7. Sedimentation and sediments of Amazonian rivers and evolution of the Amazonian landscape since Pliocene times

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1. Introduction

The Amazonian landscape is formed by Quarternary geological processes to a much larger extent than was believed some years ago. Many parts of low-lying areas belonging to the Amazon Basin are covered by sediments of mainly Pleistocene age.

In higher-lying areas, weathering processes, which began in middle or late Tertiary times, changed the mineralogical composition of the land surface very intensively and thus created the specific conditions for the development of recent Amazonian ecosystems.

The significance of the Quarternary period for the Amazonian landscape was recognized during the last third of the 19th century. The first Quarternary geological investigations were carried out by Agassiz in 1867. As a result of geomorphological and sedimentological records, he believed he had found traces of Pleistocene glaciation in the Amazonian lowland. In a comprehensive description, Katzer (1903), as well as Branner (1893), abandoned these ideas. Katzer describes Quarternary river terraces, which today are high altitude, and discusses weathering features supposedly having developed during that period.

The correlation of the niveaus of some river terraces of the Pleistocene sea level high was studied by Sombroek (1966). Klammer (1971, 1975, 1976 and 1978) describes the classification of the Lower Amazon river terraces in more detail. Tricart (1974 and 1975) worked on the radar maps (Projeto RADAM) published in 1972–74, showing the Amazon area. From observations of geomorphological features shown on these maps, he suggests an extension of savannas in nearly the whole lowland during Pleistocene times.

Journeaux (1975) dealt with some exposures along the roads built at the beginning of the seventies. Sedimentological investigations in the Amazon Prodelta were carried out by Damuth & Fairbridge (1970), Damuth & Kumar (1975) and Milliman & Barretto (1975). According to Damuth & Fairbridge (1970), the occurrence of feldspar in the sediments of the Prodelta points out to a semi-arid to

Sioli, H. (ed.), The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin. ISBN 90-6193-108-8.

arid climate in Amazonia during Pleistocene glacial times. Milliman & Barretto (1975) contradict this interpretation and attribute the increase in the feldspar content to the increase of the erosion depth at a lower sea level during glacial times.

The recently deposited sediments of the *várzea* were dealt with by Katzer (1903) and Andrade (1956) and, in more detail, by Sioli (1957).

Irion (1976 and 1978) went into the weathering processes in the Amazonian lowland and described the distribution of Pleistocene and Holocene sediments.

Our representations of Quarternary and recent sediments of the Amazon basin are mainly the results of work carried out by the author at the Max-Planck-Institut for Limnology, Department of Tropical Ecology, Plön, and at the Senckenberg Research Institute, Wilhelmshaven, in collaboration with the Instituto National de Pesquisas da Amazônia (INPA), Manaus. Investigations were financially supported by the 'Deutsche Forschungsgemeinschaft' (German Research Community) (code Ir 6/2).

2. Pleistocene

2.1 *Belterra clays and 'stone line'*

In the area of the Lower Amazon, one of the most obvious features is the appearance of high plains in altitudes approximately 100–250 m above sea-level in the central region close to the Amazon, whereas these plains are more common higher than 300 m above sea-level in areas further away from the Amazon.

Sombroek (1966) regards the clay which forms the uppermost soil horizons of these high plains as being lacustrine or a semi-marine deposit. It is said to have been deposited in a lake or in a lake-like bay existing during the Calabrium at the transition of Pliocene/Pleistocene at sea-levels 180 m higher than today. Based on the *locus typicus* of these clays, Sombroek (1966) established the name 'Belterra clay'. Sombroek's interpretation of the origin of the Belterra clays as lake deposits is accepted by most authors dealing with the soil and sediments of the Amazon area (see Klammer 1978).

In the lower beds of the Belterra clays, a horizon often appears made of Fe-oxide and -hydroxide concretions, with a varying thickness ranging from a few centimeters to some decimeters.

Journeaux (1975), Brown & Ab'Saber (1979) and the authors of Volume 18 of the 'Projeto Radambrasil', (1978) interprate this horizon as a 'stone line', a feature which is believed to solely occur in arid to semiarid climates. The formation of such a 'stone line' is thought to take place as follows: with thin or even lacking vegetation in a dry climate, the blowing-out of clay, silt and sand is promoted, whereas the coarse-grained material remains in place and therefore accumulates on the surface. Under certain conditions this process leads to the formation of a stone pavemant. When this stone pavement is covered by some other material some time later, it appears in a vertical profile (e.g. along a road section) as a band, which looks like a line from the distance. Thus the name 'stone line' came into being. Journeaux (1975) attributes the 'stone line' in the lower beds of the Belterra clays to a period of dry climate in a time before the deposition of these clays took place. Like Sombroek (1966), Journeaux (1975) places the Belterra clays into the Calabrium. Hence it follows that the age of the horizon below the stone line should be older than 2.5 million years. Brown & Ab'Saber (1979) do not deal with the Belterra clays, but believe the 'stone line' horizon to be of a much later origin. They place the formation in the maximum of the Würmian-glacial, a period about 18 000 years ago, for which they postulate a dry climate throughout the Amazonian lowland. The author's mineralogical-geochemical surveys, which were carried out along the outcrop surfaces created by the road constructions in Amazonia, do not coincide with the stratigraphical interpretation of the genesis of the uppermost soil horizons ('stone line' and Belterra clay). On the contrary, it could be shown (Chapter 21) that Belterra clay, stone line and the horizons below belong to the same weathering unit, the formation of which dates far back into the Tertiary and is still continuing.

2.2 *River terraces and alluvial plains*

Whereas the banks of the Upper Amazon only rise a few meters above the water mark during high water gauges, one can find extensive bank regions along the Lower Amazon, which rise to highs of more 100 m above the river Amazon. Along such regions, river terraces were formed at higher water marks during the Pleistocene.

Since the niveau of the river terraces in the main branch of the Amazon from the delta to the foot of the Andes and in the lower beds of the tributaries is connected directly with the mean sea-level, it is possible to correlate the altitude of the river terraces with equivalent worldwide sea-levels. For this phenomenon the coherent hydrodynamic connection and the extremely low slope of the streams are responsible. Thus the Amazon has an average slope of about 2 cm/km beginning at the Pre-Andine lowland and ending at the estuary (for comparison: the Rhine River has an average slope of approximately 35 cm/km between Lake Constance and the North Sea). As mentioned above, Klammer (1971–78) has carried out extensive studies treating the successions of river terraces at the Rio Jarí and Rio Trombetas. He was able to take measurements in the terraces at altitudes of 80, 68, 61, 36, 20 and 10 m above the recent river mark. There was no problem in correlating the terraces with high water marks of the Pleistocene ocean.

The correlation of the Belterra niveau with 180 m above the river mark during the Calabrium seems to be suitable for Klammer (1978), even though he writes that the high sea-levels cannot be explained by glacial eustatic processes only.

The areas westwards of the Madeira estuary are characterized by low altitudes. The 100 m isohypse (Fig. 1) moves away several 100 km from the Amazon. The highest altitudes are situated only a few 10m above the recent mean river mark. In this area, according to investigations up to the present, no river terraces were formed, but extensive riverscapes developed, which are similar to the recent *várzea* (see Chapter 21). The altitude of flood plains is characterized by average high water marks of the rivers; as shown above, they are directly dependent on the sea-level niveau. It is therefore to be expected that the river-scapes of different altitudes can be correlated to several Pleistocene sea-level fluctuations. It is possible to carry out such a differentiation of several altitudes by using the radar maps published in 1972 to 1974. Thus, at about 20 km north of the Solimões at 67° 15′ W, at least three generations of flood plains (alluvial soils) were able to be distinguished (Irion 1979). Their altitudes roughly correspond to the Monastir. The higher elevated plains are a little older, but they certainly should be assigned to one of the last interglacial times. According to mineralogical-geochemical investigations (Chapter 21), at least three alluvial plains of different age can be distinguished by different stages of weathering.

From the interpretation of the radar maps, a region of 300 000–400 000 km² at the Upper Amazon is covered by Pleistocene alluvial soils. In the maps published in 1978 by the Projeto RADAM (Volume 18), the Pleistocene alluvial soils are combined with the Tertiary fluviatile sediments of marginal regions to form the 'Formacão Solimoes'.

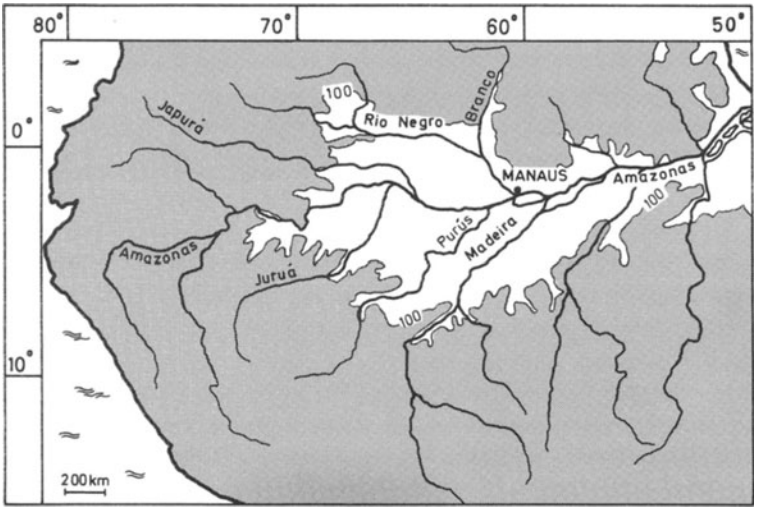

Fig. 1 Amazon area with emphasized 100 m contour line. Note the slight elevation of the lowland west of the 60th degree of longitude. During high sea-level in the Pleistocene, lakes and large-area river landscapes evolved due to water back-up.

This term goes back to Rego (1930), who first named the Miocene lacustrine, fluviatile sediments of the Upper Amazon in such a manner. The formation of these sediments might differ basically from those of the Pleistocene *várzea*.

The history of the Pleistocene landscape known so far, can be summarized as follows: the 'Belterra lake' – initially postulated by Sombroek (1966) – which was said to have covered the Amazonian lowland at the transition Pliocene/Pleistocene, does not seem to have existed. The Belterra clays are a product of weathering of the underlaying material of the Barreiras Formation (central region). The Lower Amazon river terraces were formed at different altitudes during the Pleistocene sea-level highs along the valley slopes. In the region of the Upper Amazonian lowland, extensive alluvial plains (flood plains) were able to form, but their correlations with certain interglacial times are not certain with our present state of knowledge.

3. Holocene

3.1 *The Amazon main valley*

During the Würmian glacial sea-level depression, the valleys of the Amazon main course and the lower courses of the Amazon tributaries were eroded more intensively as a result of the lowered erosion bases.

Damuth & Fairbridge (1970) found a layer of feldspar-bearing sands in the Prodelta. These sands were deposited during the Würmian maximum at the time of the sea-level depression. The predominance of feldspars in comparison with other sand layers shows that the Würmian glacial erosion penetrated to the unweathered horizons within the drainage area of the Amazon.

After the Würmian maximum with a sea-level depression of about 130 m 18 000 years ago, a rapid sea-level rise of about 125 m followed until 6000 years B.P. It is likely that a lake formed during this rise in the deeply cleared area of today's *várzea* as a result of the damming-up. The sediment load transported by the Amazon and its tributaries is not enough to fill in a lake during such a rapid sea-level rise (Irion 1976). Just after the flattening of the sea-level curve, which was about 6000 years ago (Fig. 2), a refilling of the Pleistocene Amazon valley and the formation of the *várzea* could have been possible. The expectation of the existence of an early- to middle-Holocene lake in the Amazon valley is strengthened by investigations made in the Prodelta and in the river bed of the Amazon. Damuth & Fairbridge (1970) analysed cores of the Amazon delta containing Würmian glacial sediments. They discovered the following features within the hanging layers of these sediments: 'An abrupt change to pelagic sediments at about 10 000 to 11 000 B.P. in all 39 cores demonstrates that with the beginning of the Holocene, large quantities of continental detritus no longer reached the continental rise and abyssal plains of the Guyana basin.' This observation coin-

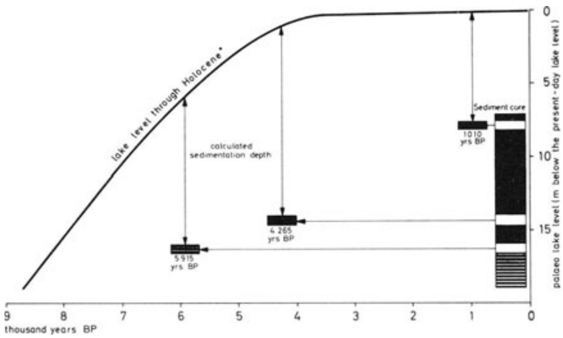

Fig. 2 [14]C-dated samples from a sediment core of a central Amazonian ria-lake (Lago Calado near Manacapuru). It can be assessed that the water-level of the ria-lakes in Amazonia during the Holocene was in accordance to the world-wide sea-level rise. Results of ^{14}C analyses support this assumption (the radiocarbonate dating is done by Dr. Geyh from the 'Niedersächsiches Landesamt für Bodenkunde', Hannover, West-Germany). x: the lake-level rise is assumed to be in accordance with the Holocene sea-level rise.

cides with the existence of an 'Amazon Lake' during early Holocene times. It can only be expected that the suspension load decreased after the extension of the lake, which must have functioned as a sediment deposit. Another aspect for the existence of such a lake is the occurence of finely-grained sediments at the bottom of the Amazon as could be seen at Santa Rita do Weil and before the estuary of the Rio Negro (Irion 1976).

3.2 *Side valleys of the Amazon*

Together with the Amazon main valley, the lower courses of the Amazon tributaries were flooded during the Holocene. Tributaries rich in suspension filled their drowned lower courses with sediments up to the altitude of today's river mark. The suspension-poor clear or black waters did not reach this state, so that extended lakes exist in their lower courses, the so-called 'ria-lakes'. The lower courses of the Rio Xingú and the Rio Tapajós, the Lago Grande de Manacapurú, Lago Aiapuá, Lago Surara, Lago Coarí and Lago Tefé are good examples of such ria-lakes. We have taken nine core samples up to a length of 15 m from such ria-lakes occuring in Central Amazonia (Irion 1982). The samples were subjected to a mineralogical-geochemical investigations. Mrs. Absy (1979, Instituto Nacional de Pesquisas da Amazônia) made palynological studies fom the same material. Among the Holocene sediments in nearly all the lakes investigated, obviously older, already consolidated lake sediments were found. The surfaces partially lay only a few meters below the surface of the recent sediments. It is very likely that they were deposited under the water level (e.g., high

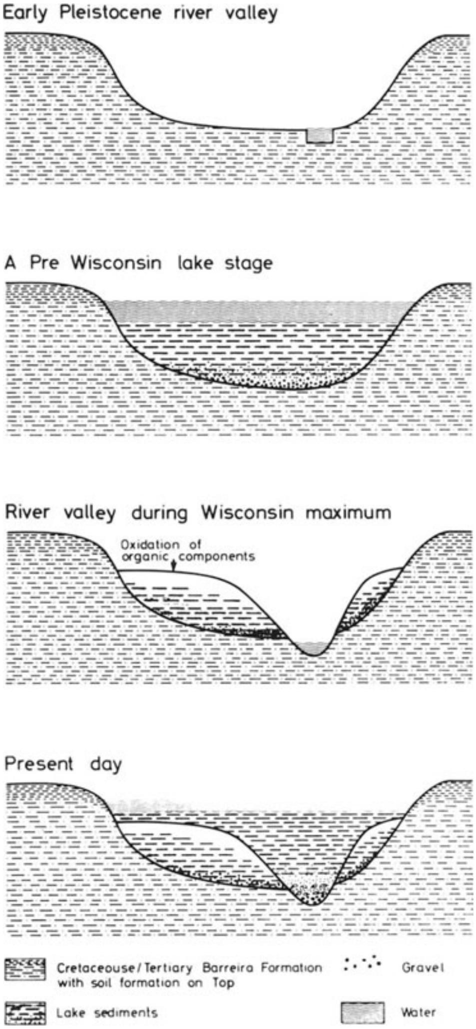

Fig. 3 Erosion and sedimentation in the lowermost section of a valley of a small tributary of the River Amazon. In the Early Pleistocene or in Late Tertiary a river system in the Amazon lowlands was well developed (uppermost picture). But during high sea-level stages of Pleistocene, lakes were formed in the Amazon valley itself and in the lowermost sections of its tributaries. During this time fine-grained sediments were deposited (second picture). In the following cold period (here Wisconsin stage, third picture) during low sea-level stages, some parts of the lake sediments were eroded due to the lowering of the erosion basis. The organic components of the old lake bottoms were oxidized when no longer covered by water. During the post-glazial sea-level rise the valleys were inundated once more, but only thick sediment formations could be established in the 'sub-river valleys' of the Wisconsin stage. It is probable that the sediments of more than two Pleistocene high sea-level stages are deposited in the old river valleys.

quantities of lacustrine diatoms) and thus under hydrogeographic circumstances similar to those of today. Such conditions probably existed during the Monastir. When the sea-level decreased during the following Würm glacial, the lake-level lowered, and finally the areas of the former lakes were occupied by the courses of rivers or creeks. (Fig. 3, third print from the top). At the same time, the organic components of the older lake sediment surfaces, which are now covered by younger sediments were oxidized and consolidated.

The development of the post-glacial ria-lakes in the smaller river tributaries started about 9000 B.P. in response to the world-wide rise in the sea-level. C^{12}/C^{14} data of such lake sediments coincide extremely well with the expected lake-level rise and the increase of sedimentation rate in the Central Amazonian lakes, due to the world-wide Flandrian sea-level rise (Fig. 2).

Not only the suspension load of the tributaries, but also the suspension load of the receiving streams is responsible for the sediment formation. In the course of the annual high-water gauge, the suspension, overburdened with the water of the receiving streams, penetrates to the lakes. The deposition of the sediment load deriving from the waters of the main river in the ria-lake area takes place at relatively low current velocities. Since the mineralogical composition of the suspension load deriving from the tributaries differs from that deriving from the receiving streams, it is possible to determine mineralogically the influence of both water-types in the sediments of the ria-lakes (Fig. 4, e.g., the Rio Tapajós).

4. Mineralogy of suspension load of the Amazonian rivers

The mineralogical composition of the suspension load of rivers naturally derives from the composition of the weathering horizons occurring within their drainage area. This property applies very well to the Amazon region. Therefore it is often possible to deduce the type of mineral association originating from the weathering process in the drainage area by analysing the suspension load. This is only useful, when the geological/mineralogical composition of the rocks outcropping within the drainage area of a river is relatively homogenous. The basement of the Amazon region provides these conditions. As shown in Chapter 21, it is possible to distinguish extensive provinces of homogenous mineral associations within the upper soil horizons of the Amazonian lowland. By doing this, five distinctive areas can be differentiated: the Andes, the Sub-Andes, the Pre-Cambrian Shields together with the Barreiras Formation, the South-Western Lowland and the Pleistocene *várzea*.

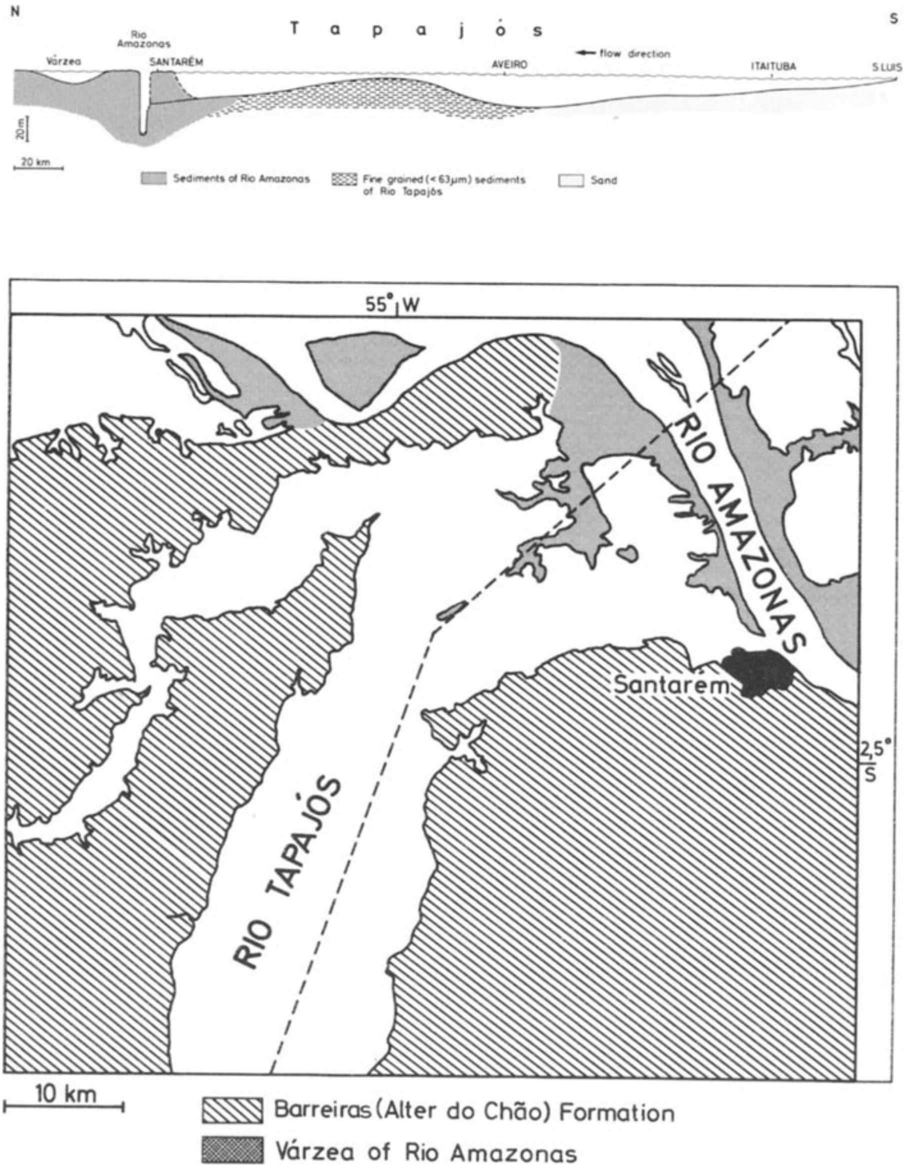

Fig. 4 Longitudinal section of the lower course of the Rio Tapajós and cross-section of the neighboring Amazon River and its *várzea* during medium high water stage. With declining flow velocities of the Tapajós, finely-grained suspension load is deposited between Aveiro and Santarém where the river broadens to a ria-lake. During the high waters of the Amazon River, its water table is higher than that of the Rio Tapajós; therefore, the water of the Amazon enters the lowest section of the ria-lake and the depositing sediments form a delta in this part of the Rio Tapajós.

The location sketch depicts the middle and lower part of the Tapajós together with the adjoining part of the Amazon. The dashed line indicates the position of the profile.

5. Main course of the Amazon

Within the main course of the Amazon, the mineral composition of the river sediments changes between the Andes and the Pre-Andes. Whereas the sediments of the Andine rivers are characterized by a predominance of unweathered minerals, such as mica and Fe-rich chlorite, the suspension load of the Pre-Andine rivers mainly consists of montmorillonite and, on a smaller scale, of kaolinite. Both minerals are formed during weathering processes.

One explanation for this feature is that the sediments of Andine rivers are deposited in the foreland, where they form extensive flood plains. The intensive formation of montmorillonite in the dam water soils of these flood plains is favored by the humid, tropical climate. Unfortunately, the duration leading to quantitatively valuable montmorillonization as well as the average time of stay regarding sediments in the Sub-Andine area are not known. Since the new formation of montmorillonite proceeds rather quickly, it is to be expected that even in profiles several meters thick which occur in the flood plains, the montmorillonization has already been processed in the course of several centuries.

After the junction of the main Sub-Andine rivers, Rio Ucayali, the Rio Marañon and the Rio Napo, the composition of the suspension load does not change to a great extent when the estuary of the Amazon is reached. This partially depends on the fact that the rivers arriving from the Andes and Pre-Andes provide the main part of the suspension load of the Amazon. Another point is that the strongly differing suspension loads of the Amazonian tributaries make up a total composition, which is very similar to the composition of the sediments of the main river.

The quantitative composition of the suspension was measured by Gibbs (1967). Analysing the Ucayali, Gibbs mentions a mean value of 350 mg/l, which decreases to a value of 80 mg/l when reaching the Amazon estuary. This strong decrease can be attributed to the low suspension loads of most of the Amazonian lowland-tributaries abundant in water. Meade *et al.* (1979), however, found more homogenous contents when treating the samples taken in 1976/77. These contents decrease from 400 mg/l (Iquitos) to 235 mg/l (Obidos), whereas Gibbs states 85 mg/l concerning suspension loads at Obidos.

Eastwards of the 65th. meridian W within nearly the whole area of the Brazil and the Guyana shield and of the Barreiras Formation (Chapter 21), weathering horizons rich in kaolinite are formed. Under forest cover the erosion in these areas generally is extremely low. As could be expected, rivers draining this area nearly exclusively carry kaolinite as suspension. The suspension loads nevertheless are extremely low; values of 2–3 mg/l (referring to the mineralogical component) are reached. This fact explains the transparency of the clear to black water. Exceptions to those rivers are those, whose valleys lead through a drained area of obviously highly erodible kaolinite soils. These rivers can carry a suspension load of more than 100 mg/l, especially at times of high water. More than 90% of the

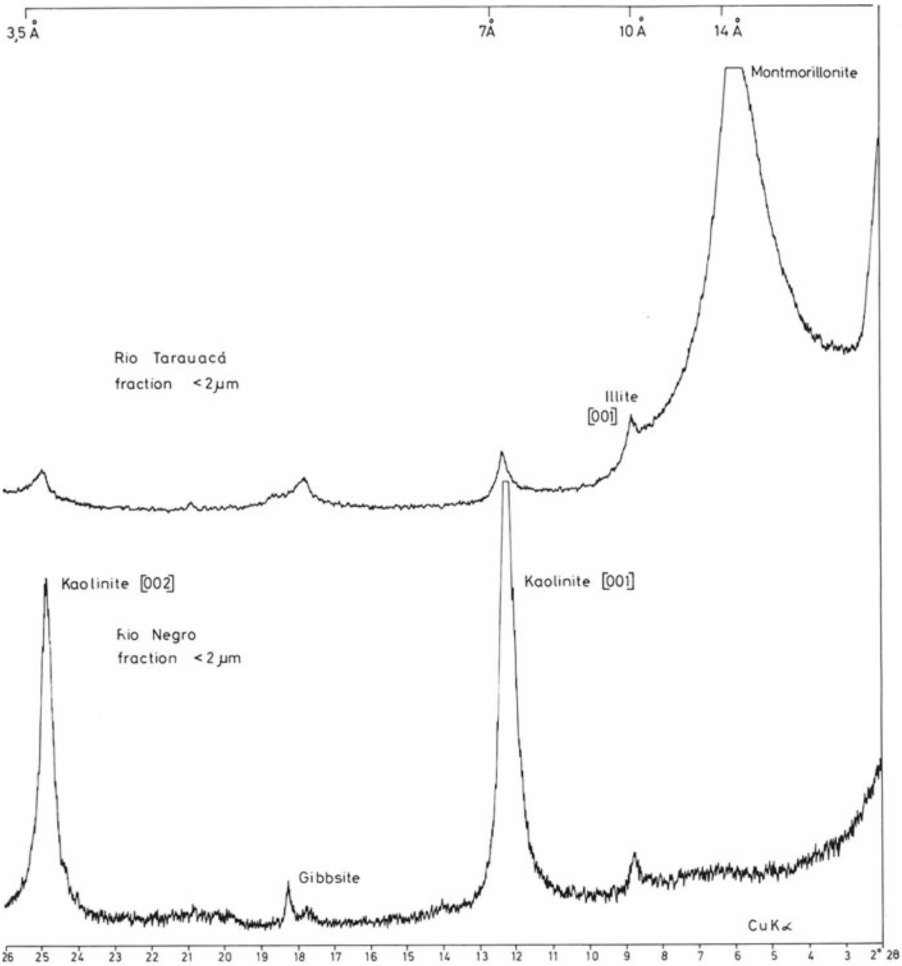

Fig. 5 X-ray diffractograms of the pelitic fraction of sediments from the Rio Tarauacá and the Rio Negro. The Rio Tarauacá is a typical whitewater river in the SW Amazonian lowlands. The pelitic fraction is dominated by montmorillonite. However, there are also traces of illite and kaolinite; chlorite is missing. The pelitic fraction of the blackwater river Rio Negro is typically composed of kaolinite; only illite and some gibbsite were able to be additionally detected in the <2 μm fraction.

suspended matter consists of kaolinite and quartz. Examples for such 'kaolinitic' white-water rivers are the Rio Branco and the Rio Parú, which drain parts of the Guyana Shield. However, rivers with higher suspension loads – at least during high water – can also be found within the Barreiras Formation.

The white-water rivers (e.g., the Rio Javarí, the Rio Juruá and the Rio Purus), are in contrast to the kaolinite-carrying rivers. Their drain areas consisting of highly erodible Cretaceous/Tertiary formations, the clay fraction of which mainly consists of montmorillonite. Montmorillonite, therefore, is the dominating mineral in the pelitic fraction of these rivers. In addition, minor amounts of illite and kaolinite occur. Chlorite was not traceable in these rivers (Fig. 5). Only a few measurements of the suspension loads of these rivers have been conducted. According to my own surveys, and according to Gibb's analyses (1967), the mean suspension load in the lower course of the Rio Juruá and the Rio Purús amounts to 70 mg/l; in the upper courses they might be twice or four times as much.

The only tributary of the lowland Amazon, which does not fit into this scheme, is the Rio Madeira. Draining the large southern Pre-Andine Basin, the suspension load of the Rio Madeira also carries minerals which have undergone minor changes through tropical weathering. These are mica/illite, chlorite and feldspars.

The rivers leading through the Pleistocene *várzea* (see Chapter 21) are characterized by kaolinite. This is not true for the weathering horizons of their drainage areas, which resemble to some degree the weathering horizons of the Estado do Acre. Whereas lateral erosion dominates in the Estado do Acre, surface-erosion is significant in the Pleistocene *várzea*, because of its low hydrogeographic position. Only the uppermost soil horizons, which are kaolinite to a large extent, are exposed to erosion. Like the rivers of the shields and the Barreiras Formation, the rivers of the Pleistocene *várzea* generally carry clear or black waters.

6. Conclusion

The results of the mineralogical composition discussed of Amazonian suspension loads can be summarized as follows: as could be seen, the suspension load of the rivers of the Amazon area is characterized by extremely strong discrepancies. Thereby, montmorillonite plays a more dominating role than kaolinite does, contrary to our expectations. The appearance of suspension loads, which are nearly mono-mineral pelitic fraction, can be explained by the regional geology of the Amazonian lowland. Additionally, it can be attributed to the old age of the Amazonian land surface.

As stated in Chapter 21, homogenous weathering profiles were able to develop in large areas due to deeply penetrating tropical weathering. A comparison with other areas (Irion & Petr 1980), leads to the conclusion that generally a monomineralic pelitic fraction is characteristic of tropical rivers draining old lowland areas. Montmorillonite normally seems to be more dominant than kaolinite, especially when analysed quantitatively.

Acknowledgments

I am very grateful to Prof. Dr. H. Sioli, Prof. Dr. G. Müller, Dr. M.L. Absy and to Dr. J. Adis for many helpful discussions and for supporting these studies. Special thanks to the co-workers of INPA, who greatly facilitated fieldwork in Amazonia. For laboratory assistance I wish to thank L. Glück, E. Harms, R. Neuser and G. Schmidt. Drafting was done by R. Flügel. Also special thanks are due to Dipl. geol. R. Düring and cand. geol. C. Tiews for translating the German manuscript. I am grateful to Dr. M.A. Geyh from the 'Niedersächsischen Landesamt für Bodenforschung', Hannover, West Germany for the radiocarbon dating of the samples.

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