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GEOSITES AND GEOSYSTEMS IN QUATERNARY AND DYNAMIC LANDSCAPES – CASE STUDIES FROM ACRATONIC SETTING AND THEIR WIDER SIGNIFICANCE

GEOSSÍTIOS E GEOSSISTEMAS EM PAISAGENS QUATERNÁRIAS E DINÂMICAS - ESTUDOS DE CASO DE UM CENÁRIO CRATÔNICO E SEU SIGNIFICADO MAIS AMPLO

GEOSITIOS Y GEOSISTEMAS EN PAISAJES CUATERNARIOS Y DINÁMICOS: ESTUDIOS DE CASO DE UN ENTORNO CRATÓNICO Y SU SIGNIFICADO MÁS AMPLIO

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ABSTRACT

The rapidly expanding literature on the related subjects of geodiversity, geosites and their place in understanding and conserving our geoheritage has produced several proposed protocols for defining and valuing key sites and landscapes. Distinctions between geosites as well-defined features of our geological heritage and geodiversity sites as landscapes or geomorphosites have been proposed, while many subdivisions of the criteria for geosite recognition are also recognised. This paper uses two areas in central Africa to illustrate the realities of many landscapes, termed geosystems in this study. Largely Quaternary and present-day dynamic geosystems are considered as essential components of geodiversity and equally aspects of our geoheritage. To understand these geosystems requires detailed fieldwork including their relationships to ecology, rural land use and sensitivity to environmental change.

Key words: geosites, geosystems, sensitivity.

RESUMO

A literatura em rápida expansão sobre os assuntos relacionados com geodiversidade, geossítios e seu lugar na compreensão e conservação de nosso geopatrimônio produziu vários protocolos propostos para definir e valorizar locais e paisagens importantes. Distinções entre geossítios como características bem definidas de nosso patrimônio geológico e locais de geodiversidade como paisagens ou geomorfosítios foram propostas, enquanto muitas subdivisões dos critérios para reconhecimento de geossítios também são reconhecidas. Este artigo usa duas áreas na África central para ilustrar as realidades de muitas paisagens, denominadas geossistemas neste estudo. Geossistemas quaternários e dinâmicos atuais são considerados como componentes essenciais da geodiversidade e igualmente como aspectos de nosso geopatrimônio. Para compreender esses geossistemas, é necessário um trabalho de campo detalhado, incluindo suas relações com a ecologia, uso do solo rural e sensibilidade às mudanças ambientais.

Palavras-chave: geossítios, geossistemas, sensibilidade.

RESUMEN

La literatura en rápida expansión sobre los temas relacionados de la geodiversidad, los geositios y su lugar en la comprensión y conservación de nuestro patrimonio geológico ha producido varios protocolos propuestos para definir y valorar sitios y paisajes clave. Se han propuesto distinciones entre geositios como características bien definidas de nuestro patrimonio geológico y sitios de geodiversidad como paisajes o geomorfositos, mientras que también se reconocen muchas subdivisiones de los criterios para el reconocimiento de geositios. Este artículo utiliza dos áreas de África central para ilustrar las realidades de muchos paisajes, denominados geosistemas en este estudio. En gran parte, los geosistemas dinámicos cuaternarios y actuales se consideran componentes esenciales de la geodiversidad e igualmente aspectos de nuestro patrimonio geológico. Comprender estos geosistemas requiere un trabajo de campo detallado que incluya sus relaciones con la ecología, el uso de la tierra rural y la sensibilidad al cambio ambiental.

Palabras clave: geositios, geosistemas, sensibilidad.

INTRODUCTION – FEATURES OF CRATONIC LANDSCAPES

The separated continental-scale fragments of former Gondwanaland contain both Archean cratons and accreted belts of Neo-Proterozoic, metamorphosed crystalline rocks. The concept of a ‘cratonic regime’ (Fairbridge and Finkl, 1980) neatly encapsulates the pattern of extensive plains upwarped as great faulted swells, notably in East Africa and along their passive margins, as in India and eastern Brazil. Inland the downwarping of the crust into vast intra-cratonic basins has occurred. The tectonic processes involved in the generation of this relief have also produced lavas and sediments, the latter often only slightly disturbed from their depositional context. Periods of erosion and deposition on a regional scale have alternated with stability and extensive weathering through time with periodicities of 10^6 – 10^8 y.

Superficial materials on ancient landsurfaces are usually termed the regolith, which maybe residual or deposited by any of the agencies of sediment transport. Residual materials constitute the weathering profile that has developed *in situ*, potentially over very long timescales and indicates landsurface stability. This should not be equated with inactivity since the profile evolves both chemically and physically without traction by water, wind, or ice. Sediments transported by these agencies often record episodes of instability and usually correlate with erosion in source locations at higher levels. However, transport by wind and by marine processes does not depend on gradient, and glaciers are able to override ground elevations.

Earth scientists in Australia have long recognised the existence of an extensive *weathered landsurface* (Mabbutt, 1965), and regolith studies have formed a significant part of the government CSIRO land resource inventory. A Regolith Glossary was published by CSIRO, LEME (Eggleton Ed, 2001), who also co- authored a major text on Regolith Geology and geomorphology (Taylor and Eggleton, 2001). This emphasis can be traced to the highly seasonal and semi-arid climates of Australia, which favour the immobilisation of minerals released by weathering processes within the weathering profile, often close to its surface where crusts of iron oxides (ferricrete)and calcium carbonate (calcrete) become exposed. Although such crusts offer protection to the underlying sands and clays of the decomposing rock, in their absence such materials readily succumb to surface erosion, by both slope failure and by fluvial transport. It has long been understood that discontinuities play an important role in slope sensitivity, and the narrow zone of initial rock weathering and disintegration is often the plane of slope failure. On ancient land-surfaces hillslope deposits below low cliffs of ferricrete often exhibit complex stratigraphies.

The regolith frequently obscures the solid geology and where it forms a thick blanket, as often in the humid tropics, may present serious problems for geological mapping. Most ancient landscapes have progressed through many latitudes as their underlying plates respond to plate tectonic movement. Superimposed on such trajectories are the impacts of environmental changes on variable but generally shorter timescales. (Thomas,1994; Tardy and Roquin, 1998; Peulvast and Claudino-Sales, 2005). They are often studied as records of episodic landscape instability, as a function of contemporary landscape dynamics, or a result of long-term evolution of landforms. Diagnostic weathering covers have also been mapped, for example in West Africa (Chardon et al., 2006). The ancient planation surfaces such as the African Surface have great complexity (Burke and Gunnell, 2008) and a variety of regional levels.

The prolonged evolution of the African landsurface has led to the formation complex regolith materials. Large scale warping and passive marginal uplift, associated with the break-up of Gondwanaland plus continued volcanism and faulting, have also energised the landscape to produce younger erosional forms. But the existence of big rivers, which evolved to drain the Gondwana continents (Potter, 1978; Ashworth and Lewin, 2012) is a striking feature of Africa and Brazil. Scarp retreat from passive margins, combined with deep incision of the drainage is also characteristic which applies to each fragmented part of Gondwanaland, even if the individual geographies at first appear strikingly different.

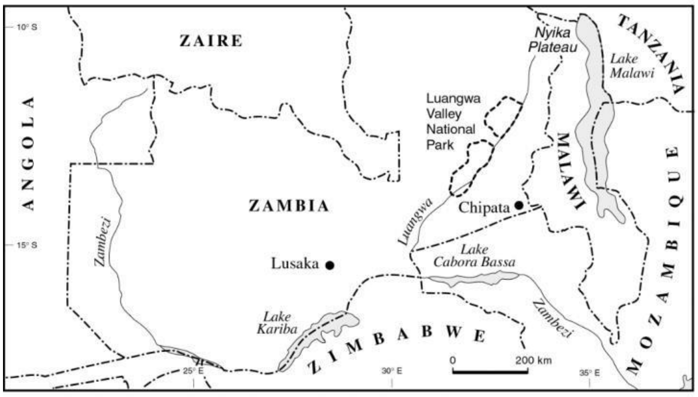
THE SURFICIAL GEOLOGY OF TROPICAL CRATONS AND THEIR GEOSITES

It follows that, despite the major constructional forms resulting from recent volcanic activity; the fault scarps of major rift systems, and the dramatic scenery of the passive marginal uplifts, many landscapes result from prolonged weathering and denudation (Rabassa, 2010; Migon, 2013), but also contain the impacts of Quaternary climate changes, and the actions of contemporary processes. It is these forms and deposits that justify more attention as part of an ever-changing geoheritage. Two geosystems in eastern Zambia are chosen to illustrate contrasting examples, which also pose general questions about timescales of formative eventsand the geoheritage of dynamic landscapes.

EASTERN ZAMBIA: A. QUATERNARY LANDFORMS ON THE METAMORPHIC NEO-PROTEROZOIC BASEMENT

In the centre of Africa, in an area around Chipata (Figure 1) a landscape developed on a typical suite of crystalline rocks belonging to the Southern Mesoproterozoic Irumide Belt, which is a deformed basement with metamorphosed supracrustal sediments according to De Waele, et al, (2006) and Fritz et al (2013). Itcontains granulite and amphibolite facies (Figure 2). To the NW of Chipata the Luangwa River follows a major shear zone south to its confluence with the Zambezi. This feature is also recognised as a Karoo age (Carboniferous-Triassic) monoclinal fault system, extending from the East African Rift System (EARS) (Banks et al. 1995).

Figure 1 - Location map of Zambia, indicating the town of Chipata and The Luangwa Valley National Parks.



The town of Chipata lies at 1137m and is part of the African Surface, with higher elevations rising to 1600m. The topography is subdued but punctuated by sinuous, linear ranges of hills with a relief of less than 500m. These coincide with quartzite bands in the metamorphic sequence and have steep flanking slopes, exceeding 30° in places, and underlain by weathered schists (Figure 3). An artificial cutting in the area displayed advanced weathering to depths exceeding 15m. A striking pattern of palaeo-landslides flanking the quartzite ridges could be of similar ages, and the slopes appear stable under current environmental conditions. Attempts to date a more alluvial lens in Chipata Quarry using Optical Stimulated Luminescence (OSL) protocol returned only one finite age >180 Ka, which cannot be accepted as reliable (Thomas, 1999; Thomas and Murray, 2001).

Figure 2 - Geology of the Chipata area showing the Long sinuous ridges of prominent quartzite hills 200-400m high.

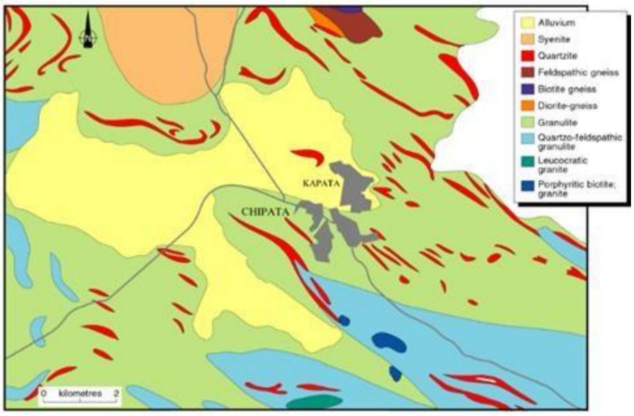


Figure 3 - Geomorphology of the Chipata area showing the landslides flanking Chipata Hill (1280m) and Kanjala Hill (1400m): illustrated by the hillslope profile in Figure 4, and photographs in Figure 5.

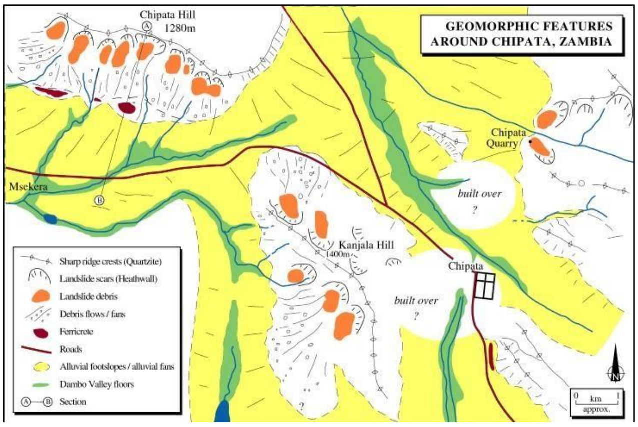


Figure 4 - Characteristic hillslope profile at Chipata Hill, Zambia. The granulite/quartzite bands support the ridges, which are flanked by weathered schists. Rotational slides have occurred along most local hillslopes >27^{0} giving rise to debris flows containing quartzite blocks, beyond which there are fans leading towards colluvium infilled valley floors of small, often channel-less streams known locally as *dambos*. Where the coarse fan deposits meet the fine colluvium iron oxide precipitation has led to the formation of ferricrete in this highly seasonal savanna environment.

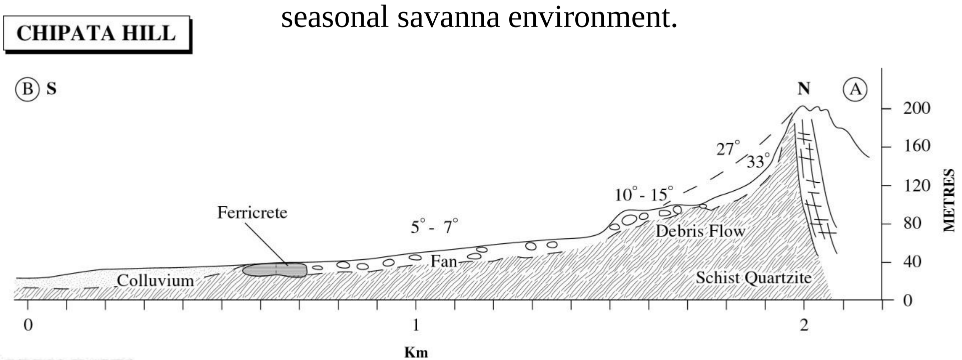


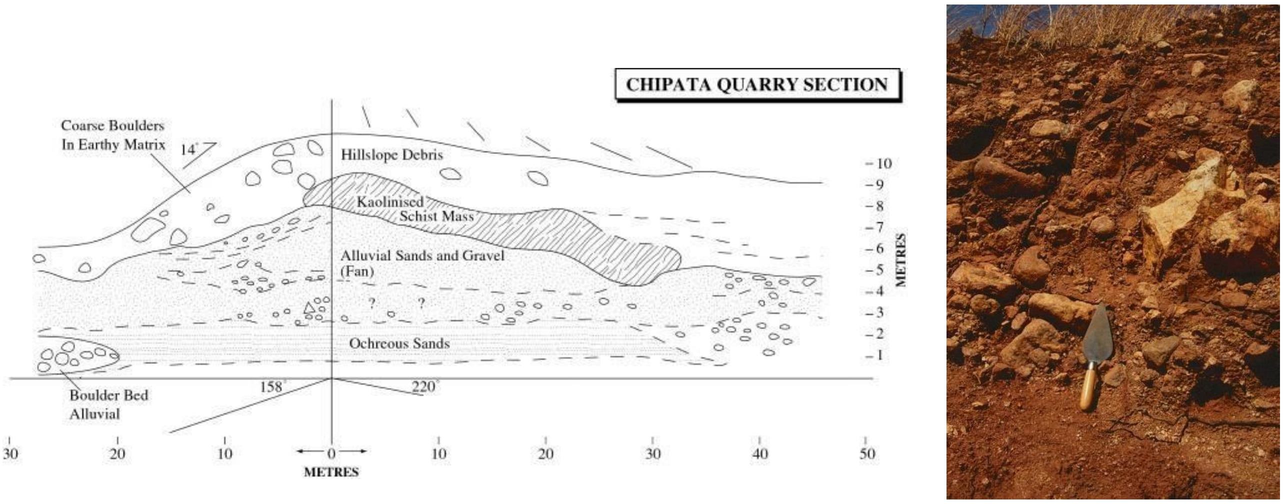
Figure 5 - Ramparts and benches (A) of coarse debris (B) mark the extent of debris flows carrying quartzite blocks from the summit to rest on lower slopes.

A

B

The section at Chipata Quarry (Figure 6A) demonstrates the complexity of some these deposits, with indications of more than one period of instability.

Figure 6 - The complex deposit at Chipata Quarry (A), and (B) a roadside exposure of clay-coated, angular debris that has spread across lower slopes.

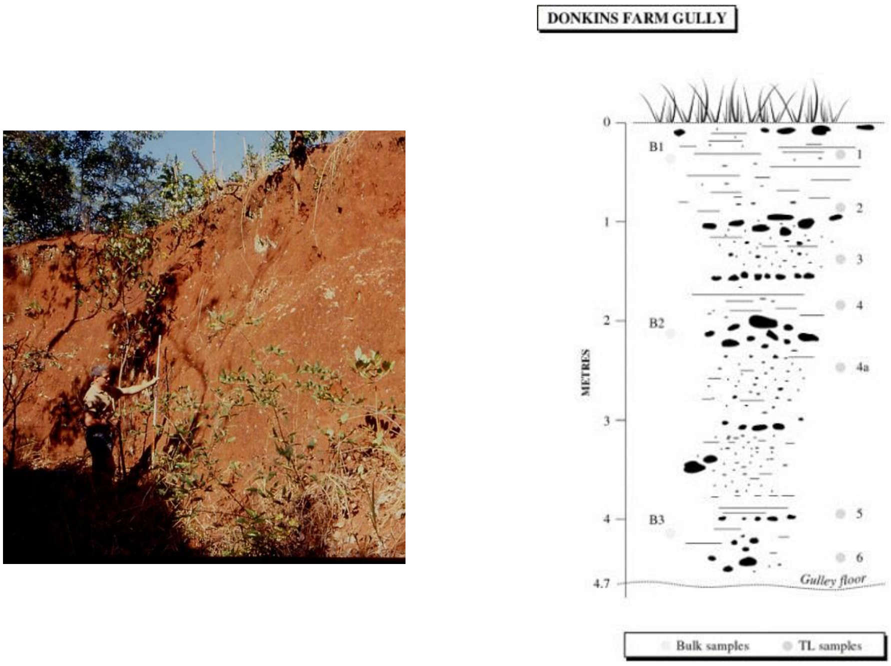


A

B

Most of the lower ground has a covering of colluvium, in places over 5m thick (Figure 7), and distinctive pebble gravels with sand content, marking fluvial deposition returned OSL ages of circa 70 Ka from the base to 9 ka (Holocene) and recent at the surface (Thomas and Murray, 2001).

Figure 7 - A. and B. Nearly 5m of colluvium exhibits periodic accumulation of fine pebble gravels.



A

B

A much younger colluvium has accumulated on lower slopes leading the to valley floor. This is unconsolidated and subject to sheet and gully erosion under field crops (mainly maize) (Figure 8), which has been replaced by more protective crops such as avocado pear by some commercial farmers. Figure 8B also illustrates the typical views of the Chipata are, and to a casual observer might appear a rather simple pattern of plains and hills. It is hoped that this study may help alert those studying such landscapes in other locations to the potential complications, resulting from past extreme events and environmental changes.

Figure 8 - Recent and current gullying across lower slopes due to unwise exposure to early rains during field cropping.

A

B

EASTERN ZAMBIA: B. FLUVIAL LANDFORMS OF THE LUANGWA VALLEY

The Luangwa River follows a shear zone, which is also a half-graben and occupies a wide valley several kmacross at 565m a.s.l at Mfuwe airport (nearly 600m below the plateau). The inner valley is flanked by dry terraces beyond the reach of floods, while the dynamic floodplain has shifted its position many times, creating classical meander scrolls and cut-offs (Figure 9).

Figure 9 - Meander patterns of the Luangwa River, where it crosses the South Luangwa National Park (Figure 1) Zambia. The riverregime is highly seasonal and subject to major floods in the wet season of this savanna (cerrado) landscape. Abandoned meanders, sediment splays and other features A are visible, and the river channel has altered B course many times (Gilvear et al, 2000). The area shown in Figure 9 is part of a famous wildlife reserve of the South Luangwa National Park. There are many safari camps and access tracks (some camps have had to relocate as the river shifted its channel). (A Google Earth Image, 2021. Notethe river stage and suspended load contrasts must reflect 2 different imaging times).

On mainly ‘dry’ terrace levels Mopane woodland savanna supports herds of ungulates (A), and some ox- bow lakes persist (B); occasional floodways accumulate silt and clay which contain nutrients (‘salt licks’) important for antelope and smaller mammals (C). Sandy levees are marked by termite mounds which are nutrient rich, and cut-off lakes can contain water much of the year. Bordering areas with high water-tables can sustain rich plant and birdlife (D). Erosion on the open terraces is a constant problem, particulalry where large mammals come to the river bank to drink. Gullies are often triggered by collapse of sub-soil pipes under the weight of large animals and most work their way headwards from channel bank breaches, caused by animal herds (hippopotamus are particularly responsible for eroding the banks, making frquent journeys to and fro) (Figure 11, E, F).

Figure 10 indicates the range of landforms and habitats found in this section of the river.

Figure 10 - Component features of the Luangwa River vallay landscape in the South Luangwa National Park .

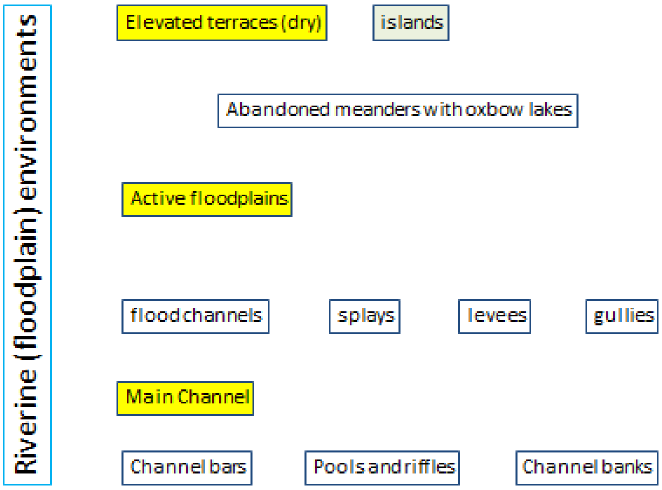
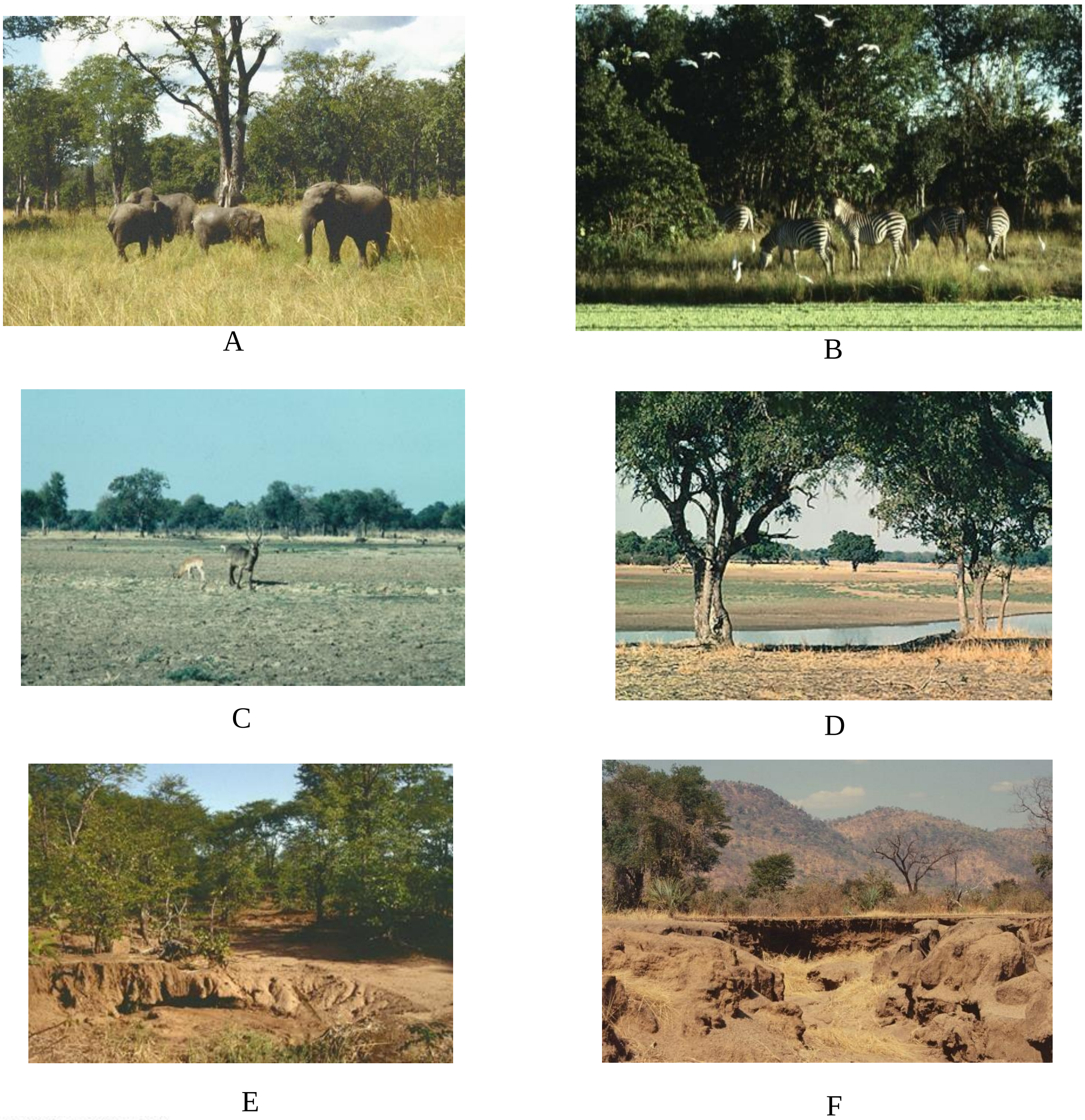


Figure 11 - In the diagram (Figure 10) the components of the geosystem are shown. Each is in reality a separate **geosite** (or geomorphosite): A-D, plus E/F representing the erosion gullies on the dry terraces.



DISCUSSION

The examples of descriptive geomorphology discussed offer two series of linked *geosites* comprising contrasting *geosystems*, and they illustrate the methodological comments about the importance of scale in the study of geosites and geosystems by Santos et al, (2019; 2020). The examples are selected for two reasons: they have been studied in the field, and they illustrate the importance of palaeoenvironments and active processes in the study of geosystems as part of the geoheritage. As stated in the introduction, various forms of regolith form the surface and near surface materials of many landscapes. In tropical areas, as in Zambia, much of the regolith is a weathering profile or saprolite, but a variety of transported materials are found as a surface layer (Thomas, 1994).

The influence of bedrock geology remains dominant in defining the Chipata landscape, and surface processes are shown to have been more active in the past. By contrast the Luangwa River, although it occupies a geologically defined corridor, actively modifies its imprint on the riverine landscape: seasonally, annually, and over longer time periods. Geosites in riverine landscapes are often of recent or late Quaternary origin, and are essentially temporary, often within the few decades we have of recorded change. This has profound implications for human settlement and affects the possibilities of finding and dating archaeological sites from Palaeolithic (Mode 1) societies and their successors. Barham et al. (2011) have analysed and reported these issues from a site in the Luangwa Valley.

This raises the related question: can ephemeral forms and deposits be considered as part of the geoheritage? An answer to this question comes back to the issue of scale, because although many individual geosites may be subject to frequent change, even elimination, they become rearranged or re- formed within the wider, more durable geosystem. This implies that the dynamic geosystem will exhibit the same categories of geosites and habitats over longer time periods but still be subject to changing patterns. The magnitude, frequency and impact of extreme events is very important in this context, and as climate changes such events may trigger larger-scale transformations of dynamic geosystems, especially in riverine, deltaic, and coastal sedimentary environments (Thomas, 2004, 2008).

It is also the case that although most geosystems occupy defined spatial areas, the hydrological systems, which propel change often fluctuate in areal extent, expanding during wet seasons or individual storms, and contracting during dry seasons and droughts. This means that setting the boundaries for dynamic geosystems must include areas visited only infrequently by high floods.

Hillslope geosystems, as illustrated from Chipata, often lack direct connection to active river channels. In this case they can only respond to meteorological events, earthquake shocks or land use pressures. In the Chipata geosystem no reorganisation of component geosites has occurred on the hillslopes since the generation of the slope failures probably over 200 ky ago. At that time re-modelling an entire geosystem took place, with the near simultaneous occurrence of landslides and debris flows. These created a range of new geosites that have survived many subsequent climatic fluctuations over $10^3 – 10^5$ y.

By focussing on geosystems rather than geosites in these, soft sediment and regolith landscapes much more can be understood regarding their relationships to animal habitats and ecological potential to supply services to local communities. It has been argued that geosites belong more to the consolidated rocks of the geological record, while geosystems define geomorphological landscapes. However, this argument does not hold when faced with many examples. For example, the Grand Canyon (USA) can only be described at scales capable of encompassing its length and depth; stratigraphy and lithologies.

The approach taken in this paper is clearly different from the widespread use of quantitative indices and subsequent valorisation of geosites for potential users. Also, it does not include geosites featuring hard- rock geology and paleontology, which are clearly vital to record and illustrate earth history and evolution. Many geomorphologists would prefer the term geomorphosite for what are essentially landscape features, but geomorphosites are but one of many sub-types of geosite. Fassoulas et al. (2012) have revived the term 'geotope' for their study of Crete. This emphasises links with biologically defined 'ecotopes', and this accords with the view expressed here that field-based mapping at scales relevant to ecologists is important. The link then must be made to quantitative description using GIS and rankings in terms of importance to geoheritage or to the provision of ecological services, or for tourism. Not all these applications can be served by a single scale of enquiry or unique methodology (Thomas, 2016).

This paper does not offer a review of the rapidly expanding literature on geodiversity and geoconservation, but some reports appear important in the current context. Bruno et al. (2014) addressed the need to understand and classify 'paleogeography as geoheritage'. Betard and Peulvast (2019) have recently applied the concept of geodiversity 'hotspots', a term used in conservation biology, to the identification of the most important or sensitive geosites and offered some ways to quantify such assessments, while Brilha (2016) has addressed the question of inventory and assessment of geosites and geodiversity sites, using a practical separation of the two concepts. The question of scale is discussed by Santos et al. (2019, 2020), while Araujo, and Pereira (2018) and do Nascimento (2021) have addressed some of the methodological issues for an area in NE Brazil. It should also be noted that the Geological Service of Brazil completed their classification and description of 12 categories of geosite in 2012 (Schobbenhaus S., Winge, M., 2012) and have subsequently adopted methodology advanced by Brilha (2016), (Schobbenhaus and Berbert-Born, 2021) for assessing geosites of international value; separately considering geomorphosites for tourism and education.

On the question of applications of information acquired about geosites, some difficult questions about sensitivity to change are less well understood. Phillips (2019) advocates a systems/network approach, emphasising the interconnectedness of geosites and the problems of predicting the impacts of extreme events, climate change, and land use pressures. The analysis of two areas from Zambia certainly points toward education and tourism, but there are also a range of ecosystem services and have direct relevance to soil and land-use management, including areas that might be re-forested for example. The sensitivities to change of different substrates and landforms discussed here have broad relevance, but we are still a long way from being able to predict accurately when and where most environmental hazards and disasterswill strike.

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