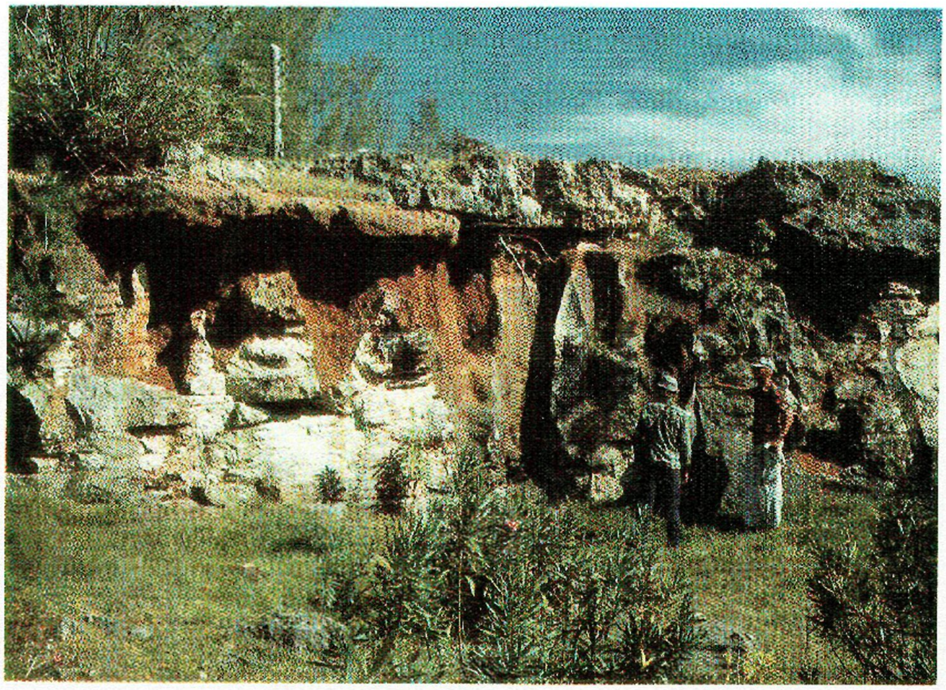

Figure 15—Fossilized rundkarren and solution pipe. Terra-rossa type soils fill depressions in karst landforms. Pleistocene, Bermuda.

Figure 16—Fossilized rundkarren. Intra-Triassic karst development on Lower Muschelkalk carbonates overlain by Upper Muschelkalk dolostones. Middle Muschelkalk red beds are represented as a condensed sequence of red soils covering the karst surface. Barcelona, Spain.

mon features of the coastal environment are shown in Figure 2a for rocky shores and in Figure 2b for sediment shores. Very irregular surfaces produced by wave action and bioerosion are characteristic of the rocky shore environment. Stabilization by plants is important in the sediment shore environment.

Of special interest for our purposes is the upper part of the coastal environment with rock pools infested by blue-green algae (Schneider, 1976), pelagosite crusts (Purser and Loreau, 1973) and the dissolution forms referred to as coastal marine karst. The coastal environment is of interest because of its juxtaposition to the subaerial meteoric environment and its high preservation potential in the geologic record. With changes of sea level, complicated patterns of superimposed coastal and subaerial processes may act on the same exposure surface. Renewed sedimentation will preserve this polygenetic surface.

Subaerial exposure surfaces — Sediments and rocks are exposed to the atmosphere landward of any marine influence. Lake bottoms and deflation flats are excluded from this discussion. First evidence of subaerial

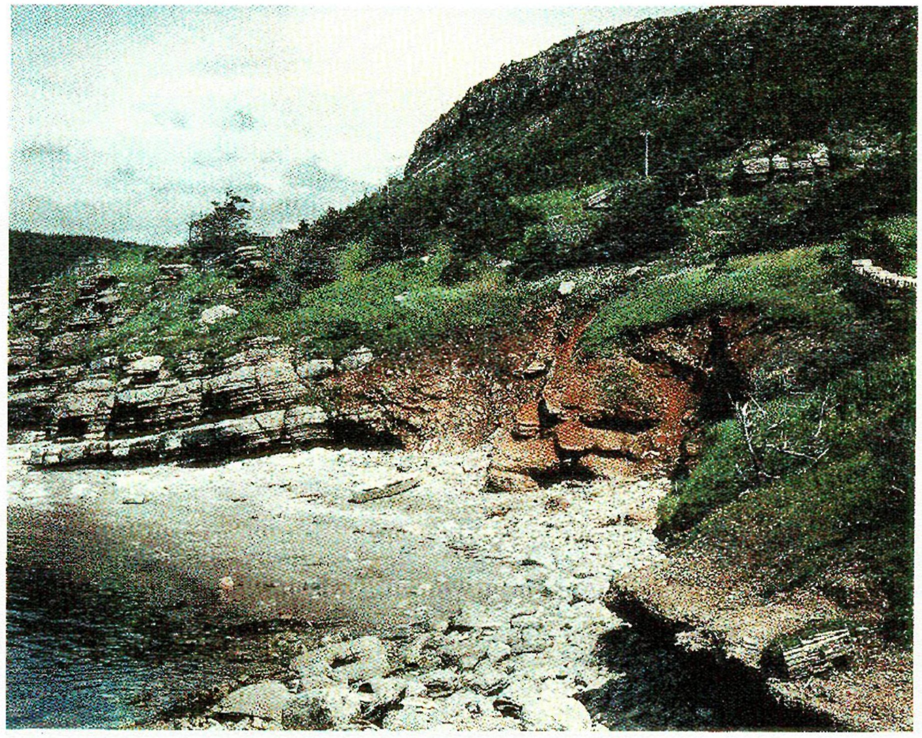

Figure 17—Sink-hole. Chaotic mass of red-stained brecciated blocks and sediments with marine Carboniferous fossils, developed as sink-hole fill in gray gently dipping Middle Ordovician limestones. Western Newfoundland, Canada.

exposure can be established by the appearance of endolithic lichens which represent the first stage of colonization and subsequent community succession in subaerial environments. This limit, established on the basis of lichen colonization, is not generally recognizable in the fossil record. A more practical limit for the geologist is the first appearance of karst and caliche diagenetic facies.

Succession and Modification of Exposure Surfaces

Sea level oscillations and variations in tectonic activity will produce important modifications and successions in exposure surfaces. With a relative sea level rise, areas subaerially exposed will eventually be overlain by a marine sediment (Fig. 3). During a relative fall of sea level, subaerial exposure surfaces will develop superimposed on the coastal and submarine exposure surfaces (Fig. 3) and eventually be overlain by a continental sequence (eolian sands, alluvial fans, lacustrine and palustrine sediments, fluvial sediments, porous and dense plant tufas). The last exposure surface prior to renewed sedimentation is the only one preserved on most occasions; it is of no coincidence that the best evidence of subaerial exposure is found generally at the base of a sequence of continental deposits.

The profile of exposure surfaces may also change with time without relative sea level oscillations. Many exposure surfaces are accompanied by destructive processes and the general trend is toward lowering of elevation and planation of surfaces. Exposure surfaces may also be modified tectonically (fracturing, orogenic and epeirogenic uplifts) with the consequent reactivation of erosional and depositional processes.

Climate exerts an important control, both in time and space, on morphology and profile development of subaerial exposure surfaces. Spatially, a single extensive subaerial exposure surface can be subjected to different climatic regimes (for example, from a dry warm low plain to a wet cool mountainous region). With time, climatic belts may shift, subjecting a given point on a subaerial exposure surface to a new set (or new intensity) of climate-sensitive processes.

All these controls, position with respect to sea level, tectonic activity and climate, together with the incessant evolution of diagenetic processes, will modify the topographic expression of exposure surfaces.

Subaerial Exposure Facies

Although caliche can develop in rock or sediment of any composition and karst may develop in evaporite bodies in addition to carbonate terrains, only karst and caliche developed in carbonate hosts are relevant to this discussion.

Generalities — Two major diagenetic carbonate facies are produced as a consequence of subaerial exposure, the karst facies and the caliche facies. Both diagenetic facies involve mobility of calcium carbonate. In the karst facies there is a net loss of calcium carbonate because of dissolution and removal of $CaCO_3$ solutions (supplemented by mechanical erosion). In the caliche facies there is a zero balance (local dissolution and reprecipitation of $CaCO_3$ without external sources) or a net gain (addition of $CaCO_3$) from elsewhere. Movement of $CaCO_3$-bearing solutions occurs both in the meteoric vadose and meteoric phreatic zones. These hydrologic zones are depicted in Figure 4, show-

Figure 18—Lapies. Irregular, jagged surface truncates Upper Miocene reef limestone overlain by Pliocene beach complex. Red-stained silt, probably derived from terra-rossa soils, covers karst surface. Mallorca, Spain.

ing the meteoric vadose zone subdivided into an upper dissolution zone of infiltration and a lower percolation zone of downward movement with negligible dissolution of calcium carbonate. Similarly the meteoric phreatic zone can be subdivided into an upper active lenticular zone (Jakucs, 1977) and a lower inactive deep zone (imbibition zone) which grades downward into connate or formation waters.

In the zone of infiltration, waters are active and may either (1) dissolve calcium carbonate because of aggressive atmospheric CO_2 and/or high levels of biogenic CO_2 derived from overlying soil cover, or (2) precipitate calcium carbonate if CO_2 levels are lowered by degassing or plant uptake. By the time water reaches the underlying percolation zone it is at $CaCO_3$-H_2CO_3 equilibrium and dissolution or precipitation of calcium carbonate is minimal. In contrast, in the uppermost part of the phreatic zone just below the water table, water movement is essentially horizontal and $CaCO_3$ is either removed by dissolution and mechanical erosion or precipitated. Continuing downward to the lenticular zone, whose position is determined by an underlying impermeable horizon or by the base level of erosion, direction of water movement is controlled by hydraulic pressure rather than direct gravity. Limestone in this zone may undergo dissolution because of increased hydrostatic pressure and mixing corrosion, or precipitation may take place if mixed waters become supersaturated with respect to calcium carbonate. Water below the lenticular zone, even though under hydrostatic pressure, does not play a role in the hydrographic cycle of the overlying lenticular zone; it therefore attains equilibrium with its surroundings and becomes stagnant. This inactive zone grades downward through a transitional zone into connate waters whose properties and effects on calcium carbonate are poorly understood or unknown.

Karst Facies

The term karst has been used to designate specific landforms (including subterranean landforms) and a geographic region characterized by these landforms. Modern developments (Thrailkill, 1968, 1971; Sweeting, 1973; Jakucs, 1977) have stressed the concept of karst as a result of a complex set of processes (climatic, tectonic, edaphic, hydrologic, petrologic) with different evolutionary stages. On this basis, the following definition is more useful to geologists: "Karst is a diagenetic facies, an overprint in subaerially exposed carbonate bodies, produced and controlled by dissolution and migration of calcium carbonate in meteoric waters, occurring in a wide variety of climatic and tectonic settings, and generating a recognizable landscape." Karst facies represent a net loss of calcium carbonate, although in some stages of karst evolution or in some parts of the profile, it is possible to have equilibrium or gain in the carbonate budget. A descriptive characterization of karst should be based on: (1) surface landforms (lapies, dolinas, poljes); (2) subterranean landforms (varieties of pores, caves, vugs, pipes); (3) speleothems (stalactites, stalagmites, flowstones, rimstones, globulites, cave pearls, lily pads, helictites, moon-milk); and (4) collapse structures due to removal of underlying carbonate.

Mineralogy of the karst facies is dominantly low magnesian calcite (LMC), although caves in dolostones show a wider variability in mineralogy with local deposits of aragonite, hydromagnesite, dolomite and nesquehonite. In this chapter we will refer generally to LMC deposits because they are more abundant and

Figure 19—Collapsed roof of cavern. Cavern formed in Upper Miocene reef limestone during time of formation of subaerial exposure surface of Figure 18. Mallorca, Spain.

cave deposits of other mineralogies show roughly the same gross morphologies.

Karst Profile — Karst presents a generalized facies pattern that can be summarized in a profile (Fig. 5) as follows:

(1) Infiltration (upper vadose) zone, characterized by surface landforms, with or without a developed soil cover (exposed carbonate usually has a lichen or algal cover, a protosoil) and by production of dominantly vertical caves (pecina, Figs. 20, 26). Most of the speleothems of this zone are the result of intense corrosion and degradation of carbonate host walls. These speleothems are fine grained deposits (moon-milk) made of random needle fibers of low magnesian calcite (LMC) and some types of globulites (popcorn) growing in degraded carbonate hosts. The final product is a characteristic accumulation in walls and cavern floors of white, fine-grained deposits of chalky or friable consistency, abundantly colonized by fungi and bacteria. The dominant processes in this zone are physicochemical dissolution and biological corrosion related to intense organic activity. Collapse breccia deposits can also be very abundant (Fig. 25) in zones up to 20 m (66 ft) thick in many European and North American karst profiles.

(2) Percolation (lower vadose) zone, characterized by net vertical water movement through pre-existing permeability pathways. In percolation zones dominated by vadose water seepage there is little dissolution, but localized areas of vadose flow (underlying major sinkholes, thick soil covers, open fractures) show active dissolution and hydraulic erosion. As a facies this zone is poorly defined, oscillating between 0 to 200 m (0 to 660 ft) thick, but the lower part near the phreatic water table is where speleothem formation is more abundant and more varied than elsewhere in the karst profile. The presence of a capillary fringe (up to 2 m or 6.6 ft above the water table) is likely related to this intense carbonate precipitation.

(3) Lenticular (upper phreatic) zone, characterized by intense formation of subhorizontal caves (jama) by hydraulic erosion and dissolution as a result of mixing corrosion and increasing hydrostatic pressure. Subvertical caves can also be formed but they are subsidiary to horizontal drainage patterns. Most karst cavern porosity is produced in this zone, especially just below the water table (Thrailkill, 1968) in allogenic karsts. Speleothem formation in this zone can also be important in senile stages of evolution, mainly at and a few centimeters below the water table (floating carbonate flakes or rafts, isopachous coatings, cave pearls, lily pads). Collapse breccias and water laid deposits are very abundant locally. In karst facies it is common to have perched water tables at various levels, thus introducing more complexity to the profile.

The lower limit of the karst profile is difficult to establish. Lenticular zones can be up to 100 m (330 ft) thick or more. The increase in hydrostatic pressure at the base of the lenticular zone may favor dissolution but, at a deeper level, waters will become stagnant and a diagenetic overprint related to subaerial exposure is no longer recognizable. On the other hand, the lenticular zone could be the ideal setting for pervasive phreatic cementation, a process accepted by many carbonate petrologists. Intergranular cements and speleothem deposits of the phreatic lenticular zone may be different products of the same cementation process; the differences being controlled by two factors — pore geometry and water flow pattern.

Evolution — The karst profile of Figure 5 could represent a mature stage of evolution of a karst facies. A dynamic view of the karst facies of-

Figure 20—Speleothem. Plan view of vertical solution pipe in Upper Miocene reef dolostone. Solution pipe wall is delineated by iron-rich crust which is overlain by banded calcite and minor aragonite flowstones and globulite (popcorn). Karst event is same as in Figures 18 and 19, but located here in Alicante, Spain.

Figure 21—Kamenitza. Recent solution rock pools developed on Tertiary carbonates in tropical climate, Yucatan, Mexico.

fers more complexity. To start with, in an absolutely massive, pure and homogeneous carbonate host, early stages of karst evolution would be confined to surface landforms (for example the experimental studies of Purdy, 1974). Heterogeneities such as fractures, joints, bedding planes, impurities in the carbonate host and vegetation favor the development of subterranean landforms. With a stable phreatic base level, the evolution of the karst profile (Fig. 6) implies the lowering of the surface and the downward shift of the infiltration zone. The surface evolves into complex landforms such as dolinas, uvalas, poljes and karst valleys and plains (Fig. 12). Insoluble residues of the carbonate host play a major role in karst facies evolution; they are the basic contributors to the formation of soil cover (with the consequent increase of biogenic CO_2 taken up partly by meteoric waters). Deposition of insoluble residues in subterranean pores (Fig. 33) and conduits controls the hydrologic patterns of karst. With the exception of tropical climates, the tendency is toward a limestone plateau where the infiltration and lenticular zones merge. The lenticular zone is drastically reduced because of clogging by insoluble residues. Tropical karst, on the other hand, differs from this model. Accentuation of surface morphology, because of the relatively higher soil permeability and aggressiveness of waters in the lower depressed areas occupied by soils, produces conical and tower karst (Figs. 6, 13).

Profiles of karst facies are usually complicated by repeated changes in position of the phreatic water level (variations in tectonic and climatic setting, sea level oscillations). For example, products of the phreatic zone can be subjected to processes in the upper vadose zone and become coated, corroded, dissolved or remodelled. Similarly, former vadose products can be drowned and modified in the phreatic zone (Fig. 6). In general, the karst profile is more active during periods following orogenic episodes because of: (1) the

Figure 22—Lapies. Enlarged open joint (kluftkarren) and root lapies modified by incipient rillenkarren. Kluftkarren and root lapies are possibly relic karst forms of wetter climate than present day, semiarid Mediterranean climate. Miocene limestones, Almeria, Spain.

creation of new joints and fractures in the host rock which allows percolation of more meteoric water, (2) the increase in topographic irregularities, with deepening of the water table and easy removal of soils on unstable slopes; and (3) the formation of topographic highs which can control local climatic patterns favoring orographic rains. The repetition of these changes strongly alters the host rock, with recognition of these multicyclic episodes and modifications extremely difficult but possible with careful geomorphological, petrological and paleontological studies. In the fossil record, only parts of the karst facies and profiles are likely to be preserved and the study of karst zones and their inferred evolution will be generally impossible.

The profile summarized here corresponds to authigenic karst (holokarst) where meteoric waters in the profile are collected in the infiltration zone of the same profile. Other possible types of profile occur where meteoric waters arrive into the profile from adjacent or suprajacent nonkarstic terrains (allogenic karst of Jakucs, 1977). Most karst profiles in nature are combinations of authigenic and allogenic types. Allogenic karst is very important in mature and senile stages of authigenic karst, typically under thick soil cover or below noncarbonate formations. The allogenic karst facies results from valley sculpture by linear stream bed erosion and differs from authigenic karst mainly because in allogenic karst: (1) the drainage pattern has a marked polarity which clearly resembles an underground river, (2) deposition of speleothems and cave sediments is more abundant, and (3) scour caverns, typically with flat roofs, are abundant. For geologists working in the fossil record, the distinction between the authigenic and allogenic karst is extremely difficult; our discussion will refer to both types together.

Another important aspect of karst evolution is the intimate relationship with the soil cover. The definition of the term karst does not include soil-forming processes, although a variety of soils are common on different types of karst. These soils are an important control and consequence of karstification. As a control, soils are sites of biogenic CO_2 production and meteoric water storage. As a consequence, soils are formed from insoluble residues as a by-product of karstification. In general, early stages of karst evolution show poorly developed soil cover while later stages usually imply thicker and more extensive soil cover. The climatic setting, together with lithological and topographic patterns of the carbonate host, are major factors which control development of the soil cover.

Residual soil deposits, such as terra-rossa and laterites, may be characteristic of specific climatic types of karst (Mediterranean, tropical) and can be recognized within fossil carbonate sequences (Figs. 18, 27, 36, 37). The soil cover of karst may also evolve in the direction of carbonate-rich soils of the caliche type (Fig. 38), particularly in mature and late stages of karst evolution. Because of their high lithification potential, caliche soils are one of the most useful criteria for recognition of fossil subaerial exposure surfaces and deserve careful attention.

Caliche Facies

Caliche (calcrete) is commonly defined as a fine-grained, chalky to well-cemented, low magnesian calcite deposit that formed as a soil in or on pre-existing sediments, soils or rocks in semiarid environments (Bretz and Horberg, 1949; Brown, 1956; Swineford et al, 1958; Durand, 1963; Blank and Tynes, 1965; Gile et al, 1966; Ruellan, 1967; Aristarain, 1970; Reeves, 1970; James, 1972; Esteban, 1972, 1974; Read, 1974). This essentially genetic definition is of limited

Figure 23—Rillenkarren and small kamenitza. Modern surface karst features developed on fine-grained limestone of Cretaceous age. Castello de la Plana, Spain.

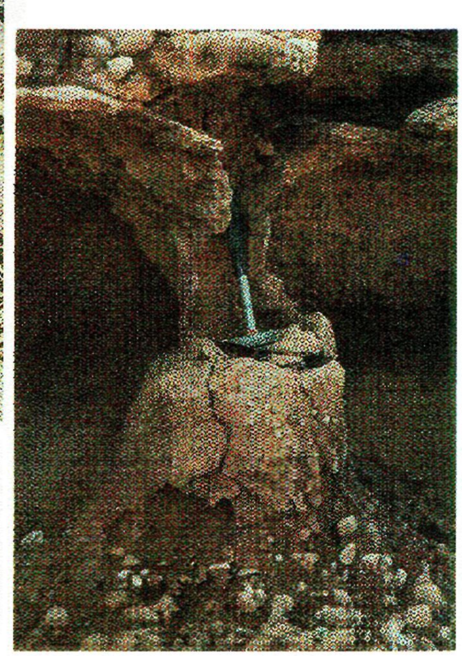

Figure 24—Solution pipe and caliche profile. Solution pipe, developed in red-brown Pleistocene calcareous silts, lined with laminar micritic crust. Overlain by hardpan and nodular caliche of later Pleistocene age. Ibiza, Spain.

use to geologists looking for caliche in the fossil record. It is necessary to have a more descriptive definition which includes regional setting, lithologies and their sequences, structures, textures and fabrics. A descriptive definition has been proposed by Esteban (1976) and is adapted here, with some modifications, as follows: "Caliche is a vertically zoned, subhorizontal to horizontal carbonate deposit, developed normally with four rock types: (1) massive-chalky, (2) nodular-crumbly, (3) platy or sheet-like, and (4) compact crust or hardpan. The position and development of these rock types in a vertical sequence (profile) and laterally is highly variable. The only rather consistent relation is that the massive-chalky rock grades downward into the original rock or sediment through a transition zone, with strong evidence for both in-place alteration and replacement of the original rocks or sediment. Colors are commonly white and light brown, but red and black may be important. The predominant caliche fabric is a clotted, peloidal micrite with microspar channels and cracks. Accessory fabrics are rhizoliths, glaebules (pisoliths, ooliths, nodules, peloids), poorly laminated micrite and karst products. Microspar areas usually show evidence of replacement of relic grains and of other primary and earlier diagenetic microfabrics." Caliche is an informal term used by geologists. Probably any carbonate-rich soil, with $CaCO_3$ concentrated in the form of glaebules, can be fossilized to form different types of caliche rocks.

Caliche Profiles — An idealized caliche profile is shown in Figure 7, and though only one of many possible variations it is the most common of modern western Mediterranean and Texas caliches. Other common profiles are shown in Figure 8. The term caliche profile refers to the complete vertical succession of morphologically distinct layers or horizons. Boundaries between horizons tend to show gradual transitions rather than abrupt changes. The main features of each horizon are summarized in Figure 7 and Table 1 and described as follows:

Hardpan — Being well indurated and lacking visible porosity, the hardpan is generally more resistant to weathering than underlying horizons and, thus, commonly stands out as a prominent feature. Vertical thicknesses vary from 1 mm (0.04 in.) laminar layers (Fig. 75) to massive horizons, 1.5 m (5 ft) thick. The horizon is made up dominantly of well cemented microcrystalline or cryptocrystalline calcite. The thicker hardpans commonly show evidence of fracturing, non-tectonic brecciation (Figs. 41, 44, 60, 63, 68, 72), dissolution and recementation, and may contain glaebules (pisoliths) and rhizoliths. Colors are generally white or cream, although pale orange to brown are not uncommon. The hardpan may be macroscopically structureless or massive, laminated (Fig. 58), brecciated (Fig. 60) or nodular (Fig. 74).

Platy caliche — Platy caliche invariably occurs immediately below the hardpan horizon (Fig. 43) or, in profiles lacking a hardpan, occurs as the uppermost calcareous horizon or below a more recent soil cover. Platy caliche is distinguished from hardpan caliche by its horizontal to subhorizontal, platy, wavy or thinly bedded habit (Fig. 44), its planar fracture

Figure 25—Collapse breccia. Part of fill in solution pipe formed in Pleistocene carbonates. Angular blocks of carbonate host coated with flowstone. Flowstone forms a geopetal fill within interblock porosity. Jamaica.

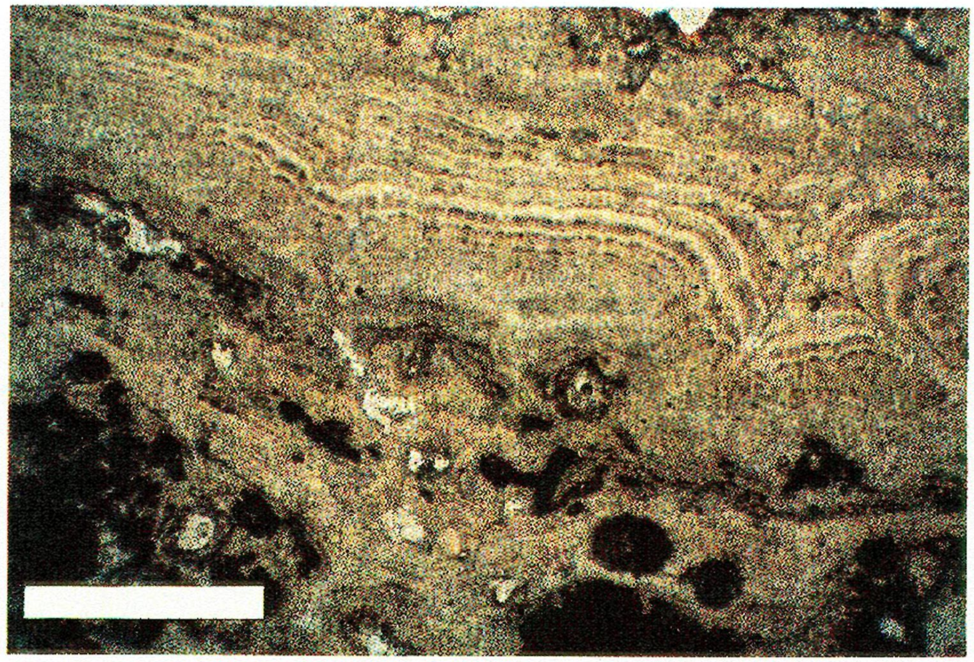

Figure 26—Speleothem. Laminar flowstone of Pleistocene age. (Field view of flowstone and host rock shown in Fig. 29). Ibiza, Spain. Thin section, plane polarized light. Scale bar = 1.0 mm.

porosity and greater friability, and the abundance of alveolar textures, rhizoliths and needle fiber fabrics. Recognizable transitional stages suggest that hardpans represent advanced stages of platy caliche development. Maximum and average thicknesses of platy caliche horizons are greater than those of hardpans, the maximum thickness recorded for platy caliche from Spain being 3.1 m (10 ft). Platy caliche generally grades downward into nodular caliche.

Nodular caliche — Nodular caliche is made up of glaebules which consist of discrete, powdery to indurated concentrations of calcium carbonate embedded in a less carbonate-rich matrix (Figs. 39, 40, 47). Individual glaebules range from silt-sized to pebble-sized particles. They may be spherical or subspherical, irregular or cylindrical in shape. Most cylindrical forms are vertically elongate (Fig. 43); some, however, show branching patterns. Glaebules occur either as isolated particles or as coalesced masses. In addition to greater concentrations of calcium carbonate and greater cohesion, glaebules usually can be distinguished from the surrounding matrix by color differences. Glaebules are commonly white to cream in color, whereas the matrix tends to be red or red-brown (Fig. 40) because of higher concentrations of acid-insoluble residues such as layer lattice minerals and ferric hydroxides. However, some glaebules, especially sand-sized glaebules with internal concentric fabrics, are dark red-brown whereas the matrix is pale brown to cream. Iron salt impregnation within these darker glaebules is usually responsible for this color difference. Nodular horizons invariably show diffuse upper and lower boundaries. In many profiles, the boundary between nodular and chalky-powdery horizons is so indistinct that this "boundary" can commonly be treated as a separated horizon, that is, the nodular-chalky horizon.

Chalky caliche — The chalky caliche is characterized by white to cream, unconsolidated silt-sized calcite grains. Cementation between grains is absent so that the material has the consistency of a powder. This horizon tends to be homogeneous structurally and texturally, although scattered, isolated glaebules are locally present (Figs. 39, 46). Areas around plant root systems appear to be favored sites for $CaCO_3$ accumulation, and this phenomenon gives rise to incipient nodular development. Maximum thicknesses of this horizon rarely exceed 1 m (3.3 ft). Chalky horizons are poorly developed or absent in most profiles where the host material has high interparticle porosity (for example, eolianites). The chalky horizon generally grades upward into nodular caliche and downward into the transitional horizon.

Transitional horizon — The term transitional horizon refers to the zone between unaltered host material and overlying caliche horizons that lack macroscopically discernible features inherited from the host material. The transitional horizon itself contains macroscopically discernible evidence of in-place alteration and partial replacement of the original host material (Fig. 51). This evidence includes: (1) relic sedimentary structures such as bedding (Fig. 46), (2) in-place relic fossils embedded in otherwise calichified host material, (3) in-place relic siliciclastic grains with distribu-

Figure 27—Cavern sediment fill. Light-cream areas are host carbonate (Cretaceous). Horizontally laminated, light brown areas are lateritic, granule to sand size sediments (younger Cretaceous) filling paleokarst cavities (D'Argenio, 1967). These fossil karst deposits are micrite-rich and are related to overlying lateritic soils, Southern Apennines, Italy.

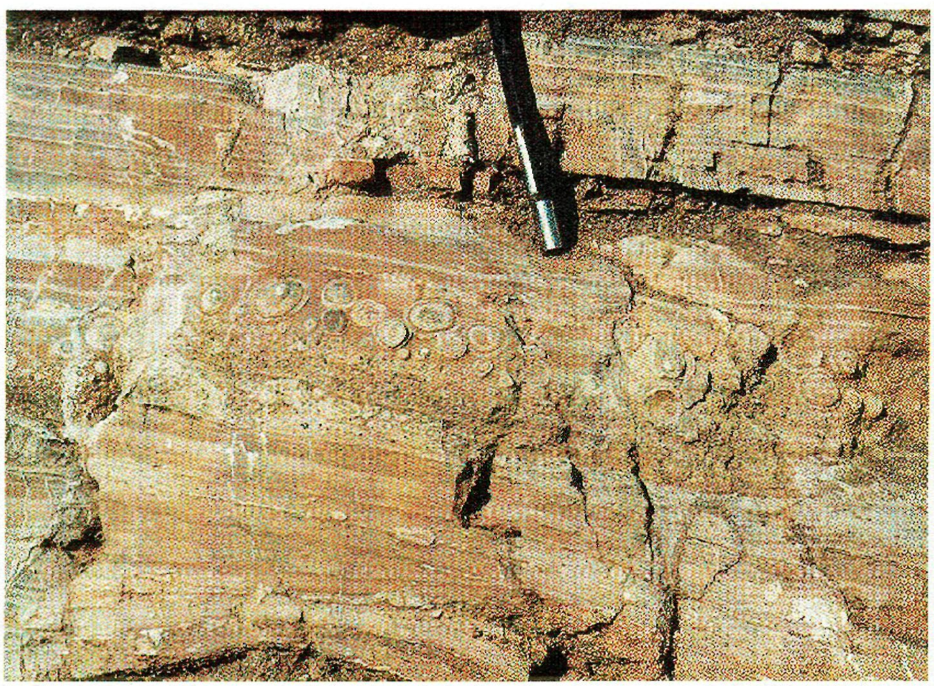

Figure 28—Cave pearls and laminated cavern sediment. Same locality as in Figure 27. Cave pearls are also micrite-rich and occur in layers with characteristic coarsening upward grain size arrangements.

tion patterns inherited from the host material, and (4) relic mineral veins traceable from the underlying host material into the caliche profile without deviation or disruption. In profiles developed within bedded sedimentary deposits, dipping beds of unaltered host material can be traced upward into transitional and chalky horizons. Alteration takes place preferentially along bedding and joint planes (Fig. 68). These planes of access allow water to move through host material more easily and are, thus, sites susceptible to diagenetic alteration and to penetration by roots. This horizon is essentially an in-place weathered zone consisting of partially degraded host material, making it difficult to fix the lower boundary. The transitional horizon may grade into the upper vadose zone of karst and may show thicknesses of several meters (feet). In other profiles the transition horizon can be minimal or apparently absent.

Host material — The host material may be of any composition, texture, age and origin. The only significant factor of host material that influences caliche development is its mechanical stability; development of a caliche profile requires a stable substrate suf-

Figure 29—Speloethem and breccia. Brecciated (karst collapse breccia?) and recemented (and calichified) Kimmeridgian dolostone and laminar flowstone of Pleistocene age. Thin section photomicrograph of flowstone shown in Figure 26. Ibiza, Spain.

Figure 30—Endolithic lichens. Rock surface (Cretaceous limestone) shows an early development of rillenkarren which is smoothed out by endolithic lichens. Sharp, irregular contacts (L) between different lichen communities correspond to areas of intense frugal penetration into the rock. Garraf Mountains, Barcelona, Spain.

ficiently long for pedogenetic and diagenetic processes to operate. Even so, other factors of the host material such as permeability and calcium carbonate content can influence the rate of caliche development. The host material is distinguished from its overlying caliche profile by the absence of typical features which characterize caliche. Original structures, textures and fabrics of the host material are clearly recognizable; they have not been modified or obliterated by subsequent calichification in contrast to the transitional, chalky, nodular, platy and hardpan horizons which do show such alterations with increasing intensity upward and away from the host material.

Evolution — Unconsolidated caliches may be active, relic or fossil $CaCO_3$-rich soils. Indurated caliches are lithified fossil $CaCO_3$-rich soils. Soils are products of weathering and also the natural medium in which plants grow. The evolution, from a subaerially exposed marine carbonate to an indurated caliche rock, can be delineated simplistically into five stages:

Stage 1: Preparation of host material; weathering. Mechanical, physicochemical and biological dis-

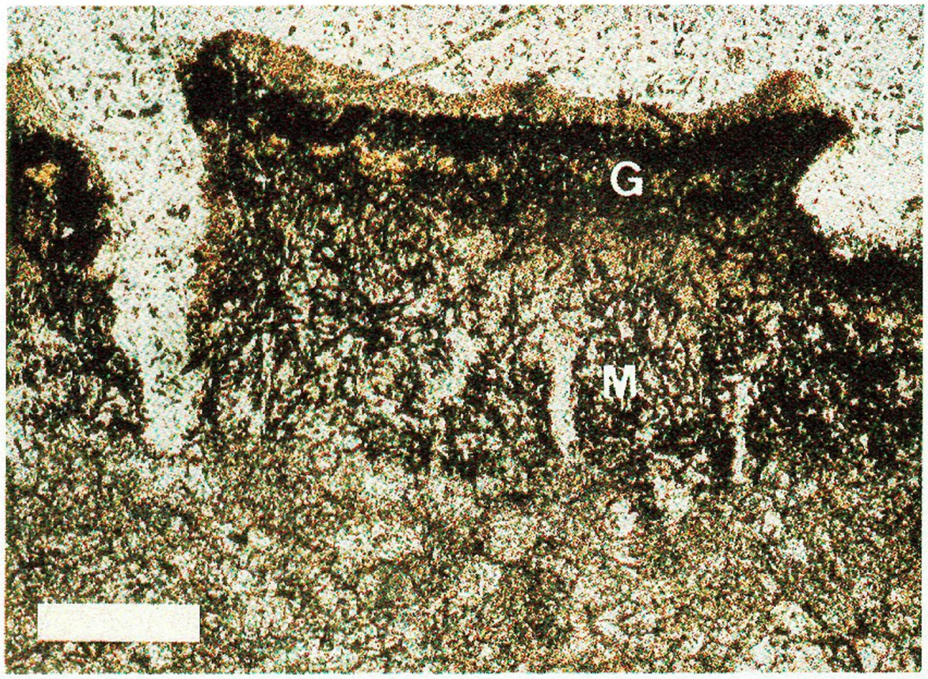

Figure 31—Endolithic lichens. Profile of modern endolithic lichen colonization in Jurassic dolostone. Green cavities below the surface are the algal components of the lichen symbiosis (gonidial zone, **G**). Black filaments correspond to the fungal hyphae (medulla zone, **M**). The lower part contains unaltered host rock. Spheroidal depressions and cracks in the surface are made by former reproductive bodies of the lichen, Mallorca, Spain. Photograph courtesy of L. Pomar. Thin section, plane polarized light. Scale bar = 0.5 mm.

integration generate a regolith or accumulation of weathered detritus. Soil development implies rates of accumulation exceeding rates of removal.

Stage 2: Soil development; pedogenesis. Unconsolidated sediment or weathered detritus is developed into a soil by changes produced by the action of organisms and by movement of water through the sediment.

Stage 3: Accumulation of calcium carbonate and differentiation into horizons. In the early stages of caliche development, the profile is composed of weathered materials with high porosities and permeabilities. Vertical movements of meteoric vadose water can take place relatively easily, and insufficient water is retained to supply the requirements of the vegetation. Some plants have to extend taproots vertically downward to the proximity of local water tables. Roots extend downward into fractures and joints within host material, modifying original structures and contributing to the disintegration of the substrate. Biological and physicochemical alterations of the host material culminate in the formation of a transitional horizon. Precipitation of calcium carbonate, without significant cementation because of mechanical and biochemical instability of the profile, forms most of the chalky horizon. Pedoturbation (physical, chemical and biological disturbance of soil materials) precludes the formation of indurated layers.

As the accumulation of calcium carbonates increases, porosity and permeability of the profile decrease. Biological constituents of the soil may become calcified, thus forming biogenetic carbonate structures such as rhizoliths, calcified filaments, calcified fecal pellets, calcified cocoons and *Microcodium* aggregates. Wetting and drying of the soil favors development of shrinkage cracks and, later, precipitation of $CaCO_3$ within voids. In earlier stages of profile development, vertical water movements and vertical taproots tend to form vertically oriented elongate carbonate nodules. But at some point of profile development, it becomes easier for soil water to move horizontally rather than vertically. By this stage most plants form lateral root systems, their corresponding rhizoliths form the bulk of the platy caliche horizon. Vertical rhizoliths in lower parts of the profile tend to be large (5 to 20 cm; 2 to 8 in) and isolated; platy horizon rhizoliths are smaller (0.5 to 2 mm; 0.02 to 0.08 in), extremely abundant, branching and horizontally oriented. Development of the platy caliche horizon from the nodular horizon may be a reflection of plant succession in a developing soil.

Stage 4: Lithification, cementation and fossilization. As accumulation of calcium carbonate increases, a point will be reached when soil organisms can no longer maintain viability. The intensity of soil-forming processes diminish and eventually cease to be important. Diagenetic processes, mainly cementation by low magnesian calcite, lead to the lithification and fossilization of the soil profile and formation of a hardpan.

Stage 5: Reworking, brecciation, weathering (new Stage 1). The lithified caliche profile, if it remains at the land surface, is subjected to further processes which will alter or destroy the profile. Lower plant (lichens, algae, fungi, bacteria) activities will form a protosoil, a pioneer stage in plant community succession. Eventually the developing soil profile is able to support higher plants. The root systems of these plants penetrate, dissolve and fracture the indurated hardpan. Disturbance of the caliche profile by vegetation may form tepee structures and rhizobreccias. Further pedoturbation, with carbonate dissolution and reprecipitation, leads to the formation of a

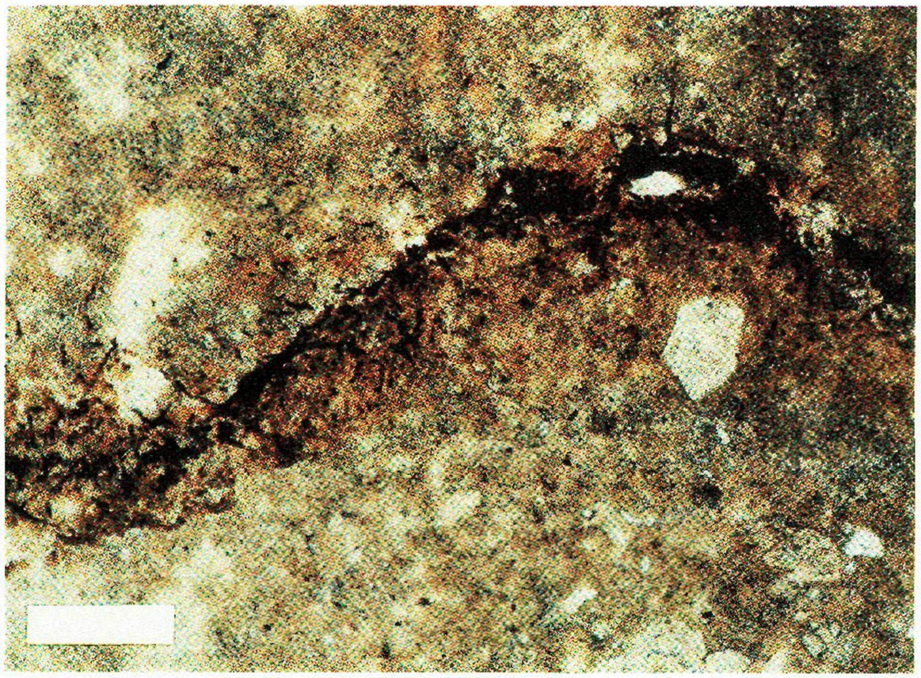

Figure 32—Fossilized lichen-colonized surface. Iron stained fungal hyphae of endolithic lichen overlain by dark iron-stained and organic-rich layer. Lichen-synthesized calcite prism shown on right both within and below organic-rich layer. Pleistocene caliche hardpan. Ibiza, Spain. Thin section, plane polarized light. Scale bar = 1.25 μm.

reworked, recemented, breccia-conglomeratic caliche hardpan. To complicate matters, the reworked recemented profile may be later subjected to a karst over-print.

Spatial and Time Relationships Between Karst and Caliche Facies

Processes operating in both karst and caliche diagenetic environments are not mutually exclusive. Different stages of karst and caliche evolution may co-exist at any one time and overlap in any one area (Fig. 9). In addition, with time the caliche facies may be subjected to karstification and renewed soil formation and, likewise, karstified surfaces may become calichified. Caliche and karst facies are dynamic systems involving complex processes controlled by many factors and including climatic variations, organic activity, and characteristics of the host substrate. Moreover, both facies influence their own evolution.

Some important differences between the karst and caliche facies do exist, however. One difference is that caliche is attributed to a specific climatic regimen (Goudie, 1973), namely a semiarid zone, whereas karst facies develop in all climates with water. In addition, while the caliche facies is restricted essentially to the surface and near-surface subaerial vadose environment, the karst facies is a three-dimensional unit which occurs both at the surface of the Earth and extends downward through the vadose and into the meteoric phreatic environment. The karst and caliche facies thus show differences in magnitude and hydrologic regimen. Nevertheless, as will be seen later, some caliche products are similar to those which form in the upper vadose zone of the karst facies. The subaerial vadose zone is the location where lithosphere, atmosphere and biosphere interact in a complex manner to produce features common to both karst and caliche facies.

Subaerial Exposure Surfaces in the Geologic Record

Subaerial exposure surfaces from Silurian-Devonian times onward are well documented (see Bibliography). Earlier occurrences are scanty (Geldsetzer, 1976) and present more problems of interpretation. The weathering processes inferred above are heavily dependent on the presence and evolution of higher plants, mainly because of the production of biogenic CO_2 which increases the aggressiveness of meteoric waters. Before the Silurian, ? caliche and ? karst processes would necessarily be governed by CO_2 obtained from lichens, algae, fungi and, possibly, from higher concentrations of atmospheric CO_2. We suspect that karst and caliche facies before the Silurian, without higher plant influence, had different features than the ones described in this paper. However, available references are not detailed enough for conclusive results in this respect.

It is well known that some intervals or episodes of the geologic record contain, simultaneously world-wide, abundant mineral deposits of lead-zinc and bauxites in karst terrains (Bernard, 1976; Geldsetzer, 1976; Padalino et al, 1976; Valeton, 1972 for general references). The references to possible fossil caliches (see Bibliography) also occur at times of mineralized karst; the same appears to be true for oil reservoirs in karst caverns. Some of these periods of generalized subaerial exposure have been frequently reported in the literature, either because of their economic importance or because of their intensive and widespread development, or both. As shown in Figure 10, these intervals of more pronounced or more studied subaerial exposure follow (by 10 to 15 m.y.) major stages or milestones in plant domination. This apparent coin-

Figure 33—Karst sediment fill. View looking downward onto upper surface (parallel to bedding). Reddish brown terra-rossa fill between coral heads of Pleistocene limestone, Florida.

cidence can be explained in two interrelated ways: (1) major episodes of generalized subaerial exposure may favor mass extinction of established terrestrial plants and expansion of new types, and (2) onset of domination stages of terrestrial plants may be reflected in the type and intensity of subaerial exposure facies. During extended periods of subaerial exposure, land colonized by expanding new types of plants could produce most intense diagenetic modifications in the host rocks, resulting in easily recognizable subaerial exposure facies and in most intense accumulation of mineral deposits.

As should be expected, major subaerial exposure facies occur during the global cycles of sea level fall (Fig. 10) established by Vail and others (1977). Global cycles of relative sea level oscillation are thought to be controlled by tectonic plate dynamics (Sloss, 1979; Vail et al, 1977). In this context, links between plate tectonics, global relative sea level oscillations, generalized subaerial exposure, plant evolution and the cycle of CO_2 deserve much more attention than can be given here. However, it is also important to remember that minor subaerial exposure surfaces will be produced independently of global episodes in parts of specific sediment packages subject to shallowing and shoaling upward sedimentation (sand shoals, reefs, deltas, tidal flats). These local subaerial exposures may or may not be sites for development of economically significant mineral deposits but, either way, they will still be of interest for deciphering regional geology.

The effects of Pleistocene sea level fluctuations in the Caribbean are recorded by relic yet distinctive morphological features in the present day landscape. Emergent shorelines, terraces and reef tracts are common around the perimeter of many Caribbean islands. On Barbados, where gradual but continued tectonic uplift has combined with the effects of glacio-eustatic sea level changes, a sequential record of emergent coral reef terraces has been produced. On the coastal plains of Belize and parts of Florida, dolinas and cenotes pepper the landscape and testify to a Pleistocene or earlier period of karsting. In the reef tract of Belize, drowned cenotes (blue holes) have been found with their floors 120 m (400 ft) below present sea level. Such observations record evidence of karsting during a glacial, low sea level stand followed by a rise during an interglacial. Karsting during interglacial stages of the Pleistocene has significantly increased macroporosity of exposed carbonate terrains in the Caribbean. Similar effects, with economic benefit, are seen further back in the geologic record, for example the Cretaceous El Abra of Mexico.

RECOGNITION OF SUBAERIAL EXPOSURE

General Procedure

The identification of subaerial exposure surfaces in the geologic record should be based on the following considerations: (1) understanding of the regional geology, including stratigraphy, structure and tectonic evolution, sea level oscillations, location of the regional and local paleotopographic highs, depositional facies and paleoenvironments, (2) detailed study of rock sequences, especially below marked discontinuity surfaces and within or at the base of continental deposits (e.g., alluvial fan, lake, swamp, glacial till, plant tufa); our aim will be eventual identification of a sequence assignable to a karst or a soil profile (Fig. 11), and (3) study of rock types, both in the field and in the laboratory, to identify characteristic macro- and microfeatures (Table 2). Any conclusion should be supported with the interpretation of

Figure 34—Karst breccia. Clasts of brecciated and corroded white limestone embedded in red terra-rossa sediment. Note laminar rind on clasts. Tubular voids are root molds. Pleistocene, Florida.

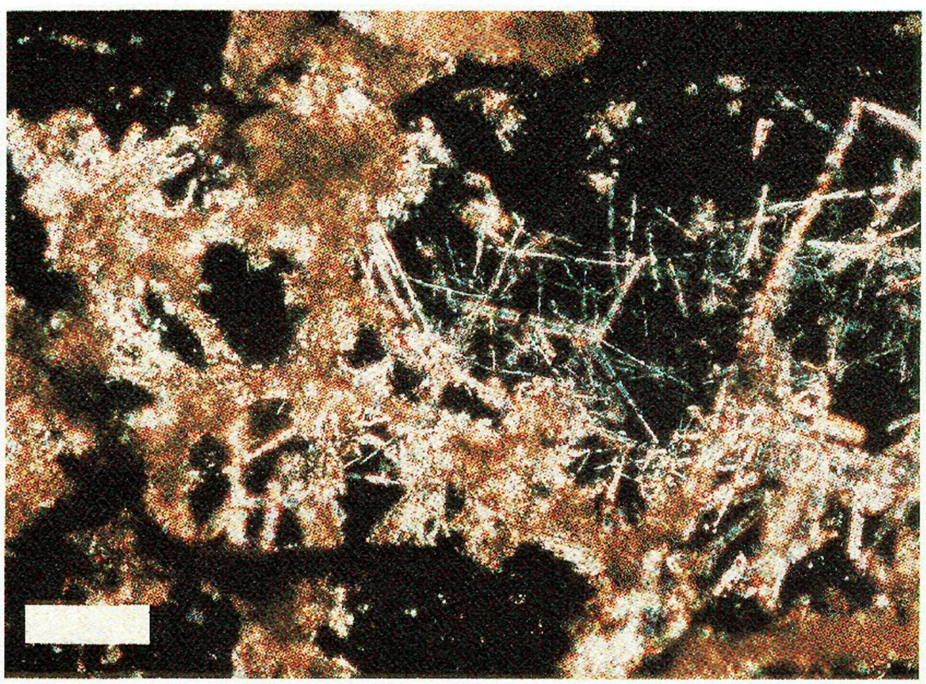

Figure 35—Moon-milk. Located in an open joint of the upper vadose zone of karst profile. Random needle fibers of low magnesian calcite (right) are progressively neomorphosed into microsparite mottles. Some of these mottles also contain relics of corroded carbonate host, Garraf Mountains, Barcelona, Spain. Photograph courtesy of L. Pomar. Thin section, XN. Scale bar = 0.1 mm.

lithologic sequences by integrating diagnostic and non-diagnostic but commonly present features of subaerial exposure facies (as in the examples of Figs. 11, 18, 48, 52). Of these three procedure stages, we will concentrate on the last, namely the study of the rock types, but without denying equal importance of the other two.

Different levels of security in the recognition of evidence of subaerial exposure can be established from relatively diagnostic features to commonly present but not indicative ones. Features listed below, taken in isolation, occur in distinctive but completely unrelated sedimentary and diagenetic environments. But, as stated so succinctly by Bathurst (1975, p. 417), ". . .safety is in numbers and a satisfactory decision can be reached if several criteria are combined." At the same time, it should always be remembered that many subaerial exposure surfaces may not contain characteristic features; but absence of these features does not necessarily mean that the deposit is not a subaerial exposure facies.