Journal of African Earth Sciences, Vol. 12, No. 1/2, pp. 283-295, 1991.
Printed in Thailand

0899-5362/91 $3.00 + 0.00

Mineralogical composition and geographical distribution of African and Brazilian periatlantic laterites. The influence of continental drift and tropical paleoclimates during the past 150 million years and implications for India and Australia

Y. TARDY, B. KOBILSEK and H. PAQUET

Centre de Géochimie de la Surface (CNRS), Institut de Géologie (ULP), 1 rue Blessig, 67084 Strasbourg Cedex, France
Institut Français de Recherche pour le Développement en Coopération (ORSTOM)
B.P. 2528, Bamako, Mali

Abstract - Following the break-up of Pangea at the end of the Jurassic time, the African and South American continents and then India and Australia drifted into the fringes of the equatorial or tropical climatic zone with the humidity varying according to the epochs. India, Brazil and the southern part of East Africa which were previously more arid and probably hotter during the Jurassic, became progressively more humid and cooler. By contrast, West Africa, Central Africa and Australia, formerly subject to very humid climates became subject to warmer and drier climatic conditions.

In the first case, the ferricretes were rarely preserved intact but bauxites, generally massive and non pisolitic and essentially formed of gibbsite ($Al(OH)_3$) are abundant. In the second case, hematite (Fe_2O_3) occurring as nodular ferricretes are extensively developed together with gibbsite-bearing pisolitic bauxites and boehmite (AlOOH). Gibbsite and goethite are hydrated minerals related to humid and rather cool climates, whereas hematite and boehmite are dehydrated minerals related to less humid and warmer climatic conditions. Thus temperature, relative humidity of the atmosphere and the activity of water are the major climatic and thermodynamic parameters controlling the mechanisms of formation, the processes of evolution and the geographical distribution of bauxites and ferricretes.

Furthermore, the geographical distribution and the mineralogical composition of ferricretes and bauxites are considered to be controlled not only by the different present-day climates but also and perhaps above all by the succession of paleoclimates during the past 150 million years.

Key words: Climates, Paleoclimates, Bauxites, Ferricretes, Africa, Brazil, India, Australia

Résumé - A la suite de la dérive continentale qui commence avec la fragmentation de la Pangée, à la fin du Jurassique, les continents africain et sud-américain tout d'abord, l'Inde et l'Australie plus tardivement, se sont déplacés dans des franges climatiques équatoriales ou tropicales plus ou moins humides ou plus ou moins sèches, selon les époques.

L'Inde, le Brésil et la partie méridionale de l'Afrique de l'Est, au Jurassique plus arides, sont devenus progressivement plus humides et moins chauds. En revanche, l'Afrique de l'Ouest, l'Afrique centrale et l'Australie, autrefois soumises à des climats très humides, ont évolué vers des climats plus contrastés, plus chauds et plus secs.

Dans le premier cas, les cuirasses ferrugineuses subsistant intactes sont rares et les cuirasses bauxitiques, généralement massives et sans nodule contiennent essentiellement de la gibbsite ($Al(OH)_3$). Dans le second cas, les cuirasses ferrugineuses, nodulaires à hématite (Fe_2O_3) sont très abondantes, tandis que les bauxites à gibbsite montrent très fréquemment, en surface, des pisolites de boehmite (AlOOH). La gibbsite et la goethite (FeOOH) sont des minéraux hydratés qui apparaissent liés aux climats humides ou plutot frais, tandis que l'hématite et la boehmite sont des minéraux déshydratés qui apparaissent comme plutôt liés à des climats moins humides et plus chauds.

La distribution géographique, de même que la composition minéralogique des bauxites et des cuirasses ferrugineuses apparaissent ainsi non seulement réglées par la diversité des climats actuels, mais encore et surtout comme le reflet de l'évolution des climats anciens qui se sont succédé au cours des 150 derniers millions d'années.

INTRODUCTION

On both sides of the Atlantic Ocean, areas subject to present-day tropical and equatorial climatic conditions, on the South American and African continents, are covered by a thick lateritic mantle. Those laterites including bauxites, ferricretes and nodular soils which have similar features but also some different chemical, mineralogical and structural characteristics.

The purpose of this paper is to demonstrate that such features result as much from latitudinal differences in present-day climates as from separate paleoclimatic histories since the break-up of Pangea and the opening of Atlantic ocean during the Mesozoic. Such an interpretative approach may also explain the differences observed in the laterites of India and Australia.

RELATIONS BETWEEN CLIMATIC AND THERMODYNAMIC FACTORS

Temperature and water activity

The two principal climatic factors governing the mineralogical composition of lateritic covers are temperature and atmospheric relative humidity. The latter is closely related to what chemists call water activity. In fact, by definition (Garrels and Christ, 1965) water activity written as a_w or $[H_2O]$ is a dimensionless number equal to the f_w/f°_w ratio of the fugacity values of water vapor in air. f_w is the fugacity value of water vapor in air, in equilibrium with an assemblage of minerals in equilibrium in turn with capillary water. f°_w is the fugacity value of water vapor at saturation with respect to liquid water at the same temperature. In air, f_w is not equal to the partial pressure of water vapor p_w. However, f_w/f°_w ratio may be considered as equal to the p/p° ratio of the partial pressures of water vapor and consequently water activity may also be considered as equal to the atmospheric relative humidity ($p/p^\circ = HR(\%)/100$) which characterizes a given climate (Tardy and Novikoff, 1988):

$$a_w\,[H_2O] = f_w/f^\circ_w = p/p^\circ = HR/100$$

The chemical potential μ_w of bound water in soil capillaries is calculated from the normal chemical potential μ°_w of liquid and free water and from bound water activity by the following relation:

$$\mu_w = \mu^\circ_w + RT\,Ln a_w$$

Chemical equilibria between hydrated and dehydrated minerals as well as reactions of mineral hydration and dehydration are ruled by the fluctuations of water activity. Equilibrium between goethite (FeOOH) and hematite (Fe_2O_3):

$$2\,FeOOH = Fe_2O_3 + H_2O$$

is thus reached if:

$$\mu(Fe_2O_3) + \mu(H_2O) = 2\,\mu(FeOOH)$$

As hematite and goethite are pure minerals and thus in a standard state, it follows so that:

$$\mu(Fe_2O_3) = \mu^\circ(Fe_2O_3) \text{ and } \mu(FeOOH) = \mu^\circ(FeOOH)$$

so that:

$$-RTLn\,[H_2O] = -RT\,Lna_w = \mu^\circ(Fe_2O_3) + \mu^\circ(H_2O) - 2\,\mu^\circ(FeOOH)$$

A similar relation can be written for the equilibrium between gibbsite ($Al(OH)_3$) and boehmite (AlOOH), as follows:

$$-RT\,Ln[H_2O] = -RT\,Lna_w = \mu^\circ(AlOOH) + \mu^\circ(H_2O) - \mu^\circ(Al(OH)_3)$$

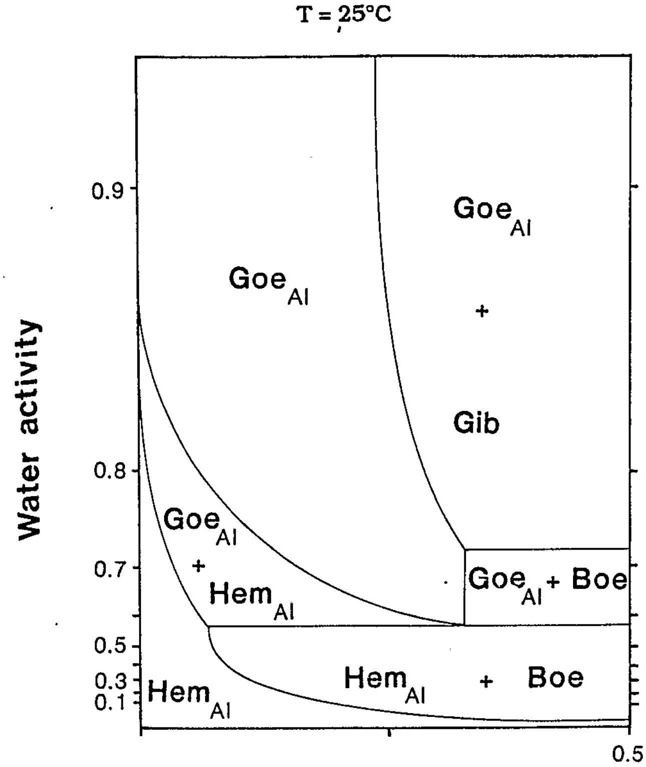
Normal chemical potentials are a function of temperature so that, at equilibrium, water activity is itself a function of temperature for both reactions.

Thus, the relations between climatic and thermodynamic factors can be explained. A very humid climate corresponds to a permanently water-saturated atmosphere ($p/p^\circ = 1$, HR = 100%) and a water activity equal of 1 ($[H_2O] = 1$). An arid or less humid climate corresponds to a drier atmosphere ($p/p^\circ < 1$, HR < 100%) and a water activity lower than 1, such as $[H_2O] < 1$, is equal to the capillary-water activity which governs the equilibria between iron and aluminium oxides or hydroxides in laterites (Tardy and Nahon, 1985; Tardy and Novikoff, 1988; Tardy *et al.*, 1988b).

Thermodynamic and climatic equilibria between goethite, hematite, gibbsite and boehmite in lateritic profiles

In lateritic mantles, besides gibbsite and boehmite which are always Fe-depleted minerals, goethites and hematites are Al-bearing minerals and are thus considered as solid solutions between goethite and diaspore ($(Al_xFe_{1-x})OOH$) on one hand or between hematite and corindon ($(Al_yFe_{1-y})_2O_3$) on the other hand (Didier *et al.*, 1985). The equilibrium conditions then become more complicated and the stability fields of minerals depend on water activity (Fig. 1a), on temperature (Fig. 1b) and on the chemical composition of the material (Trolard and Tardy, 1987). The effect of a water activity decrease at fixed temperature (Fig. 1a) is equivalent to a temperature increase at fixed water activity, in stimulating dehydration reactions and thus in favouring the formation of boehmite (AlOOH) with respect to gibbsite ($Al(OH)_3$) and of hematite (Fe_2O_3) with respect to goethite (FeOOH). When goethite and hematite are associated to gibbsite, the content of substituted Al increases as water activity or temperature decreases.

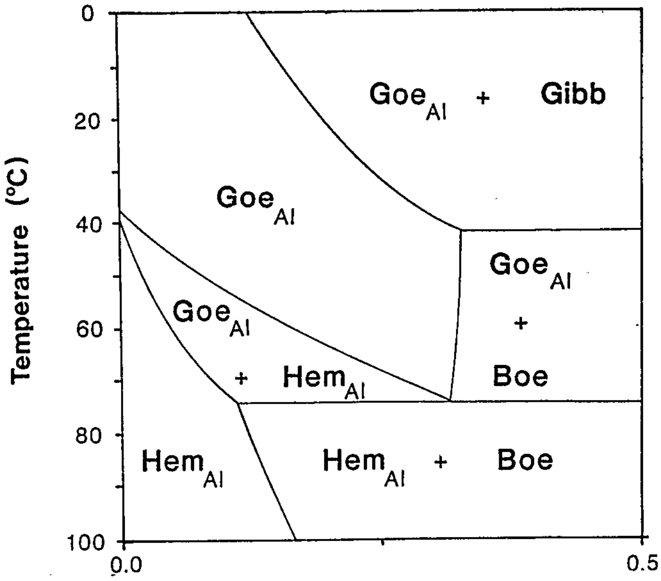
This behavior fits perfectly with the observations made on laterites in West Africa. In ferricretes of Senegal and Mauritania, the hematite-bearing horizons develop over the goethitic ones, located close to the water table (Nahon, 1976). The most Al-substituted hematite is found in the uppermost part of profiles (Tardy and Nahon, 1985). Moreover, the goethite contents decrease from East Senegal to Mauritania (Nahon, 1987). In the case of bauxites, the boehmite content increases from



·Moles of Al_2O_3 for 1 mole of F_2O_3

Fig. 1a. Stability diagram in the system Fe_2O_3-Al_2O_3-H_2O as a function of the aluminum content and the water activity at a temperature of 25°C and at a total pressure of 1 bar (after Trolard and Tardy, 1987).

Fig. 1a. Diagramme de stabilité dans le système Fe_2O_3-Al_2O_3-H_2O en fonction de la teneur en aluminium et de l'activité hydrique à une température de 25°C et à une pression totale de 1 bar (d'après Trolard et Tardy, 1987).



Moles of Al_2O_3 for 1 mole of F_2O_3

Fig. 1b. Stability diagram in the system Fe_2O_3-Al_2O_3-H_2O as a function of the temperature and the aluminum content for a water activity $[H_2O] = 1$, at a total pressure of 1 bar (after Trolard and Tardy, 1987).

Fig. 1b. Diagramme de stabilité dans le système Fe_2O_3-Al_2O_3-H_2O en fonction de la température et de la teneur en aluminium pour une activité hydrique $[H_2O] = 1$, à une pression totale de 1 bar (d'après Trolard et Tardy, 1987).

South to North in the Côte d'Ivoire region (Boulangé, 1984). They also increase in the northern border of Fouta-Djalon mountains, towards the warmer and more arid conditions of the Sahara (Balkay and Bardossy, 1967).

Clearly, gibbsitic bauxites continuously form under permanently humid equatorial climates while hematitic ferricretes at the present times and on the same parent rocks, continue to develop under contrasted tropical climates.

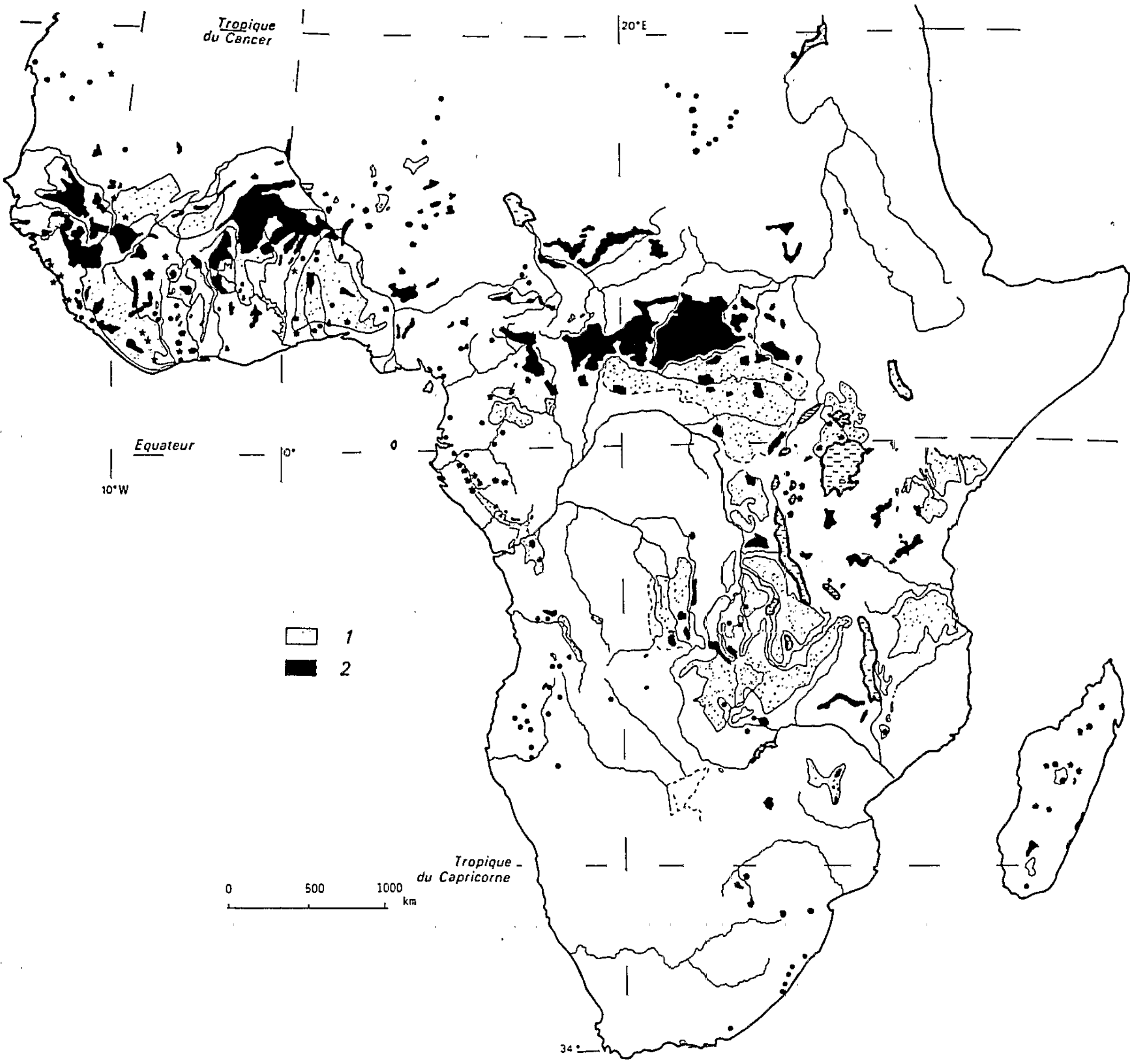
Goethite and gibbsite are hydrated minerals which are to be related to constantly humid climates. Hematite and boehmite are both dehydrated minerals compared to goethite and gibbsite. Their occurrence in laterites is related to tropical climates with a marked dry season and relatively high temperatures (mean annual temperature 28°C). In such climates, humidity is usually sufficient to induce a strong weathering during rainfall but the temporary aridity of the dry season results in dehydration of gibbsite and goethite into boehmite and hematite respectively. Accompanying these mineralogical changes is also the formation of nodular or pisolitic structures and induration of ferricretes and bauxites (Fig. 2).

PERIATLANTIC CLIMATES AND PALEOCLIMATES

Main features of present-day periatlantic climates equatorial or tropical climates with contrasted seasons prevail in West Africa, Central Africa and East Africa.

In equatorial areas, climate is characterized by mean annual temperature ranging between 25 and 28°C, mean annual rainfall higher than 1700 mm, atmospheric relative humidity close to saturation, and a short or non-existent dry season. For higher latitudes in areas situated between the equator and the tropics, climates are characterized by contrasted seasons, higher temperatures, ranging between 28°C and 35°C, annual rainfall lower than 1700 mm and long dry seasons during which atmospheric relative humidity decreases, sometimes below 50%.

However, striking differences are evident between Africa and South America, as well as between the equatorial areas and the tropical zones (Ratisbona, 1976; Griffiths, 1972; Leroux, 1983). First, the predominantly low-altitude areas, Amazonia, Central Africa (Zaire, Congo, Gabon), and a part of West Africa (Sierra Leone, Guinea, South Côte d'Ivoire) are subject to a humid tropical climate close to equatorial. Second, the equatorial and tropical areas of South-East Africa (Kenya, Uganda, Tanzania) and the tropical zones of Central Brazil (Goias, Mato Grosso) are character-



$[H_2O] = 1.0$
Fig. 2. Distribution of ferricretes in Africa (after Petit, 1985). Discontinuous indurations (1); continuous ferricrete (2).

$[H_2O] = 1.0$
Fig. 2. Distribution des ferricrètes en Afrique (d'après Petit, 1985). Indurations discontinues (1); ferricrète continu (2).

ized by usually lower temperatures, related to higher altitudes. Last the contrasted season domain of Western and Central Africa (Senegal, Mali, Burkina Faso, Central Africa) are hotter and drier, and desert areas are better developed and closer one to other desert areas in West Africa and Sudan, whereas the desert areas are reduced in size in Brazil (Nordeste) or westwards decentred in South Africa (Kalahari). This results in higher temperatures in Central and West Africa (5-6°C higher at the equator, more than 20°C higher at the tropics) than for the same latitude in Brazil and East Africa. Thus, when going North from the equator to the Tropic of Cancer, the mean annual temperature increases, whilst a temperature decrease is observed when going South from Congo basin to the Tropic of Capricorn. Important differences in the mean annual rainfalls are also evident. At a same latitude, Brazil and East Africa are in general cooler and more humid, whilst West and Central Africa are hotter and drier. Some global climatic similarity thus exists between Brazil and East Africa, South of equator, whilst there are important climatic differences between these areas and the region of West and Central Africa, North of the equator (Table 1).

Moreover, evolving but persistent differences in periatlantic climates have been affecting Africa and South America for more than 100 M.a. These paleoclimatic changes have now been overprinted by the present-day climatic characteristics.

Table 1. Climatic datas from African stations (1), (2), (3) and from Brasilian stations (4), (5), (6) (after Ratisbona, 1976; Griffiths, 1972 and Leroux, 1983).

	Lat(°)	T(°C)	HR(%)	P(mm)	E(mm)	Nbms
Dabou (1)	4°55'N	29,0	93	2383	-	1
Tabora (2)	4°53'S	28,0	53	977	-	6
Niamey (3)	13°30°N	37	58	384	2057	8
Belem (4)	1°28'S	25,7	86	2732	639	0
Manaus (5)	3°08'S	26,9	82	1996	772	1
Formosa (6)	15°32'S	21,1	72	1595	1234	5

Lat(*) latitude in degree
T(*C) temperature in degree
HR(%) relative humidity of the atmosphere in percent
P(mm) precipitation in millimeters per year
E(mm) evaporation in millimeters per year in millimeters per year
Nmbs number of dry months per year

Paleoclimates

Recent paleogeographical maps provide reconstructions of the arrangement of continents and of the probable past distribution of the earth's major climatic zones since he break-up of Pangea and the opening of the Atlantic ocean, i.e. over the past 100 M.a. (Parrish *et al.*, 1982; Tardy *et al.*, 1988a).

During Jurassic times, the equator was located near present-day Mauritania and Egypt in Africa, and at the northern extremity of South America (Figs. 3a and b). Present-day South Africa and the greater part of present-day Brazilian shield were then subject to arid climates. During Cretaceous and Cenozoic times, a northward drift of these both continents took place, whilst, at the same time, a slow rotation of Africa occurred. An equatorial climate was affecting Amazonia since the Maastrichtian; this climatic zone progressively extended southwards, and, at the same time, there was a reduction in size of the dry areas of Central Brazil. In Africa, the equatorial climatic zone which was well-developed during the Maastrichtian progressively contracted as equator moved southwards. Because it was close to the equator, South-East Africa was subject to high rainfall. From the Jurassic to present times, the previously arid climates of South America and South-East Africa became progressively more humid, whilst the formerly humid climates of West Africa progressively became more arid. Consequently, paleoclimatic successions are similar in South-East Africa and in Brazil: both these areas changed

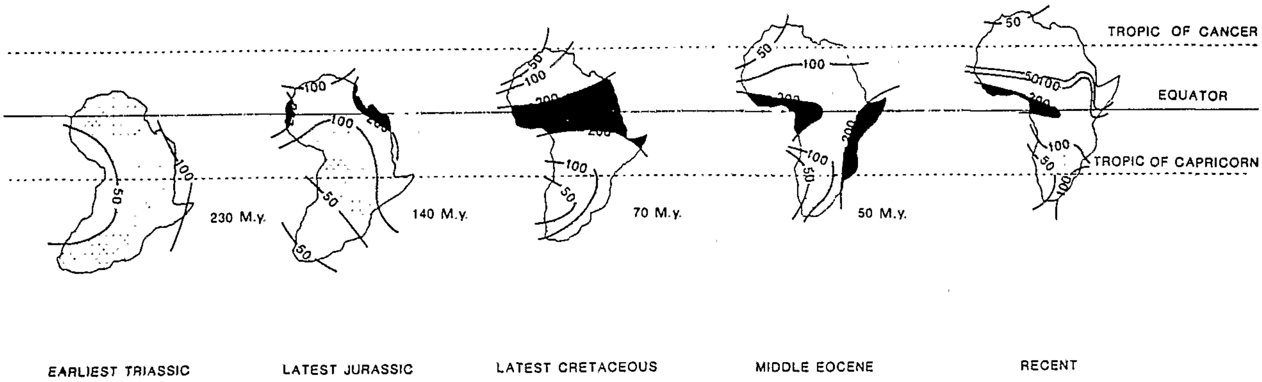


Fig. 3a. Predicted distribution of rainfall through geological times. Numbers are to show relative values only: no units are implied. The rainfall is divided into four categories: < 50 = low rainfall, 50-100 = moderately low rainfall, 100-200 = moderately high rainfall, > 200 = high rainfall (after Parrish *et al.*, 1982). Example of Africa.

Fig. 3a. Distribution supposée des précipitations au cours des temps géologiques. Les nombres indiquent seulement des valeurs relatives sans unités. Les précipitations sont réparties en 4 catégories: < 50: faibles; 50-100: assez faibles; 100-200: assez élevées; > 200: élevées (d'après Parrish *et al.*, 1982). Exemple de l'Afrique.

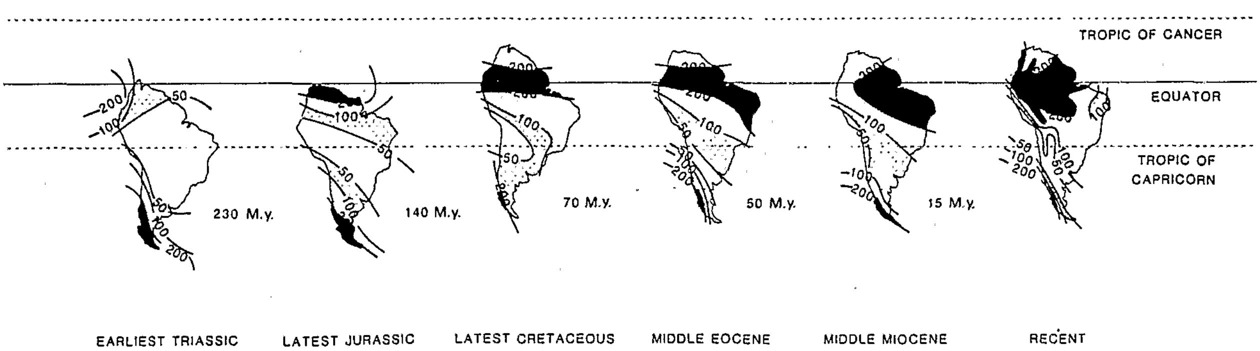


Fig. 3b. Example of South America.
Fig. 3b. Exemple de l'Amérique du Sud.

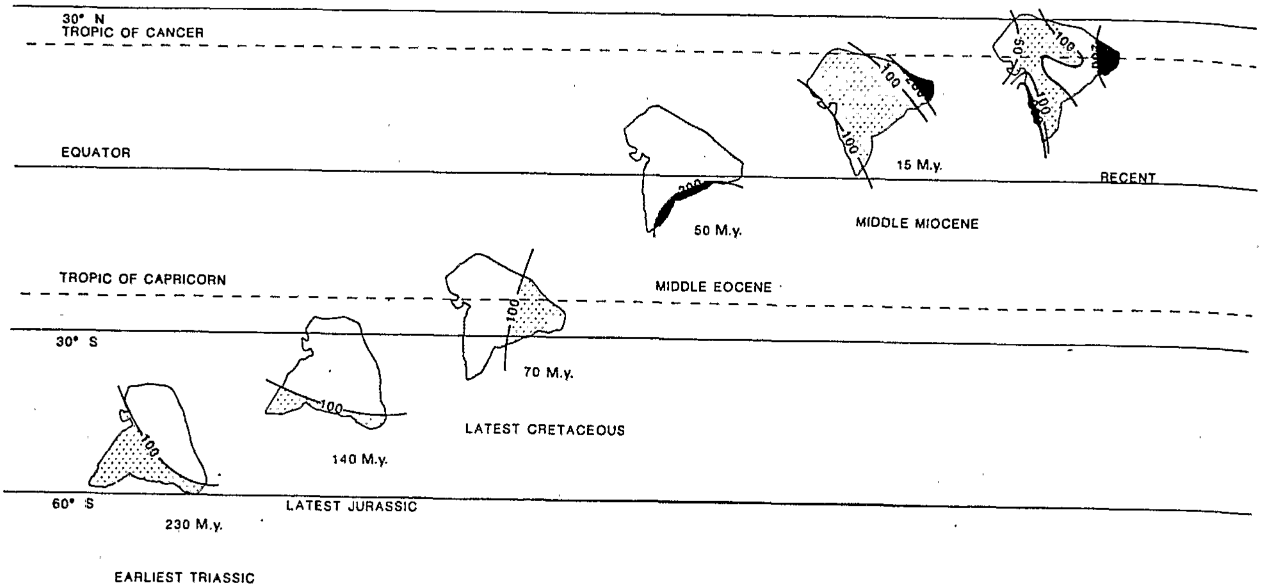


Fig. 3c. Example of India.
Fig. 3c. Exemple de l'Inde.

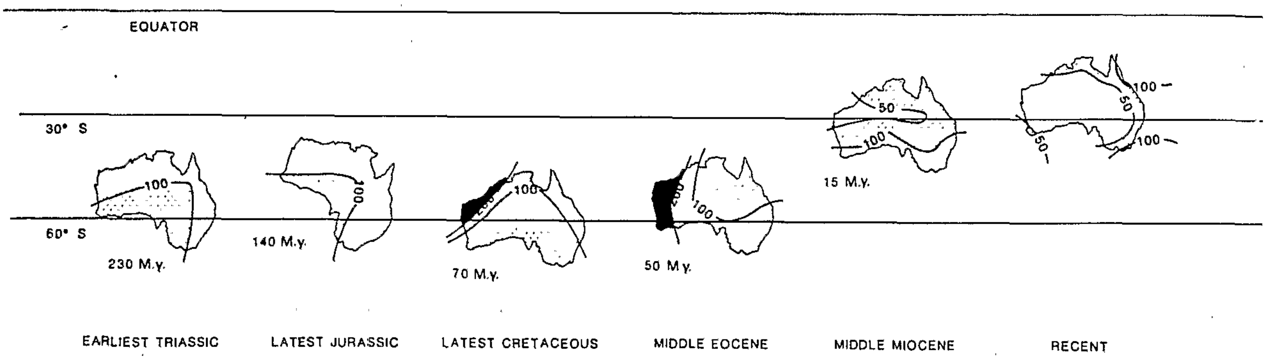


Fig. 3d. Example of Australia.
Fig. 3d. Exemple de l'Australie

progressively from dry to humid climates. By contrast, West Africa became more and more subject to the arid Saharan influence, lying in the belt around the Tropic of Cancer.

Thus, Southern Africa and South America have similar present-day climates as well as similar paleoclimatic history which are very different from those of West Africa.

It is notable that in intertropical areas, the geographical distribution and the mineralogical composition of ferricretes and bauxites can be correlated with these climatic changes during geological times.

DISTRIBUTION AND MINERALOGICAL COMPOSITION OF LATERITES IN AFRICA AND BRAZIL (Figs. 4, 5)

The distribution of the different lateritic formations has been correlated with climatic zonations by many authors.

Ferricretes are found and develop principally in humid tropical zone characterized by: mean annual rainfall ranging between 1200 to 1700 mm a year, 4 months of dry season, mean atmospheric relative humidity smaller than 80%, mean annual temperature around 28°C. In West Africa, Central Africa and Uganda where ferricretes are continuing at the present-day to form (Maignien, 1958; Brückner, 1957; Quantin, 1965; Delvigne and Grandin, 1969; McFarlane, 1976; Beaudet, 1978; Fritsch, 1978; Michel, 1978; Petit, 1985). In Africa (Fig. 2), the development of ferricretes gradually decreases northwards, as humidity decreases and Saharan influence increases, and eastwards, as temperature decreases and altitude increases.

In the case of bauxites, many authors such as Bardossy (1979, 1981), McFarlane (1983) and Valeton (1983) have described the most favourable climatic zones as follows: tropical to humid subtropical zones with mean annual temperature greater than 20°C and mean annual rainfall of more than 1200 mm, approximately located in a belt between 30° latitude North and 30° latitude South. But, it seems to us that these characteristics are not

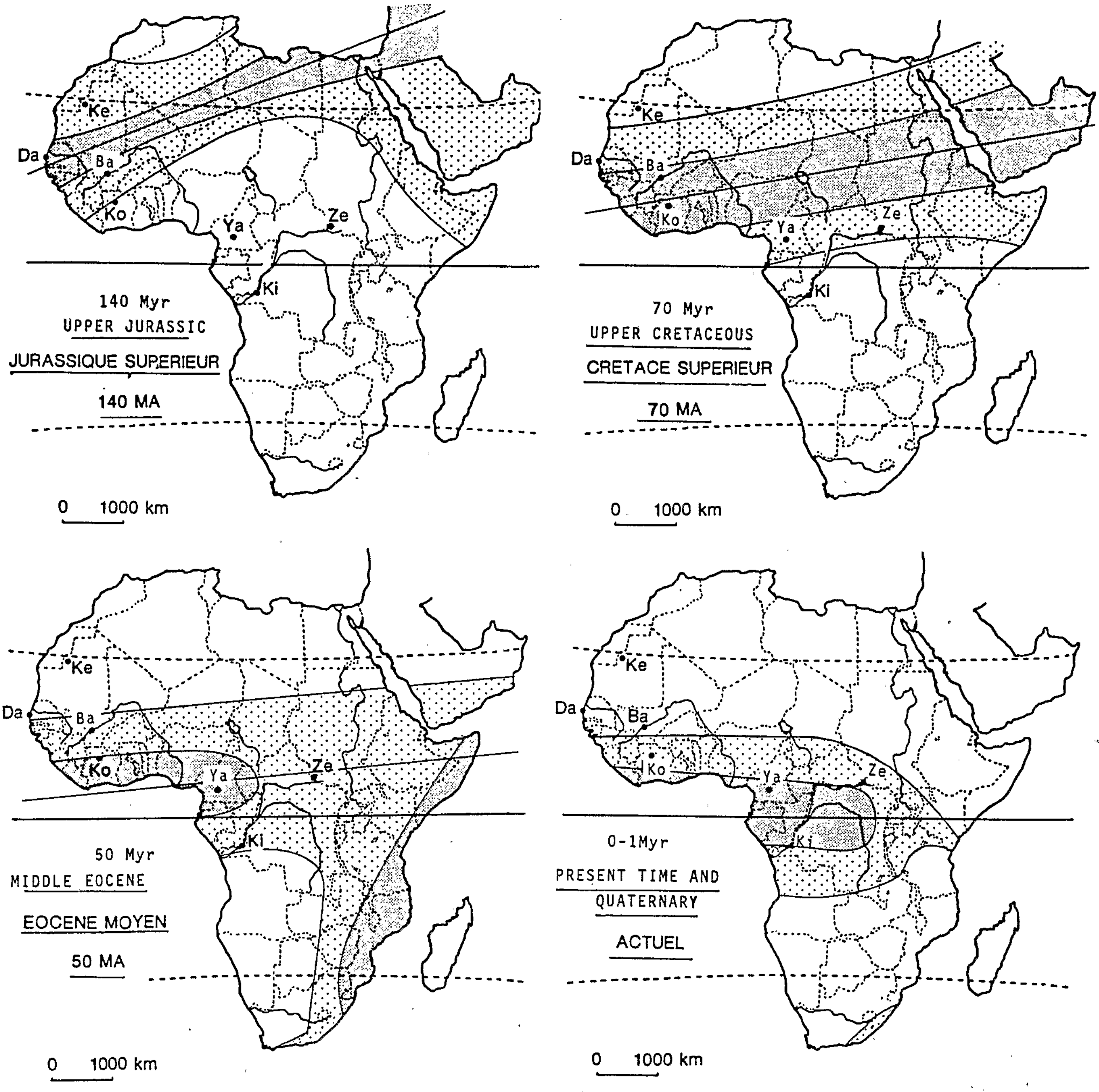


Fig. 4. Possible distribution of bauxites **and ferricretes** in Africa over the past 150 million years (dotted = ferricretes; grey = bauxites).

Fig. 4. Distribution possible des bauxites et ferricrètes en Afrique depuis 150 millions d'années (pointillé: ferricrètes; grisé: bauxites).

restrictive enough. For our part, we consider that bauxitization requires not only equatorial or tropical warm conditions but also very humid zones, mean annual temperature greater than 20°C, mean annual rainfall higher than 1700 mm, less than 4 months of dry season, mean atmospheric relative humidity greater than 80%.

The comparison of laterites in Africa and in South America (Brazil) leads us to emphasize variations in the distribution and mineralogical composition, both of these variations being due to climatic and paleoclimatic differences.

Ferricretes

Ferricretes are most wide-spread in warm climatic zones with a marked dry season, where induration can occur and nodular or pisolitic forms can develop.

In West Africa, they stepped on landsurfaces which succeeded one another from the Tertiary to the present-time (Maignien, 1958; Grandin and Delvigne, 1969; Eschenbrenner and Grandin, 1970; Boulangé *et al.*, 1973; Rognon, 1978; Morin and Pascual, 1978; Coque, 1978).

Fragments of ferricretes are found in the forest equatorial zones of Central Africa (Martin, 1966;

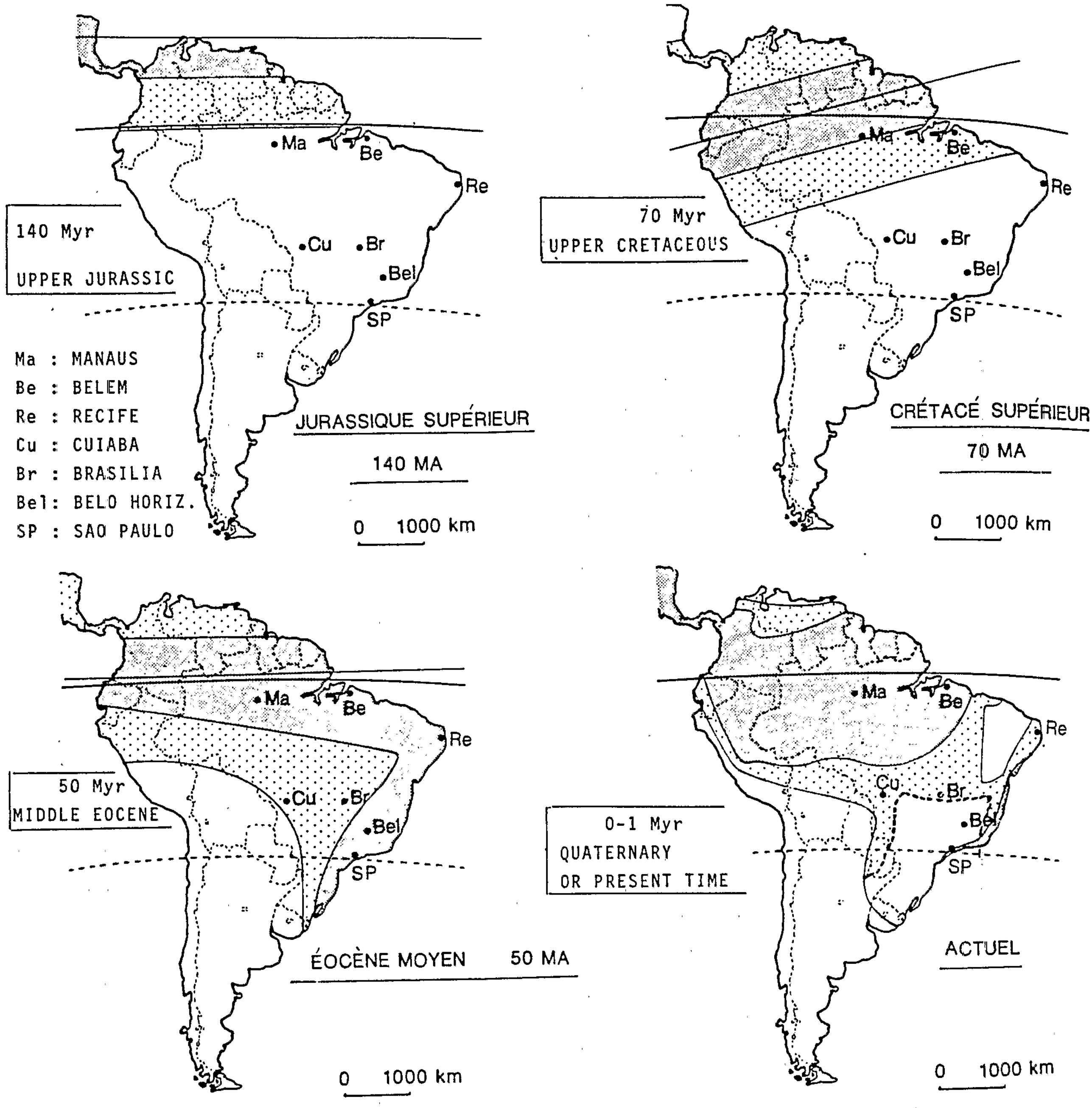


Fig. 5. Possible distribution of bauxites and ferricretes in South America over the past 150 million years (dotted = ferricretes; grey = bauxites).

Fig. 5. Distribution possible des bauxites et ferricrètes en Amérique du Sud depuis 150 millions d'années (pointillé: ferricrètes; grisé: bauxites).

Novikoff, 1974; Martin *et al.*, 1981; Boulvert, 1983) where they are more or less eroded remnants of ferricretes associated to ferruginous nodular layers and overlaid by a loose ferrallitic layer (Muller *et al.*, 1981 ; Bocquier *et al.*, 1984).

Some ferricretes also occur in the Sahara (Nahon, 1976; Leprun, 1979), but they are fossil ferricretes evidencing more humid ancient climates.

Ferricretes are rare in South-East Africa (Tanzania, Rhodesia) (Grubb, 1981; Valeton and Mutakyawa, 1987) and in Brazil (Volkoff, 1986; Tardy *et al.*, 1988a), where climate is cooler and more humid and where non-indurated lateritic soils prevail. However, some relatively thick ferricretes have been observed on an Eocene land-surface (called South-American surface) (King, 1956) in areas subject to a contrasted tropical climate in Nordeste, Goias and Mato Grosso (Dorr, 1964; Journaux, 1978; Melfi *et al.*, 1979; Trescases and Melfi, 1985; Weggen, 1986). In addition, nodular ferruginous accumulations formed under a loose surficial cover in the Amazonia equatorial zone (Chauvel *et al.*, 1982; Lucas *et al.*, 1986) can be compared to those of Central Africa. According to Nahon *et al.* (1989), the scientists working on the southern border of the Amazonia basin frequently find ferricretes currently being degraded with the rain forest.

The nodular ferruginous soils observed under forest covers could appear to be relics of ancient ferricretes which developed when these areas were subject to a tropical climate with a well defined dry season but which are now being destroyed under the very humid tropical conditions that prevail to-day. The ferricretes of the Goias are similarly destined for future destruction, if present-day climate continues or if the equator continues to move southwards.

In summary, two hypotheses were proposed by Martin and Volkoff (1987) to explain nodular ferruginous accumulations.

(1) An old ferricrete which was destroyed generating nodular ferruginous layers. When only the layers are preserved, they correspond to a pedological horizon. However in some cases this horizon was destroyed and then regenerated by geochemical deepening of the weathering cover. This resulted in the formation of a "'stone-line" whose ferruginous gravel clasts are older than the soil in which they are found.

(2) The occurrence of nodular ferruginous accumulations alone does not necessarily indicate a pre-existing ferricrete. Ferruginous accumulation can develop without ever reaching the "ironcrust" state and can instead be considered as "aborted" ferricretes. But in every case, these ferruginous accumulations appear to have been herited from ancient landscapes found under less humid conditions than prevail at the present-day.

Our preference is far the first hypothesis.

The induration of ferruginous accumulations leading to ferricrete formation results from an accumulation of hematite in the small pores in a pre-existing accumulation of kaolinite (Tardy and Nahon, 1985) resulting from a decrease of water activity and of atmospheric relative humidity and from a temperature increase, as shown previously.

Ferricretes are thus typical of hot, humid tropical climates but with long dry season. Under more arid climates (Leprun, 1979) or under permanently humid conditions in equatorial forests (Martin and Volkoff, 1987), ferricretes do not develop or are destroyed. When going from wet-dry tropical zones to arid ones (Sahara), ferricretes are marked by decreasing goethite contents and by increasing hematite contents and by nodule formation (Nahon, 1987). In contrast, a decrease in induration together with a goethite development is evident when going from contrasted tropical zones to equatorial ones.

Bauxites

Bauxites are wide-spread in West Africa. They formed in various latitudes, in humid zones like Guinea, Nigeria, Cameroon or Côte d'Ivoire or in drier areas such as Burkina Faso, Mali etc. (Boulangé, 1984; Patterson *et al.*, 1986). They are generally considered to have formed during Jurassic, Cretaceous or Eocene times (Michel, 1973), under more humid climates than those of the present time. In West Africa, bauxites are characterized by high gibbsite ($Al(OH)_3$) contents, but they also contain boehmite (AlOOH) in the surficial horizon. This dehydrated mineral forms like hematite in ferricretes, as pisolites develop in the uppermost horizons (Belinga, 1968; Hieronymus, 1973; Boulangé, 1984; Valeton and Beissner, 1986). The boehmite content is higher because of the proximity to the Saharan zone with its hot and dry climate (Balkay and Bardossy, 1967). This mineral is also common in Egyptian bauxites (Germann *et al.*, 1987).

It is interesting to note that the bauxites of Southeast Africa, Rhodesia, Mozambic and Malawi (Grubb, 1973a, b), the bauxites of the different landsurfaces of Tanzania (Valeton and Mutakyawa, 1987) and of numerous Brazilian deposits such as those of Amazonia or Minas Gerais (Weber, 1959; Valeton, 1973; Dennen and Norton, 1977; Grubb, 1979; Aleva, 1981; Kotschoubey and Truckenbrodt, 1981; Groke *et al.*, 1982; Kronberg *et al.*, 1982; Lemos and Villas, 1983; Melfi and Carvalho, 1983; Trescases and Melfi, 1985) are usually massive and essentially composed of gibbsite. No pisolite is found and boehmite is rare.

Consequently, we can assume that lateritic bauxites only develop under very humid equatorial or tropical climates; in that case, gibbiste is the prevailing mineral. Boehmite is considered to be a probable secondary mineral whose formation took place at a later stage in the development of tropical climates with long dry season, i.e. low atmopheric relative humidity and high temperature. During the paleoclimatic history of West Africa, for example, boehmite formation could be considered as secondary and contemporaneous to hematite and ferricrete formation in the ferruginous accumulations located downslope to have developed later i.e. from the Miocene to the present-day times.

EXAMPLES OF INDIA AND AUSTRALIA

Present-day climates

India is subject to a tropical climate with contrasted seasons. The arrangement of reliefs controls high rainfall on the western coast and the eastern foothills of the Himalaya which are covered with dense forest. Additionally aridity in the inner part of Deccan which is covered with savannah is in part a consequence of the relief.

The principal climatic features of Australia are its generally low relief, its insular character and its location around the Tropic of Capricorn; 40 % of the area is subject to a tropical climate. The Australian continent is also relatively arid with mean annual rainfall of only 600 mm or less affecting 80 % of the area. Deserts are widely developed (mean annual temperature higher than 30°C, atmospheric relative humidity of 20 %). The humid tropical zone is restricted to the northeastern coast whilst temperate to mediterranean type climatic conditions prevail on the south-eastern, southern and south-western margins of the continent.

Paleoclimates

At about the time when South America and Africa separated, India also separated from Gondwana, rotating and moving northwards (Fig. 3c). From the end of the Triassic to the Cretaceous the Indian continent's climate evolved from hot and dry to hot and humid. Climatic conditions were favourable for lateritization from Cretaceous to Paleocene times for during that period, the Indian continent crossed the zone between 30° latitude South and 0° latitude North (Kumar, 1986). After the collision of India against Eurasia at the end of the Miocene, climate became more temperate or more tropical but remained humid with no important arid episode.

The present-day configuration of Australia developed during the Tertiary. From a tectonic point of view, Australia has been relatively stable since the terminal Jurassic. During the Cretaceous, Australia together with Antarctic separated from the African continent and moved eastwards (Fig. 3d). The separation of Antarctic from the Australian continent was completed by the end of the Paleocene and during the Tertiary, Australia started moving 25° latitude northwards and was affected by an about 70° dextral rotation at the same time. Important climatic variations were generated by the fragmentation of Gondwana due to a shift of oceanic circulations southwards and the development of a circum-polar current system. A warm to hot and humid climate prevailed from the Paleocene to the Miocene times, favouring lateritization (Beckmann, 1983) but during the Quaternary, the climate of the Australian continent became predominantly arid.

Lateritic formations

In India, laterites are very wide-spread. Their development began at the end of the Cretaceous and continued during the Tertiary. On the western coast (Balasubramania, 1978; Valeton, 1983; Patterson *et al.*, 1986), bauxites have similar features to those of Brazil due to the similar humid tropical climatic conditions and to a plateau location. The Indian deposits are essentially gibbsitic and contain little or no boehmite. In central and southern India, however, bauxitic formations show some boehmitic pisolitic layers due to present-day semi-arid conditions (Ghosh and Dutta, 1978; Patterson *et al.*, 1986) and associated with low landsurfaces ferricretes (Demangeot, 1978). In the northern and north-eastern part of India, bauxites contain boehmite and diaspore but this mineralogical content could be the result of tectonic movements caused by the collision of India against Eurasia rather than of climatic variations (Hasan Ziaul, 1966; Caillère and Singh, 1967).

In Australia, lateritic formations are found throughout and cover 20 % of the whole continent. Ferruginous laterites are nodular or massive, and they contain goethite and hematite. In the arid zone, they are preserved in the form of relictual plateaus and reliefs, resulting from the destruction of former peneplains (Hubble *et al.*, 1983). Bauxitic deposits are restricted to the northern, southeastern and southwestern coastal zones. They are Tertiary in age and contain predominantly gibbsite (Grubb, 1970; Grubb, 1971a and b; Valeton, 1972; Ball and Gilkes, 1987). Pisolitic structures related to boehmite formation are observed near the surface (Schellmann and Jepsen, 1973; Grubb, 1973a; White, 1976; Patterson *et al.*, 1986).

Thus, the distribution of ferricretes and bauxites as well as of boehmite in Australia and India might be controlled by the same factors as those operating in Africa and Brazil, namely the evolution of the prevailing climate through time and the resulting formation and destruction of bauxites and laterites.

CONCLUSIONS

The areas where ferricretes are numerous and well-developed, are also the areas with high boehmite contents in the bauxites. This is the case in West Africa and Australia which were formerly (until the Eocene) subject to very humid climates, which resulted in the wide-spread development of gibbsite-bearing bauxites but was probably not favourable for ferricrete formation. As the climate became characterized by marked wet and dry seasons, as well as hotter and drier, hematite-bearing ferricretes developed and secondary transformation of gibbsite into boehmite took place in the bauxites.

Paralleling this trend in the areas of Brazil, South-East Africa and India, ferricretes are rare, the bauxites do not generally contain boehmite. In India, however, boehmite is almost always present in small amounts (0,3-3 %) but locally, in the Kutch Peninsula, boehmite reaches 10 % (Bardossy, 1982). Unlike the more marked wet-dry hotter and drier climate of West Africa and Australia, those of South-West Africa, Brazil and India are cooler and more humid. Unlike the paleoclimates of West Africa and Australia which evolved from humid to arid leading to the progressive extension of Saharan and Australian deserts, the climates of Brazil, East Africa and India evolved from arid to humid together with the progressive enlargment of the equatorial or humid tropical zone on continents.

The variation in distribution of ferricretes as well as the different mineralogical compositions of bauxites in Africa, Brazil, Australia and India are the consequence of paleoclimatic evolutions over the past 150 million years rather than of present-day climatic differences.

In conclusion, the differentiation of the lateritic covers are mainly due to continental drift and movement of continents relative to the equator and to the tropics.

Acknowledgements - This study was supported by the "Action Thématique Programmée (ATP) LATERITES" of CNRS, by the "Programme PIRAT" of INSU-ORSTOM and by EUROLAT, the European Network for study of laterites. The manuscript has benefitted of the critical comments of B. Volkoff and G. Bardossy. The authors are indebted to Peter Cook for his very useful contribution to the english translation.

REFERENCES

Aleva, G. J. J. 1981. Essential differences between the bauxite deposits along the Southern and Northern Edges of the Guiana shield, South America. *Econ. Geol., New Haven*, **76**, 1142-1152.

Balasubramaniam, K. S. 1978. Mineralogy, geochemistry and genesis of certain profiles from Western India. In: *ICSOBA, 4th Intern. Symp.*, Athens, Greece, **1**, 35-76.

Balkay, B. and Bardossy, Gy. 1967. Lateritesedési részfolyamat vizsgalatok Guineai lateriteken (Study of partial processes of laterization on Guinean laterites). *Földt. Közl., Budapest*, **XCVII(1)**, 91-110.

Ball, P. J. and Gilkes, R. J. 1987. The Mount Saddleback bauxite deposit, southernwestern Australia. *Chem. Geol., Amsterdam*, **60**, 215-225.

Bardossy, Gy. 1979. The role of tectonism in the formation of bauxite deposits. In: *Travaux de l'ICSOBA*, Zagreb, **15**, 15-34.

Bardossy, Gy. 1981. Paleoenvironments of laterites and lateritic bauxites, effect of global tectonism on bauxite formation. *Proc. Irst Intern. Seminar on Lateritization Processes, Trivandrum, India*, 287-294.

Bardossy, Gy. 1982. *Karst bauxite. Bauxite deposits on carbonate rocks.* Elsevier Scientific Publishing Co., Amsterdam-Oxford-New York, 441 p.

Beaudet, G. 1978. Essai sur la zonation et la signification géomorphologique des cuirasses ferrugineuses en Afrique occidentale. *Trav. Doc. CEGET*, Talence, **33**, 35-52.

Beckmann, G. G. 1983. Evolution of australian landscapes and soils. Chapter 4: Development of old landscapes and soils. In: *Soils, an Australian viewpoint*. CSIRO, Academic Press, 51-72.

Belinga, S. 1968. Composition minéralogique des bauxites de l'Adamaoua (Cameroun). *Ann. de la Fac. des Sciences du Cameroun. Yaoundé*, **2**, 59-76.

Bocquier, G., Muller, J. P. and Boulangé, B. 1984. Les latérites. Connaissances et perspectives actuelles sur les mécanismes de leur différenciation. In: *AFES, Livre Jubilaire du Cinquantenaire*, Paris, 123-138.

Boulangé, B., Delvigne, J. and Eschenbrenner, V. 1973. Descriptions morphoscopiques, géochimiques et minéralogiques des faciès cuirassés des principaux niveaux géomorphologiques de Côte d'Ivoire. *Cah. ORSTOM, sér. Géol.*, Paris, **V(1)**, 59-81.

Boulangé, B. 1984. Les formations bauxitiques latéritiques de Côte d'Ivoire. Trav. Doc. ORSTOM, Paris, 341 p.

Boulvert, Y. 1983. Carte pédologique de la République Centrafricaine à 1/1 000 000. Notice explicative n° 100, ORSTOM, Paris, 126 p.

Brückner, W. D. 1957. Laterite and bauxite profiles of West Africa as an index of rhytmical climatic variations in the tropical belt. *Eclogae geol. Helv.*, Bâle, **50(2)**, 238-256.

Caillère, S. and Singh, A. 1967. Contribution à l'étude des bauxites de la province de Jammu au Kashmir. *C.R. Acad. Sci. Paris*, **264**, série D, 18, 2177-2180.

Chauvel, A., Boulet, R., Join, P. and Bocquier, G. 1982. Aluminium and iron oxihydroxide segregation in nodules of latosols developed on Tertiary sediments (Barreiras group) near Manaus (Amazon Bassin) Brazil. In: *Proceedings of the II Intern. Seminar on Lateritization Processes, Sao Paulo*, (Melfi and Carvalho Eds.), 507-526.

Coque, R. 1978. Observations sur la limite septentrionale des accumulations ferrugineuses de l'Afrique de l'Ouest. *Trav. Doc. CEGET*, Talence, **33**, 66-80.

Demangeot, J. 1978. Les reliefs cuirassés de l'Inde du Sud. *Trav. Doc. CEGET, Talence*, **33**, 99-111.

Delvigne, J. and Grandin, G. 1969. Etude des cycles morphologiques et tentative de chronologie paléoclimatique dans la région de Toumodi, en Côte d'Ivoire. *C.R. Acad. Sci. Paris*, **269**, série D, 1372-1375.

Dennen, W. H. and Norton, H. A. 1977. Geology and geochemistry of bauxite deposits in the lower Amazon Basin. *Econ. Geol.*, New Haven, **72**, 82-89.

Didier, P., Perret, D., Tardy, Y. and Nahon, D. 1985. Equilibres entre kaolinites ferrifères, goethites alumineuses et hématites alumineuses dans les systèmes cuirassés. Rôle de l'activité de l'eau et de la taille des pores. *Sci. Géol. Bull.*, Strasbourg, **38(4)**, 383-397.

Dorr, J. V. N. 1964. Supergene iron ores of Minas Gerais, Brazil. *Econ. Geol.*, New Haven, **59(7)**, 1203-1240.

Eschenbrenner, V. and Grandin, G. 1970. La séquence des cuirasses et ses différenciations entre Agnibilekrou (Côte d'Ivoire) et Diebougou (Haute Volta). *Cah. ORSTOM, sér. Géol.*, Paris, **II(2)**, 205-245.

Fritsch, P. 1978. Chronologie relative des formations cuirassées et analyse géographique des facteurs de cuirassement au Cameroun. *Trav. Doc. CEGET*, Talence, **33**, 115-132.

Garrels, R. M. and Christ, C. R., 1965. *Solutions, minerals and equilibria.* (Harper and Row Eds.), New York, 450 p.

Germann, K., Mocke, A., Doering, T. and Fischer, K. 1987. Late Cretaceous Laterite derived sedimentary deposits (oolite ironstones, kaolins, bauxites) in Upper Egypt. *Berliner geowiss. Abh.*, Berlin, (A), **75(3)**, 727-758.

Ghosh, K. P. and Dutta, B. C. 1978. Mineralogy and genesis of Phutkapahar bauxite deposits of eastern Madha Pradesh, India. In: *ICSOBA, 4th Intern. Symp.*, Athens, Greece, **1**, 204-255.

Grandin, G. and Delvigne, J. 1969. Les cuirasses de la région birrimienne volcano-sédimentaire de Toumodi: jalons de l'histoire morphologique de Côte d'Ivoire. *C.R. Acad. Sci.* Paris, **269**, série D, 1477-1479.

Griffiths, J. F. 1972. *Climates of Africa.* Elsevier Ed., 604 p.

Groke, M. C. T., Melfi, A. J. and Carvalho, A. 1982. Bauxitic alteration on basic and alkaline rocks in the state of Sao Paulo, Brazil, under tropical humid climate. In: *Proc. IInd Intern. Seminar on Lateritization Processes, Sao Paulo,* (Melfi and Carvalho Eds.), 237-250.

Grubb, P. L. C. 1970. Mineralogy, geochemistry and genesis of the bauxite deposits on the Gove and Mitchell Plateaus, Northern Australia. *Mineral. Deposita,* Berlin, **5**, 248- 272.

Grubb, P. L. C. 1971a. Genesis of bauxite deposits in the Boolarra Mirboo area of Gipps-land, Victoria. *J. of the Geol. Soc. of Australia,* Adelaïde, **18(2)**, 107-1113.

Grubb P. L. C. 1971b. Mineralogical anomalies in the Darling Range bauxites at Jarrahdale, Western Australia. *Econ. Geol.*, New Haven, **66**, 1005-1016.

Grubb, P. L. C. 1973a. High level and low level bauxitization: a criterion for classification. *Miner. Sci. Engng.*, **5(3)**, 219-231.

Grubb, P. L. C. 1973b. A preliminary account of bauxite in Rhodesia, Mozambique and Malawi. In: *ICSOBA Intern. Symp., 3d,* Nice, France, 223-232.

Grubb, P. L. C. 1979. Genesis of bauxite deposits in the Lower Amazon Basin and Guianas Coastal Plain. *Econ. Geol.*, New Haven, *74(4)*, 735-750.

Grubb, P. L. C. 1981. Lateritization phenomena associated with the tertiary african surface in Zimbawe Rhodesia. In: *Proc. Irst Intern. Seminar on Lateritization Processes, Trivandrum, India,* **11-24**, 254-260.

Hasan Ziaul, 1966. On the occurrence and geochemistry of bauxite deposits of Monghyr area, India. *Econ. Geol.*, New Haven, **61(4)**, 715-730.

Hieronymus, B. 1973. Etude minéralogique et géochimique des formations bauxitiques de l'Ouest du Cameroun. *Cah. ORSTOM, sér. Géol.*, Paris, **V(1)**, 97-110.

Hubble, G. D., Isbell, R. F. and Northcote, K. H. 1983. Features of australian soils. In: *Soils, an Australian viewpoint.* CSIRO, Academic Press, 17-48.

Journeaux, A. 1978. Cuirasses et carapaces au Brésil. *Trav. Doc. CEGET,* Talence, **33(8)**, 1-96.

King, L. C. 1956. A geomorfologia do Brazil oriental. *Rev. Bras. de Geografia,* Sao Paulo, **XVIII(2)**, 3-121.

Kotschoubey, B. and Truckenbrodt, W. 1981. Evoluçao poligenetica das bauxitas do distrito de Paragominas, Acailandia (estados do Para e Maranhao). *Rev. Bras. de Geociencias,* Sao Paulo, **11(3)**, 193-202.

Kronberg, B. I., Fyfe, W. S., Mc Kinnon, B. J., Stilianidifilho, B. and Nash, R. A. 1982. Model for bauxite formation: Paragominas, Brazil. *Chem. Geol.*, Amsterdam, **35(3/4)**, 311-320.

Kumar, A. 1986. Paleolatitudes and the age of indian laterites. *Paleogeogr., Paleoclimatol., Paleoecol.*, Amsterdam, **53**, 231-237.

Lemos, V. P. and Villas, R. N. 1983. Alteraçao supergenica das rochas basicas do grupo Grao-Para. Implicaçoes sobre a genese do deposito de bauxita de N5, Serra dos Carajas. *Rev. Bras. de Geociencias., Sao Paulo,* **13(3)**, 165-177.

Leprun, J. C. 1979. Les cuirasses ferrugineuses des pays cristallins de l'Afrique Occidentale sèche. *Mém. Sci. Géol.*, Strasbourg, **58**, 1979, 224 p.

Leroux, M. 1983. *Le climat de l'Afrique tropicale.* Champion Ed., Paris, 633 p.

Lucas, Y., Chauvel, A. and Ambrosi, J. P. 1986. Processes of aluminium and iron accumulation in latosols developed on quartz rich sediments from Central Amazonia (Manaus, Brazil). In: *Comm. 1° Int. Symp. on Geoch. of the Earth Surface,* Granada (Spain), abstracts.

McFarlane, M. J. 1976. Laterite and landscape. Academic Press London, 151 p.

McFarlane, M. J. 1983. Laterites. In: *Chemical sediments and geomorphology: precipitates and residua in the near surface environment,* Goudie A. S. and Pye K. Eds., Academic Press London, 7-59.

Maignien, R. 1958. Le cuirassement des sols en Guinée, Afrique Occidentale. *Mém. Serv. Carte Géol. Als. Lorr.*, Strasbourg, **16**, 239 p.

Martin, D. 1966. Etude pédologique dans le Centre Cameroun (Nanga-Eboko à Bertoua). *Cah. ORSTOM, sér., Pédol.*, Paris, **5(2)**, 189-218.

Martin, D., Chatelin, Y., Collinet, J. and Guichard, E. 1981. Les sols du Gabon. Pédogenèse, répartition et aptitudes. Carte à 1/200.000. Notice explicative n° 92, ORSTOM, Paris, 66 p.

Martin, D. and Volkoff, B. 1987. Signification paléoclimatique des cuirasses et des nappes de nodules ferrugineux dans les sols d'Afrique Centrale (Rive droite du Zaïre) (sous presse).

Melfi, A. J., Pedro, G. and Volkoff, B. 1979. Naturesa e distribuçao dos compostos ferriferos nos solos do Brasil. *R. Bras. Ci. Solo,* Sao Paulo, **3**, 47-54.

Melfi, A. J. and Carvalho, A. 1983. Bauxitization of alkaline rocks in southern Brazil. *Mém. Sci. Géol.*, Strasbourg, **73**, 161-172.

Michel, P. 1973. Les bassins des fleuves Sénégal et Gambie. Etude géomorphologique. *Mém. ORSTOM,* Paris, **63(3)**, 752 p.

Michel, P. 1978. Cuirasses bauxitiques et ferrugineuses d'Afrique occidentale. Aperçu chronologique. *Trav. Doc. CEGET,* Talence, **33**, 11-32.

Morin, S. and Pascual, J. F. 1978. Les cuirasses de la bordure septentrionale du massif de Ndias dans la région de Pout (Sénégal occidental). *Trav. Doc. CEGET,* Talence, **33**, 291-315.

Muller, D., Bocquier, G., Nahon, D. and Paquet, H. 1980-1981. Analyse des différenciations minéralogiques et structurales d'un sol ferrallitique à horizons nodulaires du Congo. *Cah. ORSTOM, sér. Pédol.*, Paris **XVIII(2)**, 87-109.

Nahon, D. 1976. Cuirasses ferrugineuses et encroûtements calcaires au Sénégal Oriental et en Mauritanie. *Mém. Sci. Géol.*, Strasbourg, **44**, 232 p.

Nahon, D. 1987. Communication orale.

Nahon, D., Melfi, A. J. and Conte, C. N. 1989. Présence d'un vieux système de cuirasses ferrugineuses latéritiques en Amazonie du Sud. Sa transformation *in-situ* en latosols sous la forêt équatoriale actuelle. *C.R. Acad. Sci.* Paris, **308**, série II, 755-760.

Novikoff, A. 1974. L'altération des roches dans le Massif du Chaillu (République Populaire du Congo). *Thèse Doct. es-Sciences ULP*, Strasbourg, 298 p.

Parrish, J. T., Zirgler, A. M. and Scotese, C. R. 1982. Rainfall patterns and the distribution of the Mesozoic and Cenozoic. *Paleogeogr., Paleoclimatol., Paleoecol.*, Amsterdam, **40**, 67-101.

Patterson, S. H., Kurtz, H. F., Olson, J. C. and Neeley, C. L. 1986. World bauxite resources. Geology and resources of aluminium. *U. S. Geol. Surv. prof. paper*, Washington, **1076-B**, 151 p.

Petit, M. 1985. A previsional world map of duricrust. In: *Environment change and tropical geomorphology*, (I. Douglas and T. Spencer Eds), 269-279.

Quantin, P. 1965. Les sols de la République Centrafricaine. *Mém. ORSTOM*, Paris, **16**, 113 p.

Ratisbona, L. R. 1976. The climate of Brazil. In: *World survey climatology*. Elsevier Publ. Co., Amsterdam, Schwerdtfeger Ed., 219-293.

Rognon,, P. 1978. Observations sur les cuirasses ferrugineuses du Niger méridional. *Trav. Doc. CEGET*, Talence, **33**, 56-64.

Schellmann, W. and Jepsen, K. 1973. Die Bauxitbildung in der Lagerstätte Weipa Australien als ein Beispeil der lateritischen Verwitterung. In: *ICSOBA, Intern. Symp.*, *3rd*, Nice, France, 253-261.

Tardy, Y. and Nahon, D. 1985. Geochemistry of laterites, stability of Al-Goethite, Al-Hematite and Fe^{3+}-Kaolinite in bauxites and ferricretes: an approach to the mechanism of concretion formation. *Amer. J. Sci*, New Haven, **285**, 865-903.

Tardy, Y. and Novikoff, A. 1988. Activité de l'eau et déplacement des équilibres gibbsite-kaolinite dans les profils latéritiques. *C.R. Acad. Sci.* Paris, **306**, série II, 39-44.

Tardy, Y., Melfi, A. J. and Valeton, I. 1988a. Climats et paléoclimats tropicaux périatlantiques. Rôle des facteurs climatiques et thermodynamiques: température et activité de l'eau, sur la répartition et la composition minéralogique des bauxites et des cuirasses ferrugineuses au Brésil et en Afrique. *C.R. Acad. Sci.*, Paris, **306**, série II, 289-295.

Tardy, Y., Bardossy, G. and Nahon, D. 1988b. Fluctuations de l'activité de l'eau et succession des minéraux hydratés et déshydratés au sein des profils latéritiques, ferrugineux et bauxitiques. *C.R. Acad. Sci.*, Paris, **307**, série II, 753-759.

Trescases, J. J. and Melfi, A. 1985. Les gisements latéritiques du Brésil. *PANGEA* (Centre International pour les échanges géologiques). Paris, **5**, 7-16.

Trolard, F. and Tardy, Y. 1987. The stabilities of gibbsite, boehmite, aluminous goethites and aluminous hematite in bauxites, ferricretes and laterites as function of water activity, temperature and particle size. *Geochim. Cosmochim. Acta.* Oxford, **51**, 945-957.

Valeton, I. 1972. Bauxites. Developments in soil science, Elsevier Publ. Co., Amsterdam, 226 p.

Valeton, I. 1973. Diagenèse et épigenèse de la bauxite d'Onverdacht, Surinam. In: *ICSOBA Intern. Symp.*, 3rd, Nice, France, 245-251.

Valeton, I. 1983. Klimaperioden lateritischer Verwitterung und ihr Abbild in den synchronen Sedimentationsraümen. *Z. dt. geol. Ges.*, Hannover, **134**, 413-452.

Valeton, I. and Beissner, H. 1986. Geochemistry and mineralogy of the lower Tertiary *in-situ* laterites on the Jos Plateau, Nigeria. *J. Afri. Earth Sci.*, Oxford, **5(5)**, 535-550.

Valeton, I. and Mutakayawa, M. 1987. Communication in the 14th Coll. of African Geology, Berlin.

Volkoff, B. 1986. Organisations régionales de la couverture pédologique du Brésil. Chronologie des différenciations. *Cah. ORSTOM, sér. Pédol.*, Paris, **21(4)**, 225-236.

Weber, B. N. 1959. Bauxitizaçao no distrito de Poços de Caldas, Minas Gerais, Brazil, *Bol. Soc. Bras. Geol.*, Sao Paulo, **8(1)**, 17-30.

Weggen, J. 1986. Mineralogy and geochemistry of weathering zones on itabirites, Quadrilaterro Ferrifero, Minas Gerais, Brazil. Zbl. Geol. Palaont., Stuttgart, Teil I. (9/10), 1547-1579.

White, A. H. 1976. Genesis of low-iron bauxite northeastern Cape York, Queensland, Australia. *Econ. Geol.*, New Haven, **71**, 1526-1532.