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Quaternary deposits in the Serra da Capivara National Park and surrounding area, Southeastern Piauí state, Brazil

Depósitos quaternários no Parque Nacional Serra da Capivara e circunvizinhanças, Sudeste do Piauí, Brasil

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Abstract

Serra da Capivara National Park and surrounding areas in Southeastern Piauí State (Brazil) were subjected to morphostratigraphical, sedimentological, and geochronological studies about superficial deposits in order to interpret quaternary paleoenvironmental events. The following sedimentary deposits associated with morphostructural units were identified: colluvial fans at Serra Branca Valley and Structural Staircases, and eluvial-colluvial deposits at Reverse of the Cuesta. There are also colluvial and alluvial deposits outside Serra da Capivara National Park. Many colluvial and alluvial deposits are contemporaneous and indicate a semiarid climate. According to luminescence dating (thermoluminescence and optically stimulated luminescence), the present landscape evolution began around 436 ± 51.5 ka when the Piauí River deposited clayey sediments. From 296.55 ± 46.95 ka to 116.3 ± 19.52 ka, the fluvial channel likely exhibited a braided pattern and deposited sand and gravel bars. Penecontemporaneous sands and muds with ages ranging from 202.75 ± 32.81 ka, 135 ± 16.4 ka to 117 ± 14.5 ka were deposited on Serra da Capivara National Park hillslopes. A colluviation episode occurred between 84.7 ± 13.4 ka to 76.2 ± 9.35 ka, which lacks correlatable alluvial deposits. In the Northern hemisphere last glacial maximum, the colluviation and alluviation processes intensified. These depositional processes likely occurred between 15.8 ± 1.9 and 10.35 ± 1.76 ka, during the Holocene-Pleistocene transition.

Keywords: Sedimentary deposits; Morphostratigraphical; Sedimentology; Luminescence dating; Quaternary paleoenvironmental; Serra da Capivara National Park.

Resumo

No Parque Nacional Serra da Capivara e nas circunvizinhanças, na região Sudeste do Piauí, no Brasil, foram realizados estudos morfoestratigráficos, sedimentológicos e geocronológicos de depósitos superficiais para a interpretação de eventos paleoambientais, principalmente paleoclimáticos quaternários. Os depósitos sedimentares associados às unidades morfoestruturais são: leques coluviais no Vale da Serra Branca; depósitos elúvio-coluviais no Reverso da Cuesta e depósitos coluviais do Patamar Estrutural. Fora do Parque Nacional Serra da Capivara ocorrem também colúvios e depósitos aluviais do Rio Piauí. Muitos depósitos coluviais e aluviais são contemporâneos e indicativos de clima semiárido. De acordo com datações obtidas por luminescência (termoluminescência e luminescência opticamente estimulada), a evolução da paisagem atual iniciou-se há no mínimo 436 ± 51,5 ka, quando o rio Piauí depositou sedimentos argilosos. Entre 296,55 ± 46,95 ka e 114,8 ± 14,2 ka, o canal fluvial deste rio exibia provavelmente padrão entrelaçado e depositava barras de areia e cascalhos. Areias e lamas penecontemporâneas, com idades entre 202,75 ± 32,81 ka, 135 ± 16,4 ka e 117 ± 14,5 ka, foram depositadas nas vertentes do Parque Nacional da Serra da Capivara. Novo episódio de coluviação ocorreu entre 84,7 ± 13,4 ka a 76,2 ± 9,35 ka, sem depósitos aluviais correspondentes. Durante o último máximo glacial do Hemisfério Norte parece ter ocorrido intensificação dos processos de coluviação e aluviação. Nova retomada desses processos deposicionais teria ocorrido entre 15,8 ± 1,9 e 8,9 ± 1,52 ka na transição Pleistoceno-Holoceno.

Palavras-chave: Depósitos sedimentares; Morfoestratigrafia; Sedimentologia; Datação por luminescência; Paleoambientes quaternários; Parque Nacional Serra da Capivara.

INTRODUCTION

Relief that is significantly covered with loose materials derived from rocky substrate weathering characterizes tropical landscapes. The loose materials are found at several topographic locations, including the highest and flattest portions of the relief, and they are classified as eluvium (in place) and colluvium, which were transported from higher to lower altitudes by gravitational flows. Even loose material could be partially transported to drainage channels, where the so-called alluvial deposits are constituted (Bigarella and Mousinho, 1965; Warke, 2007). The study of depositional dynamics allowed identifying and understanding the landscape's evolutionary sequence and chronology of obtained data. Sedimentological, stratigraphic, morphostratigraphical, and geochronological information were essential to outline the landscape's history and evolution.

In the context of the Quaternary environment, the sedimentary cover of Serra da Capivara National Park (PNSC) and its surroundings are in need of geological and geomorphological characterizations. The studied area is globally know because it contains the largest concentration of rock paintings in the American continent, and contains over one thousand archaeological sites. Local archaeological studies during the last 39 years suggest evidence for the presence of human beings since 48,000 years before present – BP (Guidon et al., 1994), whose chronological range extends from 230 to approximately 48,000 years BP (Felice, 2000).

In order to understand the evolution of the sedimentary environments and their deposits, research was conducted, and provided morphostratigraphic, sedimentologic, and chronologic data. It is part of the doctoral thesis of Santos (2007) and allowed the first delineation of the local Quaternary geological evolution.

STUDY AREA

The PNSC occupies an area of ~129,953 ha that extends throughout the Brejo do Piauí, João Costa, São Raimundo Nonato, and Coronel José Dias municipalities in Southeastern Piauí State, Brazil (Figure 1). According to Koppen's classification, the local climate is Shw, which is hot and semiarid with summer rains. The average annual temperature is 28°C, and the rainy season extends from October to April, characterized by an irregular rainfall regime with an average annual precipitation of approximately 689 mm (Emperaire, 1980).

The study area resided within Piauí-Canindé river sub-basin, which is related to the Parnaíba River hydrographic basin. Piauí river and its tributaries present a temporary torrential flow regime (Pellerin, 1984). The vegetation type is *caatinga*, which is composed of typical Northeastern Brazilian semiarid vegetation. According to Emperaire (1980), the area has different types of *caatinga* including tall and thick shrubby, arboreal plants, medium dense arboreal, low shrubby, and shrubby-arboreal.

Geological and geomorphological contexts

The PNSC is located at the frontier of two distinct geological domains, the Borborema Structural Province represented by Riacho do Pontal Folded Belt and the Parnaíba Sedimentary Basin (Figure 2). Riacho do Pontal Folded Belt exhibits folded-structural systems that have irregular shapes. It occupies an area of approximately 28,000 km^2, which was formed during the Brazilian cycle and is Neoproterozoic in age (Neves, 1975; Almeida et al., 1977). According to Oliveira (1998), the study area contains the Neoproterozoic Barra do Bonito shearing subzone, which is composed of metamorphic and magmatic rocks.

The Parnaíba Sedimentary Basin is a representation of the Northeastern Brazil, encompassing an area of 600,000 km^2 that extends throughout Pará, Tocantins, Maranhão, Piauí, Ceará and Bahia states, and is Paleozoic and Mesozoic in age (Mesner and Wooldridge, 1964). In the study area outcrop, Serra Grande and Canindé Groups are Silurian and Devonian in age. Serra Grande Group is composed of Ipú, Tianguá and Jaicós Formations, and Canindé Group is composed of the Itaim, Pimenteira, Cabeças, Longá and Poti Formations. However, the last two formations do not outcrop within the study area (Góes and Feijó, 1994).

Santos (2007) recognized the existence of the following morphostructural-geomorphological units: Serra Branca Valley, Reverse of the Cuesta, and Structural Staircases (Figure 1). Serra Branca Valley unit occurs at the Northern and in Western portions of the park, and its hillslopes may or may not be covered by sediments. The summits are 520 m high, the valley reaches 400 m of altitude, and the colluvial fans are present at the middle portions of the hillslope. The Reverse of the Cuesta unit is at a higher elevation with a flat morphology, the altitudes change between 520 to 600 m, commonly covered by eluvial-colluvial deposits. The Structural Staircases are characterized by the presence of a staircase relief, which can be subdivided into two subunits: Southern Structural Staircases with four steps and Northeastern Structural ones with two steps. In its Southern portion, whose lower third of the hillslope is covered by Quaternary colluvial deposits, it presents two different steps at Northeastern portion without sedimentary deposits.

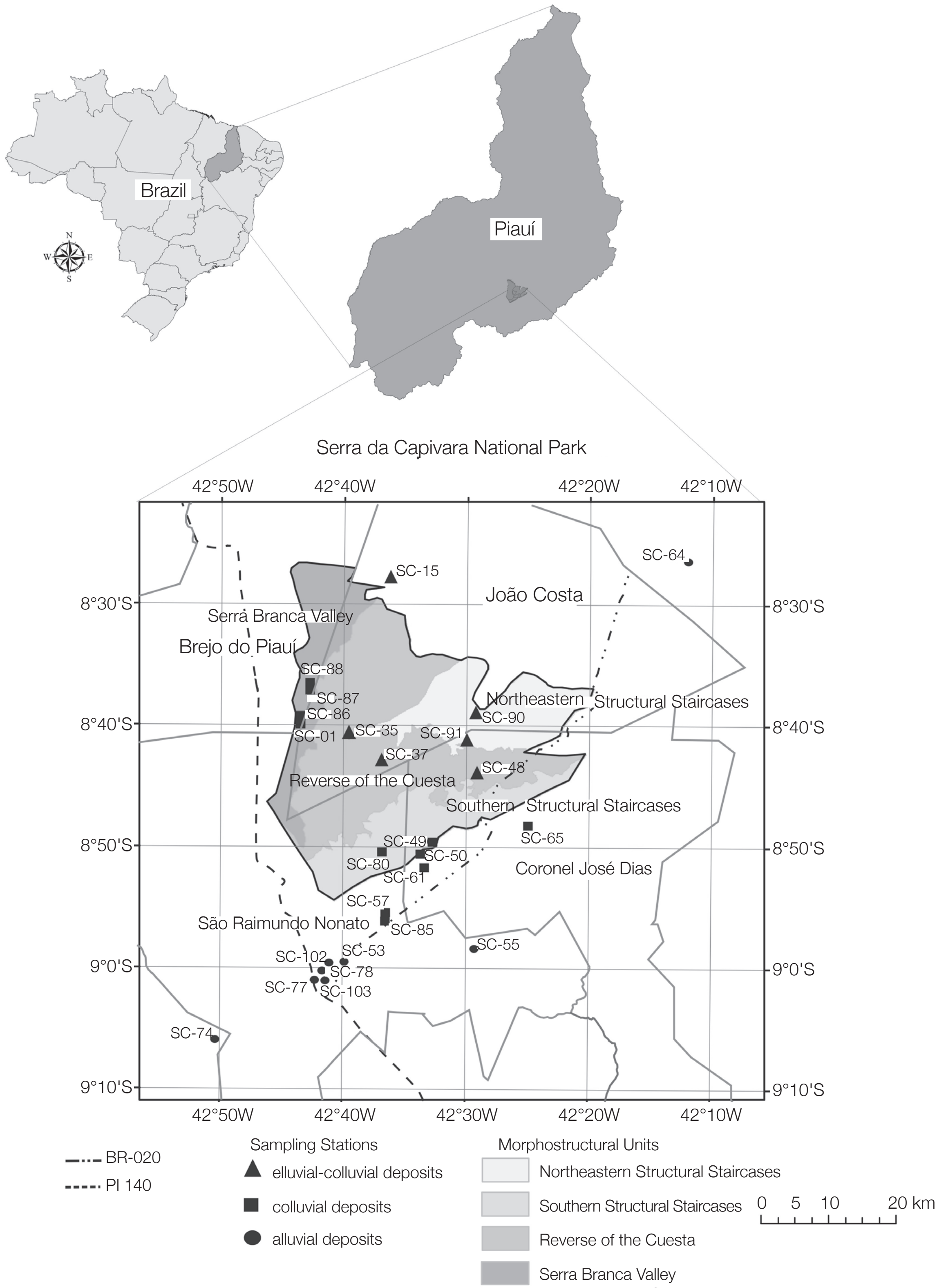
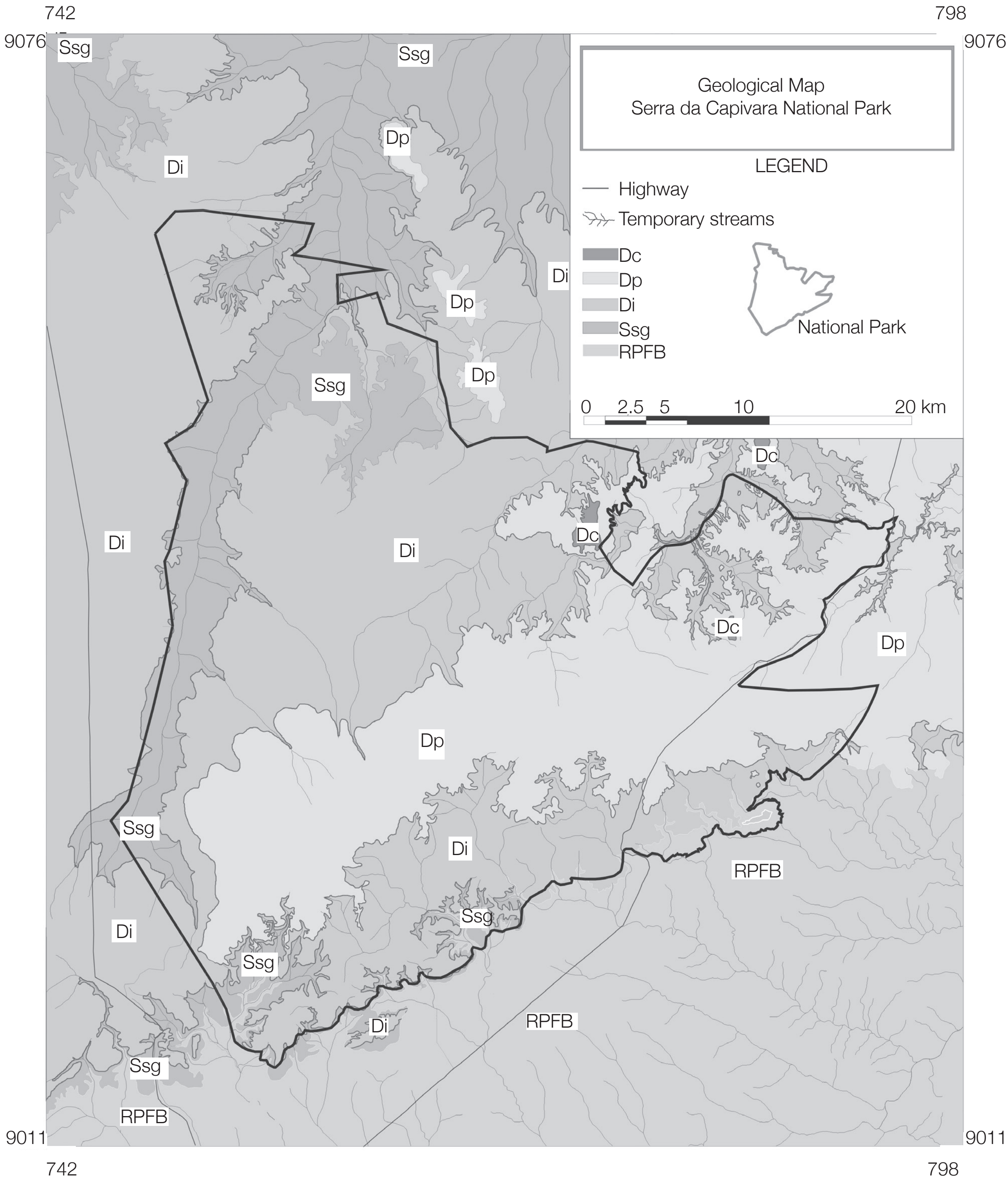


Figure 1. Location map of the study area, morphostructural units, sampling sites.



Dc: Cabeças Formation; Dp: Pimenteira Formation; Di: Itaim Formation; Ssg: Serra Grande Group. Outside the National Park there is a crystalline terrain that is RPFB – Riacho do Pontal Folded Belt. Modified from LAGESE (2002).

Figure 2. Geological map of Serra da Capivara National Park.

MATERIAL AND METHODS

The various geomorphological and topographical compartments were investigated for identification of sedimentary deposits, descriptions of their geological and geomorphological aspects, and sampling for laboratory analyses.

Twenty-nine samples of eluvial-colluvial deposits, 63 ones of colluvial deposits and 35 of alluvial deposits were collected for grain-size analysis. Seven samples of eluvial-colluvial deposits, 26 of colluvial deposits and 19 of alluvial deposits were collected for luminescence dating. The sampling sites visited during the fieldwork and the geographic positions of the sampling stations are detailed in Table 1 and Figure 1. The grain-size analyses were performed using the Empresa Brasileira de Agropecuária – EMBRAPA (1997) densimeter technique. Statistical data were obtained according to Shepard (1954) and Folk and Ward (1957). Samples for luminescence dating were dated using thermoluminescence (TL) and optically stimulated luminescence (OSL), and the multiple aliquot method (Murray and Wintle, 2000) was used. The samples were analyzed in the Laboratory of Glass and Dating at the São Paulo Technological Faculty (FATEC). The luminescence curves were obtained by the TL-OSL Automated System, Model 110-series, from Daybreak Nuclear Instrument. The quartz grains were subjected to ^{60}Co radiation, and the accumulated doses were obtained by the total regeneration method. The annual doses were calculated using the ^{40}K, ^{232}Th, ^{238}U and ^{235}U concentrations measured by γ-spectroscopy from the Institute of Energy and Nuclear Research (IPEN) of the National Nuclear Energy Commission (CNEN) in São Paulo, using 200.18 μGy/year (Sallun et al., 2007) gamma radiation.

Table 1. Sampling sites visited during the fieldwork.

Sampling sites	Latitude S	Longitude W
SC-01	8° 39,71’	42° 43,58’
SC-15	8° 28,15’	42° 36,28’
SC-35	8° 40,93’	42° 39,46’
SC-37	8° 42,75’	42° 36,75’
SC-48	8° 43,7’	42° 29,03’
SC-49	8° 49,7’	42° 32,7’
SC-50	8° 50,66’	42° 33,68’
SC-53	8° 59,65’	42° 39,9’
SC-55	8° 58,7’	42° 29,25’
SC-57	8° 55,5’	42° 36,51’
SC-61	8° 51,81’	42° 33,43’
SC-63	8° 36,96’	42° 19,1’
SC-64	8° 26,5’	42° 11,98’
SC-65	8° 48,31’	42° 24,95’
SC-74	9° 5,98’	42° 50,4’
SC-77	9° 1,13’	42° 41,95’
SC-78	9° 0,46’	42° 41,61’
SC-80	8° 50,53’	42° 36,8’
SC-85	8° 56,11’	42° 36,6’
SC-86	8° 39,48’	42° 43,58’
SC-87	8° 36,83’	42° 42,73’
SC-88	8° 36,8’	42° 42,7’
SC-90	8° 38,81’	42° 29,15’
SC-91	8° 41,36’	42° 29,8’
SC-102	8° 59,76’	42° 41,13’
SC-103	9° 1,21’	42° 41,38’

QUATERNARY SEDIMENTARY DEPOSITS

Fieldwork allowed identification of the following quaternary sedimentary deposits: eluvial-colluvial, colluvial and alluvial, which are further described.

Eluvial-colluvial deposits

These elluvial-colluvial deposits occur at the Reverse of the Cuesta at an elevation from 560 to 600 m. They were originated through in-place weathering of the source rock and were transported laterally by creeping over a short distance. They cover the Itaim and Pimenteira Formations, as thin multicolored, yellowish, whitish, violetish, and reddish massive loose sands (Figure 3).

The Itaim Formation, in accordance with Kegel (1953 *apud* Góes and Feijó, 1994), is constituted by fine sandstone and shale deposited in a deltaic to shelf environments,

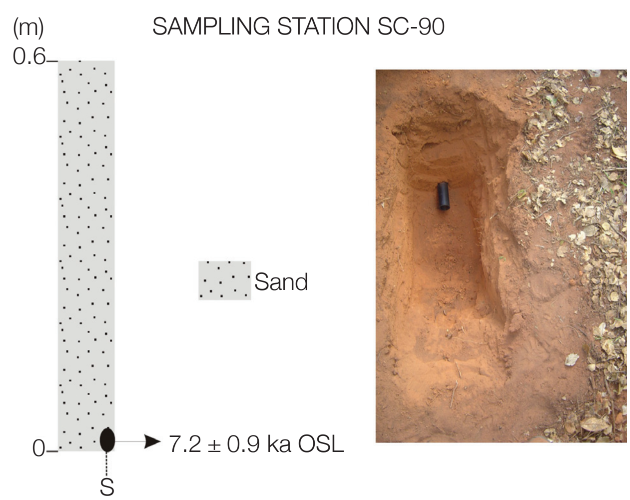


Figure 3. Sampling station SC-90 composed of sandy eluvial-colluvial deposits. Observe the PVC sampling tube for luminescence dating.

dominated by tidal currents and storms. The Pimenteira Formation, according to Small (1914 *apud* Baptista et al., 1984), is composed of shales, sedimented in a shelf neritic environment and dominated by storms, where thin beds of very fine sands were also deposited.

The grain-size classification indicates that these sediments are sand, muddy, sand and gravelly-sandy-mud. The average diameters range from very fine to fine sand. The degree of sorting for these sediments ranges from poorly to very poorly. The asymmetry degrees range from negative, symmetrical to very positive.

These deposits are closely related to the source rocks (sandstones and shales), and they probably reflect the depositional environments of the matrix rocks. The kurtosis values range from very leptokurtic to platikurtic and are associated with poorly-sorted sediments, which, according to Suguio (1973), show the source rock, and not the transport distance.

According to Heimsath et al. (2002), the process of creeping is very slow, but promotes the successive reworking of unconsolidated cover materials, from higher to lower topographic levels. When the quartz grains are exposed to solar light, their age returns to ‘zero’ on the geological clock. Over time, successive gravitational movements would aggregate new unconsolidated sediments beds, which are vertically piled according to the principle of superposition, like in sedimentary deposits (Sallun and Suguio, 2005).

Due to reworking by creeping, it was possible to date these sediments by OSL, and the obtained ages are documented in Table 2. These data indicated that the eluvial-colluvial deposits moved by creeping at the end of the Pleistocene (sample SC-15) and during the Holocene (others samples), but most of the transport happened during the medium Holocene, between 3.5 to 7.7 ka.

Colluvial deposits

The colluvial deposits are associated with two distinct geologic and geomorphologic units and, therefore, they are different from morphostratigraphical and sedimentological viewpoints. This kind of deposit was identified in association with Parnaíba Sedimentary Basin, on Serra Branca Valley and on the Southern Structural Staircases, as well as associated with Riacho do Pontal Folded Belt, on the geomorphological unit named Pediment.

Table 2. OLS ages of the Serra da Capivara National Park eluvial-colluvial deposits in thousands of years.

Sampling station	Annual doses ($\mu G\gamma$/year)	Accumulated doses ($G\gamma$)	OSL Ages
SC-15	1.20 ± 0.025	14.2	11.8 ± 1.45
SC-35	0.88 ± 0.016	no signal	no signal
SC-37	0.8 ± 0.016	2.8	3.5 ± 0.42
SC-48	0.84 ± 0.017	5.6	6.7 ± 0.8
SC-90	1.4 ± 0.1	10	7.2 ± 0.9
SC-91	0.71 ± 0.08	5.5	7.76 ± 1.255

Serra Branca Valley

Within the Serra Branca Valley stratigraphic, some profiles of superficial deposits, revealed through archaeological research, were studied. They were represented by the following sampling station in four rock shelters (*Toca*): SC-01 (Toca do Vento), 5 m deep; SC-86 (Toca da Gamela), 2.1 m deep; SC-87 (Toca do Pica-pau), 4.4 m deep (Figure 4); and SC-88 (Toca do Inharé), 5 m deep.

All profiles were found at medium hillslopes and represent products derived from Serra Grande Group’s physical and chemical weathering, and they were likely transported as debris flows. These deposits are represented by two distinct lithologies, arenaceous and rudaceous, which are both characterized by massive structure; each of these represents a colluviation event. The sandy unit is found at the base of all outcrops, with the exception of SC-86. The rudaceous one is composed of clasts of Serra Grande Group angular and subangular sandstone blocks with sizes ranging from 0.03 to 0.5 m, but most of times they are generally 0.1 to 0.2 m. These blocks replace the sand sediments and fortuitously occur as rounded quartz pebbles. In SC-01, there are two beds, with 0.24 and 0.32 m thicknesses, while in SC-86, there is a basal bed that is 0.3 m thick, composed of pebbles and sandstones blocks within a sandy matrix. SC-87 contains three different beds with blocks of 0.27, 0.05 and 0.15 m thicknesses. SC-88 contains a 0.1 m thick bed.

Charcoal fragments with diameter of approximately 3 cm are commonly found in the stratigraphic profiles, with the exception of SC-86. There are also scattered discontinuous charcoal in all profiles, and the charcoal can also be found concentrated in the remains of anthropogenic fires.

The sediments were classified as muddy sand at the base of outcrops SC-01 and SC-87, the others had only sands. The samples from bases SC-01 and SC-87 were generally very fine sand, but some of them were fine. These samples are considered to be poorly sorted, and Mello (1992), Camargo-Filho and Bigarella (1998) and Corrêa (2001) suggest, for other regions, that the degree of sorting is related to changes in the conditions of the transportation fluid. A poor degree of sorting is related to small sorting capacity, such as that of gravitational flows, which is the most important process in the transportation of colluvial deposits. The positive to very positive asymmetries reflect the sandy nature of the studied materials. The values

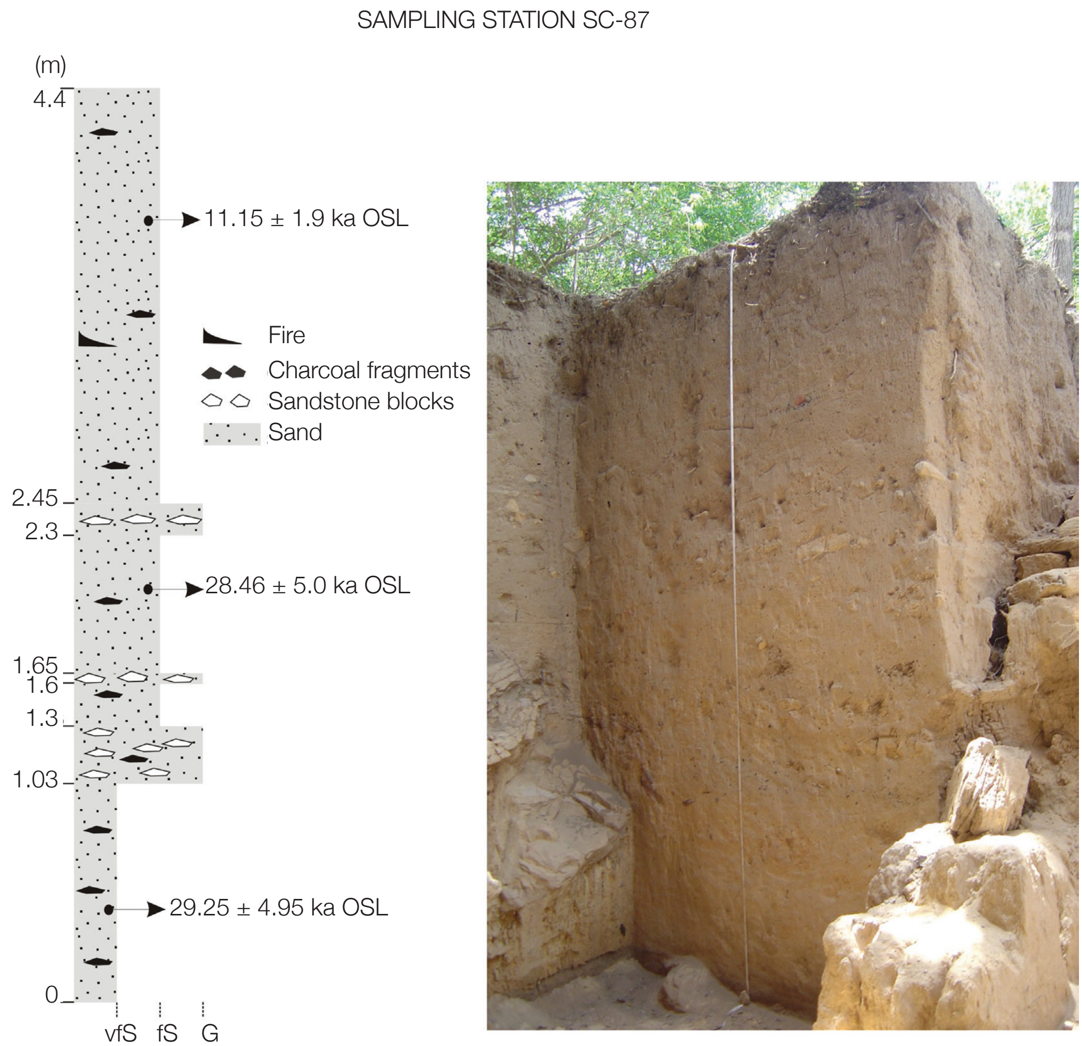


Figure 4. Sampling station SC-87 (Toca do Pica-pau rock shelter) is situated within the Serra Branca Valley morphostructural unit, and exhibits sandy colluvial deposits with three layers of sandstone and charcoal fragments.

of kurtosis are dominantly leptokurtic, followed by very leptokurtic to platikurtic. According to Suguio (1973), theses values, when associated with poorly-sorted sediments, mostly reflect the source area, not the transportation distance.

Structural Staircases

These deposits occur on Southern Structural Staircases, such as sampling station SC-80 (Toca do Perna I rock shelter), illustrated in Figure 5, at their top or in association with rocky cliffs at the border of Cuesta, such as at sampling station SC-49 (Sítio do Meio rock shelter), as in Figure 6, at elevations of 440 and 410 m at sampling station SC-50 (Toca do Elias rock shelter). The stratigraphic profiles were exposed by archaeological research and are located at the lower third section of hillsides, where Serra Grande Group sandstones and conglomerates were subjected to physical and chemical weathering and transported by debris flows.

The sampling station SC-49 is 4.75 m deep and presents massive sediments. Two colluviation events are represented in the unit, which include gravel beds that are separated by a layer characterized by concentrated Serra Grande Group sandstones blocks, cobbles, and boulders. The basal gravel bed is composed of a sandy-gravelly matrix, with clasts of rounded quartzose pebbles and subangular sandstone fragments of blocks. At the top of the outcrop, the gravel bed is composed of a sandy-gravelly matrix, whereas the coarse clasts are composed of quartzoses sub rounded to rounded pebbles. The roundness of the pebbles reflects their source area and suggests that these pebbles are derived from Serra Grande Group fluvial conglomerates. Serra Grande Group rock fragment bed exhibits blocks, cobbles, and boulders and separates two gravel beds, which are composed of fragments derived from the ceiling collapse, caused by fracture systems that enhanced weathering and gravitational processes, resulting in rock fragments to fall.

Sampling station SC-50 is 3.70 m deep and presents two distinct sedimentary massive beds. A 1.45 m thick basal gravel bed is supported by sandy and gravelly mud, with sub rounded to rounded coarse quartz pebbles. The second bed is 2.25 m thick and is composed of muddy sand with scattered sandy granules and blocks. They record two colluviation events, differentiated by grain-size constitutions that are possibly related to source rock availability.

The sampling station SC-80 is located at Southern Structural Staircases in the lower third of a rock wall within a very narrow 75 m wide alluvial valley. This valley configuration suggests that the deposits were supplied by hillside sediments carried by water flows (flash flows) during torrential rains, as suggested by incipient parallel laminations. These colluvial-alluvial deposits contain 3.20 m thick beds. The basal bed is composed of muddy sand, with incipient plane-parallel stratifications. The second one is a 1.74 m thick gravel bed supported by sand matrix, in which the coarse pebbles of quartz are rounded to sub rounded, and incipient plane-parallel stratification is recognizable.

The grain-size analyses indicated that these sediments could be classified as gravelly sand, muddy and gravelly sand, and muddy sand (from gravel to muddy sand). The medium diameters ranged from medium, to fine to very fine sand.

The sorting degrees ranged from poorly to very poorly sorted, reflecting their colluvial nature. The asymmetry was positive to very positive, which reflects their sandy nature. The kurtosis results are platikurtic, very platikurtic and mesokurtic, which are associated with poorly-sorted sediments and reflect the nature of the source rock, not the transportation processes.

Colluvial deposits on the pediment

Outside the PNSC, colluvial deposits also occur and are resting on the pediment, which is directly associated with

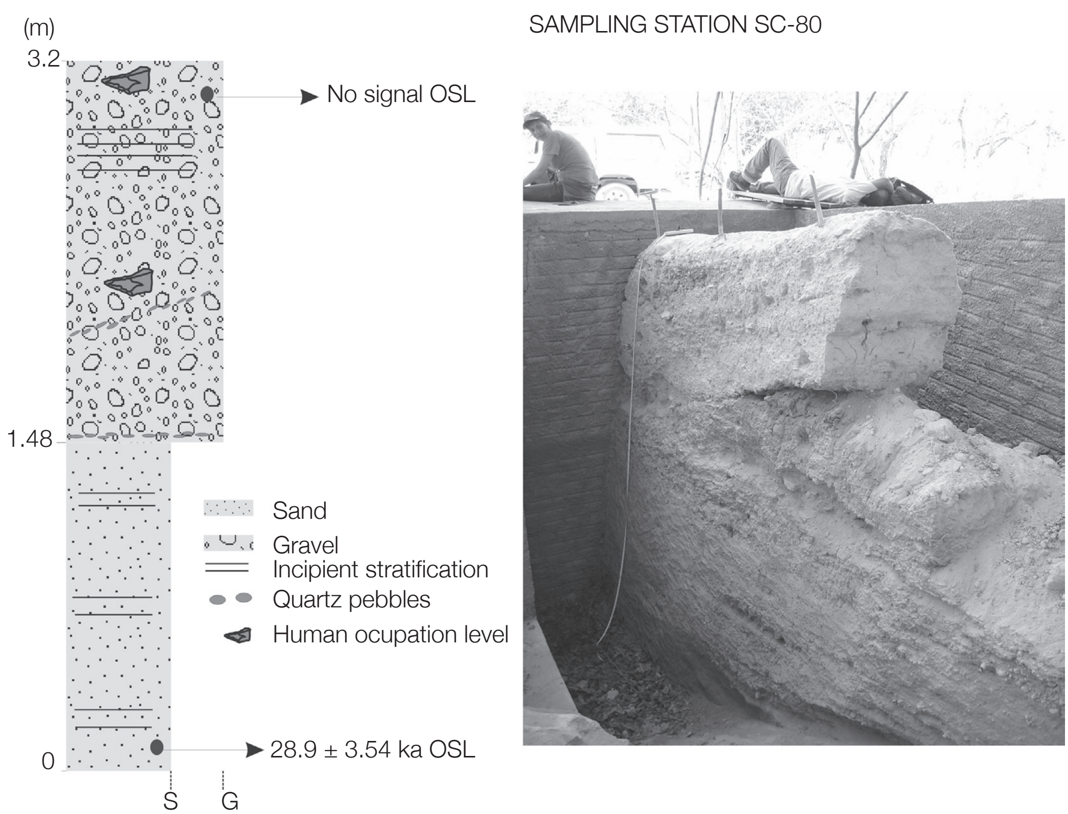


Figure 5. Sampling station SC-80 (Toca do Perna I rock shelter), in the Southern Structural Staircases colluvial deposit the base is composed of very fine sand and is superimposed by matrix supported gravel. An incipient plane-parallel stratification follows the terrain topography.

karst topography that is carved on the Riacho do Pontal Folded Belt marbles.

The pediment is a huge, smooth surface produced by erosion of marble (Pellerin, 1984), whose geomorphological evolution occurred departing from a convex break of the *cuesta* wall, from which the pediment is gently tilting towards the Piauí River central channel. In this area, outcrops of the sculptured marbles with very steep and karstified slopes occur.

At sampling stations SC-57 (Toca do Gordo do Garrincho rock shelter) and SC-65 (Toca do Barrigudo rock shelter), there are stratigraphic profiles excavated for archaeological researchers that are situated at the lower third of the hillside. The sampling station SC-61 (Toca de Cima dos Pilão cave) is represented by a cave-filling deposit, whose sediments represent a dissolution product of marble mixed with sands carried from the cuesta. SC-85 is represented by calcrete and sediments produced by dissolution of marble mixed with sands and gravels carried from the cuesta.

The sampling station SC-57 is located beside the Garrincho cave entrance. The deposit is composed of two lithologies. The first is rudaceous, and the second one is sandy clayey, but both have a massive structure. The rudaceous deposit occurs at the base and top of the outcrop and is sustained by a clayey-sandy matrix, and the coarse clasts are composed of pebbles and angular blocks of marble. Between two rudaceous beds, there is a clayey-sandy bed.

The sediments of the sampling site SC-61 (Figure 7) represent an ancient cave pipe filling deposit, which is about 6 m thick with three distinct lithologies. The basal sandy clay is the thickest and was transported into the cave by a mudflow. Superimposed over this bed is gravel sustained by a matrix, where the coarse clasts are composed of angular marble blocks derived from the cave. The third sediment is represented by calcareous tuffs intercalated with muds. According to Ford and Pedley (1996), the calcareous tuff is a product of calcium carbonate precipitation in water with low-magnesium content under freshwater at a surface temperature. The occurrence of calcareous tuff is significant because it suggests a local paleoclimate, which was likely wetter than the present semiarid climate. Pedley (1990) suggests that colder climates delay the calcareous tuff precipitation, and the semiarid condition does

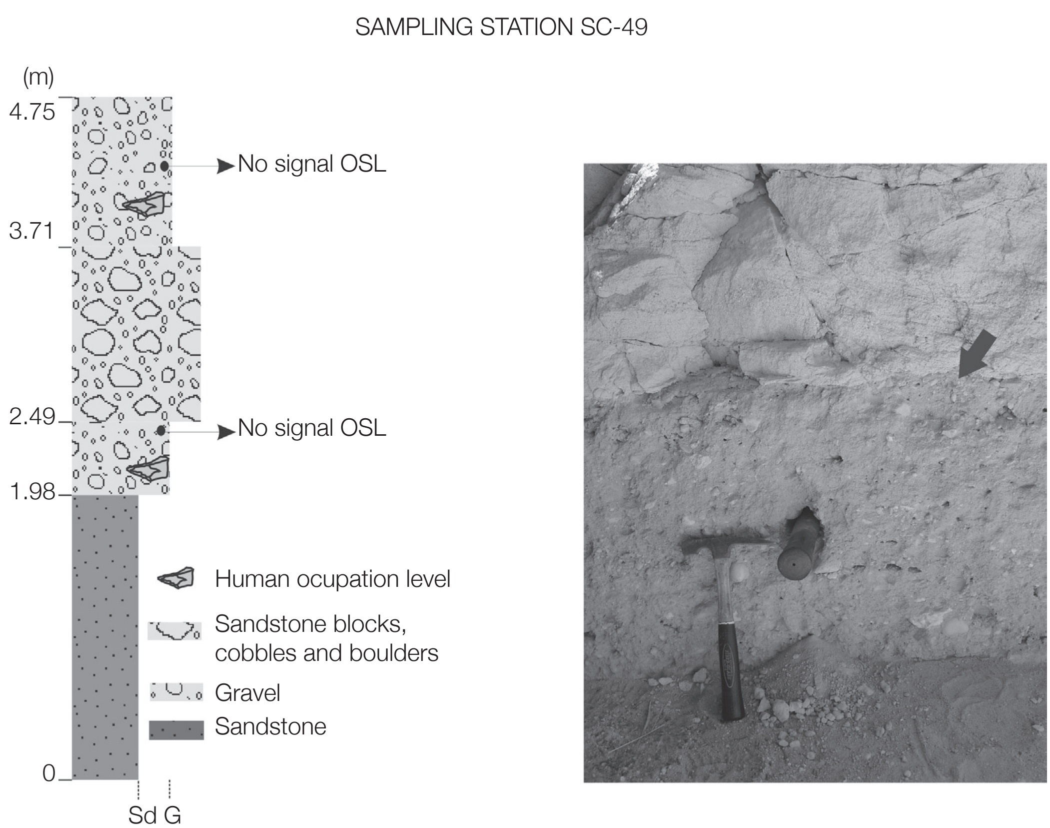


Figure 6. Sampling station SC-49 (Sítio do Meio rock shelter) in the Southern Structural Staircases colluvial deposit presents two gravel beds and a bed of fallen rock. This photograph shows the contact between the first gravel bed and a bed of fallen rock.

not possess a continuous water supply that is necessary for precipitation. There are three distinct calcareous tuff beds, 0.31, 0.12 and 0.8 m in thickness, suggesting that there was a water supply for the cave.

The sampling station SC-65 shows an outcrop of 4.8 m thick massive deposits composed of sandy clay with marble angular fragments of blocks, which are more frequent at the top and scattered quartz grains.

SC-85 is located at the margin of federal highway BR-020, approximately 1 km away from Garrincho, where an outcrop with there are three distinct lithologies. The first bed is approximately 2 m thick and is formed by a calcrete type secondary nodular limestone that originated under a semiarid paleoclimate as a consequence of Precambrian marble weathering. The second one is approximately 0.57 m thick and is composed of gravel sustained by a sandy mud matrix, with coarser quartz sub rounded to rounded granules and pebbles. The last bed is composed of sandy mud.

The grain sizes of the colluvial deposits found on the pediment are distinct from the sedimentary deposits related to the Parnaíba Sedimentary Basin, where sands are dominant. On the contrary, there is a dominance of mud in Quaternary deposits derived from the rocks of the Riacho do Pontal Folded Belt, showing the importance of source area in sedimentation.

The sediments are muddy, and the mean diameter is silt, but can also contain fine sand. The kurtosis is dominantly platikurtic, and the asymmetry of the colluvial deposits on the pediment is very negative, which is a consequence of the fine sand in the analyzed samples.

Geochronology of the colluvial deposits

The ages of the colluviation episodes were obtained by the OSL method (Table 3), and these episodes had time intervals that ranged from the middle Pleistocene to the late Pleistocene to the Pleistocene-Holocene transition.

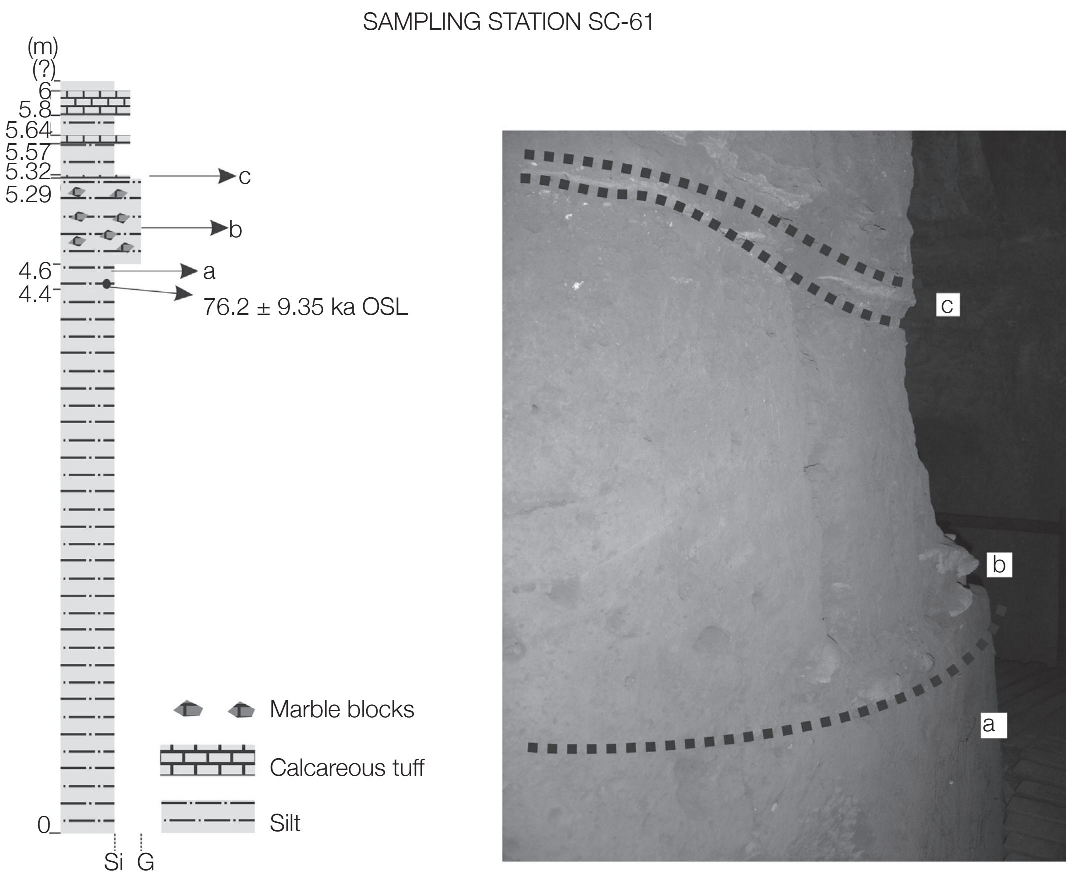


Figure 7. Columnar section of the sampling station SC-61 (Toca de Cima dos Pilão cave), which is a cave filled by at least 6 m thick sediments. At the top, there is an alternated sequence of calcareous tuff and mud. The photo shows sandy mud (a) and gravelly (b) and calcareous tuff (c) deposits.

Plotting the obtained ages on the global δ ^{18}O variation curve outlined by Ericson and Wollin (1968) made it possible to recognize the existence of four colluviation episodes (Figure 8). Even considering the error margins, some obtained ages could not be included and the oldest colluviation probably occurred approximately 202.75 ± 32.81 ka, when muddy deposits happened during a warmer interstadial event intercalated in the Northern Hemisphere Illinoisan glaciation, which is in the isotope stage 7.

The colluviation episode 1 is conspicuously recorded by ages ranging from 135 ± 16.4 ka to 117 ± 14.3 ka in two outcrops, is composed of sand and mud, and is correlated with the Northern Hemisphere Sangamon interglaciation, which corresponds to the isotope stage 5e.

The second episode is recorded by ages ranging from 84.7 ± 13.4 ka to 76.2 ± 9.35 ka and is recognized in sandy and muddy samples, which are probably correlatable with the warmer interstadial episodes within the Wisconsin glaciation, situated between the isotope stages 5a and 4.

The colluviation episode 3 likely occurred from 36.1 ± 4.9 ka to 21.77 ± 3.61 ka and was recorded in six outcrops composed of gravel, sand and mud deposits, which supplied seven ages. This event is related to the LGM that characterizes the coldest phase of the Wisconsin glaciation, which is situated at the limit between the isotope stages 3 and 2.

The colluviation episode 4 likely extended from 15.8 ± 1.9 ka to 11.15 ± 1.9 ka and was recognized in three outcrops composed of sand and mud, which includes these ages. They are situated within the Pleistocene-Holocene transition, which is between the isotope stages 2 and 1, probably attained by De Oliveira et al. (1999) studies in the Icatu River (Bahia State) peat deposits, and both studies suggest a paleoclimate that was likely wetter.

There is a concentration of ages between 11.15 ± 1.9 ka to 36.1 ± 4.9 ka that represent the last glacial maximum (LGM) of the Wisconsin glaciation, near the transition to the Holocene interglaciation.

Table 3. OSL ages of the Serra da Capivara National Park colluvial deposits in thousands of years.

Sampling station	Annual doses (μGγ/year)	Accumulated doses (Gγ)	OSL Ages
SC-01a	1.14 ± 0.025	153.6	135 ± 16.4
SC-01b	0.95 ± 0.023	no signal	no signal
SC-01c	0.85 ± 0.017	no signal	no signal
SC-49a	0.5 ± 0.001	no signal	no signal
SC-49b	0.48 ± 0.007	no signal	no signal
SC-50a	1.7 ± 0.14	61.2	36.1 ± 4.9
SC-50b	0.615 ± 0.011	no signal	no signal
SC-57a	1.28 ± 0.03	16.7	117 ± 14.5
SC-57b	0.95 ± 0.019	150	15.8 ± 1.9
SC-61	1.660 ± 37	126	76.2 ± 9.35
SC-65a	1.9 ± 0.21	385	202.75 ± 32.81
SC-65b	1.75 ± 0.06	144	83 ± 7
SC-65c	1.4 ± 0.032	33.5	23.9 ± 3
SC-80	0.83 ± 0.02	23.9	28.9 ± 3.54
SC-80b	2.53 ± 0.0295	no signal	no signal
SC-85	0.915 ± 0.02	21	23 ± 2.8
SC-86a	2.35 ± 0.11	29	12.4 ± 1.2
SC-86b	1.52 ± 0.155	17.3	11.36 ± 1.73
SC-87a	2.03 ± 0.24	59.4	29.25 ± 3.95
SC-87b	1.88 ± 0.24	53.5	28.46 ± 5
SC-87c	1.12 ± 0.135	12.5	11.15 ± 1.9
SC-88a	1.1 ± 0.115	89.9	84.7 ±13.4
SC-88b	1.5 ± 0.18	33	21.77 ± 3.61
SC-88c	1.11 ± 0.095	no signal	no signal

Alluvial deposits

The last type of the Quaternary deposit in the study area is associated with the Piauí River alluvium, which is dominantly represented by bed load coarse sediments. They are composed of sands and gravels deposited in bars within low sinuosity braided channels, which are dry during most of the year.

The sampling site SC-53, at the margin of the BR-020 highway in a locality named Queimadinha, exhibits 3 m thick deposits with a 0.62 m thick basal bed with horizontal and parallel lamination. It is superimposed by three beds that characteristically show fining upward sequences.

This grain-size grading was a result of a decrease in hydraulic energy. The grain sizes range from quartzose granules, rounded pebbles to muddy sand to sandy mud with incipient and horizontal parallel laminations. This deposit is interpreted as a fluvial channel overwash deposit, which was dispersed on a floodplain.

The sampling station SC-55 is located at the left margin of the road towards the Petronio Portela dam. This deposit is composed of rounded to sub rounded quartz, quartzite and chert clasts sustained in a polymictic gravel, with sandy matrix that lies directly over gneisses. The pebbles of this deposit exhibit incipient gradation and normal grading.

The sampling site SC-64 corresponds to a Piauí River terrace, located in the São João do Piauí municipality, at the margin of a road towards the Jenipapo dam. It is composed of a sand massive bed, 3.5 m thick.

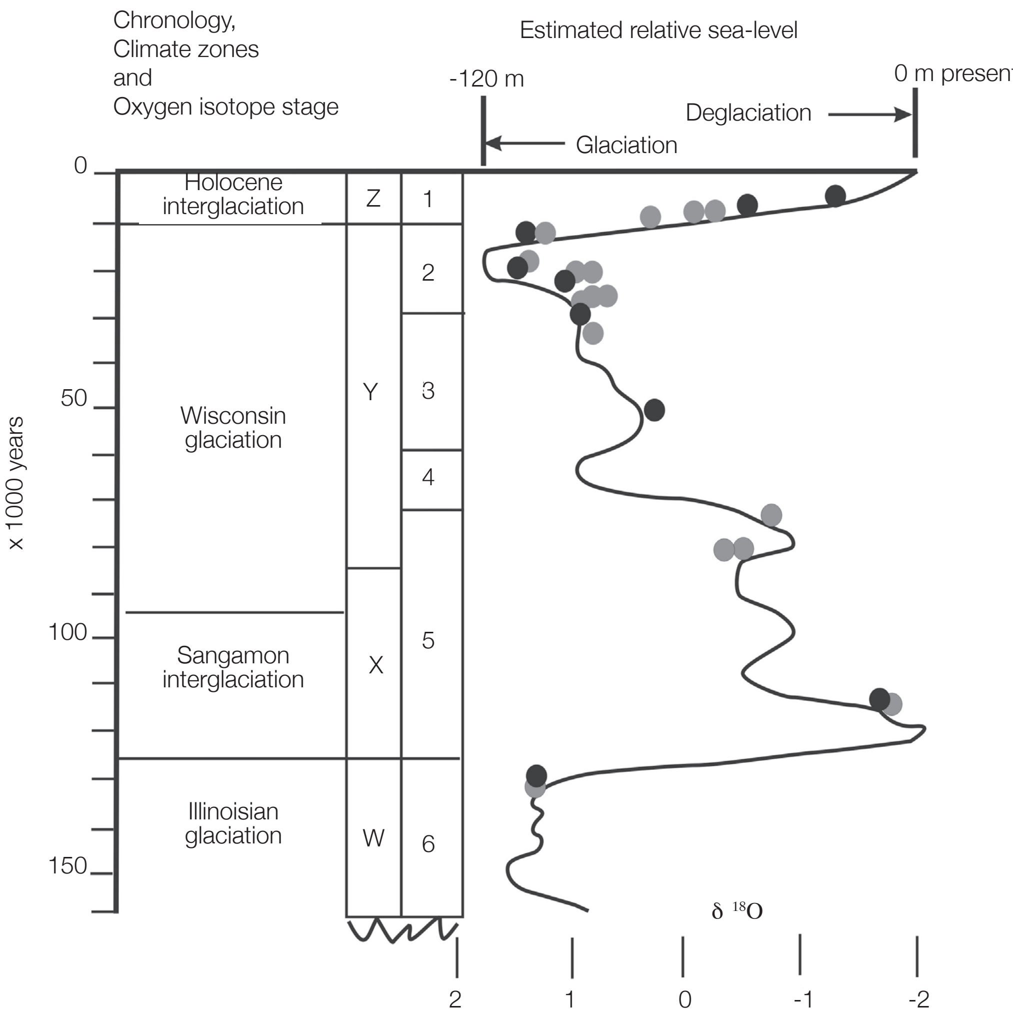


Figure 8. Ages of colluvial deposits plotted on the global δ ^{18}O change curve (Ericson and Wollin, 1968). Circles indicate data from this study. The black circles represent the alluvial deposits and the gray ones the colluvial deposits.

SC-74 is within the Piauí river trough, in a rural road towards the town of São Raimundo Nonato. It is composed of a 1.6 m thick massive bed that represents a sand bar.

The deposit at SC-77 (Figure 9) represents a Piauí river terrace within the São Raimundo Nonato urban area. The basal bed is composed of clast-supported gravel with a massive structure. The middle one is composed of muddy sand with ferruginous nodules scattered throughout the sandy bed. Above this bed lies another gravel bed that is superimposed by a sandy one.

The deposit at SC-78 is situated at the background of a motorcycle shop named Serrana in the town of São Raimundo Nonato. At its base lies a massive, 1 m thick clay bed that is overlain by clast-supported gravel, and is composed of rounded to sub rounded quartz pebbles with incipient imbrications and normal grading with a clayey sand matrix.

The sampling site SC-102 is situated near the BR-020 highway fork in the São Raimundo Nonato town Western entrance. It has a basal bed composed of sand overlain by rounded to sub rounded quartz clasts supported gravel deposits. At the basal part of the gravel, there are ferruginous nodules. These deposits look like SC-77, however they exhibit liquefaction structures that were probably originated during a seismic event. These structures are originated when a loose granular material is subject to a sudden pore water pressure increase, which is promoted by shocks that are commonly attributed to seismic events (Youd, 1973). According to Bezerra et al. (2005), sandy pillars are represented by column-shaped, vertical pebbles and blocks, which can be several decimeters to meters thick and normally display an incipient cone shape, wider at the top than at the base. The gravel pockets commonly represent the 'roots' of this pillar's structure.

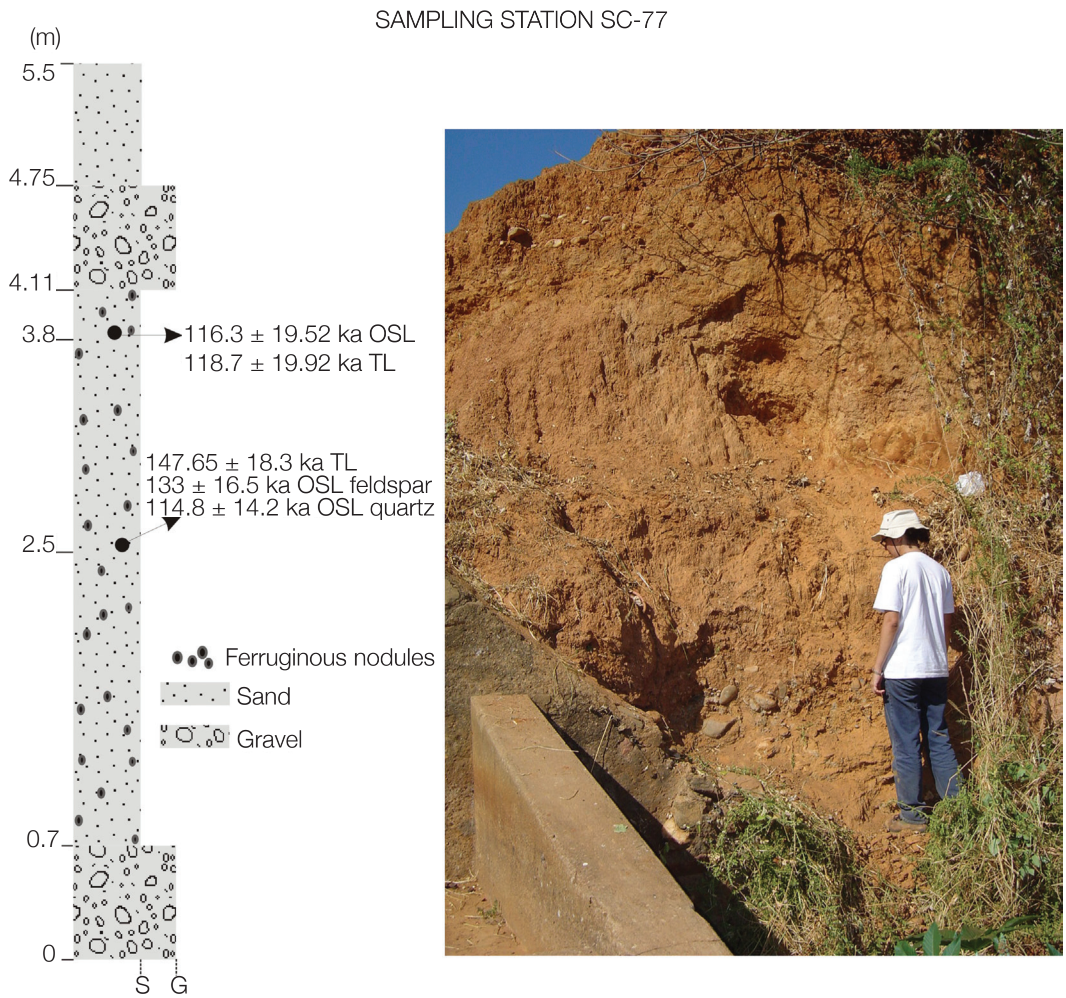


Figure 9. Sampling station SC-77, it is possible to see a 5.5 m thick alluvial deposit composed of alternating gravel and sand beds deposited by the Piauí River.

SC-103 is situated within the São Raimundo Nonato town at the Umbelinda district and displays a rounded to subangular quartz clast supported gravel, with a sandy mud matrix that is characterized by a massive structure.

The Piauí River deposits described here indicate two episodes of differentiated fluvial activities. The gravel deposits are related to higher energy and greater competence hydrodynamic flows that are probably related to flooding episodes. The sandy deposits are representative of low energy flows, where the fluvial discharge was smaller.

Aside from the alternative hydrodynamic energies within the Piauí River channel and Palaeochannel, there are two outcrops, SC-53 and SC-64, that represent floodplain deposits, formed during flooding episodes related to intense rainfalls. These could increase river discharge and availability of suspended sediments that were deposited as overwashed sediments on the floodplain of the neighboring river channel.

There is a lacustrine deposit at sampling site SC-78, which is probably related to the Piauí River floodplain. The clay deposit was formed as a setting product of the suspension load that occurs only in a low-energy environment. A gravel bed represents the total change to higher energy conditions.

Sediments were classified as sandy mud, muddy sand, muddy-gravelly sand and sandy gravel, which are related to the weathering and erosion of the Parnaíba Sedimentary Basin and Riacho do Pontal Folded Belt rocks. These are dominated by very poorly to poorly sorted sediments. The asymmetry is mainly very positive, which suggests deposition under a unidirectional flow regime. The kurtosis ranges from very leptokurtic to platikurtic.

Geochronology of the alluvial deposits

The ages obtained by OSL and TL methods were used for chronological positioning of the fluvial activity episodes. Table 4 shows 13 ones distributed from the middle to upper Pleistocene, until the Pleistocene-Holocene limit.

Clay deposition in the Piauí River floodplain around 436 ± 51.5 ka occurred during a warmer period of the Aftonian interglaciation, corresponding to isotope stage 12 (Ericson and Wollin, 1968). The sedimentation of gravel deposits happened approximately 296.55 ± 46.95 ka during a warmer episode of the Yarmouth interglaciation, related to isotope stage 8 (Ericson and Wollin, 1968). The last age of gravel deposition was around 178.9 ± 21.6 ka and corresponds to the Northern Hemisphere Illinoisan glaciations, related to isotope stage 7 (Ericson and Wollin, 1968).

The obtained ages are more recent than the above-mentioned ones, when plotted on the $\delta^{18}O$ change global curve (Figure 8), suggesting three main fluvial activity episodes, possibly related to the Northern Hemisphere paleoclimate changes.

Episode 1 lasted from 133 ± 16.5 ka to 116.3 ± 19.52 ka and was recorded on sand gravel bars that outcrop in two localities. This event corresponds to the warmer period of the Sangamom interglaciation, between isotope stages 5 c and e (Ericson and Wollin, 1968).

Episode 2 lasted from 54 ± 6.3 ka to 22.25 ± 3.59 ka, it was measured on gravel and sand bars, and on floodplain deposits found in three sites, which supplied four ages that correlated to the coldest time of the LGM in the Wisconsin glaciation, between isotope stages 3 and 2.

Episode 3 happened between 15.6 ± 1.9 ka to 10.35 ± 1.76 ka and was recorded on sand bars and floodplain deposits found in two localities, which reflect a transition from the Wisconsin glaciation to the Holocene interglaciation, between isotope stages 2 and 1.

DATA INTEGRATION

Three main events were recognized at Parnaíba Sedimentary Basin cuesta areas, as well as on the Riacho do Pontal Folding Belt pediments, represented by eluvial-colluvial, colluvial and alluvial deposits.

The eluvial-colluvial deposits were composed of poorly to very poorly sorted sands, with very changeable colors that were practically derived in place by weathering of the sandstones and shales of Itaim and Pimenteira Formations. Transportation by creeping was very limited, but was sufficient to promote exposure of

Table 4. TL and OSL ages of the Serra da Capivara National Park alluvial deposits in thousands of years.

Sampling station	Annual doses (μGγ/year)	Accumulated doses OSL (Gγ)	Accumulated doses TL (Gγ)	OSL Ages	TL Ages
SC-53a	1.45 ± 0.15	54.25	47.80	37.3 ± 5.73	32.9 ± 5.05
SC-53b	2.08 ± 0.25	21.50	18.50	10.35 ± 1.76	8.9 ± 1.52
SC-55	0.58 ± 0.01	no signal	31.4	54 ± 6.3	no signal
SC-64	1.07 ± 0.024	16.8	13.4	12.5 ± 1.55	15.6 ± 1.9
SC-74a	1.3 ± 0.032	33.2	39.5	25.5 ± 3.2	30 ± 3.75
SC-74b	1.86 ± 0.2	41.45	44.10	23.68 ± 3.82	22.25 ± 3.59
SC-77a Quartz	1.79 ± 0.043	205.5	264.3	114.8 ± 14.2	147.65 ± 18.3
SC-77a Feldspar	1.79 ± 0.043	238.6		133 ± 16.5	
SC-77b	2 ± 0.25	245	250	116.3 ±19.52	118.7 ± 19.92
SC-78a	0.68 ± 0.012	295	290	436 ± 51.5	429 ± 50.5
SC-78b	1.21 ± .0.025	216	215	178.9 ± 21.6	178 ± 21.5
SC-102a	no signal	no signal	no signal	no signal	no signal
SC-102b	no signal	no signal	no signal	no signal	no signal
SC-103	1 ± 0.11	290	305	311.9 ± 49.4	296.55 ± 46.95

the grains to sunlight, which allowed then to be dated by the OSL method and supplied Holocene ages.

To understand the origin of the colluvial deposits, three scenarios, represented by Serra Branca Valley, Structural Staircases and Pediment areas, were developed. They had deposits with distinct grain size and morphostratigraphic characteristics. They were strongly controlled by geomorphologic (relief), geologic (lithology), and paleoclimatic (temperature and pluviosity) factors.

Serra Branca Valley and Structural Staircases colluvial deposits are related to Parnaíba Sedimentary Basin Paleozoic rocks, weathering and mantle remobilization that originated from upper hillsides. Serra Branca Valley colluvial deposits were found at the middle portions, and the Structural Staircases ones were found at the lower third hillside. These sediments were evacuated by viscous nonchanneled gravity flows. Transportation was triggered by torrential floodings, which are typical of semiarid climates, and this promoted the formation of viscous flows activated by gravity forces on a very irregular terrain.

The colluvial deposits occurring outside the PNSC on the pediment are represented by weathering eluvial mantles, developed on hills of Precambrian marbles, with some contribution by Parnaíba Sedimentary Basin rocks. They were transported as nonchanneled gravity flows through translational sliding with filing of the lapias, as well as the lower portions of the hillslopes.

The studied colluvial deposits are attributed to colluvial fans shaped by transportation over a short distance. Therefore, they are very immature, poorly sorted, and represent proximal deposits, with grain sizes and other sedimentological properties closely related to the source rocks.

The alluvial deposits of the study area are related to the upstream reaches of Piauí River, whose sands and gravels are related to braided fluvial channels. The sediments are mainly massive or incipient parallel beddings and imbricated, with normal gradation of poorly sorted clasts that are indications of a torrential regime.

The paleoclimate data on Northeastern Brazil are not yet enough to establish a more detailed scenario of the Quaternary climate changes in the area. However, it is possible to derive some correlations using present data and previous literature.

The most ancient colluviation episode dated at 202.75 ± 32.81 ka. The first (135 ± 16.4 ka to 117 ± 14.3 ka) and second (84.7 ± 13.4 ka to 76.2 ± 9.35 ka) ones do not correspond to the Brazilian literature, but could probably represent warmer and wetter episodes intercalated within a semiarid climate.

The colluviation episodes 3 (36.1 ± 4.9 ka to 21.77 ± 3.61 ka) and 4 (15.8 ± 1.9 ka to 11.15 ± 1.9 ka) could be tentatively correlated with the paleoclimate data already existing in literature. For example, the work of Behling et al. (2000), who studied sediments of a submarine core obtained in Northeastern Brazil and found

Table 5. Summary of colluvial and alluvial deposition episodes in the study area. Episode 1C, from 135 ± 16.4 ka to 117 ± 14.3 ka; Episode 1A, from 133 ± 16.5 ka to 116.3 ± 19.52 ka; Episode 2C, from 84.7 ± 13.4 ka to 76.2 ± 9.35 ka; Episode 2A, 54 ± 6.3 ka to 22.25 ± 3.59; Episode 3C, from 36.1 ± 4.9 ka to 21.77 ± 3 .61 ka; Episode 4C, from 15.8 ± 1.9 ka to 11.15 ± 1.9 ka; and Episode 3A, 15.6 ± 1.9 ka to 10.35 ±1.76 ka.

Age (ka) or episode	Colluvial deposition	Alluvial deposition	Sediments	Deposits
436 ± 51.5		X	C	PRLD
296.55 ± 46.95		X	G	PRD
202.75 ± 32.81	X		M	DFD
178.90 ± 21.60		X	G	PRD
Episode 1C	X		S, M	DFD
Episode 1A		X	S, G	PRBD
Episode 2C	X		S, M	DFD
Episode 2A		X	G, S	PRBFD
Episode 3C	X		G, S, M	DFD
Episode 4C	X		S, M	DFD
Episode 3A		X	S	PRBFD

C: clay; G: gravel; M: mud; S: sand; PRLD: Piauí River lacustrine deposit; PRD: Piauí River deposit; DFD: debris flows deposit; PRBD: Piauí River bars deposit; PRBFD: Piauí River bars and floodplain deposits.

spores of *Selaginella* associated with a high deposition rate of pollen, led to the interpretation of heavy rains. Data from Auler and Smart (2001), who interpreted that the travertine precipitation would suggest wetter periods in Northeastern Brazil, between 33 (Behling et al., 2000) to 21 ka (Auler and Smart, 2001), a period that could be correlated to colluviation episode 3 in PNSC, suggest heavy rains. Similarly, the PNSC colluviation episode 4 could be compared with Paleoclimatic data obtained by Behling et al. (2000). Sifeddine et al. (2003), who studied palynomorphs of a Caçó Lake (Maranhão state) lacustrine core, showed that there was an increase in the precipitation rate. Pessenda et al. (2004) and Gouveia et al. (2005) analyzed carbon stable isotope ratios of soil organic matter in Maranhão state and concluded that there was an increase in precipitation rates between 15 to 9 ka.

FINAL CONSIDERATIONS

The OSL ages indicated that the youngest deposits in the study area are represented by Holocene eluvial-colluvial sediments. However, the ones for colluvial deposits and the TL and OSL ages for alluvial deposits suggest that the colluviation and alluviation processes were approximately contemporaneous and occurred between the middle Pleistocene and the Pleistocene Holocene transition.

Because of the penecontemporaneity between colluviation and alluviation processes, these phenomena could have occurred under semiarid conditions, where they would have been reworked from high hillsides and re-deposited in lower and middle portions. At this time, the Piauí River would exhibit a braided channel pattern, with sheet floods that deposited gravels and sands.

According to the ages obtained in this work, the evolutionary history of the landscape is present in a summary form in the Table 5.

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