Palaeosols

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Introduction

Palaeosols are ancient soils, formed on landscapes of the past. Most palaeosols have been buried in the sedimentary record, covered by flood debris, landslides, volcanic ash, or lava (**Figure 1**). Some palaeosols, however, are still at the land surface but are no longer forming in the same way that they did under different climates and vegetation in the past. Climate and vegetation change on a variety of time-scales, and the term relict palaeosol for profiles still at the surface should be used only for such distinct soil materials as laterites among non-lateritic suites of soils (**Figure 2**). Thus, not all palaeosols are fossil soils or buried soils.

An alternative spelling of paleosol has been adopted by the International Quaternary Association. Other terms such as pedoderm and geosol refer to whole landscapes of buried soils. These soil stratigraphical units are named and mapped in order to establish stratigraphical levels. The terms pedotype and soil facies are more or less equivalent and are used to refer to individual palaeosol types preserved within ancient buried landscapes. These terms are used to distinguish one type of palaeosol from another in environmental interpretations of palaeosols. Pedolith, or soil sediment, describes a sediment, as indicated by bedding and other sedimentary features, with distinctive soil clasts, such as ferruginous concretions. Pedoliths are uncommon in sedimentary sequences, because soils are readily eroded to their constituent mineral grains, which retain few distinctive soil microfabrics.

Recognition of Palaeosols

Palaeosols buried in sedimentary and volcaniclastic sequences can be difficult to distinguish from enclosing sediments, tuffs, or lavas and were not widely recognized before about 20 years ago. Three features of palaeosols in particular aid their identification: root traces, soil horizons, and soil structure.

Soil is often defined as the medium of plant growth. Geological and engineering definitions of soil are broader, but fossilized roots and traces of their former paths through the soil are universally accepted as diagnostic of palaeosols. Not all palaeosol root traces are permineralized or compressed original organic matter: some are tortuous infillings of clay with discoloured haloes or mineralized alteration (**Figure 3**). Both fossilized roots and root traces show the downward tapering and branching of roots. Soils also contain fossil burrows, but these are usually more sparsely branched and parallel-sided than root traces. The distinction between burrows and roots can be blurred in cases where soil animals feed on roots and where roots find an easier passage through the soft fill of burrows. For very old rocks, predating the Early Devonian evolution of roots, the criterion of root traces is of no use in identifying palaeosols.

Figure 1 The subtle colour banding in these cliffs is the result of a sequence of 87 Eocene and Oligocene palaeosols in 143 m of nonmarine silty claystones exposed in the Pinnacles area of Badlands National Park, South Dakota, USA.

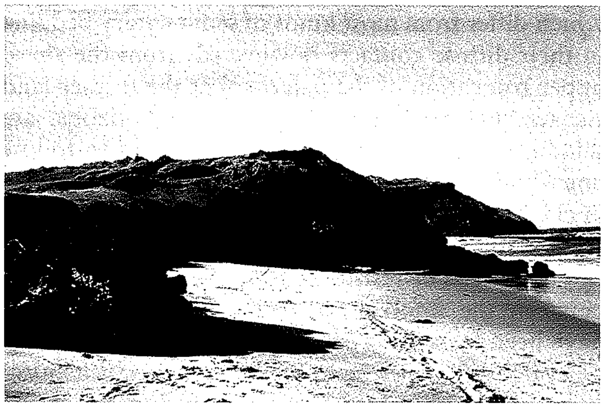

Figure 2 The red rock exposures to the left on the beach are a lateritic palaeosol of Middle Miocene age. Even though these horizons are at the surface, they are considered to be palaeosols because soil horizons of this type are not currently forming in this area. The red rock in the background is a sequence of Early Triassic palaeosols in Bald Hill Claystone, near Long Reef, New South Wales, Australia.

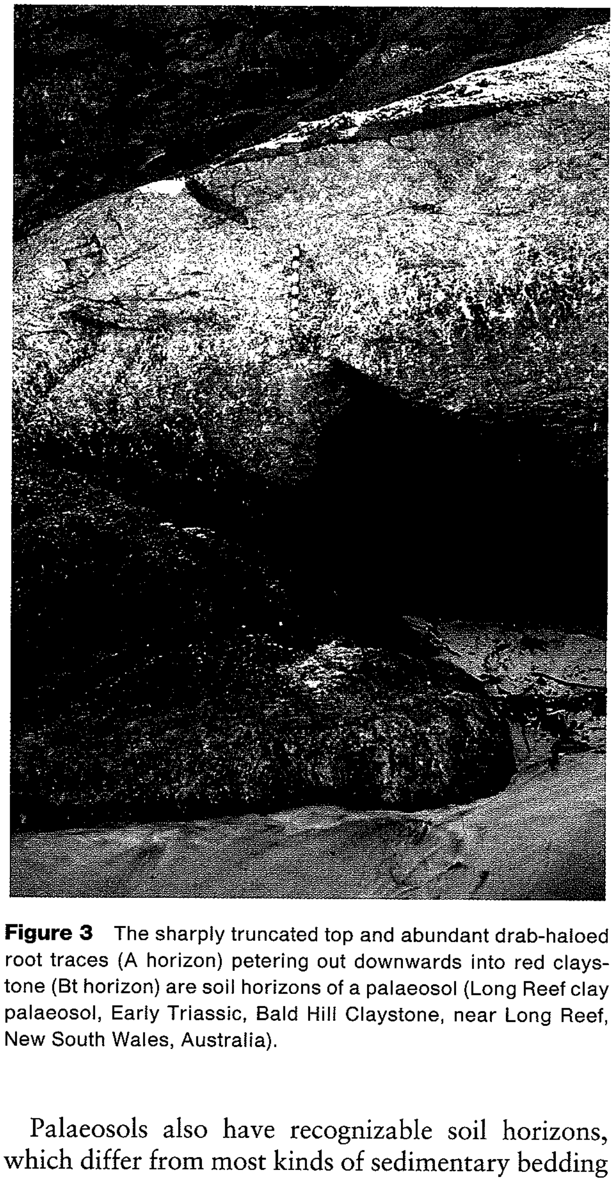

Figure 3 The sharply truncated top and abundant drab-haloed root traces (A horizon) petering out downwards into red claystone (Bt horizon) are soil horizons of a palaeosol (Long Reef clay palaeosol, Early Triassic, Bald Hill Claystone, near Long Reef, New South Wales, Australia).

Palaeosols also have recognizable soil horizons, which differ from most kinds of sedimentary bedding in their diffuse contacts downwards from the sharp upper truncation of the palaeosol at the former land surface. Palaeosol horizons, like soil horizons, are seldom more than a metre thick and tend to follow one of a few set patterns. Subsurface layers enriched in clay are called Bt horizons in the shorthand of soil science (**Figure 3**). Unlike a soil, in which clayeyness can be gauged by resistance to the shovel or plasticity between the fingers, clayeyness in palaeosols that have been turned to rock by burial compaction must be evaluated by petrographic, X-ray, or geochemical techniques. Subsurface layers enriched in pedogenic micrite are called Bk horizons in the shorthand of soil science and are generally composed of hard calcareous nodules or benches in both soils and lithified palaeosols (**Figure 4**).

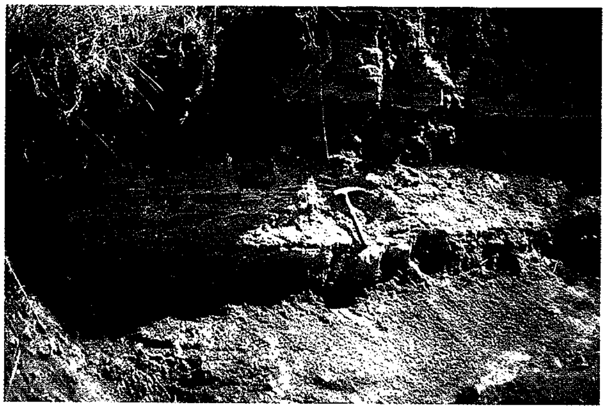

Figure 4 Two successive palaeosols overlain sharply by volcanic grits show crumb-structured organic surfaces (A horizon) over calcareous-nodule-studded subsurfaces (Bk horizon). In the upper right corner is a comparable modern soil (Middle Miocene fossil quarry near Fort Ternan, Kenya).

A final distinctive feature of palaeosols is soil structure, which varies in its degree of expression and replaces sedimentary structures such as bedding planes and ripple marks, metamorphic structures such as schistosity and porphyoblasts, and igneous structures such as crystal outlines and columnar jointing. Because they lack such familiar geological structures, palaeosols are commonly described as featureless, massive, hackly, or jointed. Palaeosols, like soils, have distinctive systems of cracks and clods. The technical term for a natural soil clod is a ped, which can be crumb, granular, blocky, or columnar, among other shapes. Peds are bounded by open cracks in a soil and by surfaces that are modified by plastering over with clay, by rusting, or by other alterations. These irregular altered surfaces are called cutans, and they are vital in recognizing soil peds in palaeosols that have been lithified so that the original cracks are crushed. The rounded 3–4 mm ellipsoidal crumb peds of grassland soils and palaeosols (**Figure 4**) are quite distinct from the angular blocky peds of forest palaeosols (**Figure 3**). Common cutans in soils and palaeosols include rusty alteration rinds (ferrans) and laminated coatings of washed-in clay (argillans). Cutans and other features of lithified palaeosols are best studied in petrographic thin sections and by electron microprobing and scanning electron microscopy. Some petrographic fabrics, such as the streaky birefringence of soil clays when viewed under crossed Nicols or sepic plasmic fabric, are diagnostic of soils and palaeosols.

Alteration of Soils after Burial

Palaeosols are seldom exactly like soils because of alteration after burial or exposure to additional weathering, and this can compromise their interpretation and identification with modern soils. Palaeosols, like sediments, can be altered by a wide array of burial processes: cementation with carbonate, haematite, or silica; compaction due to pressure or overburden; thermal maturation of organic matter; and metamorphic recrystallization and partial melting. These high-pressure and high-temperature alterations of palaeosols are not as difficult to disentangle from processes of original soil formation as are three common early modifications: burial decomposition, burial reddening, and burial gleization.

Some soils are buried rapidly by chemically reducing swamps or thick lava flows, preserving most of their organic matter. In contrast, many palaeosols are covered thinly by floodborne silt or colluvium, and their buried organic matter is then decomposed by aerobic bacteria and fungi deep within the newly forming soil of the palaeosol sequence. For this reason many palaeosols have much less organic carbon (fractions of a weight per cent) than comparable modern soils (usually 5–10% by weight of carbon at the surface). Thus palaeosol A horizons are seldom as dark as soil surface horizons, and must be inferred from the abundance of roots rather than from colour and carbon content.

Soils vary considerably in their degree of redness, but most palaeosols are red to reddish brown from haematite (iron oxide) or occasionally yellowish brown from goethite (iron hydroxide). Soils become redder from the poles to the tropics, from moderately drained to well drained sites, and with increasing time for development, as iron hydroxides are dehydrated to oxides. The dehydration of iron hydroxides continues with the burial of soils, so that red palaeosols are not necessarily tropical, unusually well drained, or especially well developed.

In river-valley and coastal sedimentary sequences with abundant palaeosols, formerly well-drained soils can find themselves subsiding below the water table with root traces and humus largely intact. Burial gleization is a process in which organic matter is used by microbes as a fuel for the chemical reduction of yellow and red iron oxides and hydroxides. Comparable processes of biologically induced chemical reduction are common in swamp soils, but superimposition of this process on the organic parts of formerly well-drained soils produces striking effects in some palaeosols. The whole A horizon is turned grey, with grey haloes extending outwards from individual roots, which diminish in abundance down the profile (**Figure** 3). Burial gleization is especially suspected when the lower parts of the profile are highly oxidized and have deeply penetrating roots, as in well-drained soils, and when there is no pronounced clayey layer that would perch a water table within the soil.

The combined effect of burial decomposition, dehydration, and gleization can completely change the appearance of a soil. The gaudy grey-green Triassic palaeosol shown in **Figure** 3, for example, was probably modified by all three processes from an originally dark brown over reddish brown forest soil.

Palaeosols and Palaeoclimate

Many palaeosols and soils bear clear marks of the climatic regime in which they formed. The Berkeley soil scientist Hans Jenny quantified the role of climate in soil formation by proposing a space-for-climate strategy. What was needed was a carefully selected group of soils, or climosequence, that varied in climate of formation but were comparable in vegetation, parent material, topographical setting and time for formation. He noted that mean annual rainfall and the depth in the profile to calcareous nodules decline from St Louis west to Colorado Springs, in the mid-western USA, but that temperatures and seasonality at these locations are comparable. Also common to all these soils is grassy vegetation on postglacial loess that is about 14 000–12 000 years old. From these soils he derived a climofunction or mathematical relationship between climate and soil features. A 1994 compilation of comparable data showed a clear relationship between the depth from the surface of the soil of carbonate nodules (D in cm) and the mean annual precipitation (P in mm) according to the formula:

$$P = 139.6 + 6.388D - 1.01303D^2$$

Such climofunctions can be used to interpret palaeoclimate from the depth within palaeosols of calcareous nodules (**Figure 4**), once allowance is made for reduction in depth due to burial compaction.

Climatic inferences also can be made from ice deformation features, concretions, clay mineral compositions, bioturbation, and chemical analyses of palaeosols. The thick clayey palaeosol shown in **Figure** 5 is riddled with large root traces of the kind found under forests and is very severely depleted in elemental plant nutrients such as calcium, magnesium, sodium, and potassium. Comparable modern soils are found at mid-latitudes, yet this palaeosol formed during the Triassic at a palaeolatitude of about 70° S. This palaeoclimatic anomaly indicates pronounced global warming, in this case a postapocalyptic greenhouse effect following the largest mass extinction in the history of life at the Permian-Triassic boundary.

Palaeosols and Ancient Ecosystems

Just as soils bear the imprint of the vegetation and other organisms they support, so many aspects of ancient ecosystems can be interpreted from palaeosols. The palaeosols shown in **Figure 4**, for example, have a dark crumb-textured surface horizon with abundant fine (1–2 mm) roots, comparable to the modern grassland soil seen forming on the outcrop to the upper left. Forest soils, in contrast (**Figure 3**), have large woody root traces, a blocky structure, and thick subsurface clayey horizons (Bt).

In some cases root traces in palaeosols are identifiable, although the species *Stigmaria ficoides* (**Figure 6**) is a form genus for roots of a variety of extinct tree lycopsids and not a precisely identified ancient plant. The tabular form of the roots of *Stigmaria* indicates a poorly drained soil, because roots do not photosynthesize, but rather respire using oxygen from soil air. Tabular, rather than deeply reaching, root traces (**Figure 3**) are characteristic of swamp palaeosols.

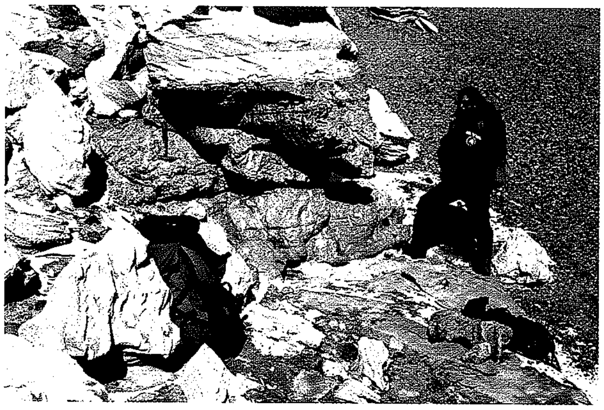

Figure 5 An unusually warm palaeoclimate is indicated by this palaeosol, which is unusually thick, clayey, and deeply weathered for its palaeolatitude of 70°S and is comparable to soils now forming no further south than 48°S (Early Triassic Feather Conglomerate, Allan Hills, Victoria Land, Antarctica).

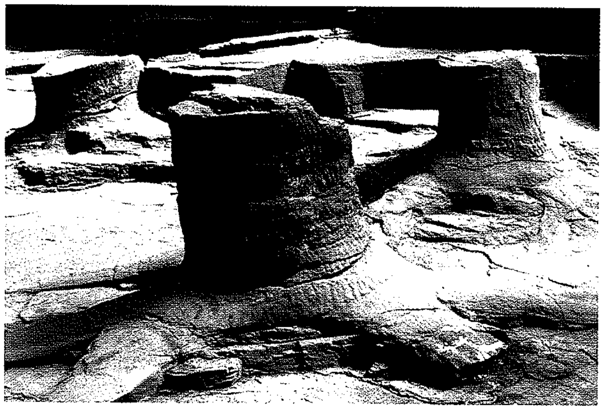

Figure 6 Swamp forests of tree lycopsids (*Stigmaria ficoides*) grew in waterlogged soils, in which lack of oxygen forced the roots to form planar mats rather than reaching deeply into the soil (Carboniferous Lower Limestone Coal Group, Victoria Park, Glasgow, Scotland).

Some palaeosols also contain fossil leaves, fruits, wood, stones, bones, and teeth. These are direct evidence of soil ecosystems. Unlike fossils in deposits of lakes and shallow seas, fossil assemblages in palaeosols have the advantage of being near the place where the organisms lived. However, the preservation of fossils in palaeosols is seldom as ideal as complete skeletons in river-channel deposits or compressed leaves in carbonaceous shales. The carbon and carbonate contents of palaeosols can be used to evaluate the Eh and pH, respectively, of the palaeosol preservational environments of the fossils.

Palaeosols and Palaeogeography

Just as soils vary from mountain tops to coastal swamps, so do palaeosols give clues to their ancient topographical setting. Many palaeosols within sedimentary sequences show clear relationships with deposits of palaeochannels and levees, so that their depositional subenvironment can be inferred from context. Water tables are close to the ground surface in many sedimentary environments, and palaeosols yield important information on their position relative to ancient water tables. Palaeosols formed below the water table include peats and are grey with chemically reduced minerals such as pyrite and siderite. Burrows of crayfish and other aquatic organisms are locally common in waterlogged soils, but burrows of most rodents and beetles are not. Root traces also do not penetrate deeply into waterlogged soils or palaeosols (**Figure 6**). Deeply penetrating roots and burrows and red oxidized minerals of iron or aluminium are common in formerly well-drained palaeosols (**Figure 3**). Palaeosols may also reveal upland sedimentary environments such as alluvial and colluvial fans, glacial moraines, river terraces, and erosional gullies (**Figure 7**).

Major geological unconformities often mark erosional landscapes of the past. Rocky cliffs and bedrock platforms are found along geological unconformities, but so are upland palaeosols. For example, the hilly erosional landscape of Lewisian Gneiss in northern Scotland had 1 km of relief (**Figure 8**).

Palaeosols and their Parent Materials

The parent material of a soil or palaeosol is the substance from which it formed and can usually be inferred from the less-weathered lower parts of the profile. The parent material may be precisely known if the palaeosol is on metamorphic or igneous rocks (**Figure 8**), because pedogenic minerals are easily

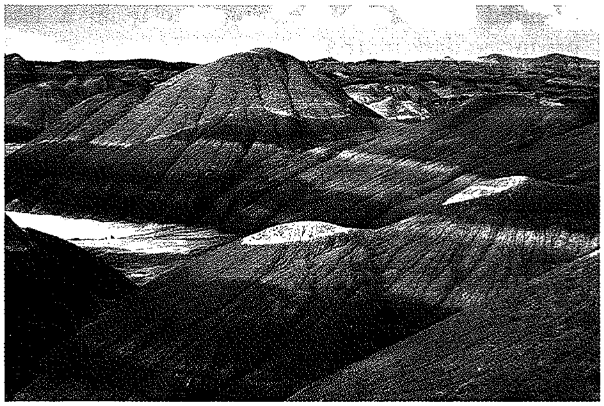

Figure 7 A palaeogully in a strongly developed sequence of palaeosols (dark coloured) is filled with alluvium including weakly developed palaeosols (Late Triassic Chinle Formation, Petrified Forest National Park, Arizona, USA). The hill in the foreground is 11 m high. Photograph courtesy of Mary Kraus.

Figure 8 The bleached pink palaeosol formed on gneiss to the right (Sheigra palaeosol) is thicker and more deeply weathered than the light green palaeosol formed on amphibolite to the left (Staca palaeosol). Both palaeosols are overlain by red quartz sandstones of the Torridonian Group (Late Precambrian, near Sheigra, Scotland).

distinquished from igneous and metamorphic minerals. Parent material is more difficult to find in palaeosols that are developed from sedimentary parent materials, especially if sedimentary facies reveal erosional relief (**Figure 7**). In such settings, the sediment is derived from pre-existing soils, whose degree of weathering can be quite varied. The kinds of soils of sediment and rock also can be very different. If soil were a commercial product, economy would dictate manufacturing it from materials that are already similar in chemical composition and physical characteristics. Soils form more readily from sediments than from rocks. Perhaps the most distinctive of parent materials is volcanic ash, because it may consist of more volcanic glass than minerals. Volcanic glass weathers to noncrystalline amorphous substances such as imogolite, which confer high fertility from loosely bound phosphorous, potassium, and other plant nutrients. Such soils also have low bulk density and good moisture-retaining properties. Such soils around tropical volcanoes support intensive agriculture, despite the hazards of the nearby active volcano, because they are so much more fertile than surrounding soils. Comparable palaeosols are commonly associated with volcanic arcs of the past (**Figure 1**).

Palaeosols and their Times for Formation

Soils develop their profiles over time, although some soils, such as peats, also accumulate layer-by-layer in the manner of sediments. Each palaeosol within a sedimentary or volcanic sequence represents a short break in sedimentary accumulation, or diastem, whose duration can be calculated from key features of the soil. The peats that become coal seams in the geological record, for example, cannot accumulate at rates of more than 1 mm year^{-1} because the roots will be suffocated by stagnant water. Nor can they accumulate at rates of less than 0.5 mm year^{-1} because aerobic decay will destroy the organic debris as fast as it accumulates. Thus, the durations of coal-bearing palaeosols can be calculated from coal thickness, once compaction is taken into account. Calcareous soils and palaeosols accumulate carbonate at first in wisps and filaments, and later in nodules, which become larger and larger (**Figure 4**). The size of the nodules thus gives us an idea of the time over which they formed. The development of clayey subsurface horizons is comparable (**Figure 3**) in that clay becomes more and more abundant over time. The amount of washed-in clay can thus be a guide to the time over which palaeosols formed.

From the times for palaeosol formation and the thickness of rock for successive palaeosols it is possible to calculate rates of sediment accumulation. In the badlands of South Dakota, for example, the clayey lower part of the section accumulated at a slower rate than the ashy and silty upper part of the section (**Figure 1**). Variations in the rate of sediment accumulation can be used to address a variety of tectonic, volcanic, and sequence stratigraphical problems using palaeosols.

Glossary

Argillan Clay skin, a kind of planar feature in a soil or cutan formed of clay.

Burial decomposition An early diagenetic modification of a palaeosol in which buried organic matter is decayed microbially.

Burial gleization An early diagenetic modification of a palaeosol in which buried organic matter fuels microbial chemical reduction of iron oxides and oxyhydraes to ferrous clays, siderite or pyrite.

Climofunction A mathematical relationship between a soil feature and a measure of climate.

Climosequence A set of soils formed under similar vegetation, topographic setting, parent material and time, but varied climate.

Concretion A seggregation of materials in a soil, harder or more cemented than the matrix, with prominent internal concentric banding, for example iron-manganese concretion.

Cutan A planar feature within a soil formed by enrichment, bleaching, coating or other alteration, for example a clay skin (argillan).

Ferran Ferruginized surface, a kind of planar feature in a soil (cutan) formed by chemical oxidation.

Geosol A mappable land surface of palaeosols, a soil stratigraphic unit in the North American Code of Stratigraphic Nomenclature.

Nodule A segregation of materials in a soil, harder or more cemented than the matrix, with massive internal fabric, for example caliche nodule.

Palaeosol A soil of a landscape of the past: a past surficial region of a planet or similar body altered in place by biological, chemical or physical processes, or a combination of these.

Ped A natural aggregate of soil: stable lumps or clods of soil between roots, burrows, cracks and other planes of weakness.

Pedoderm A mappable land surface of palaeosols, a soil stratigraphic unit in the Australian Code of Stratigraphic Nomenclature.

Pedolith Soil sediment: a seadimentary rock dominated by clasts with the internal microfabrics of soils.

Pedotype A kind of palaeosol: an ancient equivalent of soil series of the United States Soil Conservation Service.

Perched water table Level of water ponded in a soil by an impermeable subsurface layer.

Sepic plasmic fabric Birefringence microfabric: appearance of the fine grained part of a soil or palaeosol in petrographic thin sections viewed under crossed Nicols of wisps or streaks of highly oriented and highly birefringent clay in a less organized dark matrix.

See Also

Carbon Cycle. **Clay Minerals**. **Palaeoclimates**. **Sedimentary Environments:** Depositional Systems and Facies; Alluvial Fans, Alluvial Sediments and Settings. **Sedimentary Processes:** Karst and Palaeokarst. **Sedimentary Rocks:** Evaporites. **Soils:** Modern. **Weathering**.

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