GONDWANA PALEOLANDSCAPES: LONG-TERM LANDSCAPE EVOLUTION, GENESIS, DISTRIBUTION AND AGE

Jorge RABASSA [1,2]

(**1**) Laboratorio de Cuaternario y Geomorfología, CADIC-CONICET, Bernardo Houssay 200, 9410.
Tierra del Fuego, Argentina. E-mail: jrabassa@gmail.com
(**2**) Universidad Nacional de la Patagonia - San Juan Bosco, Sede Ushuaia.

"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 (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, in the northern hemisphere 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 meters. These paleolandscapes were generated when the former Gondwana super-continent was still in place and similar tectonic conditions in its drifted fragments have allowed their preservation. Remnants of equivalent surfaces, though of very fragmentary condition, have been described in Europe and the United States. These Gondwana planation surfaces are characteristic of cratonic regions, which have survived in the landscape without being covered by marine sediments over extremely long periods, having been exposed to long-term sub-aerial weathering and denudation. Their genesis is related to extremely humid and warm paleoclimates of "hyper-tropical" nature, with permanently water saturated soils, or perhaps extreme paleo-monsoonal 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 extremely deep weathering profiles, perhaps of up to many hundreds of meters deep. The weathering products are clays, kaolinite, pure quartz and other silica form sands, elimination of all other minerals and duricrust formation, such as ferricretes (iron), silcretes (silica) and calcretes (calcium carbonate). Annual precipitation in these periods would have been higher than 10,000 mm, with extremely high, mean annual temperatures, such as 25-30 ºC. This can be achieved only under extremely stable tectonic and climatic conditions. The geomorphological processes included extensive pediplanation under wet/semiarid and/or seasonally changing climates. Finally, their evolution continued with fluvial removal of the weathering products in wet climates and with hydro-eolian deflation in the areas with semiarid environments or strong climatic seasonality. The final landform products of these deep weathering/pediplanation systems are planation surfaces, inselbergs, bornhardts, duricrust remnants covering tablelands, associated pediments, granite weathered landscape, etc. Some concepts relating of these ancient landform systems were theoretically developed by Walther Penck in the early 20th century. The Gondwana paleolandscapes 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 many 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 supercontinent, Paleolandscapes, Long-term landscape evolution, Southern Hemisphere, Tropical and hyper-tropical climates, Jurassic, Cretaceous.

RESUMEN – *J. Rabassa - Paleopaisajes Gondwana: la evolución del paisaje en el largo plazo, genesis, distribución y edad.* El concepto de "Paisaje Gondwánico" fue definido por (1968, p.483) como un "paisaje ancestral" compuesto por "series de remanentes de planicies" que "registran trazas de episodios de planación más antiguos", durante el "Mesozoico tardío (localmente Jurásico o Cretácico)". Este conjunto ha sido llamado las apareciendo extensivamente en Australia, Africa del Sur, y las áreas cratónicas de América del Sur. Remanentes

de estas superficies se encuentran asimismo en la India, en el hemisferio norte, y se asume que también han sido preservadas en la Antártida Oriental, por debajo del manto de hielo antártico, que cubre la región con un espesor promedio de 3.000 metros. Estos paleopaisajes fueron generados cuando el antiguo supercontinente de Gondwana estaba todavía unido y condiciones tectónicas similares en sus fragmentos a la deriva han permitido su preservación. Asimismo, remanentes de superficies equivalentes, aunque de naturaleza muy fragmentaria. han sido descriptos en Europa y los Estados Unidos. Estas superficies de planación gondwánicas son características de regiones cratónicas, las cuales han sobrevivido en el paisaje sin ser cubiertas por sedimentos marinos a lo largo de tiempos muy prolongados, habiendo sido expuestos a relacionada a paleoclimas extremadamente húmedos y cálidos de naturaleza "hiper-tropical", con suelos permanentemente saturados de agua, o quizás climas paleomonzónicos extremos, con fluctuaciones cíclicas o estacionales, desde extremadamente húmedos a extremadamente secos. Meteorización química profunda es el proceso geomorfológico dominante, con el desarrollo de perfiles de meteorización extremadamente mientras cuarzo puro y otras formas de la sílice confirman arenas, con eliminación de todos los otros minerales y formación de duricostras, tales como ferricretas (hierro), silcretas (sílice) y calcretas (carbonato de calcio). La precipitación anual en estos periodos habría sido quizás aun más elevada que 10.000 mm, con temperaturas medias anuales extremadamente altas, quizás tanto como 25-30 ºC. Esto podría haber sido alcanzado sólo bajo condiciones tectónicas y climáticas extremadamente estables. Los procesos geomorfológicos incluyen asimismo pediplanación extensiva bajo climas húmedos/semiáridos y/o cambiantes estacionalmente. Finalmente, su evolución continuó con remoción fluvial de los productos de con deflación y procesos hidroeólicos en las áreas con ambientes semiáridos o de intensa estacionalidad climática. Los productos finales del paisaje de estos sistemas de meteorización profunda/pediplanación son superficies de planación, planicies grabadas, inselbergs, bornhardts, remanentes de duricostras que cubren mesetas, pedimentos asociados, paisaje de granitos meteorizados, etc. Algunos conceptos relacionados con siglo 20. Los paleopaisajes gondwánicos fueron estudiados por Alexander Du Toit y Lester C. King en Africa, y más recientemente por Timothy Partridge y Rodney Maud en Africa del Sur, C. Rowland Twidale y Cliff Ollier en Australia y Lester C. King y João José Bigarella en Brasil, entre muchos otros. Tanto en Australia como en Africa del Sur estos sistemas morfogenéticos han sido identificados como formados en el Jurásico medio a tardío, a través de todo el Cretácico y, en algunos casos, extendiéndose en el Paleógeno, todavía sólo parcialmente desmembrada.
Palabras clave: Supercontinente de Gondwana, Paleopaisajes, Evolución del paisaje en el largo plazo, Hemisferio Sur, Jurásico, Cretácico.

INTRODUCTION

This an extended version of the invited talk presented at the IV Congreso Argentino de Geomorfología y Cuaternario and the simultaneous Brazilian Quaternary Congress (ABEQUA), La Plata, September 2009, to open a special symposium on "Paleosurfaces". This was the first opportunity that, in recent times, the concepts of "Gondwana Paleolandscapes" and "Long-term Landscape Evolution" of cratonic areas were presented and discussed in Argentina, and perhaps, in South America. Several colleagues of Brazil, Uruguay and Argentina got together to analyze the importance of these ideas in the framework of our present knowledge and the availability of modern dating techniques.

The concept of "Gondwana Landscape" was defined by Fairbridge (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 the cratonic areas of Australia, Southern Africa and South America. All fragments of the former Gondwana super-continent 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, due to the migration of this Gondwana fragment towards the Northern Hemisphere, 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 meters.

The evolution of planation surfaces on cratons was thoroughly discussed by Fairbridge and Finkl (1978; 1980) and Finkl and Fairbridge (1979).

These paleolandscapes were generated when the former Gondwana super-continent was still in place and similar tectonic conditions in its drifted fragments have allowed their preservation. Landscapes of possibly similar genesis and age have been also described in North America and Europe. Remnants of equivalent surfaces, though of very fragmentary condition, have been described in Europe (for instance, Belgium, France, Germany, Spain; for Sweden, see Lindmar-Bergsson, 1988) and the United States, south of the Pleistocene glaciation boundary (Rabassa, 2006). However, there is no clear agreement among the scientists of these continents about the nature and age of these paleosurfaces. These paleosurfaces are likely to be found in other areas of the world with similar tectonic and paleoclimatic conditions, but they have not been described yet. So far, the concept of very old, Mesozoic landscapes that were never covered by marine sediments 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 super-continent allowed the formation of paleolandscape systems in Africa (particularly in Southern Africa), Australia, India and South America. In this latter continent, they have been studied in Brazil, Argentina, Uruguay and the Guyana Massif. Remnants of these surfaces are assumed to be preserved in Eastern Antarctica, underneath the Antarctic ice sheet which covers that region with an average thickness of 3,000 meters. These paleolandscapes were generated when the former Gondwana super-continent was still in place and similar tectonic conditions in its drifted fragments have allowed their preservation.

THE CONCEPTS OF GONDWANA PALEOLANDSCAPES 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", which were fully developed later by John Hack (1960). Dynamic equilibrium is a system in which weathering, removal by erosion and further deposition are in a balanced condition with uplifting 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).

The work of Alexander Du Toit (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; 1953; 1956[a]; 1962, among other papers) who recognized the long term action of processes such as "pediplanation", "planation surfaces", "etchplains", both in South Africa and Brazil. Lester King developed still the cyclic concept as Davis did, 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 had been later reinterpreted as pediplains, particularly in North America (see papers in Melhorn and Flemal, 1975).

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.

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 Clifford Ollier (Ollier, 1991a; Ollier and Pain, 2000, and other papers quoted there) and C.R. Twidale (2007a and b, and papers cited therein) Both authors have an outstanding record of paramount contribution 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). 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; 1993). It is important to note that some planation surfaces are cut across dominant saprolite, but others are so across fresh, hard rock. Steep inselbergs rise abruptly from these planation surfaces cut across hard bedrock.

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). 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 PALEOLANDSCAPES: BASIC SCIENTIFIC CONCEPTS RELATED

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

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. No glaciations, no orogeny and no strong tectonic activity were recorded until the Middle to Late Cretaceous in the Gondwana super-continent. Therefore, the idea of Gondwana Paleolandscapes is closely associated to the Geomorphology of the 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. 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 underneath the soil, perhaps at hundreds, even up to one thousand meters depth. This altered band is called the weathering zone. At the bottom of the weathering zone, the weathering front is found, that is, the lowermost position in which weathering is active, and where it was 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 Paleolandscape 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 a lot of information about the original scenarios. The concept of weathering front is associated with the formation of corestones and etchplains, critical landforms in Gondwana Paleolandscapes.

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. For instance, Thornbury (1954) referred that most of the Earth topography has an age that is not older than the Pleistocene, whereas it is very rare the 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, U.S.A., where almost everything is interpreted to be of glacial origin and Late Pleistocene in age.

However, during the times of the British Empire and particularly in the first decades of the 20th century, the British geomorphologists were sent around the world to the study the landscape of the colonies. Since the Empire 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 and Australia where these landscapes were very obvious and extended. In this sense, the British geomorphologists had a much wider view than their American colleagues had, likely because the latter remained at home, mostly devoted to the study of glacial landscapes of Eastern U.S.A., or remained fascinated by the arid-climate landscapes of the Rocky Mountains and Western U.S.A.

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 by continental areas thousands of km wide. The Atlantic Ocean had already been opened in its northern portion, but the South Atlantic was still inexistent. 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 had already been drifted away. Eastern Antarctica was located between India and Australia, but the characteristics of the pre-glacial Antarctic landscape is still unknown, as this continent is totally ice covered by a very thick ice sheet, lacking superficial evidence (Figure 1).

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 (Figure 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 (Figure 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.

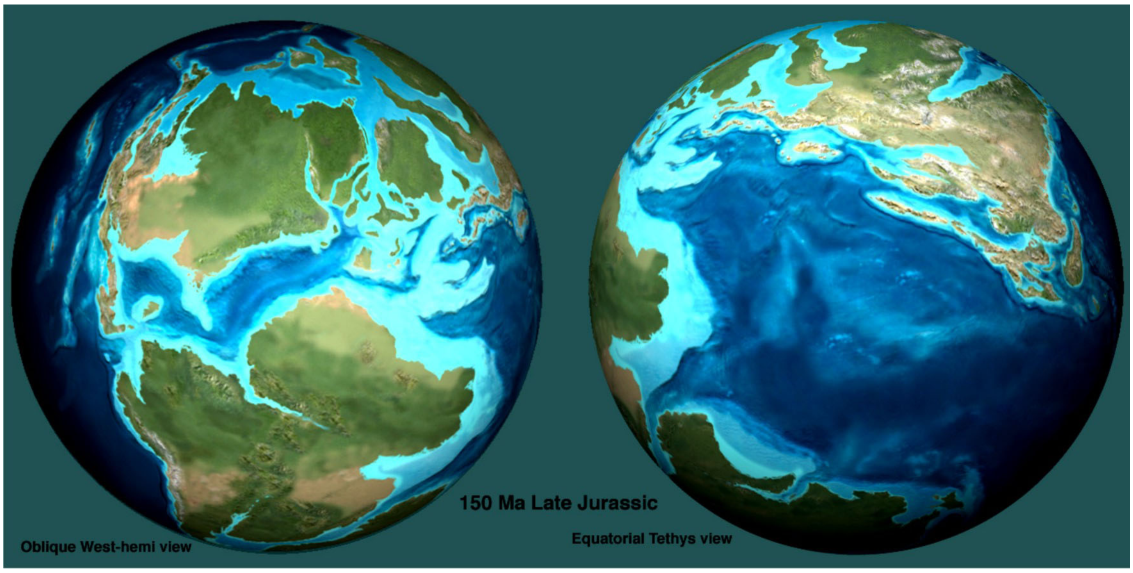

FIGURE 1. Gondwana in the Late Jurassic. From Blakey, Ronald: www.nau.edu; http://jan.ucc.nau.edu/~rcb7/globaltext2.html

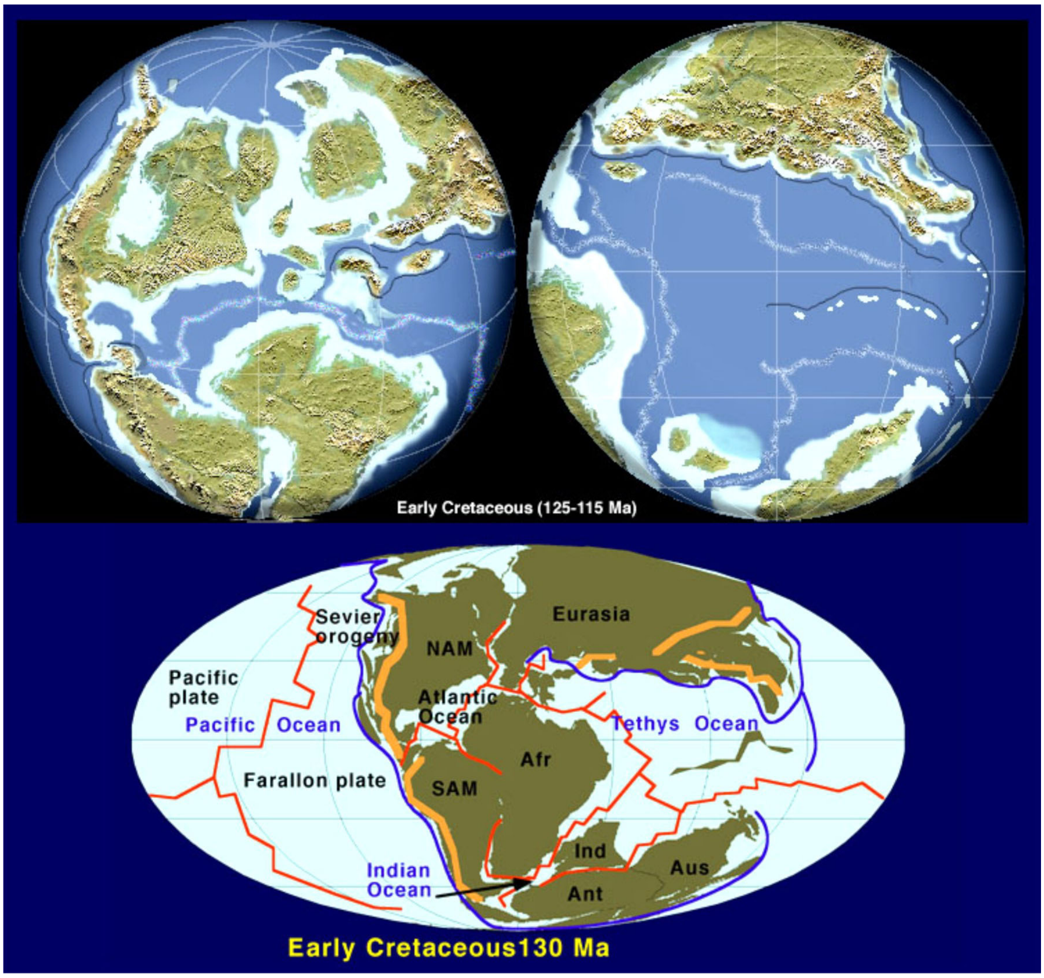

FIGURE 2. Globes and map showing Gondwana during the Early Cretaceous.
From Blakey, Ronald; www.nau.edu; http://jan.ucc.nau.edu/~rcb7/globaltext2.html.

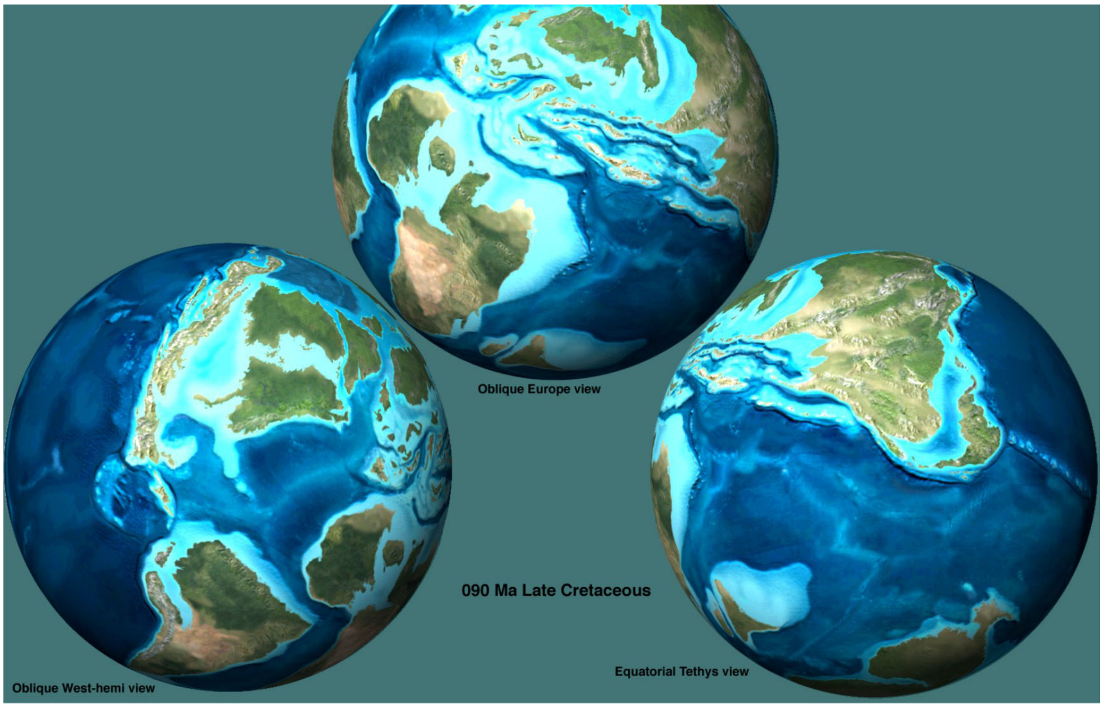

FIGURE 3. Globes showing Gondwana fragments distribution in the Late Cretaceous.
From Blakey, Ronald. www.nau.edu; http://jan.ucc.nau.edu/~rcb7/globaltext2.html

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). 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 to 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 4000 ppm, though the final figures are still uncertain (Figure 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 than 50 million years long, above 4000 ppm, up to 10 times larger than today, and

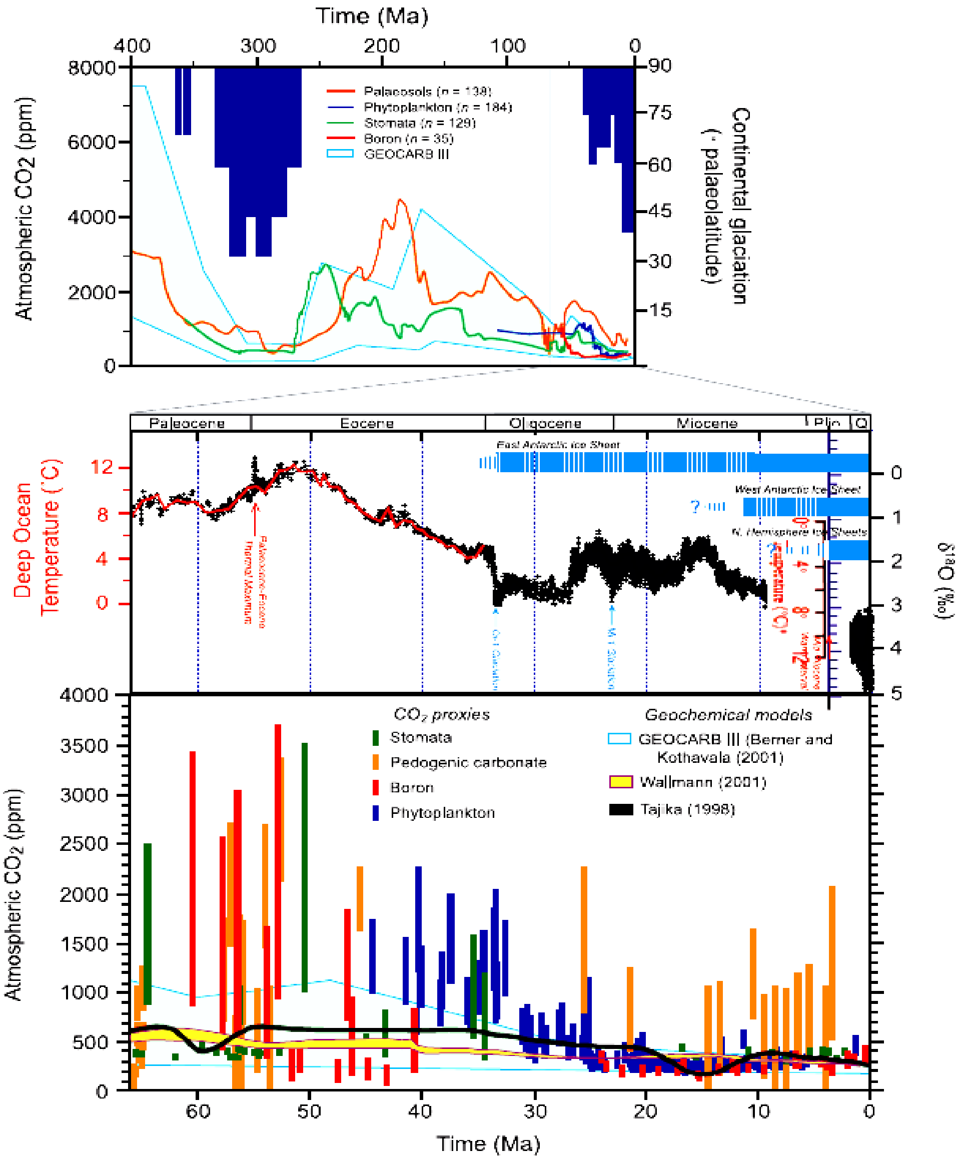

FIGURE 4. Global paleoclimatic indicators for the Mesozoic and Cenozoic.
From IPCC (2007), Fourth Assessment Report; www.ipcc.ch/publications_and_data/ar4/wg1

certainly above 2000 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 1500 and 1000 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 ºC at 75º S latitude, which would be at least 7 ºC 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. This was a time of massive limestone formation around the world which would have removed part of the CO_2 content from the atmosphere, yet it was still a warm period.

Sea expansion continued in the Cretaceous, when enormous portions of the continents were submerged. Bottom waters temperatures for the Early Cretaceous were at least 5-7 ºC warmer than today. In the Middle Cretaceous, around 100 Ma, global mean temperature at the surface was between 6 ºC and 12ºC 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 ºC. The Albian-Santonian time-lapse was the summit for global temperatures in the Late Mesozoic, before the rapid cooling of about 10 ºC in the Maastrichtian (Frakes, 1979). Tropical to subtropical conditions extended perhaps as far south as 70º 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 super-continent was undoubtedly under extremely wet/warm conditions in the Cretaceous, at least for most of the time. It should be noted that climate would have varied a lot since the Jurassic, and not hot and wet all the time. In Australia, there is evidence of glaciation in the Lower Cretaceous (Frakes, 1979).

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) stated that, between the middle Triassic and the middle Cretaceous, climates were characterized by mean annual temperatures possibly as much as 10 ºC 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 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 meters, 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 to 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 to 1000 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 sub-superficial weathering thickness and the mineralogy of the weathering products (Strakhov, 1967; Lisitzin, 1972; Figure 5). As seen in the present conditions, the thickness of the weathering layer reaches a maximum along the Equatorial wet zone, with depth values of up to 200 m, with precipitations in the order of 2100 mm/year and the minimum mean annual temperatures above 15 ºC. 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-hydromicas, and, underneath, up to additional 50 m of gruss, also with development of mechanical weathering. It could also be expected 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 meters. 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 1000 meters or more (Ollier and Pain, 1996).

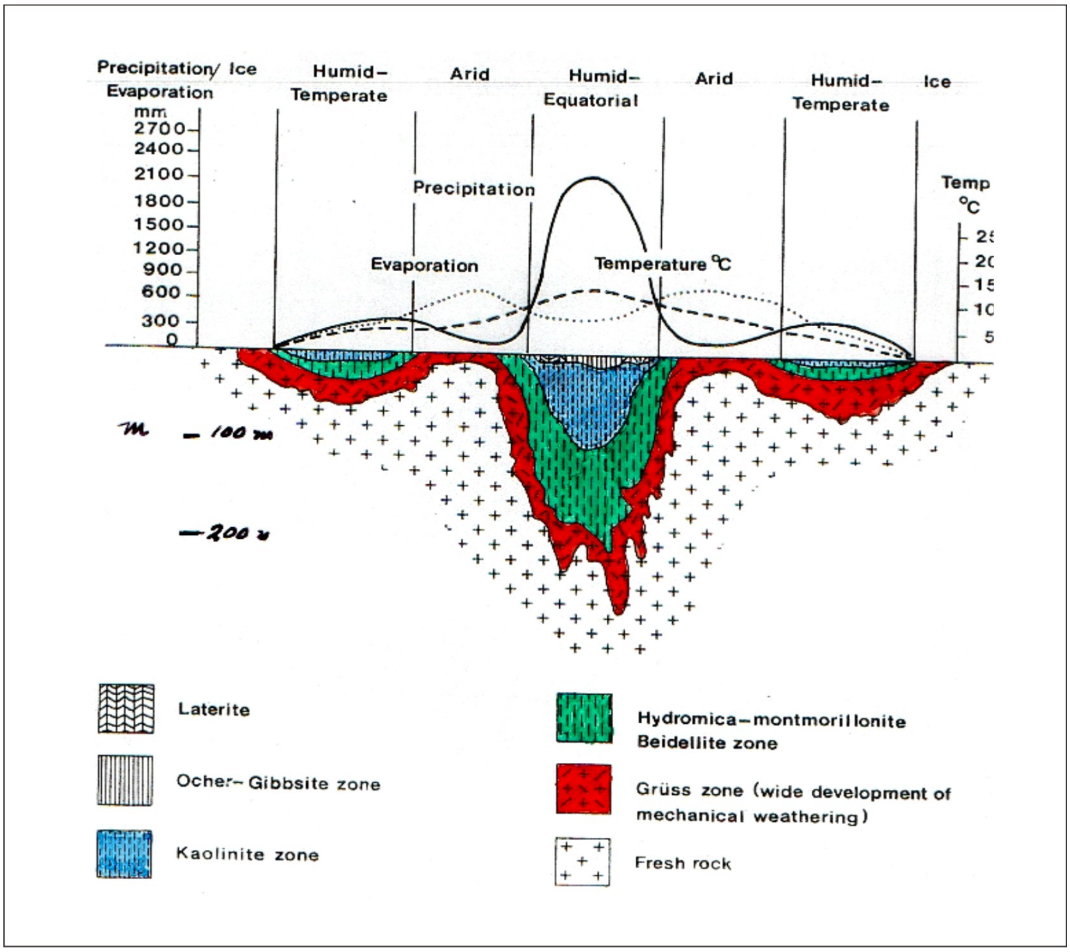

FIGURE 5. Global climatic zonation in present times, showing the relationship between depth of the weathering profile and the mineralogy of the sub-surface weathering products. From Strakhov, 1967.

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 an immense mass of weathered debris which remained stable for 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 in the Gondwana Paleolandscapes. This weathered debris cover was denudated during the Cenozoic, particular 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, 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 any more 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 paleolandscapes were unrepeatable because they could not fully develop today any where 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 Eocene, triggered worldwide denudation. The climate on the Gondwana supercontinent would have been very different from that on its fragments after break-up.

However, the upper Cretaceous and the Eocene were anomalous. It seems that the whole world was warm and wet, but perhaps the equator was still much as today whereas the poles were also like the equator today. Nevertheless, the high CO_2 content should have caused the equator to be much warmer than today (Walker and Sloane, 1992).

Paleo-monsoonal climates could have existed as well, though the present monsoon conditions seem to be a much recent event (Late Miocene-Pliocene) relating to the uplift of the Tibet plateau.

Finally, certain areas of Gondwana would have been under savannah climate conditions, which is certainly relevant in terms of duricrust formation.

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 ºC 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 is particularly significant in terms of ancient landscape interpretation is granite deep weathering. Since one of the conditions required for the development of Gondwana Paleolandscapes 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 Paleolandscapes (Twidale, 1982; Vidal Romaní and Twidale, 1998). However, the effect of surface temperature dies out rather quickly (just a few metres); therefore, the rest of the deep weathering depends basically on geothermal heat. The relevant fact is then that, due to the wet climate at the surface, abundant water availability may reach the deep layers where the weathering front is located and expand chemical weathering by dominant hydrolysis. Contrarily, carbonation is really one minor feature restricted to the top few metres of the weathering profile (C. Ollier, personal comm.).

Ollier (1990) shows a typical weathering profile in granitic rocks (Figure 6). Saprolite, or “rotten rock”, is an in-situ deeply weathered rock, which is usually indicated by the non-mobilized quartz veins, being quartz almost totally immune to weathering, unless extreme conditions are present. The alteration forced by weathering is iso-volumetric, 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).

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 it becomes the main residual material in the gruss, together with clay and 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” (Figure 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

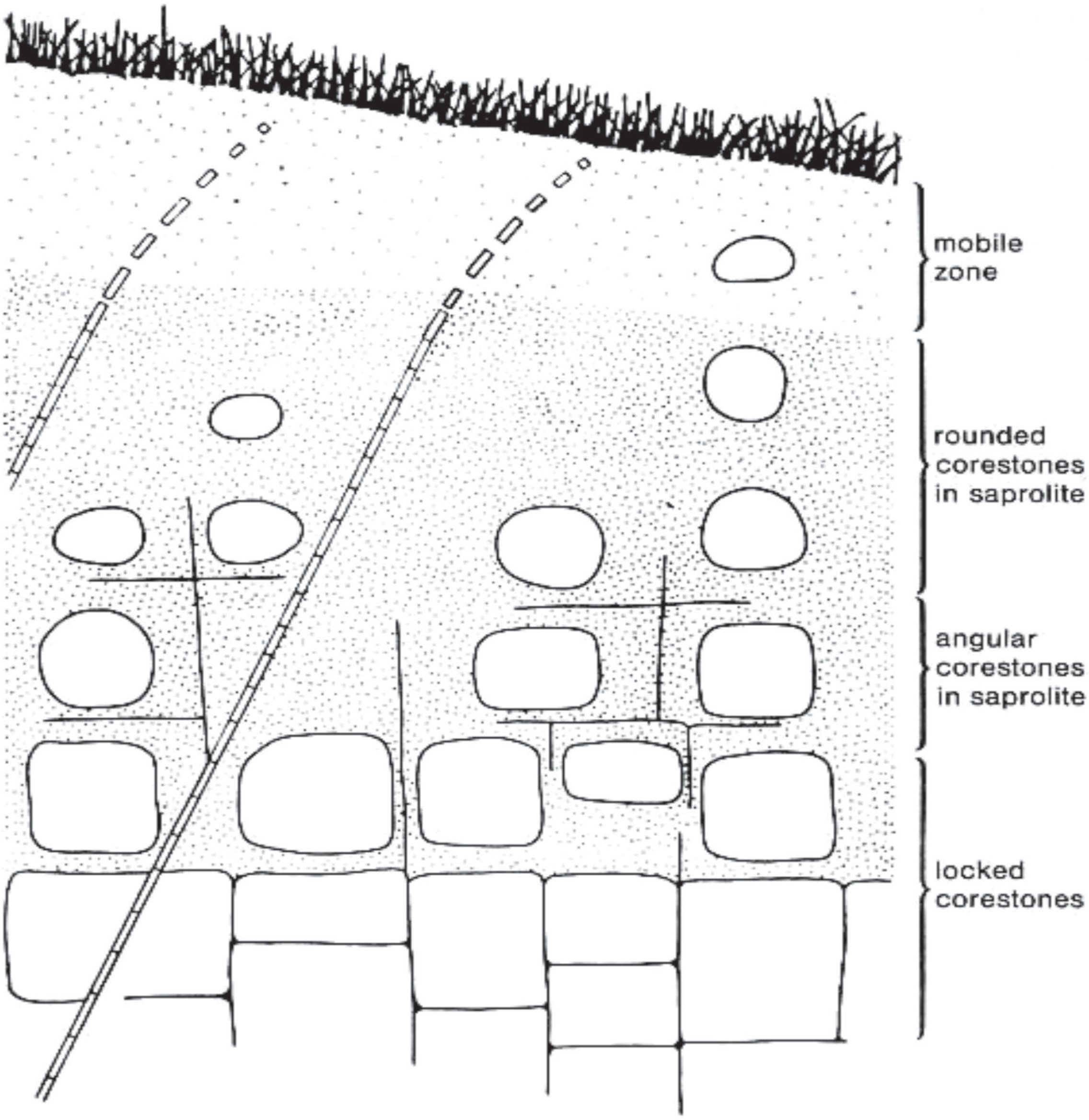

FIGURE 6. Granite weathering. A typical section of weathering in granites. Saprolite is an in-situ weathered rock, as indicated by the non-removed quartz veins. The alteration is iso-volumetric. Regolith is a term that includes all unconsolidated materials near the surface of the Earth, including saprolite. From Ollier, 1990.

unchallenged testimonies of past climates. The corestone accumulations on unweathered bedrock are called "tors" (Figure 8) and defined as "a bare rock mass surmounted and surrounded by blocks and boulders" (Linton, 1955). The equivalent term "kopje" ("koppie"), of Afrikaans origin, is used in Southern Africa. Many tors occupy the summit of "bornhardts" (Twidale, 2007b) and their evolution ends with their total dismantling (Figure 9). 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 Paleolandscapes 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 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 (Figures 10, 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 paleolandscapes. 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 arkosic 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" (Figure 12), which represent the position of the ancient weathering front. Granite inselbergs are usually showing frequent caves or smaller holes named as "taffoni". 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 (Figure 13). Landscape evolution includes several phases, from the development of the 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 (Figure 14) are "bare surfaces, dome-like summits, precipitous sides becoming steeper towards the base, an absence of talus, alluvial cones or soils, with a close adjustment of form to internal structure" (Thomas, 1968), named after the German geologist W. Bornhardt, who described these features in the early 20th century.

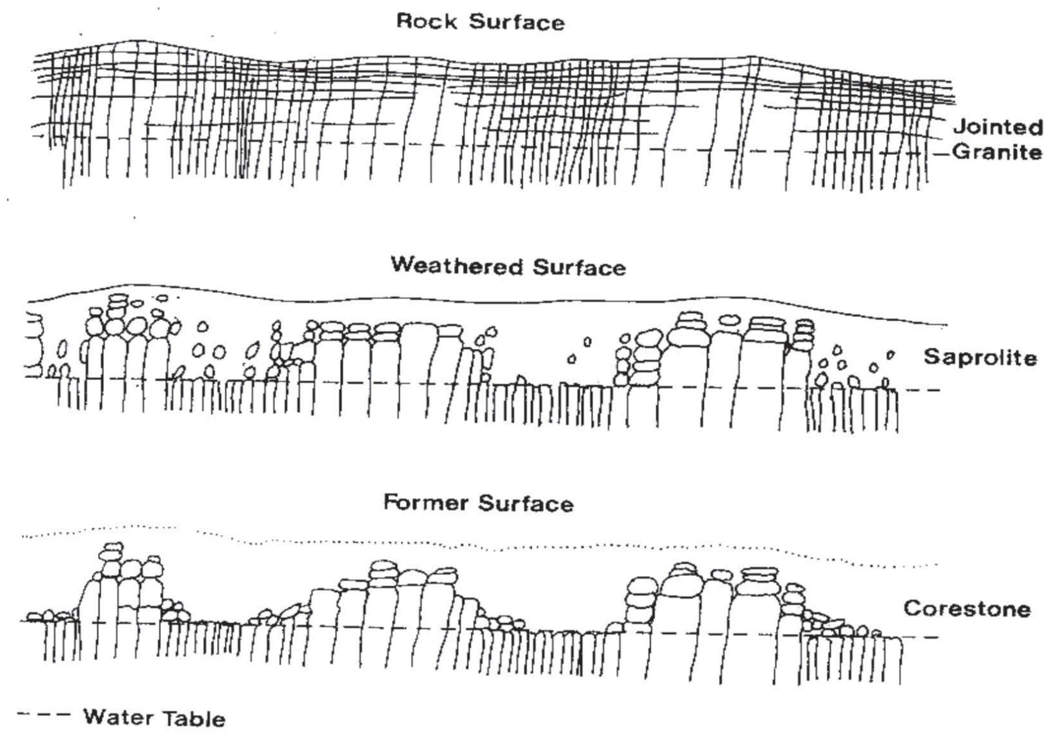

FIGURE 7. Corestone and tor development due to deep weathering and subsequent denudation, with finer, weathered material removal. From: Linton, 1955; see Fairbridge, 1968.

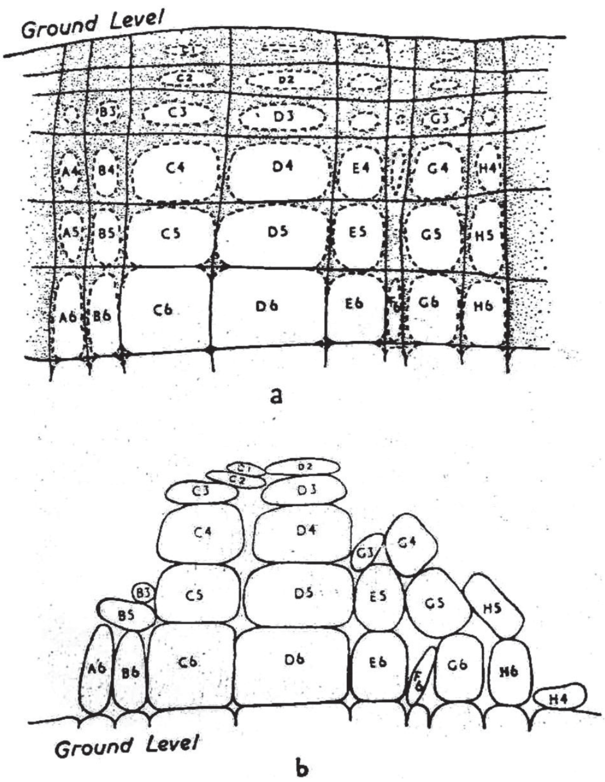

FIGURE 8. Stages in the evolution of a tor by sub-surface weathering. From Linton (1955). (a) Sub-surface corestone formation; (b) dismantling by denudation of the weathered materials.

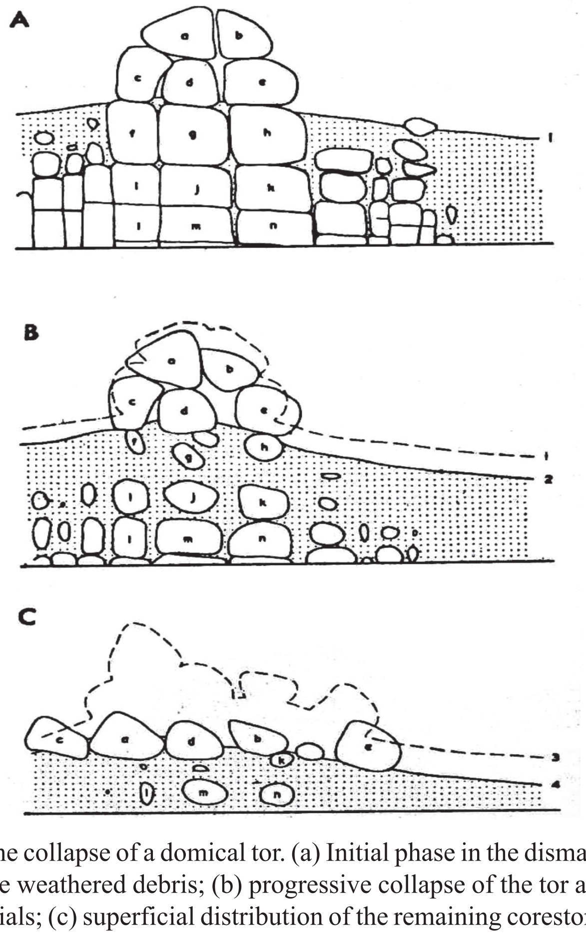

FIGURE 9. Stages in the collapse of a domical tor. (a) Initial phase in the dismantling of the tor group, with partial removal of the weathered debris; (b) progressive collapse of the tor as a result of the washing out of the weathered materials; (c) superficial distribution of the remaining corestones.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

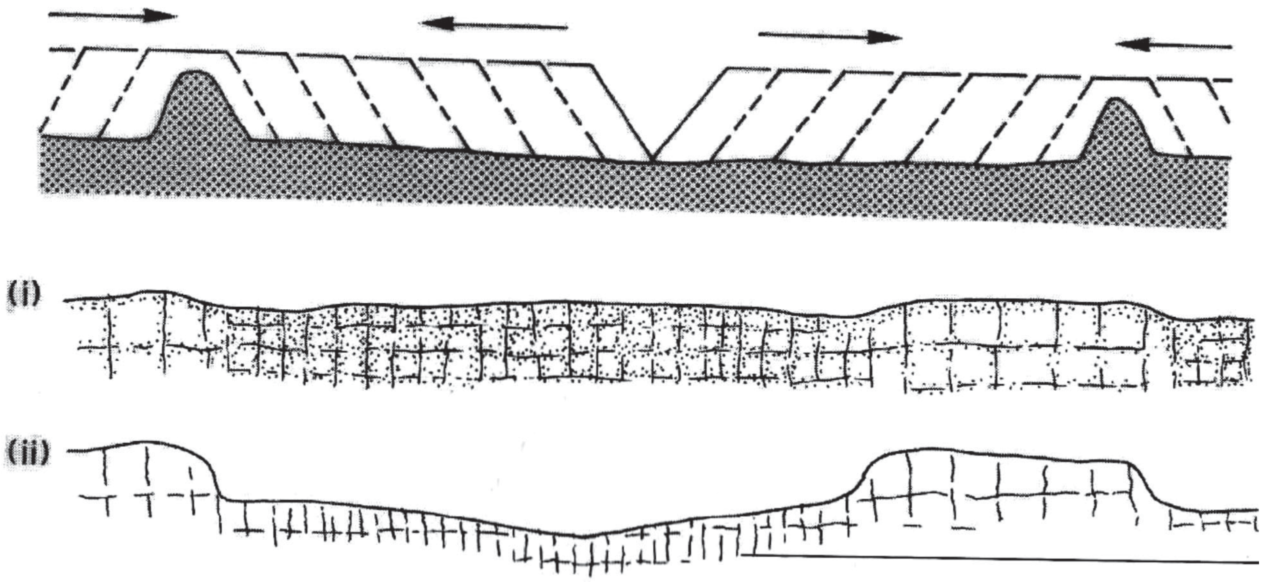

FIGURE 10. Formation of inselbergs and bornhardts. Upper figure: Inselbergs resulting from long-distance scarp retreat; lower figure (i) initial stage of etching of differentially jointed bedrock; (ii) final stage after removal of the weathered cover. From Twidale, 2007b.

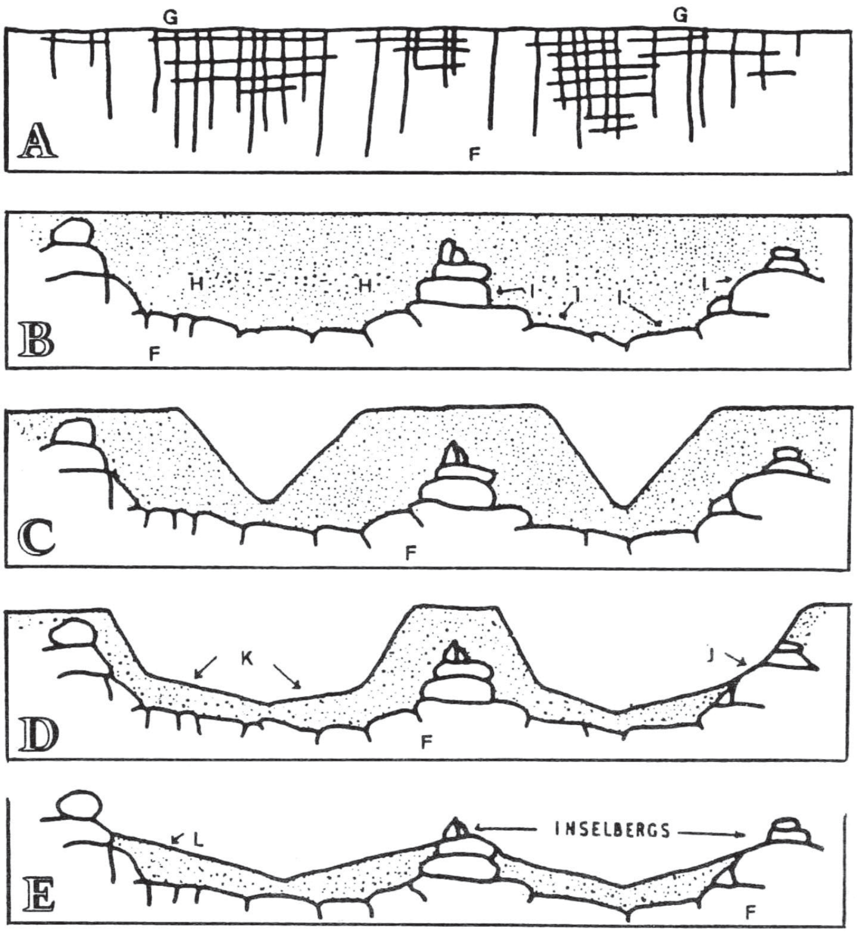

FIGURE 11. Formation of inselbergs. **A.** Gondwana erosion surface (g) developed by etching on differentially jointed rocks (f); **B.** Development of an irregular weathering front (i) with uneven weathered debris thickness (h); **C.** Partial incision of the weathered mantle, that develops in the deeper portions of the debris cover; **D.** Pediment (k) development on the weathered mantle and 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.

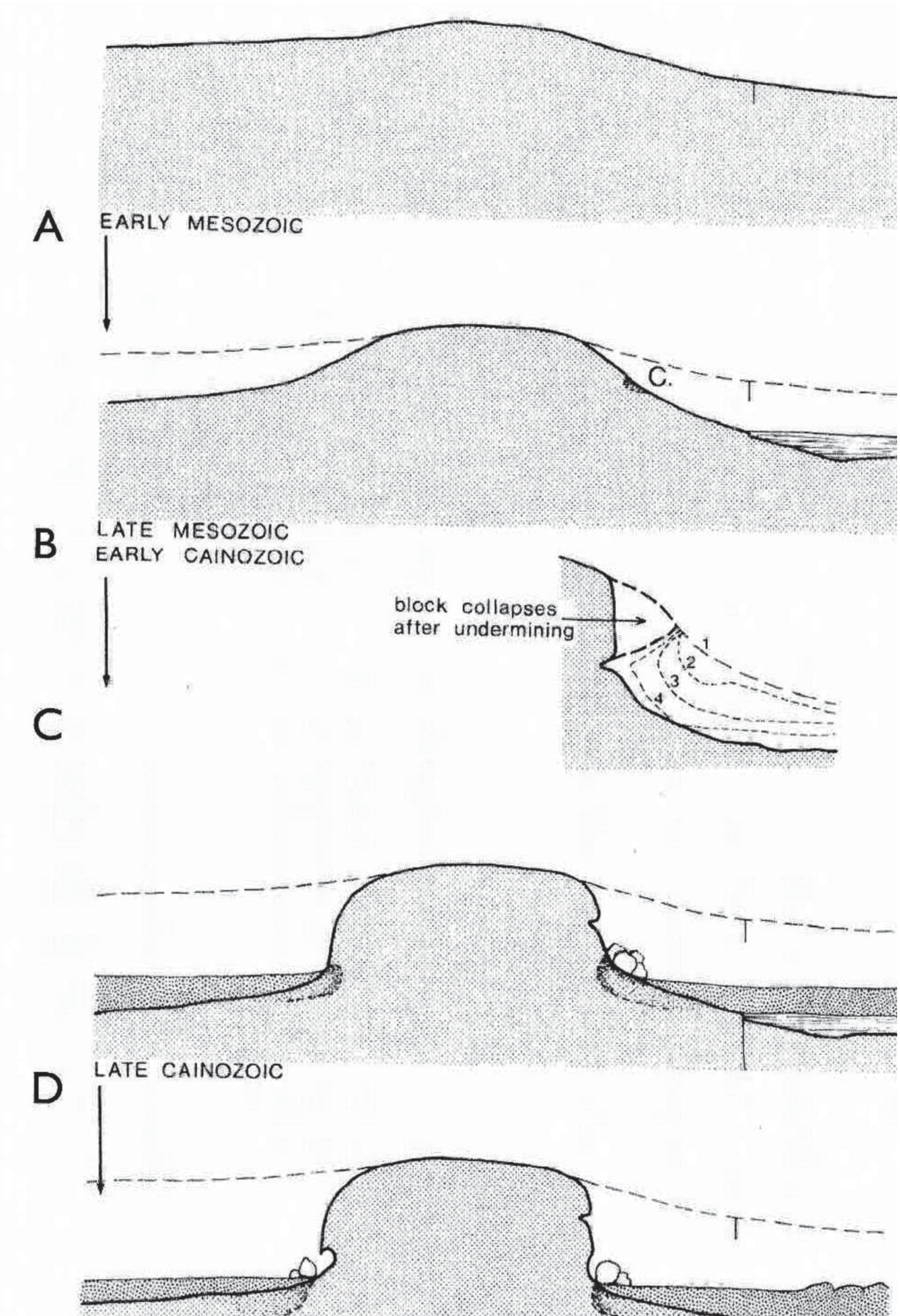

FIGURE 12. Age, evolution, and exposure sequence of Uluru (Ayers Rock), a giant inselberg in Central Australia, due to the denudation of the neighboring plains (Twidale, 2007a). **A.** Early Mesozoic bedrock landscape, under deep weathering conditions in wet tropical climate; **B.** Effect of differential weathering; (c) initial incision and origin of the flared surfaces during the Late Mesozoic-Early Cenozoic; dashed line, original surface and weathered area; **C.** A detail of the side walls, 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.

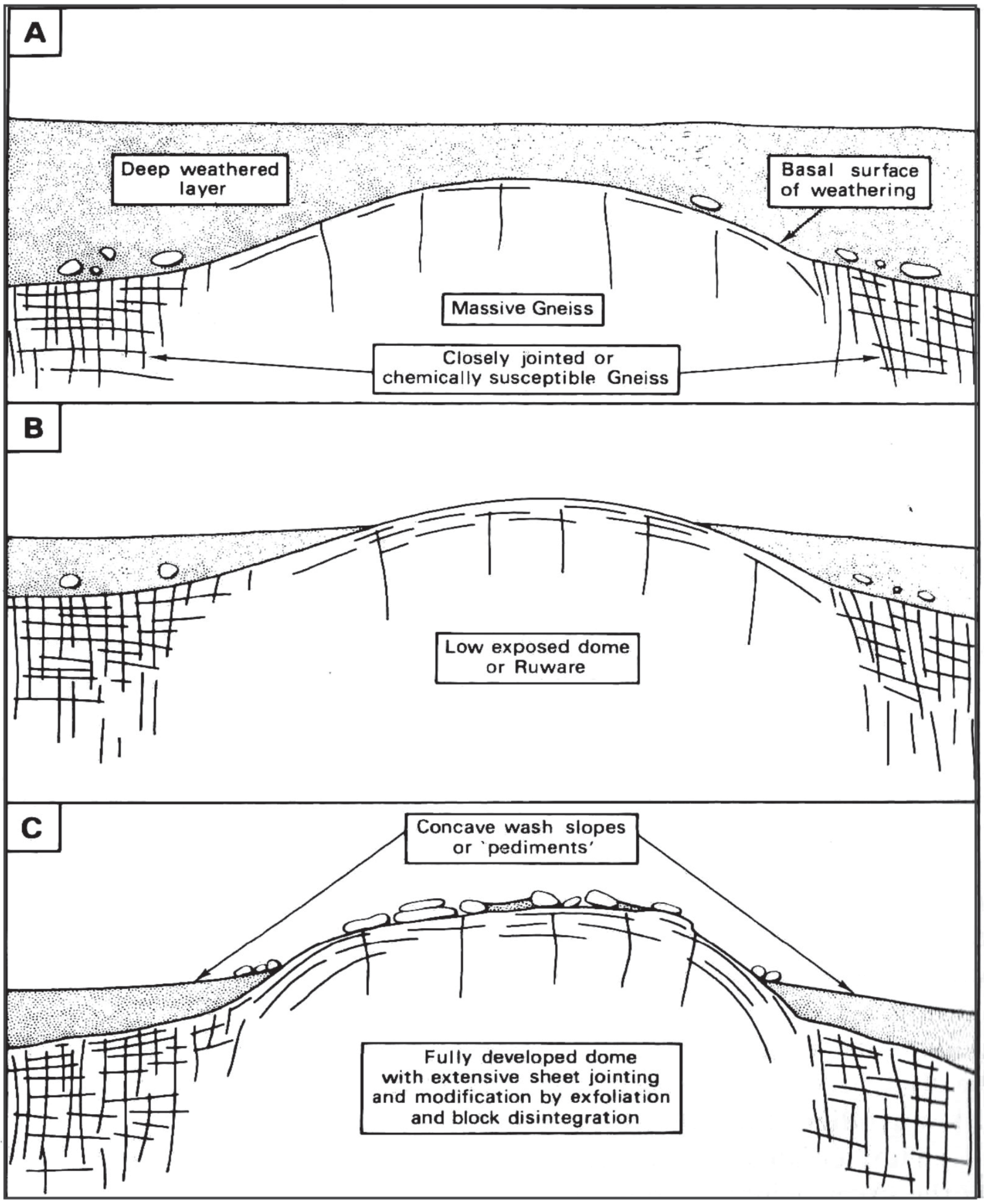

FIGURE 13. The development of ruwares and low domes by differential deep weathering and subsurface stripping of the deep weathered layers. From Small, 1978.

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).

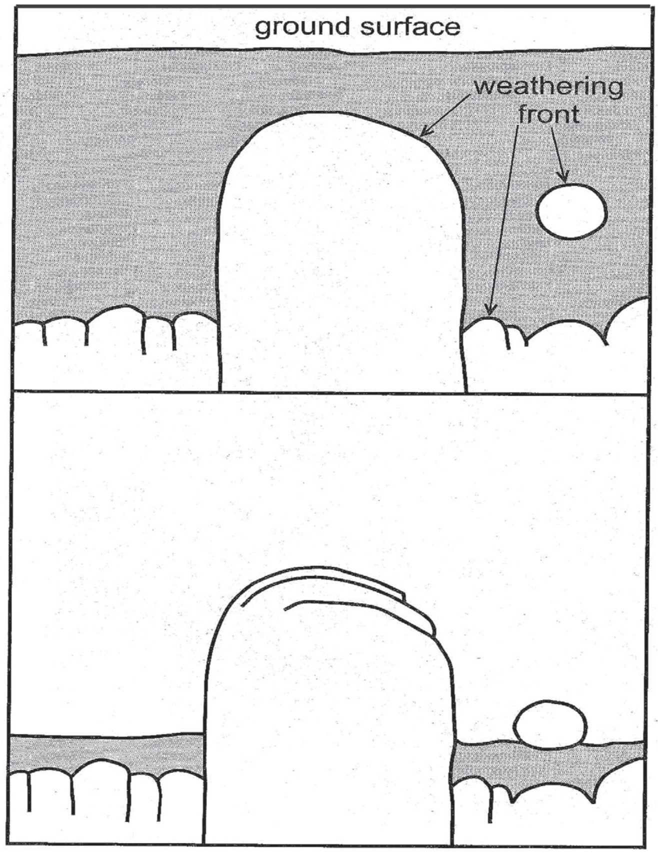

FIGURE 14. Bornhardt formation due to deep chemical weathering (etching) and subsequent removal of the weathered debris. Note that the local relief of the bornhardt is an approximate indicator clue of the ancient depth of the weathering profile. From Ollier and Pain, 2000.

PASSIVE-MARGIN GEOMORPHOLOGY

Passive-margin geomorphology is strictly related to the development of these types of landscapes. Once Gondwanaland broke up, new margins were formed, where rivers cut down and scarps retreated inland. Therefore, the different continental pieces started a new history of development in isolation. But, since all fragments were undergoing the same processes (except perhaps Antarctica) it is possible to try to correlate landscape evolution on the different continents, as Du Toit and Reed (1927) and King (1956a) did (C. Ollier, personal communication). At passive continental margins (Figure 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 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 de Mantiquiera and Serra do Mar, and in India it is represented by the Ghats Mountains. In eastern Australia, there is a very prominent erosion escarpment feature named as the "Great Dividing Range", which runs along the entire east coast of Australia inland of the coast. It includes the highest point in Australia, Mt. Kosciusko. East of it, the drainage is direct to the Pacific Ocean, but west of it, it goes into the Murray River basin (R. Maud, personal communication).

In Argentina and Uruguay, the position of the escarpment is still unclear and should be investigated.

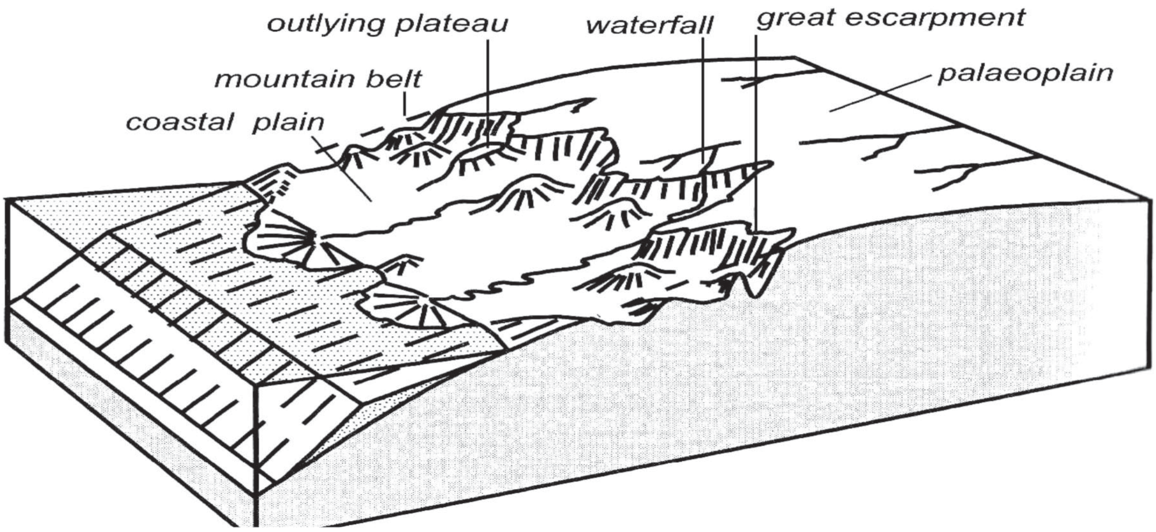

FIGURE 15. In passive continental margins, a large and continuous escarpment is developed by headward erosion from the coastal plain, degrading a former paleoplain, usually an etchplain, developed during previous stages of tropical climate with deep chemical weathering. The position of the escarpment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

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 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 is 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 re-deposited, 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 (Figure 16). The process may be repeated through time, indicating the existence of several planation surfaces or progressively younger age with lower elevations (Figure 17). 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 in-filling 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, 1991).

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, 1991). They are very good indicators of past climates and have been found in many different environments and ages.

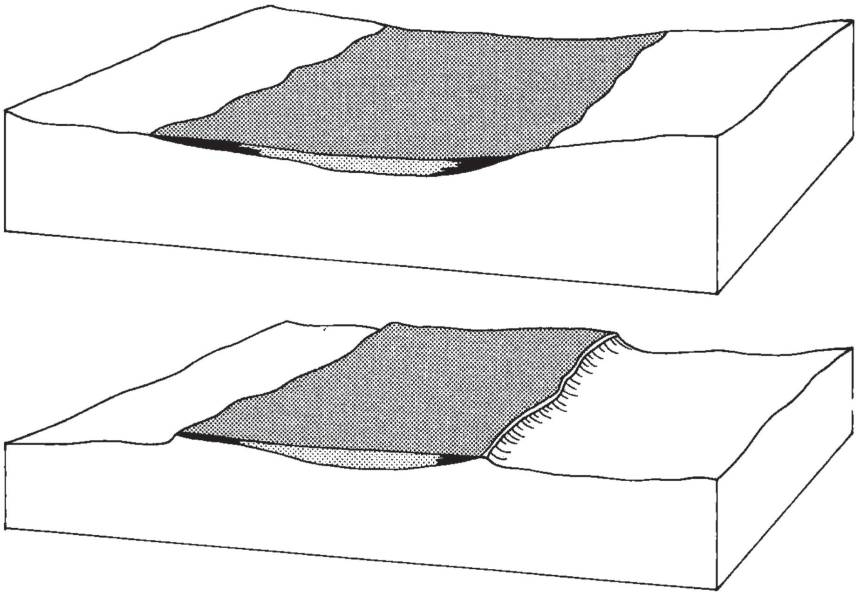

FIGURE 16. Duricrusts and inversion of relief. From Ollier, 1991. In the top figure, ferricretes are precipitated on lower slopes and valley bottoms. The bottom figure shows the inversion of relief, producing a ferricrete-capped mesa or tableland.

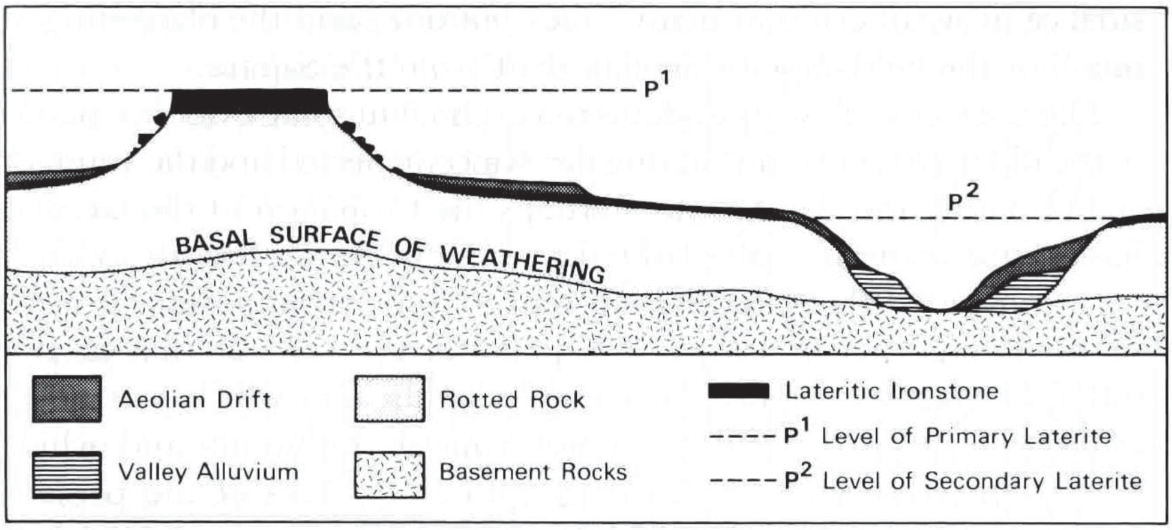

FIGURE 17. Two cycle laterite formation, landscape development and preservation of the weathered materials (Small, 1978).

A BRIEF AND PRELIMINARY REVIEW OF GONDWANA LANDSCAPES AND OTHER ANCIENT PALEOLANDSCAPES IN THE SOUTHERN HEMISPHERE AND OTHER PARTS OF THE WORLD

Du Toit (1954) 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 meters 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).

Lester C. King (1950) described global cycles of planation and extended their identification since the Jurassic (Chart 1). King (1950) provided evidence for the existence of a world-wide, 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 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. Dixey (1938; 1942; 1955a, b) also identified erosion surfaces in central and southern Africa. He was a real pioneer of erosion surface and marginal uplift work in Southern Africa, but his work was submerged by that of King.

Timothy Partridge (Figure 18) and Rodney Maud (Partridge, 1998; Partridge and Maud, 1987, 1989, 2000) represented the South African geomorphological school that was started by Lester C. King in the 50s. They completed the regional mapping of the large paleosurfaces (Figure 19; Partridge and Maud, 2000), 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, 2000) 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 remnant areas above the Cretaceous plains. However, Partridge and Maud (1987) differed very markedly from King in that they did not recognized the existence of the "Gondwana" and "Post Gondwana" erosion surfaces. They claimed that due to erosion, no remnants of these very early surfaces, even surviving from pre-Gondwana break-up times existed, unlike what Lester King claimed. For instance, Partridge and Maud (1987) stated that on the top of Lesotho where King reckoned his Gondwana surface survived, from the morphology of a kimberlite pipe penetrating the basalt, some 300 m of lava have been removed since the emplacement of the pipe in the late Cretaceous, ca. 87 Ma ago, indeed a very low erosion rate of ca. 0.35 mm per century, though. These figures were recently recalculated by Hanson et al. (2009) using also information coming from the kimberlite pipes, who estimated that, in the Karroo area, at least a thickness of 500 m of rocks was removed between 120 and 85 Ma, and approximately additional 850 m thickness was eliminated between 85 Ma and present times, with erosion rates of ca. 15 and 10 m/Ma, respectively (i.e., 1.5 and 1.0 mm per century). In any case, the study of these kimberlites has allowed the recognition of Late Jurassic and Early Cretaceous paleosurfaces. Likewise, the kimberlites and their derived

CHART 1. Sequence of global planation surfaces and paleolandscpaes in Southern Africa, according to L.C. King (1950).

	Old Name	New Name	Recognition
I	Gondwana	The Gondwana planation	Of Jurassic age, only rarely preserved.
II	Post-Gondwana	The Kretacic planation	Early mid-Cretaceous age.
III	African	The Moorland planation	Current from Late Cretaceous till the mid-Cenozoic. Planed uplands, treeless and with poor soil.
IV		The Rolling landsurface	Mostlyof Miocene age, forms undulating country above yonger incised valleys.
V	Post-African	The Widespread landscape	The most widespread global cycle, but more often in basins, lowlands and coastal plains than uplifted by recent tectonics to form mountain tops. Pliocene in age.
VI	Congo	The Yongest cycle	Quaternary in age represented by the deep valleys and gorges of the main rivers.

FIGURE 18. Timothy C. Partridge, professor of Geomorphology, University of Witwatersrand, Johannesburg, South Africa, a distinguished scholar in different fields of Gondwana Landscapes, deceased in 2009. Photo by J. Rabassa, 1991.

diamonds provided basic information to understand the eastward displacement of the Drakensberg Escarpment and subsequent modification of the drainage direction since the Early Cretaceous (De Wit et al., 2009; the present author is greatly indebted to Professor R. Maud for indicating these references).

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 (Figure 20). 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

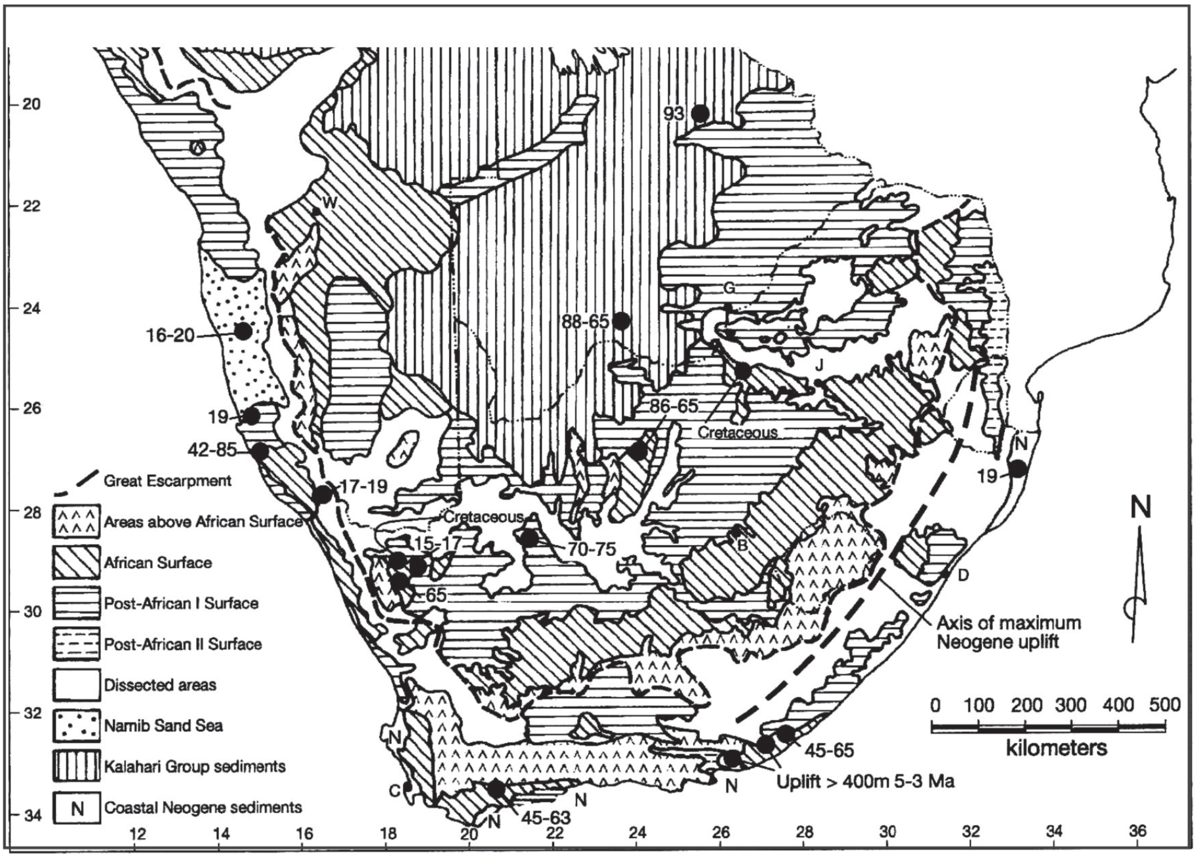

FIGURE 19. Map of the paleosurfaces of Southern Africa, according to Partridge and Maud (2000). Note the sequence starting in pre-African Surface times, that is, in Late Jurassic or Earliest Cretaceous times.

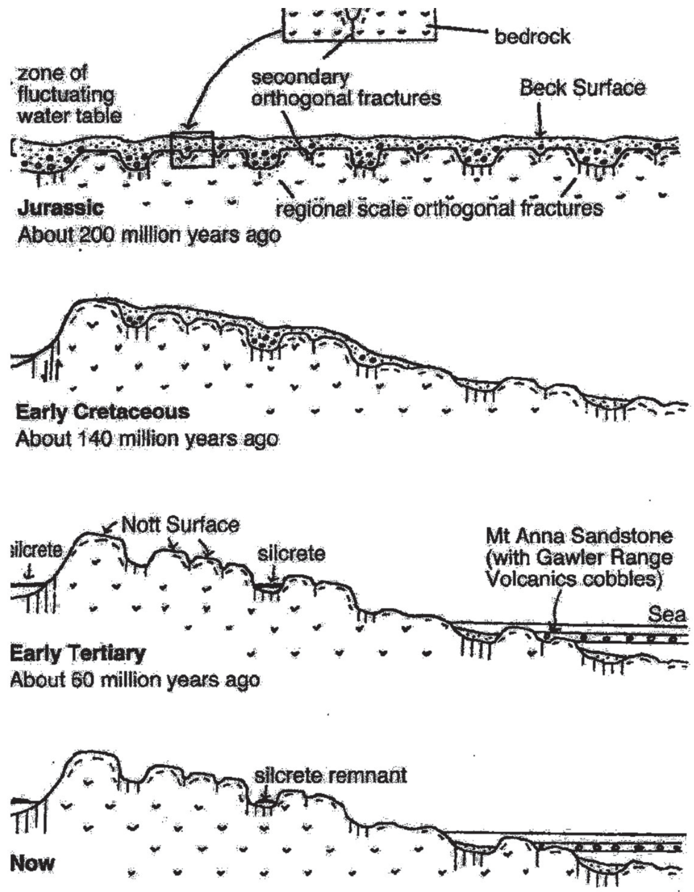

FIGURE 20. Evolution of Australian Paleolandscapes (Twidale, 2007a). Sequence of development of etchplains of Jurassic age, followed by uplifting and subsequent tilting, Cretaceous denudation, silcrete formation in the Paleogene and Late Tertiary denudation.

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 super-continent, and the "Geomorphological surfaces", chiefly developed in the Tertiary. Likewise, Geramisov (1970) proposed three megacycles in the geomorphological development of the Earth during the Mesozoic-Cenozoic. 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. They recognized the possibility of time-synchronous, world wide erosion surfaces, some of them as old as the Late Triassic (though in this case they are mostly covered surfaces) and the Jurassic (Chart 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 12-2 Ma (Pliocene, "Somerville Time) (Chart 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.

CHART 2. World correlation of the planation surfaces and erosion landscapes (from Melhorn and Edgar, 1975), in South Africa, West Africa, Brazil and Uruguay, Australia, India, Mongolia and China. Note that Jurassic Gondwanic Paleolandscapes have been identified in most areas in the Southern Hemisphere, but also in Asia, where Gondwana equivalent surfaces are named as "Laurasian".

	AGE TO BASE (M.Y.)	SOUTH AFRICA	WEST AFRICA	ANGOLA	BRAZIL/ URUGUAY	AUSTRALIA	INDIA	MONGOLIA	CHINA
PLEISTOCENE		CONGO			PARAGUAÇU	WUDINNA	XXX	PANGKIANG	PANCHAIO
————	2					KOONGAWA	JAMDA	GOBI	
PLIOCENE									
————	7	NOSSOB/ COASTAL PLAIN		XXX	VELHAS	MECKERING			
MIOCENE			HO-KETA				NAOMUNDI		TANGSHIEN
————	26								
OLIGOCENE						UN/NONNING	KIRIBIRU		
————	38		ASHANTI	NAMIB				KHANGAI/ MONGOLIAN	PEI-TEI
EOCENE		AFRICAN			SUL-AMERICANA	AUSTRALIAN PEDIPLAIN	INDIAN		
————	54								
PALEOCENE									
————	65	POST-GONDWANA			XXX	SIMMENS/NOTT	POST-GONDWANA	POST-LAURASIAN	POST-LAURASIAN
CRETACEOUS									
————	135		VOLTAIAN	BENGUELLA					
JURASSIC		GONDWANA		PLANALTO	GONDWANA	GONWANA/ MT. DALE	GONDWANA/ NILGIRI	LAURASIAN	LAURASIAN
————	200		AGU MTN.						

CHART 3. Correlation chart of North American erosion surfaces. From Melhorn and Edgar (1975).

	AGE TO BASE (M.Y.)	APPALACHIANS	INTERIOR LOW PLATEAUS	INTERIOR HIGHLANDS	CENTRAL LOWLANDS	GREAT PLAINS	ROCKY MOUNTAINS	GREAT BASIN	SIERRA/ CASCADE
		VALLEY CYCLE	DEEP STAGE	VALLEY CYCLE	DEEP STAGE	TERRACES			
PLEISTOCENE							CANYON CYCLE	PEDIMENT CYCLE	KERN RIVER CANYON CYCLE
				POST-OSAGE STRATH	HAVANNA STRATH				
————	2								
PLIOCENE		SOMERVILLE	PARKER	OSAGE STRATH	CENTRAL ILLINOIS	FLAXVILLE		ANTLER	MOUNTAIN VALLEY (?)
————	7								
MIOCENE							ROCKY MTN./ SUBSUMMIT		CHAGOOPA/ BROAD VALLEY
		HARRISBURG	LEXINGTON/ HIGHLAND RIM	HOT SPRINGS /OZARK	LANCASTER /CALHOUN				
————	26								
OLIGOCENE									
————	38								
EOCENE						PRAIRIE/ CYPRESS HILLS	FLATTOP/ SUMMIT	"BROKEN HILLS" (?)	SUBSUMMIT/ BOREAL
————	54								
PALEOCENE		SCHOOLEY		OUACHITA/ SPRINGFIELD	DODGEVILLE (?)				SIERRA/SUMMIT (?)
————	65								
CRETACEOUS									

In Central USA, 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) have described the "tepuis" of the Guyana Massif as features developed since Jurassic times (Figure 21). This diagram suggests the possibility of having remnants of even older

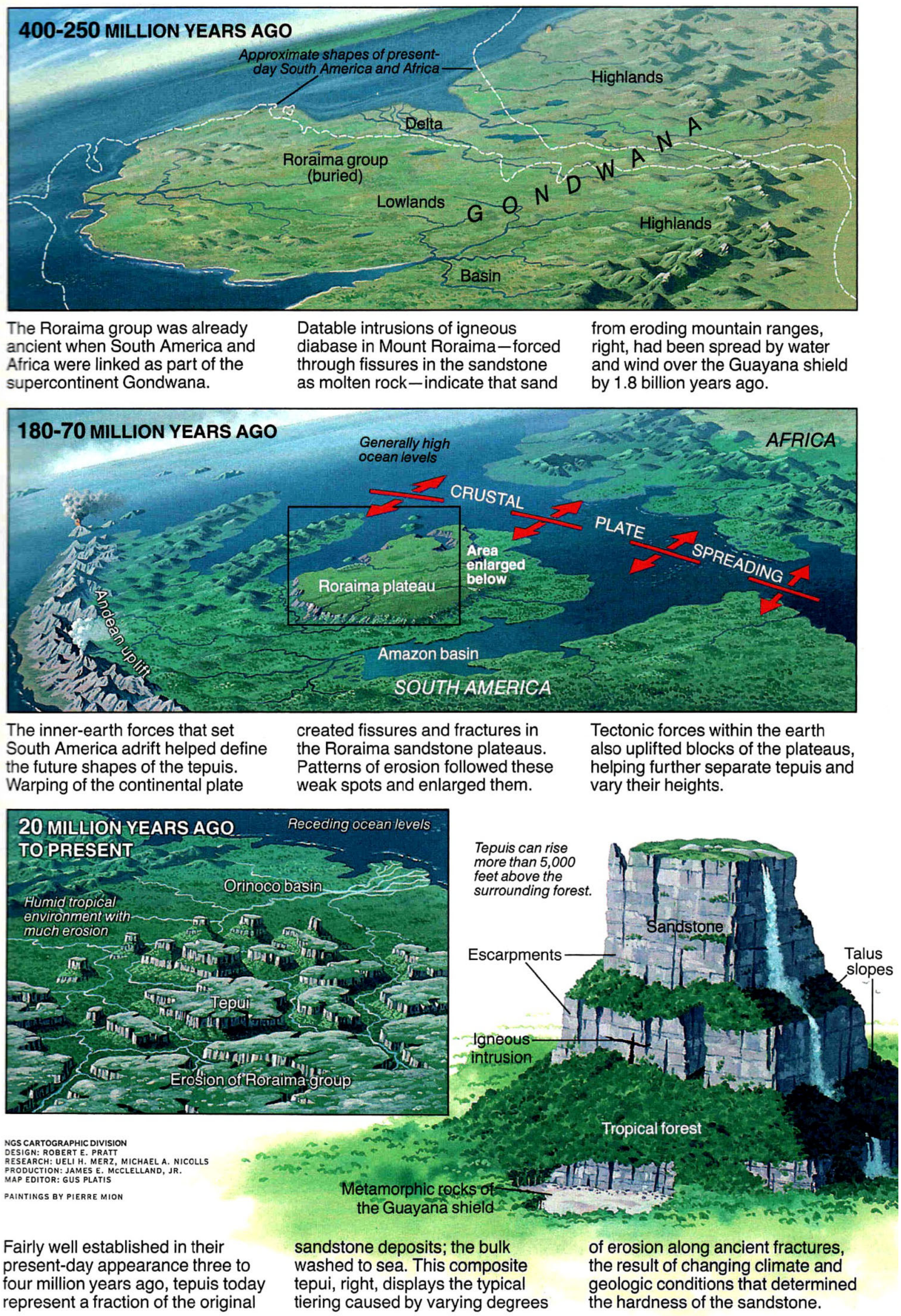

FIGURE 21. Geomorphological evolution of the Guyana "Tepuis" starting in the Late Jurassic. From George, 1989 (National Geographical Magazine).

(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; 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 (Figure 22). Schubert et al. (1986) identified six main levels, shown in Chart 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 Paleolandscapes.

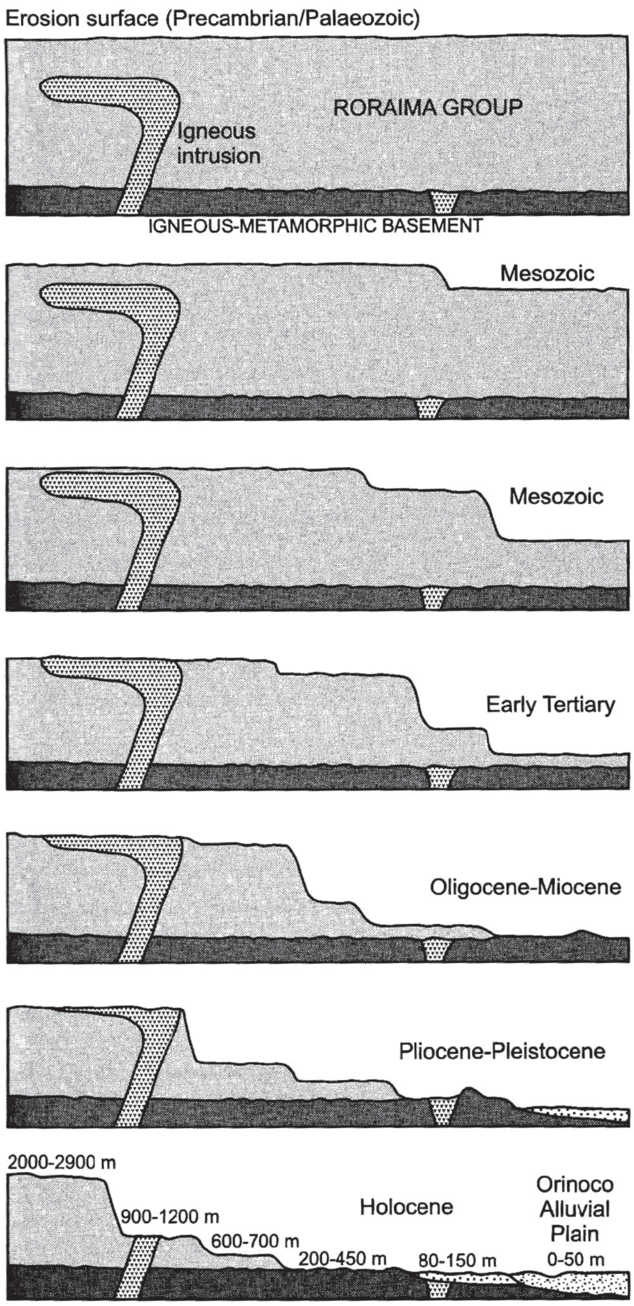

FIGURE 22. Geomorphological evolution of the "Tepuis" of the Gran Sabana of Venezuela, in the Guyana Massif. Development of planation surfaces since the Mesozoic. From Schubert and Huber, 1990 (in Ollier and Pain, 2000). This is a type example of Walther Penck's concept of "piedmonttreppen". The graph 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.

CHART 4. Erosion surfaces identified in the Guyana Massif.
From Schubert et al., 1986. In: 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	Kaietur Kuyuwini-Oronoque (Guyana), Early Velhas (Brazil), Caroni-Aro (Venezuela)	Olig-Miocene (?)
150–80	Rupununi (Guyana), Late Velhas (Brazil), Llanos (Venezuela)	Plio-Pleistocene
50–0	Mazaruni (Guyana), Parguaçu (Brazil), Orinoco Plain (Venezuela)	Holocene

King (1956 a, b) described in 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 sub-humid tropical to subtropical climate. The Brazilian landscape has probably developed continuously since Mesozoic times. João José Bigarella (Figure 23) and Aziz Ab'Sáber have been the leaders of ancient landscape studies in Brazil in the second half of the 20th century (see for example, Ab'Sáber, 1969; Bigarella et al., 1994; Bigarella and Ab'Sáber, 1964), and 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 5 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) described the landscape of the Uruguayan Sierras region, mostly in the Departamento Minas, eastern Uruguay. In an overall very flat country, 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 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 in the ancient shield and which provided most of the sedimentary materials that are infilling the neighboring accumulation basins. Panario

FIGURE 23. João José Bigarella and the summit planation surfaces in the Paraná Plateau, which he studied and described extensively. Photo by J. Rabassa, 1976.

(1988) 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 Paleolandscapes are recognized in all cratonic areas (Carignano et al., 1999). Landforms of this nature have been observed in the (a) 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-Falklands Islands. The nature and characteristics of the Gondwana Paleolandscapes in the mentioned areas are described in another paper (Rabassa et al., 2010).

Finally, in the Malvinas-Falkland islands, a continental fragment which drifted away from the southernmost portion of Africa, Clapperton (1993) 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 sub-aerial denudation, as expected in a former portion of Gondwanaland. 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 Paleolandscapes 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 paper 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 meters. 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 montmorilllonite-beidellite-hydromicas 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 significant 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 non existing 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, they 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 re-analyze the Geomorphology of the cratonic areas of different parts of the world, and particularly of Argentina, with a "Gondwanic vision" that replaces the presently dominant "Andean vision".

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This paper is dedicated to the memory of Professor Timothy C. Partridge (University of Witwatersrand, Johannesburg, South Africa; Figure 18), who died unexpectedly in South Africa, a few days after our Paleosurface Symposium was held in September 2009, during the IV Argentine Congress of Geomorphology and Quaternary Studies, at La Plata. In several letters of the last two years previous to the cited meeting, Tim had encouraged me to organize this symposium and to submit the present paper. He had also enthusiastically accepted to be then one of the main reviewers of the papers forming the present volume, for which his experience, knowledge and support would have been extremely inspiring. His early death has deprived the Geomorphology of the Ancient Surfaces of the Southern Hemisphere of one of its most distinguished scholars. We will certainly miss his much creative work and friendly collaboration.

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