Some Concepts on Gondwana Landscapes: Long-Term Landscape Evolution, Genesis, Distribution and Age

Jorge Rabassa

"Let the landscape teach me."
Lester C. King, personal letter to Charles Higgins, 1958

"While the geologist may often be in error, the Earth is never wrong."
Lester C. King, 1967

Abstract The concept of "Gondwana Landscape" was defined by Fairbridge (The encyclopedia of geomorphology. Reinhold Book Corporation, New York, p. 483, 1968) as an "ancestral landscape" composed of "series of once-planed remnants" that "record traces of older planation" episodes during the "late Mesozoic (locally Jurassic or Cretaceous)". This has been called the "Gondwana cyclic land surface" in the continents of the southern hemisphere, occurring extensively in Australia, Southern Africa and the cratonic areas of South America. Remnants of these surfaces are found also in India, and it is assumed they have been preserved in Eastern Antarctica, underneath the Antarctic ice sheet which covers that region with an average thickness of 3,000 m. These paleolandscapes were generated when the former Gondwana supercontinent was still in place and similar tectonic conditions in its drifted fragments have allowed their preservation. In Pangaea, remnants of equivalent surfaces, though of very fragmentary condition, have been described in Europe and the United States, south of the Pleistocene glaciation boundary.

These Gondwana planation surfaces are characteristic of cratonic regions, which have survived in the landscape without being covered by marine sediments along extremely long periods, having been exposed to long-term subaerial weathering and

J. Rabassa (✉)
Laboratorio de Geomorfología y Cuaternario, CADIC-CONICET, Ushuaia, Tierra del Fuego, Argentina

Universidad Nacional de Tierra del Fuego, Ushuaia, Tierra del Fuego, Argentina
e-mail: jrabassa@gmail.com

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denudation. Their genesis is related to extremely humid and warm paleoclimates of “hyper-tropical” nature, with permanently water saturated soils, or perhaps extreme climates, with seasonal and long-term cyclic fluctuations, from extremely wet to extremely dry. Deep chemical weathering is the dominant geomorphological process, with the development of enormously deep weathering profiles, perhaps of up to many hundreds of metres deep. The weathering products are clays, in some cases kaolinite, pure quartz and other silica types sands, elimination of all other minerals and duricrust formation, such as ferricretes (iron), silcretes (silica) and calcretes (calcium carbonate). Mean annual precipitation in these periods would have been perhaps higher than 10,000 mm, with extremely high, mean annual temperatures, such as 25–30 °C. These deep weathering processes can be achieved only under extremely stable tectonic and climatic conditions. The geomorphological processes continued with fluvial removal of the weathering products in wet climates and with hydro-eolian deflation in the areas with strong climatic seasonality. The final landform products of these deep weathering systems are planation surfaces, inselbergs, bornhardts, duricrust remnants covering tablelands, associated pediments, granite weathered landscape, etc.

Some concepts related of these ancient landform systems were theoretical, developed by Walther Penck in the early twentieth century. The Gondwana Landscapes were studied by Alexander Du Toit and Lester C. King in Africa and more recently, by Timothy Partridge and Rodney Maud in South Africa, C. Rowland Twidale and Cliff Ollier in Australia and Lester C. King and João José Bigarella in Brazil, among others. Both in Australia and Southern Africa, these landform systems have been identified as formed in the Middle to Late Jurassic, throughout the Cretaceous and, in some cases, extending into the Paleogene, when Gondwana was still only partially dismembered.

Keywords Gondwana • Paleosurfaces • Argentina • Planation surfaces • Etchplains

Introduction

This general introduction is a revised version of a previous paper (Rabassa 2010), which then summarized a talk presented at the IV Congreso Argentino de Geomorfología y Cuaternario and the simultaneous Brazilian Quaternary Congress (ABEQUA), La Plata, September 2009, then opening a special symposium on “Paleosurfaces”. This was a quite historical event for southern South American Geomorphology since it was the first opportunity that, in recent times, the concepts of “Gondwana Landscapes” and “Long-term Landscape Evolution” of cratonic areas were presented and discussed in Argentina. Several colleagues of Brazil, Uruguay and Argentina got together to analyse the importance of these ideas in the framework of our present knowledge and the availability of modern dating techniques. A renewed overview of the geomorphology of cratonic areas has been growing since then.

The concept of "Gondwana Landscape" was defined by Fairbridge (1968, p. 483) as an "ancestral landscape" composed of "series of once-planed remnants" that "record traces of older planation" episodes during the "late Mesozoic (locally Jurassic or Cretaceous)". This has been called the "Gondwana cyclic land surface" in the continents of the southern hemisphere, occurring extensively in the cratonic areas of Australia, Southern Africa and South America. All fragments of the former Gondwana supercontinent share similar planation conditions because these extensive landforms were all graded to the same base level of a surrounding, common, pre-break-up sea level (Mountain 1968). Remnants of these surfaces are found also in India, and it is assumed they have been preserved in Eastern Antarctica, both in exposed areas and underneath the Antarctic ice sheet which covers that region with an average thickness of 3,000 m (Ollier 2004). These landscapes were generated when the former Gondwana supercontinent was still in place and similar tectonic conditions in its drifted fragments have allowed their preservation. Landscapes of similar ages have been also described in North America and Europe, which are probably related to evolution of Pangaea. Remnants of equivalent surfaces, though of very fragmentary condition, have been described in Europe (for instance, Belgium, France, Germany, Spain (for Sweden, see Lidmar-Bergsson 1988)) and the United States, south of the Pleistocene glaciation boundary. However, there is no clear agreement among the scientists of these continents about the nature and age of these paleosurfaces. These northern hemisphere paleosurfaces are likely to be found in other areas of the world with similar tectonic and paleoclimatic conditions, but they have not been fully described yet. So far, the concept of very old, Mesozoic Landscapes that were never covered by marine sediments or thick continental sequences and that have been part of the landscape since their genesis, is still a matter of study and discussion almost restricted to southern hemisphere geomorphologists.

The Mesozoic paleoclimates and tectonic conditions in the Gondwana supercontinent allowed the formation of ancient landscape systems in Africa, particularly in Southern Africa, Australia, India, Antarctica and South America. In this latter continent, they have been studied in Brazil, Argentina, Uruguay, Venezuela and the Guyana Massif.

The Ideas of Gondwana Landscapes and Long-Term Landscape Evolution: Previous Works

Grove K. Gilbert (1877) was a pioneer of the ideas related to "long-term landscape evolution" when he published his concepts of "dynamic equilibrium". Dynamic equilibrium is a system in which weathering, removal by erosion and further deposition are in a balanced condition and therefore there is no change in form through time. William M. Davis (1899) developed his ideas of the cycle of landscape evolution and the concept of "peneplain" based on the action of fluvial processes and age. Later, Walther Penck (1924) recognized that large planation surfaces were formed by receding headward erosion. He proposed the concepts of “primarrumpf” (initial landscape development phase), “piedmont treppen” (steep erosion terraces developed by headward erosion) and “endrumpf” (final phase, with intersection of wash slopes), which may develop under a variety of paleoclimatic conditions (von Engeln 1948). It should be noted that Walther Penck did not introduce weathering in his discussion of parallel slope retreat (C. Ollier, personal communication, 2011).

The work of Alexander Du Toit (1937, 1954, and other papers cited therein; Du Toit and Reed 1927) defined the ideas of “continental drift” that had been previously suggested by Alfred Wegener (1924) based on paleoclimatic inference. This allowed for the identification of areas that were geographically very closely located in the past and which had split apart since Late Mesozoic times, like Africa and South America. Therefore, those landscape features in both continents that were formed before the rifting would have similar characteristics because they were sharing similar climates and environments. Du Toit (1954) identified that “from the Jurassic onwards, South and Central Africa underwent various cycles of prolonged planation”, whose remnants can be identified still today.

The ideas of Du Toit were deeply consolidated by the work of Lester C. King (1949, 1950, 1953, 1956a, 1962, 1963, among other papers) who recognized the long-term action of processes such as “pediplanation”, “planation surfaces” and “etchplains”, both in South Africa and Brazil. Extensive regional mapping in both continents supported King’s ideas and presented for the first time a different overview of these landscapes to the whole world. Lester King’s concept was still cyclic, like that of Davis, but he believed instead in parallel slope retreat (an idea that Walther Penck had theoretically developed). Since parallel slope retreat makes pediments, if these grow big and unite to build a larger plain, a pediplain forms. Pediplains are then formed by “backwearing”, as opposed to peneplains, which are formed by “downwearing”. Some of the landscapes that had been named as peneplains were later reinterpreted as pediplains, particularly in North America (see papers in Melhorn and Flemal 1975).

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The ideas of King were continued in Brazil by João José Bigarella (Bigarella et al. 1994, and papers cited there; Bigarella and Ab’Sáber 1964), who recognized the existence of these ancient landscapes and by Carlos Schubert and colleagues in Venezuela (Schubert et al. 1986) in his studies about the “tepuis” of the Venezuelan Guyana Shield.

Later on, in Australia, the science of ancient landscapes was deeply developed by C. R. Twidale (2007a, b, and papers cited therein) and Clifford Ollier (1991a; Ollier and Pain 2000, and other papers quoted there). Both authors have an outstanding record of paramount contributions in these fields. Twidale (2007a) recognized the existence of several planation surfaces from the Jurassic, about 200 Ma, characterized by a lateritic surface, and even perhaps from the Triassic.

The importance of weathering under tropical climates was widely recognized by Summerfield and Thomas (1987), who stated that landscape evolution is associated with the formation and removal of deep weathering profiles, which leads to the concept of "etchplanation" as proposed by Wayland (1933). An etchplain is "a form of planation surface associated with crystalline shields and other ancient massifs which do not display tectonic relief and developed under tropical conditions promoting rapid chemical decomposition of susceptible rocks" (M.F. Thomas, in Fairbridge 1968, pp. 331–332). Etchplains depend exclusively on deep weathering processes. Etchplains are formed often under weathering conditions of hundreds of metres, and the new planation surface may be cut entirely across saprolite (Ollier 1960). It is important to note that some planation surfaces are cut across dominant saprolite, but others are cut across fresh, hard rock. Inselbergs rise abruptly from these planation surfaces cut across hard bedrock. All inselbergs are steep, rising like islands, but it should make it clear there are two types – those rising from hard pediments and those rising through a mantle of saprolite, like the ones Ollier (1960), Ollier and Harrop (1959) and Ollier et al. (1969) described from Uganda.

Since there are etchplains developed on weathered volcanic and/or sedimentary rocks, the concept should not be restricted to crystalline shields.

Likewise, one of Lester C. King's doctoral students at the University of Natal, Rodney Maud and his Witwatersrand University colleague, Timothy C. Partridge, developed a similar framework in South Africa, which they later extended to the whole of Southern Africa (Partridge 1998; Partridge and Maud 1987, 1989, 2000).

Gondwana Landscapes: Basic Scientific Concepts Related

The general idea of Gondwana Landscapes is closely related to the concept of long-term landscape evolution. This implies that landscapes may be developed along extreme long time periods, provided that warm/wet climates and tectonic stability are given. These conditions are found along cratonic areas and continental passive margins.

However, it should be taken into consideration that a long-term landscape may evolve under arid conditions; it just happens that the real history for most of these landscapes was of warm-humid conditions.

The conditions of climatic and tectonic stability were active for the last 200 million years only during the Jurassic and Cretaceous, when extremely warm and humid, tropical climates were dominant. Neither orogenic movements nor strong tectonic activity was recorded until the Middle to Late Cretaceous in the Gondwana supercontinent. There were no glaciers on Earth at that time, not even in the polar regions, and sea level was extremely high, overflowing the lowlands of most continents. Therefore, the idea of Gondwana Landscapes is closely associated to the geomorphology of tropical environments. And, indeed, it is from the tropics that most of these concepts are coming from.

Tropical environments are associated with conditions of deep chemical weathering, under wet and warm climates and tectonic stability. This is true also in tectonically active areas like New Guinea. Chemical weathering is developed by percolation of warm waters in heavy rain fall terrains throughout the uppermost levels of the crust. These waters, in large amounts, warm conditions and omnipresent availability, forced the chemical weathering of rocks well beneath the soil, perhaps at hundreds, even up to one thousand metres depth. This altered layer is called the weathering zone. At the bottom of the weathering zone, the weathering front is found, that is, the boundary (often abrupt) in which weathering is active and where it stopped when the active processes were interrupted. The nature and conditions of the weathering front are extremely important to understand the past environments, because in most of the Gondwana Landscape areas, the weathering front is the one of the very few remaining evidences of the existence of an extremely deep weathering zone. Its interpretation is providing much information about the original scenarios. The concept of weathering front is associated with the formation of corestones and etchplains, critical landforms in Gondwana Landscapes.

The concept of tropical soils is clearly linked with the formation of different types of duricrusts, as pedogenetic elements, such as silcretes, ferricretes and calcretes, all of them formed under different environmental conditions. The denudation, partial or complete, of soils and superficial sediments and weathering products is related to processes of pediplanation. The combination of all these circumstances is responsible for the formation of inselbergs and bornhardts (Twidale 2007a, b).

In most of the available scientific texts in geomorphology, particularly those from the northern hemisphere, the consideration of these kinds of landscapes is very rare or absent. Newer books are dealing with these concepts much more carefully. For instance, Thornbury (1954) referred that most of the Earth topography has an age that is not older than the Pleistocene, whereas it is a very rare topography which is older than the Tertiary. Thornbury (1954) expressed his profound doubts about the actual existence of these ancient surfaces. He stated that, if they exist, it is most likely that they are just exhumed erosion surfaces which have not been exposed to degradation through vast periods of geological time. He stated that a vast majority of the present Earth surface has an age younger than the Middle Miocene. He was exposing a vision of geomorphology as seen solely from New England and United States, where everything seems to be interpreted to be of glacial origin and Late Pleistocene in age.

However, during the times of the colonial empires and particularly in the first decades of the twentieth century, the British and French geomorphologists were sent around the world to study the landscape of the colonies. Since both empires extended mostly over tropical regions, they found that the landscapes were very different from what they had observed before in the British Isles and Northern Europe. Many of them settled down in Africa, Asia and Australia, where these landscapes were very obvious and extended. In this sense, the British and French geomorphologists had a much wider view than their contemporaneous American colleagues had, likely because the latter remained at home, mostly devoted to the study of glacial landscapes of Eastern United States, or remained fascinated by the arid-climate landscapes of the Rocky Mountains and Western United States.

The Evolution of the Gondwana Cratonic Areas During the Mesozoic

According to Ronald Blakey (www.nau.edu; http://jan.ucc.nau.edu), in the Late Jurassic, 150 Ma ago, Africa and South America were still united or at least in close contact, stretching over continental areas thousands of km wide. The Atlantic Ocean had already been opened in its northern portion, but the South Atlantic was still unborn. Therefore, the continental mass was enormous and the oceanic circulation was totally different to the present one. It is then expected that there was a continuity of climates, ecosystems and landscapes on the lands located today on both sides of the present Atlantic Ocean. Thus, such landforms of continental scale are extended both in Brazil and in western and southern Africa, with Argentina, Uruguay and the Malvinas/Falklands archipelago as marginal areas. India was located along the eastern side of Africa, but Australia was starting to drift away. Eastern Antarctica was located between India and Australia, but the characteristics of the preglacial Antarctic landscape is still unknown, as most of this continent is totally ice covered by a very thick ice sheet, lacking superficial evidence (Fig. 1).

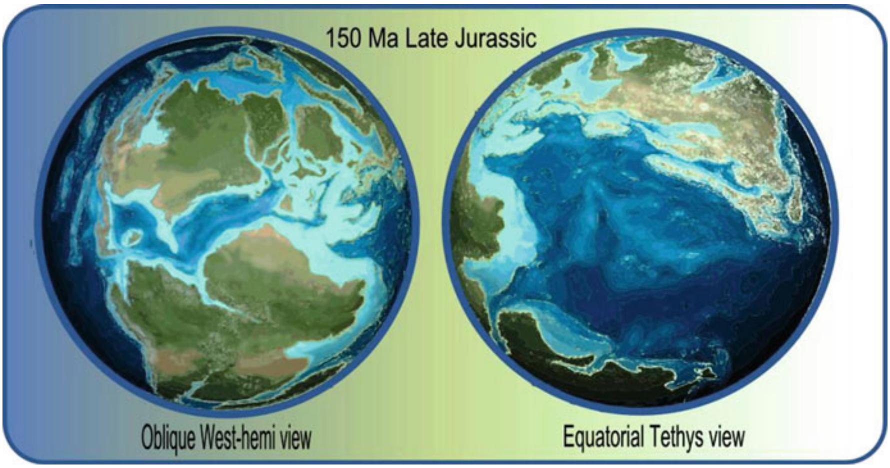

Fig. 1 Gondwana in the Late Jurassic (From Blakey, Ronald: www.nau.edu; http://jan.ucc.nau.edu/~rcb7/globaltext2.html)

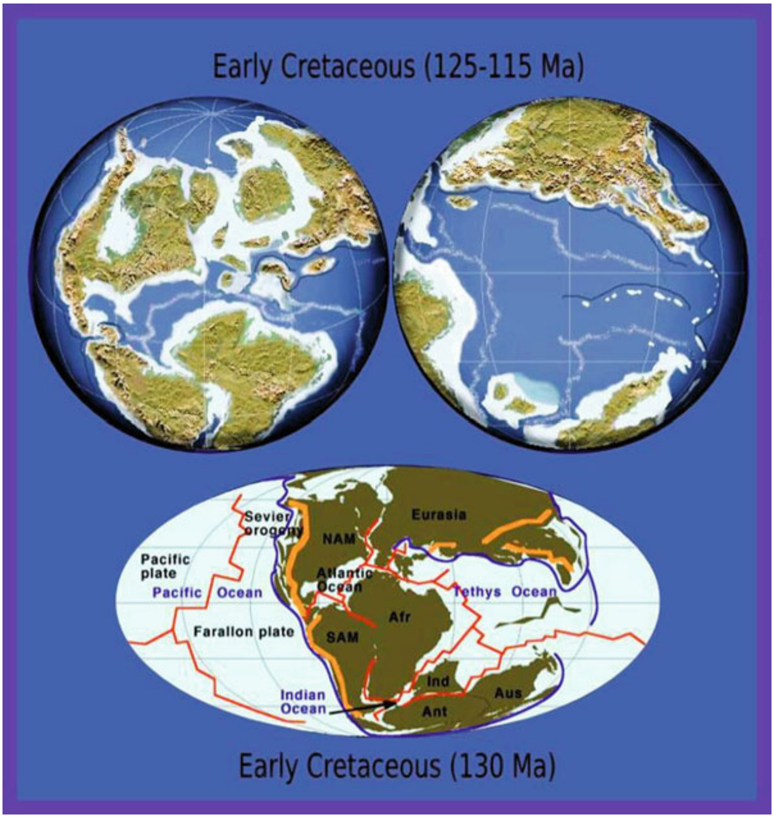

Fig. 2 Globes and map showing Gondwana during the Early Cretaceous (From Blakey, Ronald; www.nau.edu; http://jan.ucc.nau.edu/~rcb7/globaltext2.html)

These conditions were maintained during the Early Cretaceous, around 130–115 Ma, but the rifting and continental drifting had already began, with the opening of ample sectors of the continental platform between both continents, and perhaps the connection between both sides of the Atlantic Ocean had already been established (Fig. 2). It is obvious that in this epoch the environmental conditions in the adjacent areas of both continents were already somewhat different and that the regional climates had already changed as a consequence of the new geographical and tectonic conditions.

In the Late Cretaceous, around 90 Ma, the opening between both continents was ample and the sea communication in between must have been completed, with an oceanic circulation that announces the conditions during the Cenozoic (Fig. 3). As the drifting process continued, it would have generated very different environmental conditions for the landscape evolution on both sides of the Southern Atlantic Ocean.

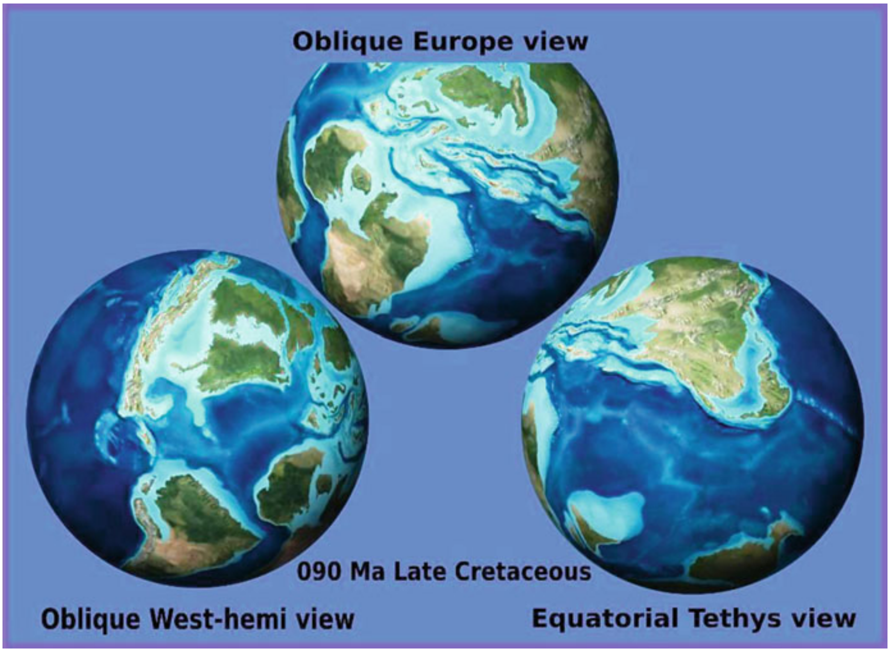

Fig. 3 Globes showing Gondwana fragments distribution in the Late Cretaceous (From Blakey, Ronald. www.nau.edu; http://jan.ucc.nau.edu/~rcb7/globaltext2.html)

Mesozoic and Paleogene Climates

The progressive breaking-up of Pangea, the then global continent at the end of the Triassic, generated much more humid climates, sea level rising and marine transgression on most continents. The relatively larger extension of the global seas reduced the albedo (i.e. reflection of sunlight back to the outer space) and allowed for warmer climates (Uriarte Cantolla 2003, p. 42). Changes in the topography of the ocean floor could also be responsible for the expansion of the shallow seas that forced an increase of evaporation. There is also evidence that methane (CH_4) was released from the bottom of the seas at a large scale during the Jurassic, increasing the atmospheric content of greenhouse gases (Hesselbo et al. 2000).

During the Middle to Late Jurassic (200–150 Ma ago), based on different proxy indicators, the CO_2 content was many times larger than today (presently, around 380 ppm), reaching perhaps above 4,000 ppm, though the final figures are still uncertain (Fig. 4). In the period that is considered in this paper, the CO_2 atmospheric content was extremely high for the Jurassic and the Early to Middle Cretaceous, as shown by paleosoil reconstruction and density of stomas in fossil tree leaves (Royer 2006, in: IPCC 2007) and also by the GEOCARB III model (Berner and Kothavala 2001, in: IPCC 2007). The high CO_2 content was sustained during the Jurassic, more

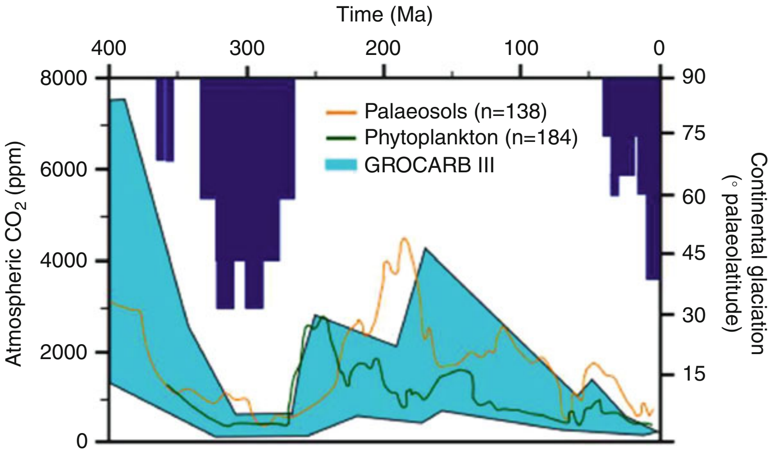

Fig. 4 Global paleoclimatic indicators for the Phanerozoic, with emphasis in the Mesozoic (Simplified and modified from IPCC (2007), Fourth Assessment Report; www.ipcc.ch/publications_and_data/ar4/wg1). The diagram shows in *vertical dark blue bars* the occurrence of global glaciation in the Late Paleozoic and the Late Cenozoic. The *curves* and *greenish-shaded zone* depict proxies indicating very high CO_2 concentration in the Early Paleozoic and most of the Mesozoic, which would be compatible with extremely warm/wet climates. For original data and models, see IPCC (2007)

than 50 million years long, above 4,000 ppm, up to 10 times larger than today, and certainly above 2,000 ppm during the Late Cretaceous, according to paleosoil data. The increased CO_2 content was also fed by huge volcanic eruptions along the rifting areas. Maximum photosynthetic capability in flowering plants should be achieved between 1,500 and 1,000 ppm, suggesting a huge expansion of rain forests and savannas in those times (Uriarte Cantolla 2003). Even beyond the K/T boundary, the ocean bottom temperatures were still very high until the Late Paleocene and Early Eocene. Evidence was also deduced from oxygen isotopes in Late Jurassic belemnites, indicating maximum temperatures of surface sea water of about 14 °C at 75° S latitude, which would be at least 7 °C warmer than present-day temperatures, indicating that this was a period of very warm Earth (Frakes 1979, 1986).

The Cretaceous was also an extended, quite homogeneous period, more than 80 million years long, with most of it under very warm and wet climate. Sea expansion continued in the Cretaceous, when enormous portions of the continents were submerged. Bottom water temperatures for the Early Cretaceous were at least 5–7 °C warmer than today. In the Middle Cretaceous, around 100 Ma, global mean temperature at the surface was between 6 and 12 °C higher than today (Uriarte Cantolla 2003). Jurassic coal and bauxite deposits around the world are related with these warm/wet climates, probably with high rainfall seasonality, at least regionally. The global climate was probably uniformly very warm. The Albian stage was the warmest part of the Cretaceous according to the sea-surface temperatures, around 28 °C. The Albian-Santonian time lapse was the summit for global temperatures in the Late Mesozoic, before the rapid cooling of about 10 °C in the Maastrichtian (Frakes 1979, p. 171). Tropical to subtropical conditions extended perhaps as far south as 70° S due to unique ocean current circulation (Frakes 1979), with large transfer of heat from the equatorial zones to the poles.

Thus, the entire Gondwana supercontinent was undoubtedly under extremely wet/warm conditions in the Cretaceous. The equatorial zone would have been heated much more intensely than today. Besides, the huge extension of the Pacific Ocean at low latitudes would have lowered the total albedo of the globe, strongly increasing the heat capacity of the oceans and, therefore, the influence of the largest heat reservoir on Earth. Frakes (1979, p. 185) stated that, between the Middle Triassic and the Middle Cretaceous, climates were characterized by mean annual temperatures possibly as much as 10 °C higher than today at the global scale, forcing unheard geographical scenarios in present times.

These conditions of very high CO_2 content in the atmosphere would have enhanced the magnitude of the greenhouse effect during this period, compared to present conditions. But temperature at the ground level could not rise indefinitely, because living beings would not bear it. It should be taken into consideration that life forms for these periods were essentially identical to those living today, because all groups that survive today in both in the continents and the oceans were already on Earth, including hair-bearing mammals and feathered birds. According to this, the resolution of this enormous greenhouse effect would have taken place in an immense evaporation rate from the oceans compared with today's conditions. Higher temperatures forced higher evaporation rates, increasing the water content of the atmosphere and the global greenhouse effect, and therefore, a much higher precipitation rate over the continents, under very warm climates. Thus, the precipitation during these times would have been enormous, several times the largest present rates, without glaciers growing on the continents and higher sea levels, forcing major transgressions. This very high precipitation would have generated huge water volumes as surface runoff and soil infiltration, perhaps down to very deep levels, many hundreds of metres, as a consequence of hydrostatic pressure of the hyper-saturated soils, all year-around.

This would have generated extremely intense weathering processes and very thick weathering mantles, with huge weathering profiles. Weathering profiles in the order of 100–200 m are found today in the very wet tropical zones, such as Indonesia or some areas of Brazil (Small 1978; Leopold et al. 1964). Thus, it may be assumed that in those CO_2-rich epochs, the thickness of the weathered zone would have been much higher, perhaps of 700–1,000 m. This would be proven by the presence of bornhardts, inselbergs and other deep weathering, residual landforms which, due to their local relief between their summits and the surrounding denudated surfaces, suggest that the weathered material thicknesses could have been around these values.

The present climatic zonation shows the close relationship between the subsuperficial weathering thickness and the mineralogy of the weathering products (Lisitzin 1972; Strakhov 1967; Fig. 5). As seen in the present conditions, the thickness of the weathering layer reaches a maximum along the Equatorial wet zone, with

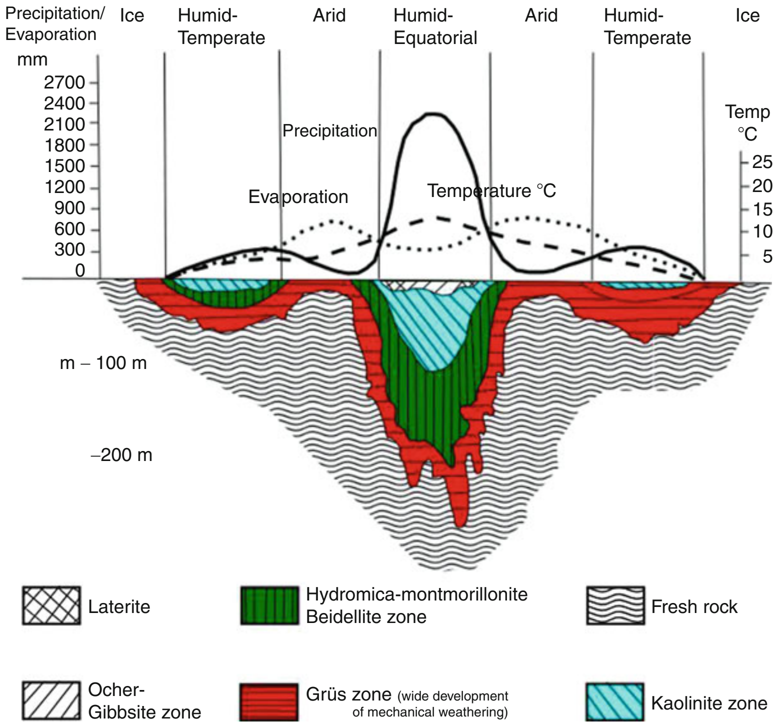

Fig. 5 Global climatic zonation in present times, showing the relationship between latitude, depth of the weathering profile and the mineralogy of the subsurface weathering products (Simplified from Strakhov 1967)

depth values of up to 200 m, with precipitations in the order of 2,100 mm/year and the minimum mean annual temperatures above 15 °C. In this case, there is a development of a thickness of 100 m of the kaolinite zone, with another 100 m of maximum thickness of montmorillonite-beidellite-hydromica and, underneath, up to additional 50 m of gruss, also with development of mechanical weathering. It could also be expected in the presence of laterites and ochre-gibbsite in the superficial zone. The expected weathered zone thicknesses would be much larger in a hyper-tropical climate than in the present conditions, a fact that supports the interpretation of thicknesses of more than 700 m. If the weathering front is today at around -200 m in selected tropical zones, how deep could it have reached during Mesozoic times in Gondwana? Probably up to 4–5 times the present figures, at least, perhaps up to 1,000 m.

According to these circumstances, the Jurassic-Early Cretaceous climates that would have dominated the Gondwana regions could be considered as hyper-tropical, with no present analogues, which would be responsible for the genesis of these noted paleolandscapes.

These climates generated immense weathered debris which remained stable for a very long time, as denudation was slow due to tectonic quietness. A long-term equilibrium was achieved between weathering and denudation, allowing for the development of the intriguing landforms that are found today in the Gondwana Landscapes. This weathered debris cover was denudated during the Cenozoic, particularly since the Middle Eocene, when the world climate changed, until the ancient weathering fronts were exposed as the weathered debris was removed. Thus, usually only the roots of the weathering profile are preserved and observed at the surface, with occasional presence of clays, most frequently kaolinite, or lateritic materials, until only the fresh, unweathered rock is exposed. These rocks cannot be further altered after denudation, because the climate is not hyper-tropical anymore and there is not enough heat and water available. The new conditions do not allow the return of these weathering processes during the entire Cenozoic, not even in tropical areas, as the greenhouse effect diminished due to the reduction in the atmospheric CO_2 content. Therefore, the cited landforms are paleoclimate indicators, and the Gondwana Landscapes were unrepeatable because they could not fully develop today anywhere in the planet.

All these conditions were accompanied by high tectonic stability in the Gondwana cratonic regions, which allowed for deep weathering without debris removal, until the Alpine-Andean tectonic reactivation in the Tertiary, particularly since the end of the Eocene, triggered worldwide denudation.

In spite of a relative cooling at the end of the Cretaceous which has been referred to several causes, the warm climates continued during the Paleocene. Moreover, around 55 Ma, at the end of the Paleocene and beginning of the Eocene, there was an abrupt and short warm peak, with mean annual global temperatures of 5–7 °C above the temperatures at the K/T boundary. This unusual warm event is probably linked to methane released from the bottom of the oceans. Global environmental conditions inherited from Cretaceous times were then sustained until the end of the Paleocene and perhaps even into the Eocene (Uriarte Cantolla 2003).

Granite Deep Weathering

One of the geomorphological processes, which are particularly significant in terms of ancient landscape interpretation, is granite deep weathering. Since one of the conditions required for the development of Gondwana Landscapes is tectonic stability, the occurrence of granites and similar intrusive and/or metamorphic rocks in shields and other cratonic regions is common in such landscapes. Since the other prerequisite is warm/wet climate, granitic rocks are highly sensitive to deep weathering under these conditions. The relatively homogenous and isotropic nature of granites enhances the development of these processes. Granite landscapes are excellent examples of deep weathering paleoclimates and usually diagnostic features for Gondwana Landscapes (Twidale 1982; Vidal Romaní and Twidale 1998).

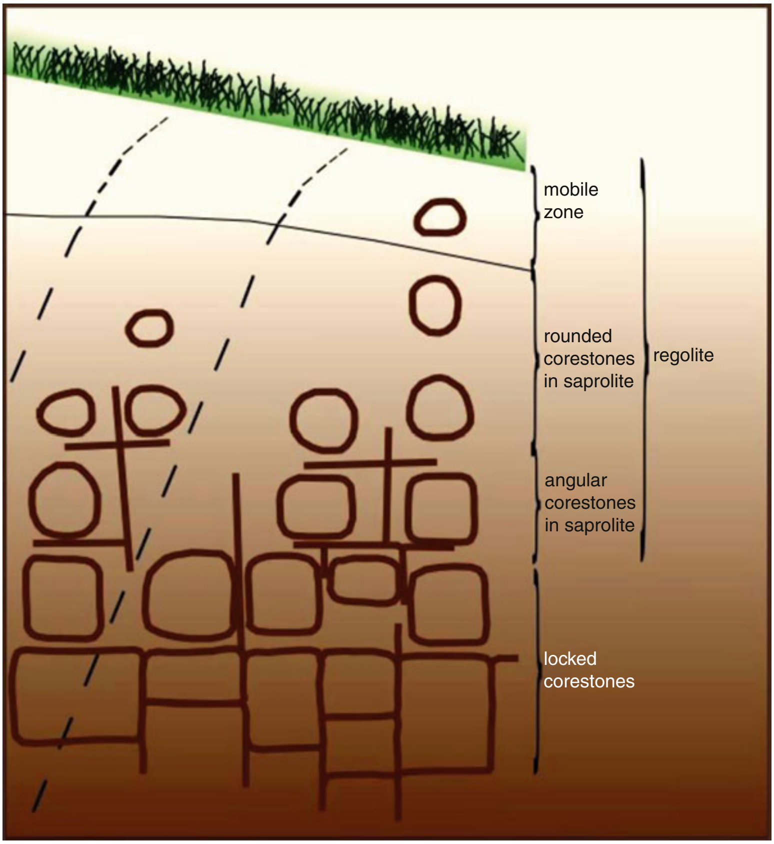

Fig. 6 Granite weathering. A typical section of deep chemical weathering in granites. Granite blocks are bounded by joints. Saprolite is an in situ weathered rock, as indicated by the unremoved quartz veins. The alteration is isovolumetric. Regolith is a term that includes all unconsolidated materials near the surface of the Earth, including saprolite (Redrawn from Ollier 1990)

Ollier (1984, 1990) discusses a typical weathering profile in granitic rocks (Fig. 6). Saprolite, or "rotten rock", is an in situ deeply weathered rock, which is usually indicated by the nonmobilized quartz veins, being quartz almost totally immune to weathering, unless extreme conditions are present. The alteration forced by weathering is isovolumetric, that is, no changes in the volume of the original minerals after being weathered are recorded. Regolith is a term that covers all unconsolidated materials at or near the Earth surface, and it includes saprolite (Fairbridge 1968, p. 933).

In tropical climates, warm, acid-rich (HCO_3) waters penetrate the granite outcrops following joints and other fractures. They react chemically with the poorly resistant minerals of the granites, such as amphiboles, micas, feldspars and other minor components. Quartz is not affected, except perhaps as surface etching, and

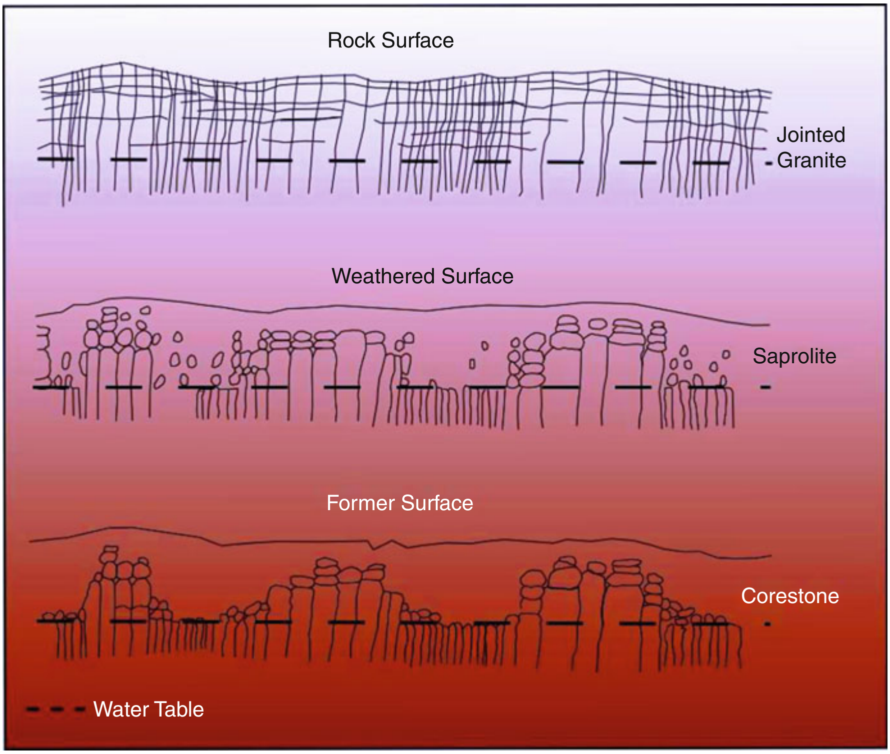

Fig. 7 Corestone and tor development due to deep weathering and subsequent denudation, with finer, weathered material removal (From: Linton 1955; see Fairbridge 1968)

it becomes the main residual material in the gruss, together with clays, usually kaolin. Weathering advances from the surface downwards and from the fracture or exfoliation planes to the inner part of the resulting blocks. This leads to the formation of unweathered cores in the blocks, surrounded by a saprolitic material. These unweathered nuclear remnants are called “corestones” (Fig. 7; Linton 1955), which become roughly rounded in situ as spheroidal weathering makes progress. The process continues indefinitely as the prevailing conditions are maintained. But, when climate changes moving towards drier conditions, denudation starts and the corestones are progressively dismantled. With time, all residual materials are removed and the corestones pile up on the surface. As the climate has changed, the corestones cannot be further weathered, and they remain as unchallenged testimonies of past climates. The corestone accumulations on unweathered bedrock are called “tors” (Fig. 8) and defined as “a bare rock mass surmounted and surrounded by blocks and boulders” (Linton 1955). The equivalent term “kopje”, of Afrikaans origin, is used in Southern Africa. Many tors occupy the summit of “bornhardts” (Twidale 2007b) and their evolution ends with the total dismantling (Fig. 9).

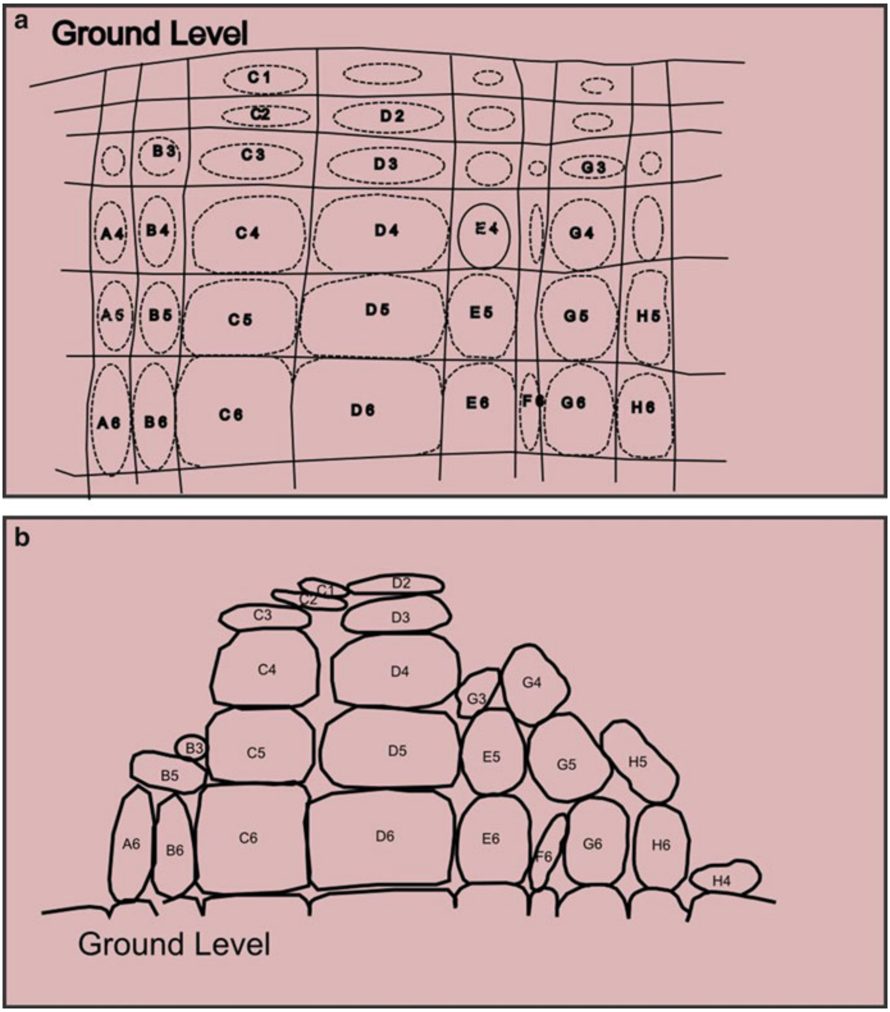

Fig. 8 Stages in the evolution of a tor by subsurface weathering (From Linton 1955). (**a**) Subsurface corestone formation. (**b**) Dismantling by denudation of the weathered materials

Thus, corestones and tors are formed by a two-stage process, involving firstly a period of prolonged subsurface groundwater weathering, under wet tropical climates and tectonic stability, followed by a period of erosion stripping with no further significant weathering. Therefore, corestones and tors are very common in Gondwana Landscapes and important features in the interpretation of ancient climates, no longer active in the study region.

Etchplains are landforms developed essentially by these deep weathering processes, and they are characterized by the abundance of corestones, domes, bornhardts and inselbergs. As denudation proceeds, etchplains are stripped off their

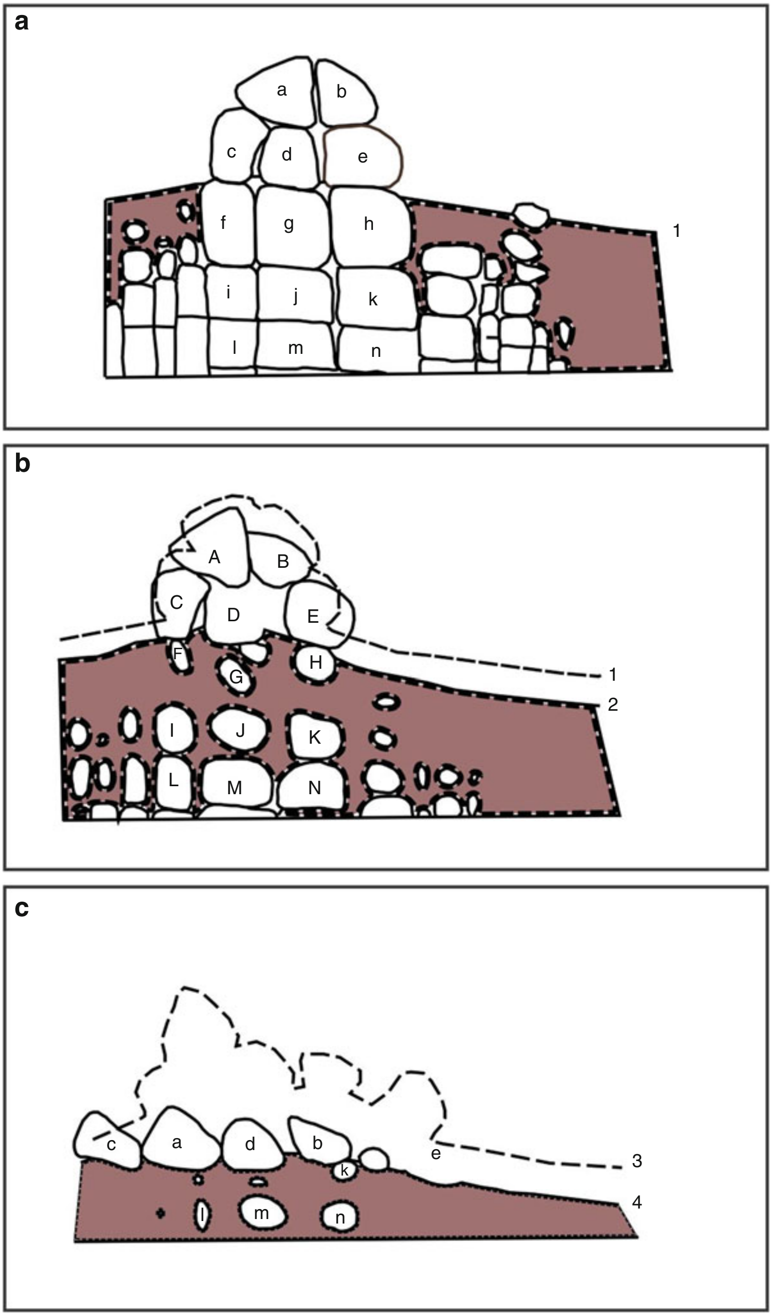

Fig. 9 Stages in the collapse of a domical tor. (**a**) Initial phase in the dismantling of the tor group, with partial removal of the weathered debris; (**b**) progressive collapse of the tor as a result of the washing out of the weathered materials; and (**c**) superficial distribution of the remaining corestones (From Thomas 1965)

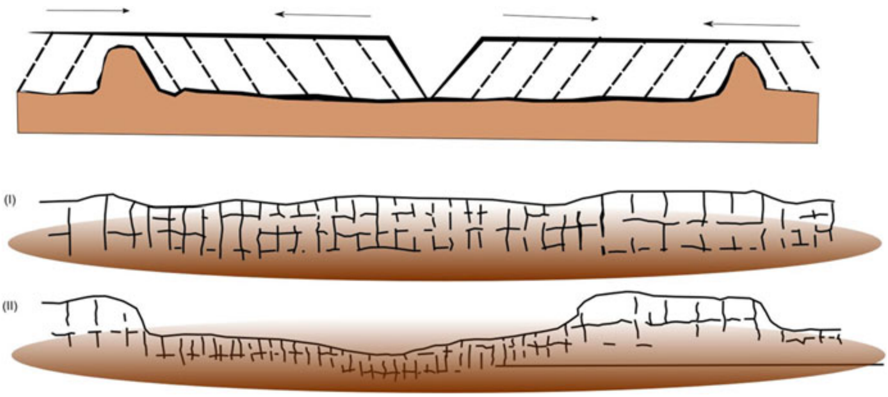

Fig. 10 Formation of inselbergs and bornhardts. *Upper figure*, inselbergs resulting from long-distance scarp retreat; *lower figure*, (*i*) initial stage of etching of differentially jointed bedrock and (*ii*) final stage after removal of the weathered cover and genesis of bornhardts (From Twidale 2007b)

weathering residues and pediplanation develops at their margins, by parallel retreat of the slope, following the processes described by Walther Penck (1924, 1953). Thus, it is highly probable that pediplanation that started in the Middle to Late Cretaceous had affected these ancient surfaces during millions of years while the regions conserved their tectonic stability.

Inselbergs are "residual landforms which stand in isolation above the general level of the surrounding plains in tropical regions" (Twidale 1968). They are formed by a combination of denudation processes of a former etchplain, with parallel retreat of the slope under the influence of differential weathering of bedrock, either due to lithological or structural characteristics (Figs. 10 and 11). The bedrock areas with scarce, closed or no jointing remain unweathered and will become the relict positive features after denudation. These processes are developed during the final phases of the evolution of the Gondwana Landscapes. Inselbergs may be formed on many different rock types. One of the better known inselbergs in the world, the Ayers Rock, in Central Australia, is made of arkose sandstones. Another one, the "Sugarloaf" (Pão de Açucar) in Rio de Janeiro, Brazil, is composed of granitic rocks. The mineralogical and structural characteristics of granitic rocks are particularly appropriate for inselberg formation. Steepened basal slopes of granite inselbergs are due to subsurface weathering, under wet tropical climates, and they are called "flared slopes" (Fig. 12), which represent the position of the ancient weathering front. Granite inselbergs are usually showing frequent caves or smaller holes named as "tafoni". These types of inselbergs should not be confused with hills developed in dry, arid climates, also by parallel retreat but without previous regional weathering. Similar processes are responsible for the formation of "ruwars" and "low domes", massive bedrock features due to differential weathering in tropical environments (Fig. 13). Landscape evolution includes several phases, from the development of the

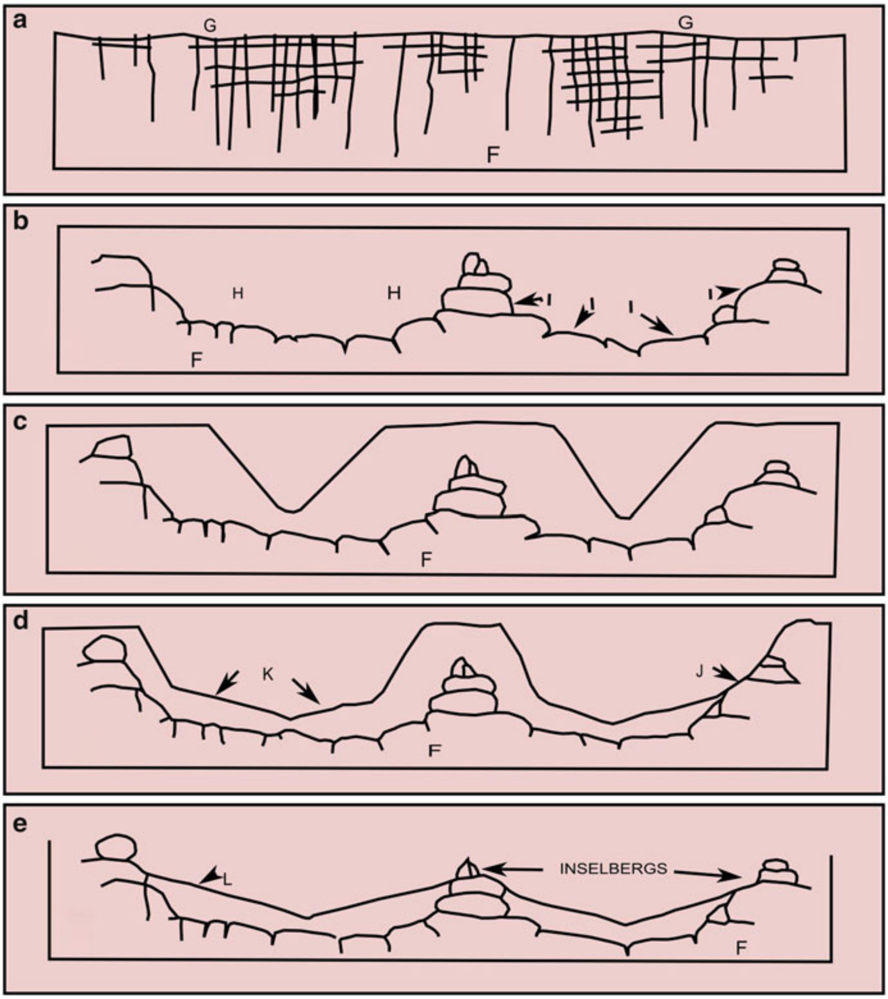

Fig. 11 Formation of inselbergs. (**a**) Gondwana erosion surface (g) developed by etching on differentially jointed, fresh rocks (f). (**b**) Development of an irregular weathering front (i) with uneven weathered debris thickness (h). (**c**) Partial incision of the weathered mantle that develops in the deeper portions of the debris cover. (**d**) Pediment (k) development on the weathered mantle and partial outcropping of the unweathered rocks (j). (**e**) Further removal of most of the weathered mantle and development of a regional surface (l) (From Ollier 1960. Reproduced also in Bigarella et al. 1994)

etchplain, the denudation of the former weathering front, removal of the weathered cover surrounding the fresher, core areas and the preservation of more resistant portions of the bedrock.

Bornhardts (Fig. 14) are “bare surfaces, dome-like summits, precipitous sides becoming steeper towards the base, an absence of talus, alluvial cones or soils, with

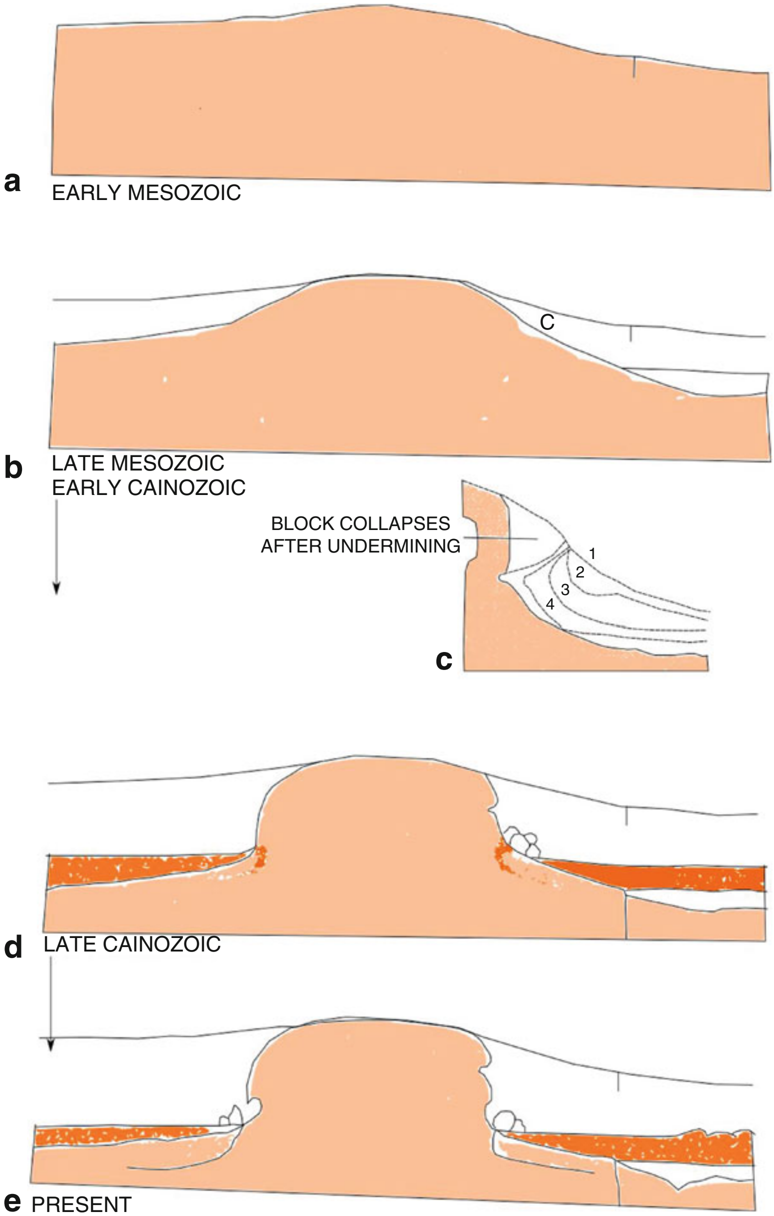

Fig. 12 Age, evolution and exposure sequence of Uluru (Ayers Rock), a giant inselberg in Central Australia, due to the denudation of the neighbouring plains (Twidale 2007a). (**a**) Early Mesozoic bedrock landscape, under deep weathering conditions in wet tropical climate; (**b**) Effect of differential weathering; (c) initial incision and origin of the flared surfaces during the Late Mesozoic-Early Cenozoic; dashed line, original surface and weathered area. (**c**) Detail of the sidewalls, showing the origin of the flared slopes. (**d**) The giant inselberg is fully developed after removal of the weathered debris in the Late Cenozoic. (**e**) Present conditions, with collapsed blocks from the flared slopes

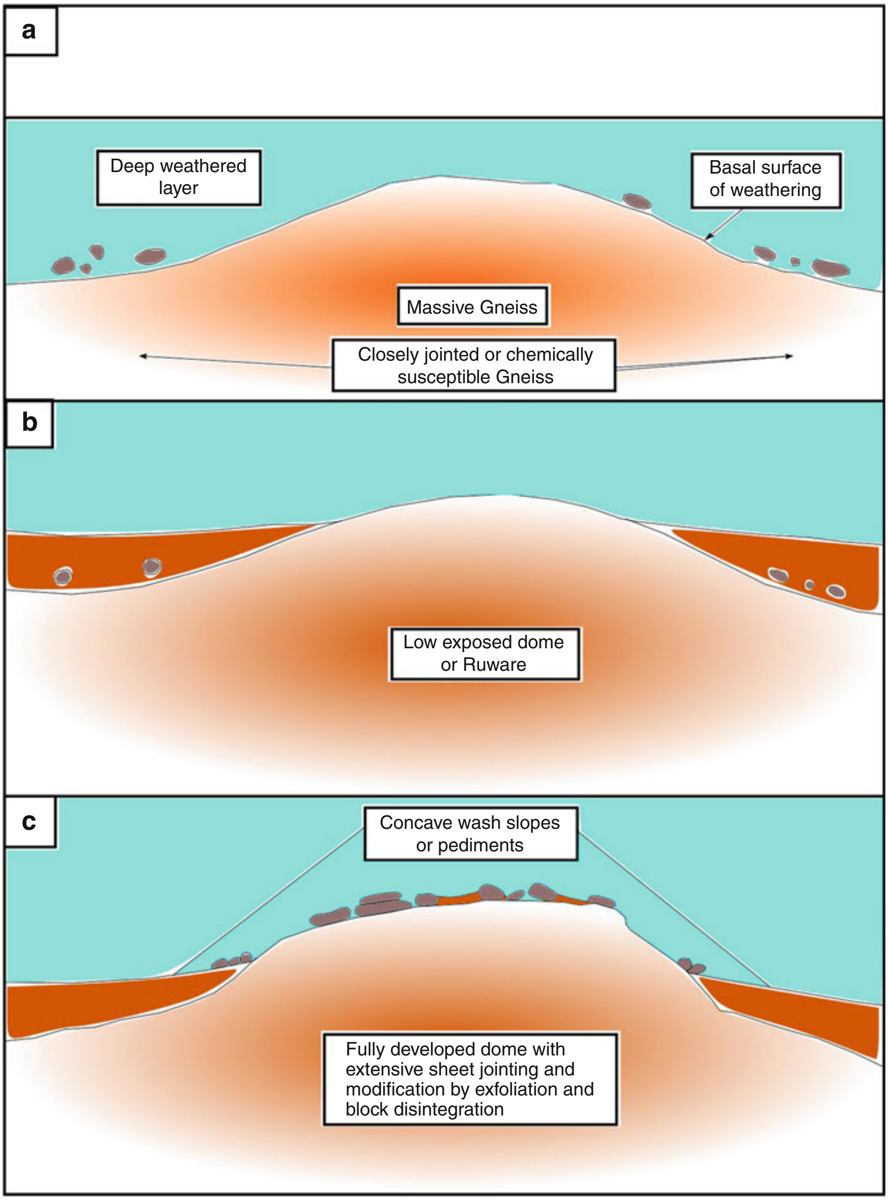

Fig. 13 The development of ruwares and low domes by differential deep weathering and subsurface stripping of the deep weathered layers. (**a**) Differential deep chemical weathering, affecting upon two bedrock types, "massive gneiss" and "closely jointed or chemically susceptible gneiss"; (**b**) after environmental and climatic conditions changed, partial removal of the weathered layer, exposing the top of the ruware; (**c**) formation of the low dome by prolonged denudation of the weathered layer, with modification of the top of the dome, due to exfoliation and block disintegration, and formation of concave wash slopes or pediments (From Small 1978)

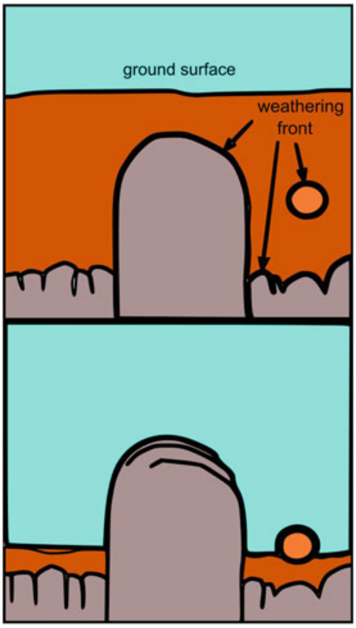

Fig. 14 Bornhardt formation due to deep chemical weathering (etching) and subsequent removal of the weathered debris. Note that the local relief of the bornhardt is an approximate, minimum indicator which becomes a clue to quantify the actual depth of the ancient weathering profile (From Ollier and Pain 2000)

a close adjustment of form to internal structure" (Thomas 1968), named after the German geologist W. Bornhardt, who described these features in the early twentieth century.

These landforms are related to bedrock type, with prevailing gneiss, migmatite and schist, granitic or aplitic intrusive veins, and vertical schistosity or jointing, and exfoliation processes due to unloading. They form in wet/warm climates, with abundant vegetation and under deep chemical weathering, due to differential etching. Twidale (1982) defined bornhardts as "domical hills with bare rock exposed over most of the surface, developed in massive bedrock in which open fractures are few". Though they are mostly developed on granites and granitic gneiss and migmatites, they may occur also in sedimentary rocks, such as sandstones or conglomerates. They are characteristically developed in multicyclic landscapes, where planation surfaces were formed and subsequently denudated, due to relative uplift and stream incision. They may be formed by long-distance scarp retreat or as two-stage or etch features which have survived thanks to their massive structure (Twidale 2007b).

Passive-Margin Geomorphology

At passive continental margins (Fig. 15), etchplains were developed during periods of tropical climate and long-term tectonic stability. Other types of paleoplains may also be present. A general slope recession took place as the tectonic conditions

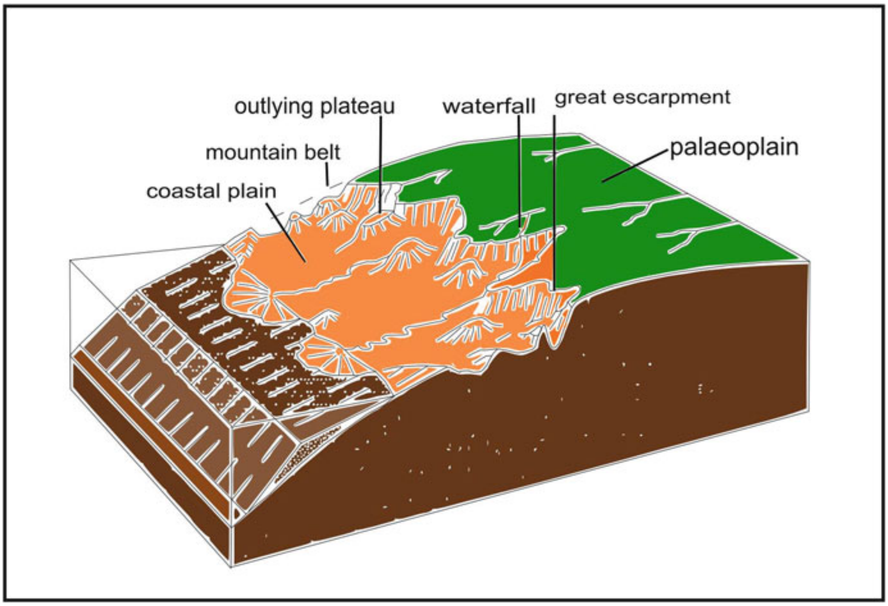

Fig. 15 In passive continental margins, a large and continuous escarpment is developed by headward erosion from the coastal plain, degrading a former paleoplain, usually an etchplain, developed during previous stages of tropical climate with deep chemical weathering. The position of the escarpment is noted by waterfalls along a very steep boundary (From Ollier and Pain 2000)

changed and a new base level is enforced due to continental uplift or sea level lowering. In Southern Africa, the uplifting process was the consequence of the passage of the continent above a hot point during the Middle to Late Cretaceous, as the rifting process made progress and the South Atlantic Ocean started to grow. Environmental changes developed and the differential response to weathering and erosion of the superficial materials. Then, an escarpment is formed as headward erosion took place from the growing coastal plain. In South Africa, it is called the "Great Escarpment"; in Brazil, the escarpment could be found in the Serra da Mantiqueira and Serra do Mar; and in India, it is represented by the Ghats Mountains. In Argentina and Uruguay, the position of the escarpment, if it existed, is still unclear and should be investigated.

Duricrusts: Ferricretes, Silcretes, Calcretes

"Duricrust" is a general term to designate hard layers found in soils and superficial deposits, basically of pedogenetic origin and related to weathering, solution and precipitation processes. Duricrusts are excellent diagnostic materials of past

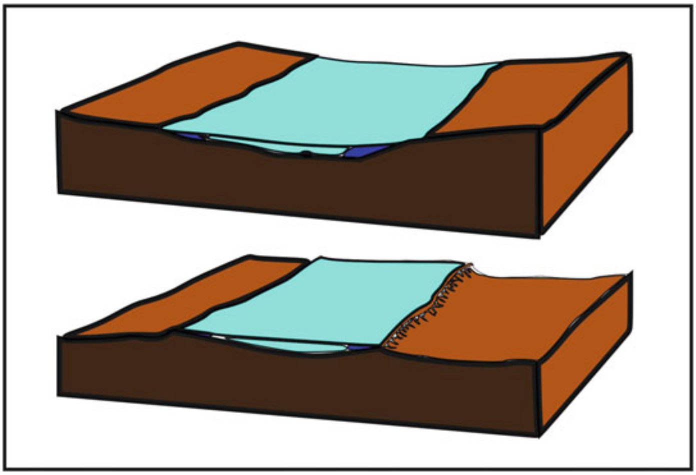

Fig. 16 Duricrusts and inversion of relief (From Ollier 1991a). In the *top figure*, ferricretes are precipitated on lower slopes and valley bottoms. The *bottom figure* shows the inversion of relief, producing a ferricrete-capped mesa or tableland

weathering conditions, and due to their varying composition, they may be found in many different bedrock conditions. Those duricrusts where iron oxide and hydroxide are dominant are called a “ferricrete”. The term “laterite” includes ferricretes, but it is also used to describe soils and weathering profiles (Ollier 1991a, b, 1995; Ollier and Galloway 1990). Aluminium duricrusts are also known as “alcrete” and most commonly called “bauxites”.

Ferricretes may be formed by iron translocation or by removal of other components of the soil. They indicate the existence of a weathering profile, where iron is removed and then redeposited, usually by groundwater circulation or capillary action under very warm/wet climates. Ferricretes are also common on fluvial gravels and alluvial plains. They may be originally deposited in the valley bottoms, but then exposed as capping materials in tablelands due to inversion of relief (Fig. 16). The process may be repeated through time, indicating the existence of several planation surfaces or progressively younger age with lower elevations. Since ferricretes are very resistant to weathering, they are very useful to reconstruct episodes of long-term landscape evolution, as in South Australia, where terrestrial landscapes have been exposed since the Permian glaciations and the ferricretes are Early Mesozoic in age (Ollier 1991a).

Silcretes are very hard, whitish rocks that are the result of silicification in pre-existing quartz-rich sediments. The silica is removed by highly acidic, deep weathering processes and deposited as infilling of the pores and voids of the original sediments when conditions change. Therefore, they are good indicators of long-term seasonality or cyclic changing climate. The silica content is usually very high, with a few other residual components such as titanium or zircon. Silcretes are frequently associated to kaolinized granites or basalts of different ages. Identified silcretes in South Africa and England were formed in the Paleocene, and Paleogene silcretes are common elsewhere (Ollier 1991a).

Calcretes are calcareous duricrusts, which form in many different environments and more rapidly than ferricretes or silcretes. They are related to pedogenetic processes under quite varying moisture and temperature conditions, but they usually imply seasonally dry or semiarid climates.

Bauxites are the end product of intense, deep weathering, under very wet tropical climates, where all soil components, including silica, but with the exception of the most stable alumina rich clays, have been leached away (Ollier 1991a). They are very good indicators of past climates and have been found in many different environments and ages.

Gondwana and Other Ancient Paleolandscapes in the Southern Hemisphere and Other Parts of the World

Du Toit (1954, p. 573) stated that "from the Jurassic onwards South and Central Africa underwent various cycles of prolonged planation, the most widespread one being that of the late Tertiary". Du Toit indicated that each of these planation episodes was followed by uplift, some depression and perhaps, some warping. He described erosion surfaces at 2,500 m above sea level in Rhodesia, 2,200 m a.s.l. in Southwest Africa and 1,500 m a.s.l. in the Zwartberg. He also described the "high level gravels" in southern South Africa, as remnants of former paleosurfaces, which were considered as equivalent to the "Conglomerado Rojo" of the Sierras Australes of Buenos Aires Province, Argentina, by Zárate et al. (1995, 1998) and Zárate and Rabassa (2005).

Lester C. King (1950) described global cycles of planation and extended their identification since the Jurassic (Table 1). King (1950) provided evidence for

Table 1 Planation cycles: sequence of global planation surfaces and paleolandscapes in Southern Africa (Slightly modified from L.C. King 1950)

Planation cycles	Old name	New name	Recognition
I	Gondwana	The "Gondwana" planation	Of Jurassic age, only rarely preserved
II	Post-Gondwana	The "Cretacic" planation	Early Mid-Cretaceous age
III	African	The "Moorland" planation	Current from Mid-Cretaceous to Mid-Cenozoic. Planed upland, treeless, poor soil development
IV		The rolling land surface	Mostly of Miocene age
V	Post-African	The widespread landscape	The most widespread global cycle. Pliocene in age
VI	Congo	The youngest cycle	Quaternary age, deep valleys and gorges

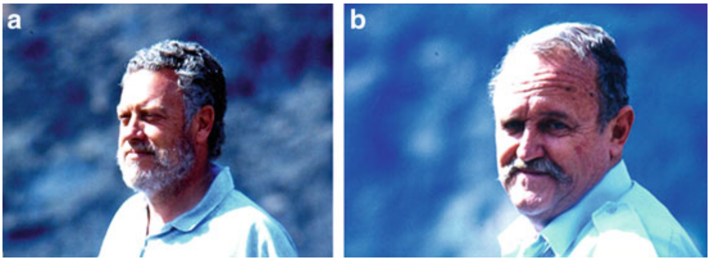

Fig. 17 (**a**) Timothy C. Partridge, who was professor of Geomorphology, University of Witwatersrand, Johannesburg, South Africa, a distinguished scholar in different fields of Gondwana Landscapes, deceased in 2009. (**b**) Rodney R. Maud, Emeritus Professor, University of Natal, Durban, who, together with Tim Partridge, opened for the present author the wonderful world of Gondwana Landscapes and made him a true "believer"

the existence of a worldwide, Jurassic age erosion surface which he called the "Gondwana surface". He also indicated that after the final rifting of Gondwana during the Cretaceous and later time, it was followed by the development of a series of younger erosion surfaces, but they would have formed independently in each continent. The second planation cycle is the post-Gondwana, of Early to Middle Cretaceous age. The most important of these surfaces is the African surface, formed through a long period from the Late Cretaceous to the Middle Tertiary. Cycles 4 and 5 are Late Tertiary and Cycle 6 is of Quaternary Age.

Tim Partridge (Fig. 17a) and Rodney Maud (Fig. 17b) (Partridge 1998; Partridge and Maud 1987, 1989, 2000) represented the South African geomorphological school that was started by Lester C. King in the 1950s. They completed the regional mapping of the larger paleosurfaces (Partridge and Maud 1989), extending the observations to other areas of Southern Africa. They distinguished the different units and their geomorphological, tectonic and economic significance due to their relationships with diamonds, bauxites, gold placers, other minerals residual concentrations, etc. They established also the importance of different types of duricrusts, such as ferricretes and silcretes, to identify different ancient surfaces and correlate them. In their papers, they established that "the inland planation surface was formed no later than the end of the Cretaceous" (Partridge and Maud 1989) and that the landscape was developed both above and below the Great Escarpment (Partridge and Maud 1987). The inland plains were developed under very wet, tropical climates during the Early Cretaceous or even before. Moreover, there are remnants of areas above the Cretaceous plains, which may have been developed during the Late Jurassic, as King (1967) had envisaged.

The Australian model of geomorphological evolution was consolidated by the work of C. R. Twidale and C. Ollier, among many other geologists and geomorphologists. A well-known example is the Gawler Ranges. This is a massif of ancient volcanic rocks located in South Australia. The area is extremely stable, and basically, the development of the present landscape began with the melting and disintegration of the Permian ice sheets (Twidale 2007a). During the Early Jurassic, the area was undergoing very intense, deep weathering in tropical climate, which generated a huge planation surface, named as the Beck Surface, which originally had a thick regolith/saprolite cover, showing differential weathering following structural controlling features. Later, uneven tectonic uplifting of the area in the Early Cretaceous forced the partial denudation of the range and the removal of most of the weathered debris, probably due to river rejuvenation after the uplifting. In the Early Tertiary, most likely during the Paleocene, climate change allowed the formation of the Nott Surface, with the almost complete removal of the Jurassic-Cretaceous regolith and development of silcretes in plains and hollows. Remnants of this ancient regolith are preserved only in a few sites at inner locations (Twidale 2007a).

In the former Soviet Union, Gorelov et al. (1970) classified the Russian erosion surfaces in two main groups, the "Ancient denudational surfaces", considered as peneplains or pediplains of Mesozoic or even pre-Mesozoic age, mostly pre-break-up to the Pangea supercontinent, and the "geomorphological surfaces", chiefly developed in the Tertiary. Likewise, Geramisov (1970) proposed three megacycles in the geomorphological development of the Earth during Mesozoic and Cenozoic times. The earliest megacycle is a Jurassic-Cretaceous basal planation surface surmounted by inselbergs, which is still present on a global scale.

Melhorn and Edgar (1975) presented a correlation of the main surfaces in the World, including North America, some of which dated from the Early Mesozoic, but their ideas were not taken in great consideration by their American colleagues, who seem to feel much more comfortable with Thornbury's (1954) classical ideas restricted to very young landscapes. Melhorn and Edgar (1975) recognized the possibility of time-synchronous, worldwide erosion surfaces, some of them as old as the Late Triassic (though in this case they are mostly covered surfaces) and the Jurassic (Table 2). For the Appalachian region, they identified periods in which appropriate conditions for net denudation and landscape planation, such as the >135–110 Ma interval (Late Jurassic-Cretaceous, which they called "Fall Zone Time"), 85–55 Ma (Late Cretaceous-Paleocene, "Schooley Time"), 45–20 Ma (Eocene-Miocene, "Harrisburg Time") and possibly between 12 and 2 Ma (Pliocene, "Somerville Time") (Table 3). Note the identification of six surfaces for the Brazil-Uruguay region, starting in the Late Triassic, with the Pre-Botucatú surface, a buried erosion surface. They agreed with King's ideas (King 1956a, b) of a Gondwana surface (Jurassic), a post-Gondwana surface (unnamed in South America, Late Cretaceous), the African surface (=the "Sul-Americana" surface; Paleocene-Eocene) and finally, two Late Cenozoic surfaces.

In Central United States, the clear delimitation of the Cretaceous Mississippi Engulfment allows to identify remnants of ancient surfaces above this ancient littoral zone and predating such transgression that developed in the non-glaciated, highly stable, cratonic areas of Southern Illinois and Arkansas, which had not been covered by the sea since perhaps the latest Paleozoic (Rabassa 2006).

In Venezuela, Schubert et al. (1986) and Schubert and Huber (1990) have described the "tepuis" of the Guiana Massif as features developed since Jurassic times (Fig. 18). This diagram suggests the possibility of having remnants of even

Table 2 World correlation of the planation surfaces and erosion landscapes (Simplified and slightly modified from Melhorn and Edgar 1975), in South Africa, West Africa, Brazil and Uruguay, Australia, India, Mongolia and China

Period	Age at the base (Ma)	South Africa	West Africa	Angola	Brazil/Uruguay	Australia	India	Mongolia	China
Pleistocene	2	Congo			Paraguaçú	Wudinna	XXX	Pankiang	Pangchaio
Pliocene	7	Coastal Plain		XXX	Velhas	Koongawa	Jamda	Gobi	
Miocene	26		Ho-Keta	Namib		Meckering	Noamundi		Tangshan
Oligocene	38					UN/Nonning	Kiriburu	Kanghai/Mongolian	
Eocene	54	African	Ashanti		Sul-Americana	Australian pediplain	Indian	Kanghai/Mongolian	Pei-Tei
Paleocene	65	Post-Gondwana			XXX	Simmens/Nott	Post-Gondwana		
Cretaceous	135	Post-Gondwana	Voltaian	Benguela		Simmens/Nott	Post-Gondwana	Post-Laurasian	Post-Laurasian
Jurassic	200	Gondwana		Planalto	Gondwana	Gondwana Mount Dale	Gondwana/Nilgiri	Laurasian	Laurasian
Triassic	250	Sub-Stormberg	Agu Mountain (?)		Sub-Botucatú	Lincoln			

Note that Jurassic Gondwana Landscapes have been identified in most areas in the Southern Hemisphere, but also in Asia, where Gondwana equivalent surfaces are named as "Laurasian". "XXX" refers to surfaces known but not named yet at the time the original paper by Melhorn and Edgar (1975) was published

Table 3 Correlation chart of North American erosion surfaces (Simplified and slightly modified from Melhorn and Edgar 1975)

	Age at the base (Ma)	Appalachian	Interior Low Plateaus	Interior Highlands	Central Low Plateaus	Great Plains	Rocky Mountains	Great Basin	Sierra/cascade
Pleistocene	2	Valley cycle	Deep stage	Valley cycle	Deep stage	Terraces	Canyon cycle	Pediment cycle	Kern River canyon cycle
Pliocene	7	Somerville	Parker	Post-Osage Strath	Havana Strath	Flaxville		Antler	Mountain valley (?)
Miocene	26	Harrisburg	Lexington/ Highland Rim	Osage-Strath	Central Illinois		Rocky Mountains/ subsummit		Chagoopa/broad valley
Oligocene	38			Hot Springs/ Ozark	Lancaster/ Calhoun				
Eocene	54					Prairie/Cypress Hills	Flat top/summit	"Broken Hills" (?)	Subsummit/ boreal
Paleocene	65	Schooley		Ouachita/ Springfield					Sierra/summit (?)
Cretaceous	135	Fall Zone		Boston Mtn./ Summit (?)	Dodgeville (?)	XXX			
Jurassic	200								

"XXX" refers to surfaces known but not named yet at the time the original paper by Melhorn and Edgar (1975) was published

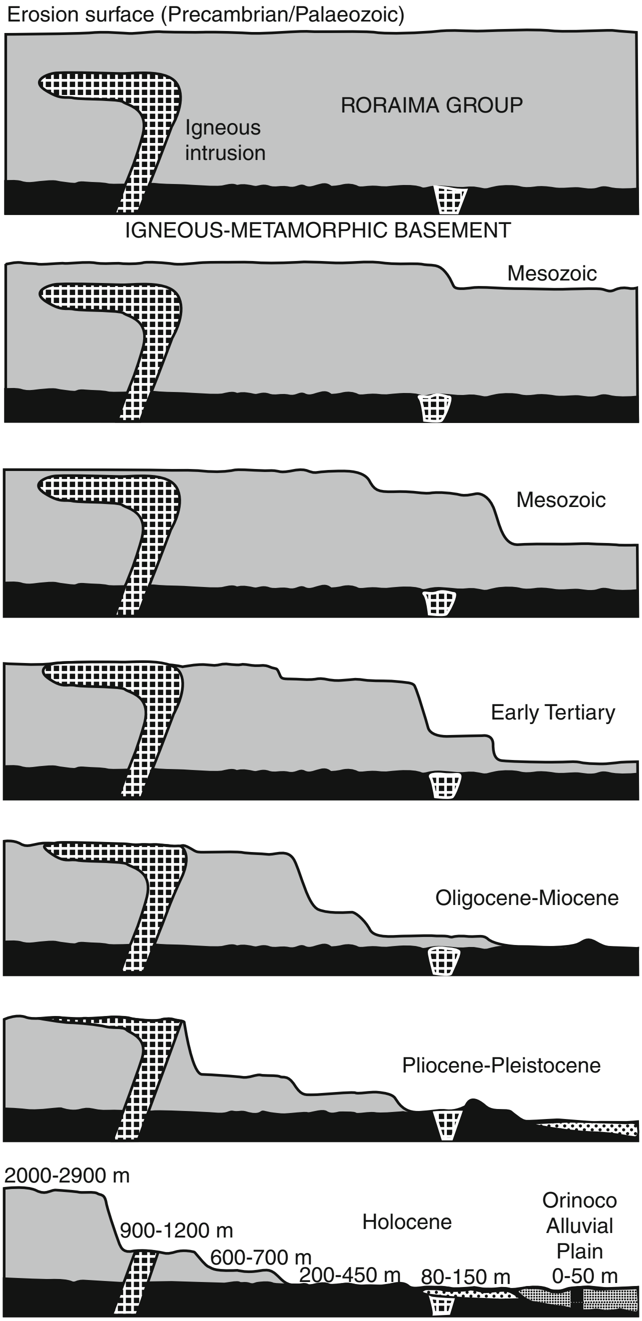

Fig. 18 Geomorphological evolution of the "tepuis" of the Gran Sabana of Venezuela, in the Guyana Massif. Development of planation surfaces since the Mesozoic (From Schubert and Huber 1990 (in Ollier and Pain 2000)). This is an example of Walther Penck's concept of "piedmont treppen". The graph implies that even remnants of Late Paleozoic surfaces may have been preserved in the uppermost portions of the massif, which have never been covered since then

Table 4 Erosion surfaces identified in the Guyana Massif, from Schubert et al. 1986 (Slightly modified from Clapperton 1993)

Elevation (m)	Name	Age
2,900–2,000	Auyán Tepui (Venezuela)	Mesozoic (?)
1,200–900	Kanuku (Guyana), Gondwana (Brazil), Kamarata-Pakaraima (Venezuela)	Mesozoic (?)
700–600	Kopinang (Guyana) Sul-Americana (Brazil), Imataca-Nuria (Venezuela)	Eocene (?)
450–200	Kaieteur/Kuyuwine-Oronoque (Guyana), Early Velhas (Brazil), Caroni-Aro (Venezuela)	Oligocene-Miocene
150–80	Rapununi (Guyana), Late Velhas (Brazil), Llanos (Venezuela)	Pliocene-Pleistocene
50–0	Mazaruni (Guyana), Paraguaçú (Brazil), Orinoco Plain (Venezuela)	Holocene

older (Paleozoic?) surfaces above the Jurassic Gondwana surface. "Tepuis" are spectacular table mountains, whose summit plateaus commonly lie above 2,500 m a.s.l. (Clapperton 1993). The tepuis and their karst-like features appear to be the result of deep chemical weathering during at least 70 Ma (Briceño et al. 1990). The landscape of the Guyana Shield is characterized by a series of planation surface remnants that are displayed in a step-like manner. George (1989; see magnificent illustrations in National Geographic Magazine, May 1989) presented a lively reconstruction of the evolution of the tepuis landscape, accepting a Jurassic age (180 Ma or older) for the summit surface. Schubert et al. (1986) identified six main levels shown in Table 4. In this table, although the ages have been disputed and considered only as tentative, the three older surfaces may be of Mesozoic-Paleogene age, thus forming part of the Gondwana Landscapes.

King (1956a, b) described Brazil planation surfaces and other features, such as inselbergs and bornhardts, which are considered to be formed under prolonged evolution under a seasonally dry to subhumid tropical to subtropical climate. The Brazilian landscape has probably developed continuously since Mesozoic times. João José Bigarella (Fig. 19) and Aziz Ab'Sáber have been the leaders of ancient landscape studies in Brazil in the second half of the twentieth century (see, e.g. Ab'Sáber 1969; Bigarella et al. 1994; Bigarella and Ab'Sáber 1964; and the papers cited there). They described planation surfaces which are essentially coincident with King's viewpoints, considering them as giant pediplains. They were named as Pd1 and Pd2, basically corresponding to the Gondwana and African surfaces. Much more recently, Rossetti (2004) has described five paleoweathering surfaces (laterites and bauxites) in northeastern Amazonia, Brazil, of which the oldest one is considered to be Campanian (Late Cretaceous), whereas the second one is of Paleogene age, corresponding to the Sul-Americana surface of southeastern Brazil, as named by King (1956a, b).

Panario (1988; for a thorough discussion of Gondwana Landscapes in Uruguay, see Panario et al. 2014) described the landscape of the Uruguayan Sierras region, mostly in the Departamento Minas, eastern Uruguay. In an overall very flat country,

Fig. 19 João José Bigarella and the summit planation surfaces in the Paraná Plateau, which he studied and described extensively

the Sierras are the areas with higher relief and potential energy. Some of the rocky ranges have very flat upper surfaces, probably reflecting very old planation processes which are very active in the Cretaceous, whereas other ranges have younger planation surfaces which are of lower elevation and Tertiary age. This set of bedrock hills and planes shows a general SE-NW orientation would have acted as a mountain front that carved pediplains and "glacis" in the ancient shield and which provided most of the sedimentary materials that are infilling the neighbouring accumulation basins. Panario (1988, p. 11) indicated the occurrence of inselbergs and other erosion features in the higher planation surfaces. Some of these ranges show inner tectonic basins where a hilly landscape was developed. The age of this tectonic subsidence is clearly postdating the formation of the higher planation surfaces. At lower elevations, several surfaces formed by pediplanation processes have been identified, which are capped by mineral reddish soils that are interpreted as formed by seasonally wetter, warmer climates. Panario and Gutiérrez (1999) concluded that the extensive planation surfaces of eastern and northern Uruguay are related to down-weathering processes during the Paleogene and particularly, the Eocene.

In Argentina, Gondwana Landscapes are recognized in all cratonic areas (Carignano et al. 1999, p. 249). Landforms of this nature have been observed in (a) the Sierras Pampeanas of Córdoba, San Luis, La Rioja, San Juan and Catamarca; (b) the Central Buenos Aires Positive area, including the Sierras Septentrionales (Tandilia), the Sierras Australes (Ventania) and the Pampa Interserrana (Demoulin et al. 2005); (c) the Sierra Pintada Block in Mendoza; (d) the Sierras de Lihuel Calel in La Pampa; (e) the Northern Patagonian Massif; (f) the Deseado Massif; and (g) the Malvinas-Falkland Islands. The nature and characteristics of the Gondwana

Landscapes in the mentioned areas are described in another paper (Rabassa et al. 2010; see also 2014).

Finally, in the Malvinas-Falkland Islands, a continental fragment which drifted away from the southernmost portion of Africa, Clapperton (1993, p. 543) described smoothly rolling uplands, at an average height of 500–600 m a.s.l., with highest summits around 700 m a.s.l., closely adjusted to underlying structure and lithology, which reflect prolonged evolution by subaerial denudation, as expected in a former portion of Gondwana. These topographic levels have been interpreted as remains of planation surfaces, but their age is still unknown, although they are clearly Triassic or younger.

Discussion and Conclusions

The nature and characteristics of Gondwana Landscapes are clearly related to the principles of the long-term landscape evolution. These paleolandscapes were developed and preserved along the passive margins of the Gondwana continents, such as Africa, South America, Australia and India. The geomorphology of passive margins assumes that these landscapes were formed during very extensive periods of tectonic and climate stability, under what it has been defined in this chapter as "hyper-tropical climates", during at least between the Late Jurassic and the Late Cretaceous, perhaps up to the Santonian (Early Senonian) and then until the Early Eocene. These extreme climates with no analogues in present times were characterized by very high greenhouse content and very high temperatures that forced unheard evaporation rates from the huge, single ocean, leading to extremely high precipitation on the continents. These conditions provided abundant moisture under very high temperatures in continental areas which, along very long stable periods, were responsible for deep chemical weathering over enormous areas that did not occurred anywhere again after the Eocene. The hyper-stable conditions were achieved because the areas where these landscapes were developed corresponded to ancient continents, with very thick crusts and deep roots in the upper mantle. When these continents started to drift due to the rifting processes in the Middle to Late Cretaceous and the South Atlantic Ocean was born, these roots scratched the mantle and generated extensive volcanic eruptions, such as the kimberlitic intrusions dykes and lavas in Southern Africa and Brazil that brought mantle diamonds up to the surface or close to it.

The deep chemical weathering was the main agent in the formation of these Mesozoic paleolandscapes, with weathering fronts reaching to depths of perhaps up to 1,000 m. When climate changed in the latest Cretaceous and then, again, later in the Paleogene, the huge thickness of weathered debris was removed by continuous denudation. The weathered materials, mostly montmorillonite-beidellite-hydromica and kaolinite, were transported by superficial runoff towards the ocean basins, most of which were opened by the rifting process in the Cretaceous, where they were deposited during most of the Tertiary. Where the denudation was complete or almost complete, the ancient weathering front became exposed, and typical landforms and deposits related to its roots are found in the most noteworthy paleolandscapes. Corestones, duricrusts of many different types (ferricretes, silcretes, calcretes), inselbergs, bornhardts, tors and domes are the most relevant landforms present in these paleolandscapes. These landforms are found as landscape elements forming part of planation surfaces, of which the most important are the etchplains, generated by deep chemical weathering and, later, by prolonged denudation. Other planation surfaces, such as pediplains, are found as well. However, in most of the studied cases, it is not possible to apply the concept of "peneplain", in the sense of Davis (1899), because the geomorphological model assumed by this author considered that these landforms were formed by lateral, sideways fluvial erosion as the dominant process, and the paleolandforms described in these regions are instead the result of deep chemical weathering (etchplains).

The observation and description of paleolandscapes formed by the aforementioned processes in all southern hemisphere continents, and even in certain areas of the northern hemisphere, allows suggesting that the landscape of cratonic regions should be reconsidered. More and renewed attention should be given for the interpretation of the genesis of extensive landforms that were formed a very long time ago, under climatic conditions nonexisting today on Earth, in very stable regions, and which were never covered again by marine transgressions, remaining steadily exposed at the atmosphere perhaps during the last 80–100 million years.

These paleolandscapes are very important because they are dominant in cratonic areas all around the world. They covered extensive areas; have very specific hydrological, hydrogeological and pedological characteristics; and, in many areas, are bearing very valuable mineral resources, such as placers of diamonds, gold and other residual minerals and thick kaolinite and bauxite deposits.

Therefore, it is very important to review the geomorphology of the cratonic areas of different parts of the world, and particularly of Argentina, with a "Gondwana vision" that replaces the presently dominant "Andean vision".

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