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# Lateritization and Bauxitization Events

GREGORY J. RETALLACK†

*Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403*

## Abstract

Laterites and bauxites are produced in tropical soils by weathering, which enriches iron (of laterites) and alumina (of bauxites)—as well as trace elements such as nickel, gold, phosphorus, and niobium—to ore grade. Laterites and bauxites can be redeposited into sedimentary sequences, and remain as ores if not transported far and diluted with other materials. The age of redeposited laterites and bauxites, and of bauxitic and lateritic paleosols, can be established from the geologic age of overlying rocks, an approach especially effective in paleosols within sequences of isotopically datable volcanic rocks. Lateritic profiles can also be dated by paleomagnetic inclination in special cases in which land masses such as in Australia and India drifted long distances northward during Cenozoic time. In addition, cryptomelane and other K-Mn oxides can be dated by K-Ar and $^{40}$Ar-$^{39}$Ar techniques to obtain multiple ages from different crystals in a single relict paleosol. Compilation of new and more accurate laterite and bauxite ages reveals unusually widespread and intense laterite and bauxite formation during events of less than 100 k.y. duration at 2, 12, 16, 35, 48, 55, 65 and 100 Ma. Such events can also be inferred at times older than 100 Ma from paleolatitudinal distribution of laterites and bauxites, but these are poorly sampled. Laterite and bauxite peaks were coeval with times of global high warmth and precipitation, elevated atmospheric carbon dioxide, oceanic anoxia, exceptional fossil preservation, and mass extinction. These $CO_2$ greenhouse events and attendant titration of carbonic acid with soils are interpreted as transient fluctuations in the atmosphere produced by meteorite impact, flood basalt volcanism, and methane outbursts. Concentration of bauxite and laterite resources, in particular stratigraphic horizons formed during greenhouse crises, suggests the usefulness of an event stratigraphic approach to exploration and exploitation of these and related ores.

## Introduction

LATERITES AND BAUXITES are rocks enriched in iron and aluminum, respectively. They can be ores of these metals, but also are mined for concentrations of nickel, gold, niobium, and phosphorus (Freyssinet et al., 2005). Bauxite has been defined as rock with more than 45.5 percent by weight alumina, and no more than 20 percent ferric iron (Valeton, 1972). Laterites and lateritic bauxites are materials with more than 20 percent total iron, usually all ferric. These are both considerable enrichments above alumina (15.9%) and total iron (6.57%) of average igneous rock (Garrels and MacKenzie, 1971). Laterites and bauxites are linked by their enrichment in sesquioxides caused by intense tropical weathering, although they can be redeposited and form duricrusts that guide landscape development in complex ways (Figs. 1, 2). Compilations of the geologic ages of laterites and bauxites are presented here to address basic questions about their genesis. What types of climates produce laterites and bauxites? When and where were the particular paleoclimates that formed laterites and bauxites? What can laterites and bauxites tell us about global $CO_2$ greenhouse events of the past? What can laterites and bauxites tell us about atmospheric and biotic evolution back through geologic time?

## Laterites

Laterites were named from the Latin for brick (*later, lateritis*) by Buchanan (1807), who observed the cutting of these ferruginized sediments ("brickstone") for use in house construction on the Malabar coastal plain, India (Paton and Williams, 1972). He described the sediment as soft and easy to cut, but hardening when removed to dry, although this is not universally true of Indian coastal laterites (Ollier and Rajaguru, 1989). The term laterite was also extended to comparably ferruginized rocks on the high plateaus of India by Medlicott and Blandford (1869), who proposed that plateau laterites formed by deep weathering of underlying Deccan Trap basalts. Some of the coastal lowland laterites of Buchanan (1807) were pedoliths (Fig. 2B), or soil sediments (Erhardt, 1965), redeposited physically from residual profiles of weathering (Bourman, 1993). The Indian coastal pedoliths are gravelly and poorly sorted (Valeton, 1983), but some lateritic pedoliths have well-sorted loose pisolites, called murram, which makes an excellent tropical road gravel (Bhaskar et al., 1999). Schwarz and Germann (1999) argue that sand-size oolitic ironstones are derived from erosion of laterites, but others consider these to be replaced oolitic limestones (Kimberley, 1981) or fully aquatic precipitates (van Houten, 1985). Oolitic ironstones are not included in the current compilation, because they differ from lateritic ironstones in containing marine or lacustrine fossils and minerals such as chamosite and berthierine (Young and Taylor, 1989).

Erosion of overlying materials in upland lateritic and bauxitic weathering profiles exposes lateritic duricrust, or cuirasse (Maignien, 1966). Typical weathering profiles of laterites have a thick lateritic cuirasse over a pallid clayey and mottled zone (Figs. 1A, 2A). A major problem for any model that indicates the origin of laterites by weathering is that their iron content and thickness are greater than could reasonably be derived from local bedrock, considering volume and mass lost by weathering (McFarlane, 1976; Brimhall et al., 1991). One solution to this problem comes from the observation that laterites are often thicker along scarps than on interior plateaus, suggesting that iron was added by lateral flow of acidic groundwater that created a highly leached pallid zone

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† E-mail: gregr@darkwing.uoregon.edu

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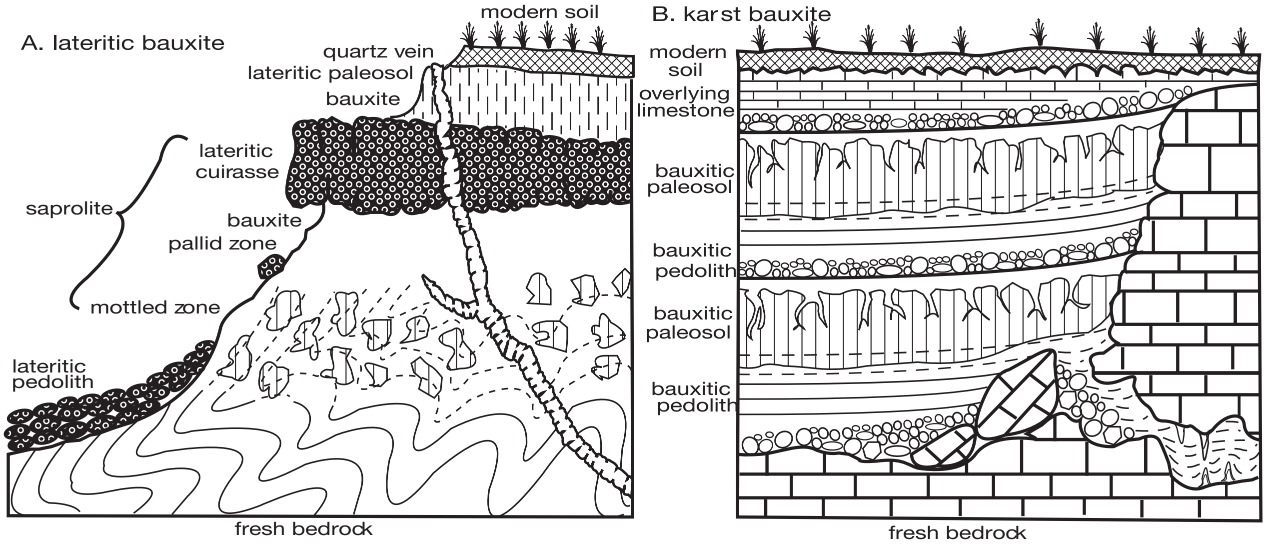

FIG. 1. Geologic cross sections of lateritic bauxite (A) and karst bauxite (B), based on observations of profiles illustrated in Figure 2. Lateritic and bauxitic soils and paleosols are unusually thick and strongly developed (A), and are commonly redeposited (as a lithologically distinct pedolith) on footslopes and alluvial plains (A) and within karst depressions (B).

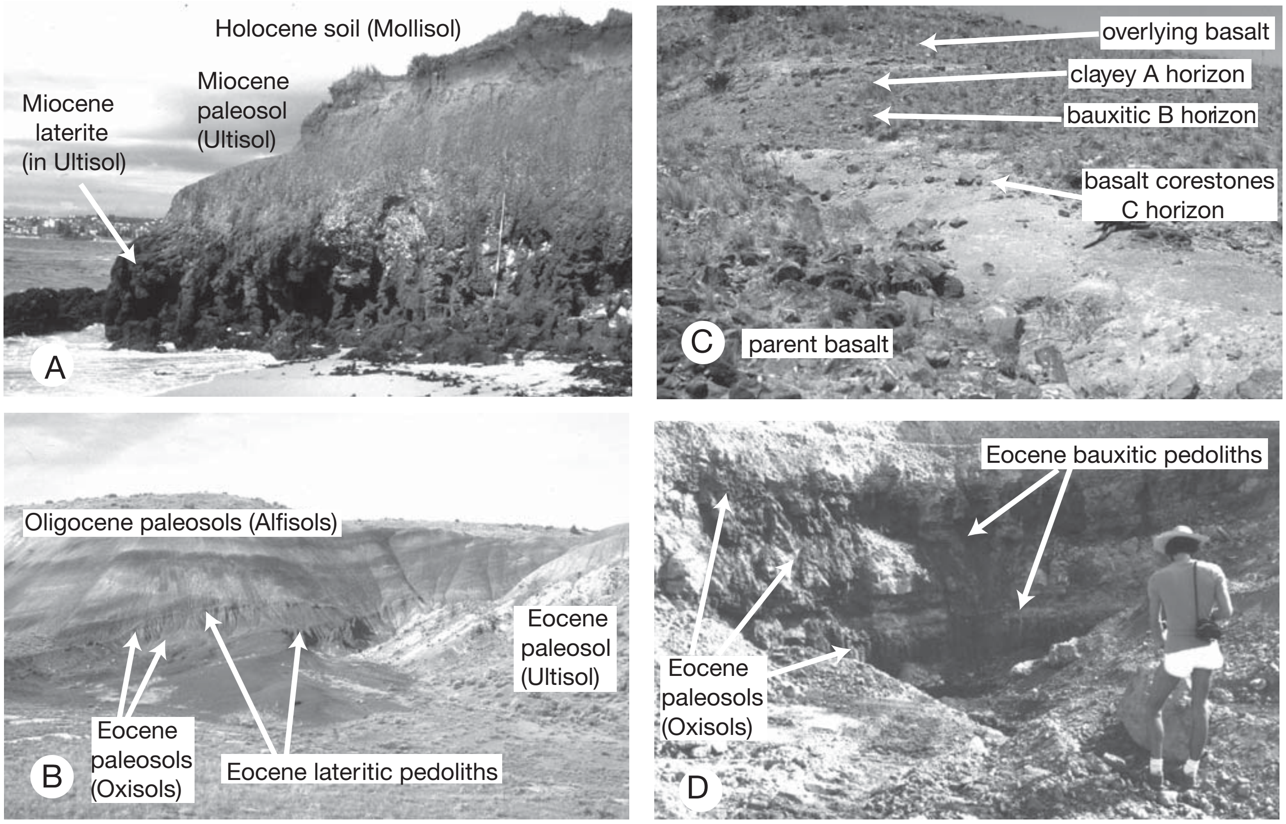

FIG. 2. Field photos of laterites and bauxites: A, early Miocene (17 Ma) lateritic paleosol (Ultisol) on the beach at Long Reef, New South Wales, Australia (S33.743269° W151.305244°: Hunt et al., 1977); B, late Eocene (39 Ma) detrital laterites, above and below paleosols (Oxisols) in Brown Grotto, Painted Hills, central Oregon, U.S.A. (N44.65306° W120.28391°: Bestland et al., 1996); C, early Eocene (52 Ma) lateritic bauxite paleosol (Oxisol) at Bridle Creek, near Cooma, New South Wales, Australia (S36.231667° E148.968333°: Retallack, 2008); D, early middle Eocene (48 Ma) detrital bauxite and paleosols (Oxisols) of the Csabpuszta deposit, near Hyirád, Hungary (N39.967669° E17.285692°: Mindszenty et al., 1988). A-C by G.J. Retallack with 6-foot tape for scale in A, hill 40 m high in B, and profile 7-m-thick in C; D is courtesy of Andrea Mindszenty with T. Bakó for scale.

(McFarlane, 1976). A second solution to the mass excess of iron and alumina is addition from windblown dust (Brimhall et al., 1991).

Laterite is a rock or horizon, and not a complete soil profile, and because of its confused history, the term plinthite was coined for comparable materials which form soft horizons within soils that harden upon exposure (U.S. Natural Resources Conservation Service, 2000). Plinthites form subsurface horizons deep within both Oxisols and Ultisols. Laterite and plinthite are both forms of ferricretes and ironstones, or cemented iron-rich rocks. They are thicker than placic horizons, which are millimeter- to centimeter-wide veins of Fe-Mn oxides, often formed near the water table in soil (U.S. Natural Resources Conservation Service, 2000). They are also thicker than surface weathering rinds and case hardening zones (Hunt et al., 1977). Laterite and plinthite are thicker and poorer in humus and quartz than spodic horizons of Spodosols (U.S. Natural Resources Conservation Service, 2000). Liesegang banding and weathering rinds are distinctly thinner (Carl and Amstutz, 1958). Gossans or oxidized pyritic ores are not necessarily lateritic if restricted in area to that of their parent mineralization (Vasconcelos and Conroy, 2003). Laterites record exceptionally intense, regionally widespread weathering under tropical temperature regimes with ample water (Bárdossy and Aleva, 1985).

Laterites are seldom mined for iron unless they have beneficiated banded iron formations, which remain the globally dominant source of iron ore. Nickeliferous laterites show enrichment of nickel in hydrous magnesian silicates and manganese oxides derived from ultramafic source rocks, but such laterite also extends laterally over other country rocks (Gaudin et al., 2005). Some lateritic gold deposits are formed by dissolution and reprecipitation of gold, but others are residual (Freyssinet et al., 2005). Lateritic niobium and phosphorus deposits are residues from deep weathering of carbonatite and limestone, respectively (Freyssinet et al., 2005). Particularly notable lateritic ores are iron-enriched channel pedoliths of the Hamersley basin and gold-bearing laterites near Kalgoorlie, both in Western Australia; nickeliferous laterites of New Caledonia; and the Araxa lateritic niobium and phosphorus deposit in Brazil.

## Bauxites

Bauxite was named by Berthier (1821) for clays within a paleokarst disconformity between limestones near the town of Les Baux in the Alpilles range of the Provence region, southeastern France. The town is named from a Provençal term for ridge (*baou*). Bauxite is a rock, or mixture of very fine grained minerals, including gibbsite, diaspore, and boehmite, usually identifiable only by X-ray diffraction (Bárdossy, 1982). Other bauxites, including the famous ores of Weipa (Queensland, Australia) and Carajás (Brazil), are parts of thick lateritic weathering profiles, usually the pallid zone (Fig. 1A), but sometimes the B or C horizons of particularly thick profiles (Fig. 2C). Lateritic bauxites form by deep tropical weathering in thick soils, and also may be a source of bauxitic clays and rubble redeposited into paleokarst depressions (Figs. 1B, 2D). Many bauxite pedoliths retain pisolitic textures and red colors of lateritic bauxites, but much karst bauxite is black to gray with admixed organic matter and sometimes such chemically reduced minerals as pyrite (Bárdossy, 1982). These layered and rubbly materials are bauxitic pedoliths. Some karst bauxite successions include paleosols with insect burrows and drab-haloed root traces, which represent colonization of pedolithic bauxite by soil-forming plants and animals (Fig. 2D). Bauxites are so extremely weathered of alkalies and alkaline earths that paleosols within them and soils developed on them qualify as Oxisols (U.S. Natural Resources Conservation Service, 2000).

Aluminum production is mainly from lateritic bauxites, which make up approximately 90 percent of global bauxite resources in five major regions of bauxite mining: northern South America, west Africa, India, southeast Asia, and northern and southwestern Australia (Freyssinet et al., 2005). Karst bauxites are more scattered in distribution, but mined in eastern Europe and the Caribbean islands (Bárdossy, 1982). Lateritic bauxites are widely available to opencast mining because of the way they mantle the landscape (Bárdossy and Aleva, 1990).

## Advances in Laterite and Bauxite Dating

Many laterites and bauxites, like other duricrusts, form scarps and tablelands, which are relicts of ancient landforms. Over wide areas of Australia, India, and Africa, laterites and bauxites mantle ancient land surfaces developed on Precambrian rocks, and ages of the laterites and bauxites are unconstrained (Firman, 1994; Chardon et al., 2006; Twidale, 2007). Fortunately, there are now ways of dating laterites and bauxites more accurately, and these are revealing pronounced paleoclimatic spikes of lateritization and bauxitization.

### *Biostratigraphic dating*

Laterites on the foreshore at Darwin, Australia, include automobile bodies and other debris attesting to continued formation (Ollier and Pain, 1996). Near Sydney, Australia, in contrast, underlying marsh deposits with well-preserved pollen and leaves, and paleomagnetic data, provide evidence that laterites are mainly middle Miocene in age (Pickett et al., 1997), although thin ferric weathering rinds continue to form today (Hunt et al., 1977). Many bauxites within paleokarst of fossiliferous limestone were overlain by additional fossiliferous limestone (Mindszenty et al., 1988). The ages of such karst bauxites tend to cluster at stage boundaries, which are commonly times of marked sea-level change, and are now isotopically dated by associated igneous rocks for most of the Phanerozoic with accuracy ($2\sigma$) of ±4 m.y. (Gradstein et al., 2004). The geologic age of overlying rocks is a minimum age for lateritic and bauxitic soils (Matthews, 1983; Mindszenty et al., 1988; Sigleo and Reinhardt, 1988; Setterholm and Morey, 1995). Underlying sediments of Quaternary age can also indicate that laterites and bauxites are still forming, because these rocks and their formative soils (Oxisols and Ultisols) require hundreds of thousands of years to form, even in warm-humid climates such as the southeastern U.S. Coastal Plain (Markewich et al., 1990) and Hawaii (Chadwick et al., 2003).

### *Ages of volcanic successions*

Lateritic and bauxitic paleosols within volcanic sequences can be dated by age models (usually linear interpolation based on stratigraphic level) using $^{40}$Ar/$^{39}$Ar and K/Ar dates of basalt flows (Fig. 2C: Retallack, 2008) or volcanic tuffs (Bestland et al., 1996; Retallack et al., 2000). The landscape position of isotopically dated lava flows is also important for dating nearby lateritic paleosols (Wray et al., 1993). In one case, large xenoliths of laterite were included within and thermally altered by a basalt flow, which was isotopically dated (Zou et al., 2004). A surprising result of such studies is that laterites and bauxites are limited to particular horizons of unusually warm, wet paleoclimates within volcanic successions, which include other paleosols indicative of paleoclimates with less intense weathering (Fig. 3).

*Paleomagnetic inclination and continental drift*

Paleomagnetic inclination can give former paleolatitudes of iron-oxide minerals in laterites (Théveniaut and Freyssinet, 2002), and is particularly useful in India and Australia, which have moved from polar to tropical paleolatitudes over the past 80 million years (Idnurm and Senior, 1978; Schmidt et al., 1983). Errors of 95 percent confidence on paleomagnetically determined paleolatitudes are large, and translate to ±15 to 20 m.y. errors on age estimation. Nevertheless, clusters of inclinations are evidence of discrete bauxitization and lateritization events (Kumar, 1986).

*Isotopic dating of Mn-oxide minerals*

Cryptomelane and other manganese oxides can be directly dated by both $^{40}$Ar/$^{39}$Ar and K-Ar methods (Vasconcelos et al., 1994; Thiry et al., 1999; Li and Vasconcelos, 2002; Beauvais et al., 2008). Plateau and isochron ages can now be obtained from single crystals and layers. Ideograms of such copious data give the probability distribution of numerous age determinations from all steps in dating, regardless of significance (Fig. 4). Remarkably, both isotopic methods also show that some periods were more favorable for lateritization than other times, including the present, which is now too dry for deep weathering in Burkina Faso (Fig. 4A) but not in Brazil (Fig. 4B). Further evidence for formation of surface profiles during discrete events in the past also comes from the distribution of radiation-induced defects in kaolinites of lateritic soils (Balan et al., 2005), aeromagnetic and isotopic measurements (Batista et al., 2008), and Mössbauer spectroscopy of lateritic oxide minerals (Hanstein et al., 1983).

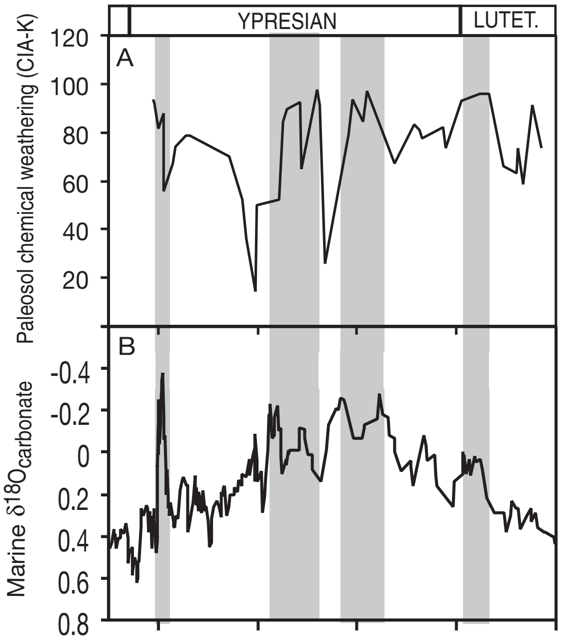

FIG. 3. Paleosol index of chemical weathering (CIA-K that increases with warmer and wetter conditions) within the isotopically dated Monaro Volcanics of the Bega no. 7 drill core from Lake Myalla near Cooma, A.C.T., Australia (A: after Retallack, 2008), compared with marine foram $\delta^{18}$O values, largely from the Southern Ocean (B: from Zachos et al., 2001).

## Methods of Compilation

There have been many prior compilations of data on the age distribution of laterites and bauxites (Habicht, 1979; Nicolas and Bildgen, 1979; Bárdossy, 1982; Hallam, 1984; Bárdossy and Aleva, 1990; Scotese et al., 1999; Boucot et al., 2004). This study presents a new compilation of localities, rather than reserves or extent that overemphasize geologically recent deposits. A locality for the purpose of this work is selected as about 1 km$^2$. Each locality was checked and its latitude and longitude determined using Google Earth© in order to bring location spellings and nationality up to date. Examination of satellite images also allowed identification of quarries, outcrops, and drill sites, rather than nearby towns and villages, which lend their names to deposits. Paleolatitudes were then determined from geographic coordinates and geologic age (mostly to nearest 10 m.y.), using the computer program Point Tracker (Scotese, 1997). Errors ($2\sigma$) on paleolatitude calculations for the Mesozoic are about ±5° latitude for 200 Ma and ±10° latitude for 300 Ma, and errors were prorated with quadratic fit to 0 for modern determinations. Comparison was also made with new records of aridland paleoclimate from calcareous paleosols and of carbon dioxide levels from the stomatal index of *Ginkgo* and related plants (Retallack, 2009). The error of carbon dioxide determinations is the standard deviation of the stomatal index determination.

Some well-known reported laterites and bauxites are not included in this new compilation because of insufficient iron enrichment and other problems that suggest previous misclassifications. The 2200 Ma Hokkalampi paleosol, for example, is deeply weathered and in places red, but has no more than 18.57 percent alumina or 5.53 percent ferric iron (Marmo, 1991). Although 2200 Ma laterites of Griqualand, South Africa are accepted as laterites (Gutzmer and Beukes, 1998), the slightly older (2250 Ma) Ongeluk and Hekpoort paleosols are not accepted as lateritic or bauxitic profiles (contrary to Beukes et al., 2002; Yamaguchi et al., 2007), because of their low alumina and iron. In addition, they exhibit structures characteristic of swelling clay soils (Vertisols), with a chemical base status that is incompatible with lateritization or bauxitization (Retallack 1986; Driese, 2004). Putative 3430 Ma "laterites" from the Pilbara region of Western Australia (Ohmoto et al., 2007) are simply banded iron formations: their dip is coherent with basement rocks of an angular unconformity, and these are unrelated to weathering and the ancient land surface on this unconformity (Retallack, unpub. data). A possible 2700 Ma laterite from Steep Rock Lake, Ontario,

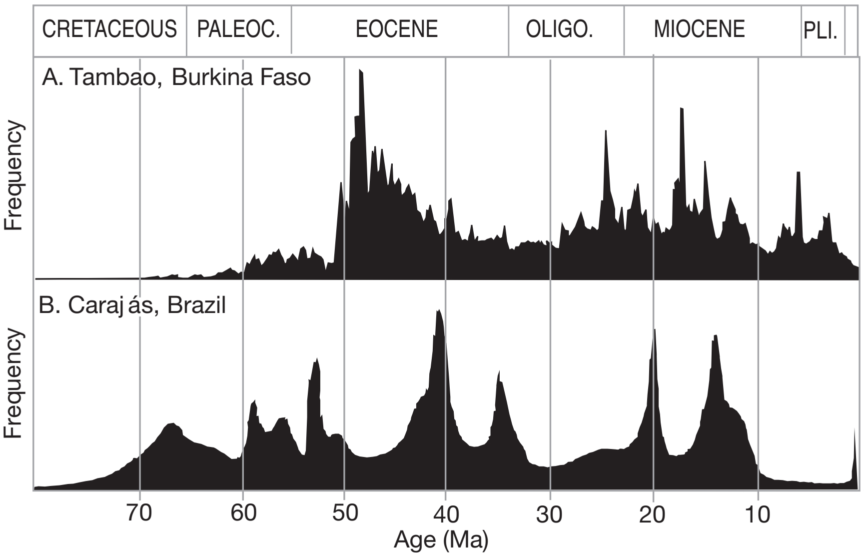

FIG. 4. Ideograms of $^{40}Ar/^{39}Ar$ ages of K-Mn minerals in lateritic soils of Africa (A, after Beauvais et al., 2008), and South America (B, after Vasconcelos et al., 1994). An ideogram plots all age determinations, unfiltered for quality, and can be considered a probability distribution.

yielded Cretaceous insect and plant remains (Machado, 1987). A supposed Devonian bauxite from Portilla de Luna, Spain, is only a minor occurrence of gibbsite in joints of Cenozoic age (Bárdossy and Fontbote, 1977).

## Results

This compilation recognizes 432 adequately dated bauxite localities and 550 adequately dated laterite localities. An additional 327 bauxite and 338 laterites are too poorly dated to be considered further in this compilation. Time series of adequately dated bauxites and laterites are presented separately for the past 4 b.y. (Fig. 5) and solely the previous 300 m.y. (Fig. 6). In Figure 5, occurrences of 0 to 2 Ma are truncated in plotting in order to highlight the less abundant, older deposits. Both laterites and bauxites are very unevenly distributed in time. Laterites and bauxites represented by more than 10 localities were most abundant at 2, 12, 16, 35, 48, 55, 65, and 100 Ma. Other, mainly older, spikes are present in less than 10 localities, and are not considered representative. These lateritization and bauxitization events are not of equal magnitude, nor equally spaced in time. The earliest known laterites are those of the 2200 Ma profile near Sishen, South Africa (Gutzmer and Beukes, 1998), but bauxites extend back to at least 3500 Ma, near Taldan in the Aldan Shield of Siberia (Kulish, 1973; Sidorenko and Tenyakov, 1976).

## Interpretation

Time series of laterites and bauxites show patterns over both long and short time scales, as well as some that are artifacts of preservation.

### *Pull of recent*

The dramatic rise in abundance of laterites and bauxites since mid-Cretaceous time (100 Ma) is in part because of the exponential decay of area and mass with geologic age of rocks (Hay and Wood, 1990; Wilkinson et al., 2009), a phenomenon termed "pull of the recent" in paleontological compilations (Jablonski et al., 2003). In other words, laterites and bauxites are preserved less often in rocks of greater geologic age. This preservational artifact is exaggerated for laterites and bauxites because they form extensive soil mantles on older soils and sediments. Thus, they are more likely to be found than geologically old lateritic and bauxitic horizons with narrow outcrop within folded and deformed sedimentary successions.

### *Long-term trends*

The greater antiquity of bauxites than laterites can be related to the later onset of atmospheric oxidation (ca. 2300 Ma) than intense tropical weathering (>3500 Ma). Some of the geologically oldest bauxites have been highly metamorphosed to distinctive corundum-fuchsite rocks (Kulish, 1973; Sidorenko and Tenyakov, 1976; Schreyer et al., 1981; Martyn and Johnson, 1986; Golani, 1989), similar to Miocene contact metamorphism of bauxites on the Greek island of Naxos (Jansen and Schuiling, 1976). The specific geologic age of most old bauxites is poorly constrained because of metamorphism, and there are few rocks or minerals on Earth older than 3500 Ma (Retallack, 2001a). Bauxitic weathering profiles are poorly known, but probably were a kind of soil no longer forming ("Green Clays" of Retallack, 2001a), produced in an atmosphere of low $O_2$ and high $CO_2$ (Sheldon, 2006).

The onset of laterite formation within tropical soils is commonly taken as evidence of a Great Oxidation Event at about 2300 Ma, a major step in the evolution of Earth's atmosphere (Rye and Holland, 1998). Alternative geochemical evidence used to support geologically older oxidation (Ohmoto, 1996) is a reflection of ancient hydrolysis, rather than oxidation (Holland et al., 1997). Also, putative 3430 Ma "laterites" (Ohmoto et al., 2007) are instead banded iron formations of the paleosol parent material, where observed, for example, at Steer Ridge (S21.18848° E119.30154°) and Trendall Ridge (S21.21577° E119.30799°), in the Pilbara region of Western Australia.

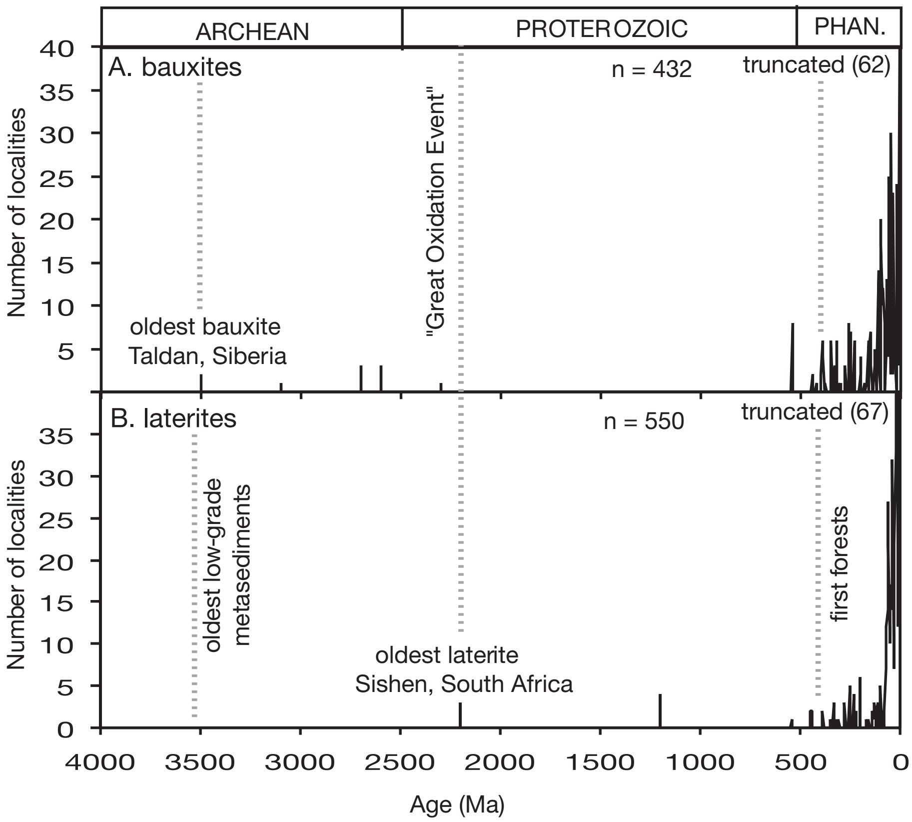

FIG. 5. Long-term (4000 Ma) time series of bauxites (A) and laterites (B). An Excel© spreadsheet with raw data is downloadable from www.uoregon.edu/~dogsci/directory/faculty/greg/about.

Erhardt (1965) advocated a role for tropical rain forest development in the formation of laterite and bauxite. There is increased abundance of laterites and bauxites after the Middle Devonian evolution of trees (Fig. 5). Early fossil trees are associated with thick, moderately weathered forest soils (Alfisols of Retallack, 1997), although the earliest documented rain forest soils (Oxisols) are not known until Late Carboniferous (Retallack and Germán-Heins, 1994). Tropical rain forests are unusual in that they generate large amounts of soil $CO_2$ for hydrolytic weathering. Soil respiration generates as much as 104,000 ppmv $CO_2$ in tropical rain forest soils, compared with 2,000 ppmv in nearby tropical deciduous thorn scrub (Matsumoto et al. 1997), 10,000 ppmv in warm temperate deciduous forest (Rightmire, 1978), 1,600 ppmv in desert (Parada et al., 1983), and 500 ppmv in tundra vegetation (Pulina et al., 2003). High levels of atmospheric $CO_2$ are not known between about 1800 and 392 Ma (Sheldon, 2006), and are a partial explanation, along with problems of preservation and recognition, for the rarity of bauxites and laterites during that time interval (Fig. 5).

Bauxites and laterites have been considered widespread at times of global tectonic quiescence and low sedimentation rates, such as the Mesozoic, compared with times of active mountain building and sedimentation, such as the late Paleozoic (Hay and Wood, 1990), and this may also be true of oolitic ironstones (van Houten, 1985). The present compilation does not support this hypothesis, although past low-resolution compilations have been considered supportive (Bárdossy 1982; Bárdossy and Aleva, 1985). Bauxites and laterites are indeed more widely preserved on geologically ancient and stable continents, such as the various fragments of Gondwanaland, Africa, India, and Australia (Valeton, 1983; Chardon et al., 2006; Twidale, 2007). However, plate boundaries were tectonically active throughout Earth history, including around these cratonic blocks.

### *Short-term events*

Spikiness of the new compilation (Figs. 5, 6) and other data (Figs. 3, 4) indicates selected times of unusually intense and widespread lateritization and bauxitization. For example, 2, 12, 16, 35, 48, 55, 65, and 100 Ma were times of formation of more than 10 laterite or bauxite localities. These were also times of unusually high latitudes for laterites and bauxites, when they formed farther north and south than they did during the late Quaternary. The distribution of "modern" (<2 Ma) laterites and bauxites is strictly tropical, between the tropics of Cancer and Capricorn (Fig. 7). The present latitudes of pre-Quaternary bauxites and laterites are well beyond this range (Fig. 8A, C), and these anomalies persist after correction for continental drift (Fig. 8B, D), contrary to speculations of Nicolas and Bildgen (1979). During the middle Miocene (16 Ma), for example, laterites formed as far north as 51° paleolatitude near Kassel, Germany (Schwarz, 1997), and south to what was then 47° paleolatitude near Bredbo, Australia (Schmidt et al., 1983). Times of these anomalies also have been recognized as times of atmospheric $CO_2$ spikes

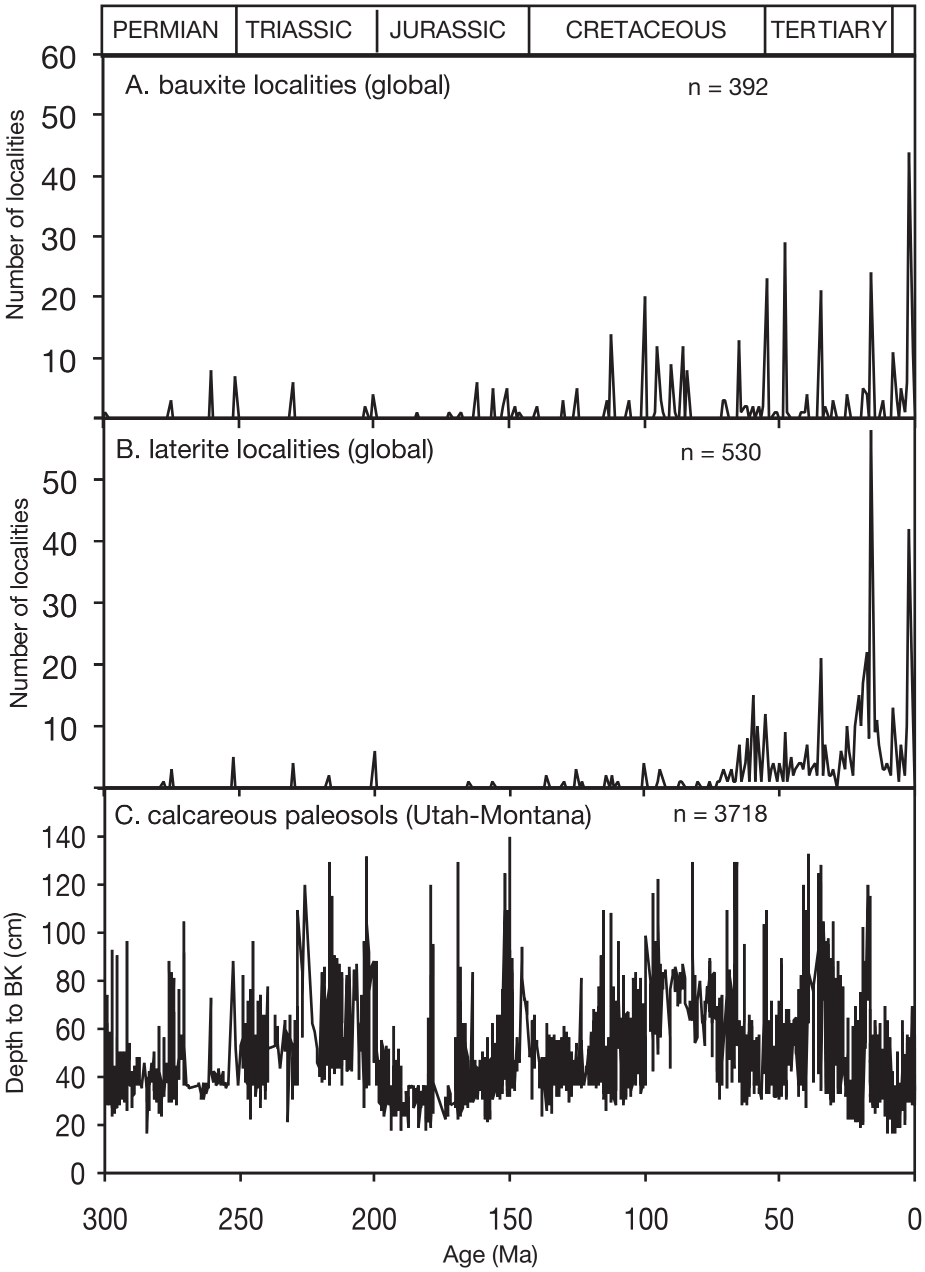

FIG. 6. Late Phanerozoic (300 Ma) localities of bauxites (A) and laterites (B), compared with a paleoprecipitation proxy, depth to calcareous nodules (Bk horizon in cm), in aridland paleosols in Utah and Montana (Retallack, 2009). The comparably spiky distributions in laterites and bauxites of humid climates and calcareous paleosols of arid climates suggest that these climatic spikes ranged through all climatic zones and were global in distribution.

recently recognized in data on stomatal index of *Ginkgo* and related fossil leaves (Retallack, 2001b, 2002, 2009; Kürschner et al., 2008). The maximum paleolatitude of bauxites and laterites shows a good correlation with magnitude of these $CO_2$ spikes (Fig. 9; Table 1).

Other evidence of transient climatic events, from a compilation of 3,718 calcareous paleosols from Montana and Utah, is revealed by the depth of the calcic (Bk) horizon in paleosols, which shows a series of spikes greater than two standard deviations of a running mean of depth (Fig. 6C). This measure is a proxy for mean annual precipitation, preserved in calcareous paleosols of aridlands (Retallack, 2005a), and thus demonstrates that climatic spikes apparent from laterites and bauxites extended across most climatic regions. Furthermore, these paleosol data and additional geochemical proxies for weathering (Retallack, 2009) show, more precisely than the laterite and bauxite data, that times of anomalous warmth and precipitation were short-lived (<100 ka). These short episodes corresponded in time with transient highs in atmospheric carbon dioxide (McElwain et al., 1999, 2005; Retallack, 2001b, 2002; Nordt et al., 2003; Tabor and Yapp, 2005; Prochnow et al., 2006; Royer, 2006; Cleveland et al., 2008),

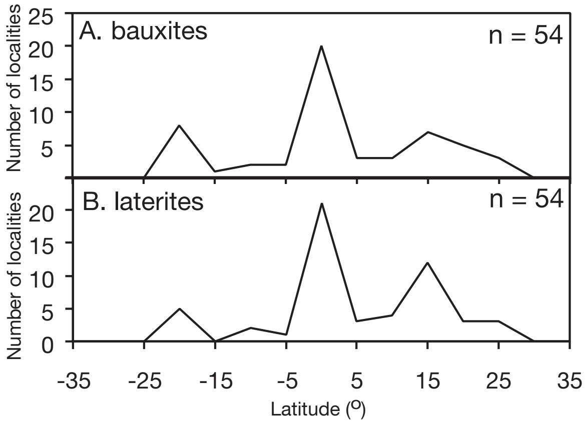

FIG. 7. Latitudinal distribution of Quaternary bauxites (A) and laterites (B).

oceanic anoxic events (Jenkyns, 2003), exceptional fossil preservation, and extinctions (Retallack, 2005b, 2009). This new view of paleoclimatic volatility contrasts with previous concepts of a protracted Mesozoic greenhouse based on data of low temporal resolution (Frakes et al., 1992). These paleoclimatic fluctuations were also times of the poleward spread of tropical soil formation.

The relationship between highest latitude laterite or bauxite and atmospheric $CO_2$ is nonlinear (Fig. 9). Small increases in $CO_2$ spread tropical weathering well beyond the Tropics of Capricorn and Cancer, but a disproportionately large $CO_2$ greenhouse expansion was required for the spread of tropical weathering to the Arctic and Antarctic Circles. Poleward spread of tropical weathering was certainly limited by local rainfall variation, as shown by the middle Miocene spread of lateritic and bauxitic Oxisols north to western Oregon and Washington in the United States (Allen, 1948; Corcoran and Libby, 1956; Hook, 1976), but not in eastern parts of those states, where contemporaneous Alfisols formed within the rain shadow of the Cascade Range (Sheldon, 2003; Takeuchi et al., 2007). Moisture variation is also the most likely explanation for episodic lateritization and bauxitization in tropical regions (Fig. 4), where precipitation, rather than temperature, is the main determinant of weathering and ecosystems (Retallack, 2001a). For example, Tambao (Burkina Faso: Fig. 4A) is currently too dry for lateritization, but Carajás (Brazil: Fig. 4B) is still covered by tropical rain forest. Precipitation does not, however, explain why laterites and bauxites seldom reached polar regions (Fig. 9), because fossil plants and soils are evidence of high latitude, non-glacial, humid climates in excess of the threshold required for Oxisols, bauxites, and laterites (1,100 mm mean annual precipitation: Retallack, 2008). Temperature may have limited chemical weathering reaction rates at very high latitude, because the minimum required temperature for Oxisols, bauxites, and laterites (17°C mean annual temperature; Retallack, 2008) did not spread to polar regions even during estimated extremely high atmospheric $CO_2$ (7,800 ppmv, Retallack, 2009) of the earliest Triassic (Retallack et al., 2007). Long winter darkness may have played a role too, because prolonged darkness was also intolerable to bauxite-forming, evergreen, broad-leaved, rain forests, with their high leaf area index, productivity, and soil respiration (Beerling and Woodward, 2001). Rain forests have an unusual capacity to generate carbonic acid for deep weathering, comparable with that of extreme $CO_2$ greenhouse conditions of the Precambrian (Sheldon, 2006). Humid tropical forests of Yunnan, China are just beyond the current latitudinal and altitudinal limits of

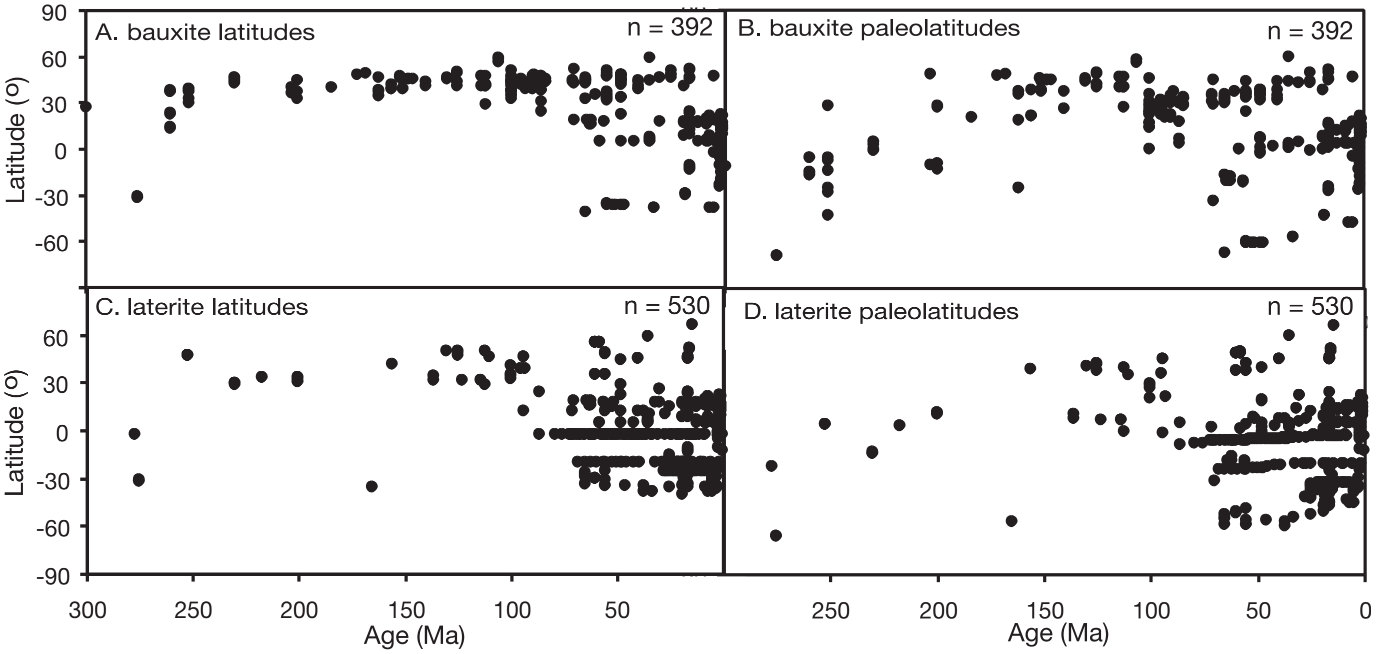

FIG. 8. Current latitudinal distribution (A-B) and paleolatitudes (C-D) calculated using Point Tracker© of C. Scotese of bauxites (A, C) and laterites (B, D) younger than 300 Ma. An Excel© spreadsheet with raw data is downloadable from www.uoregon.edu/~dogsci/directory/faculty/greg/about.

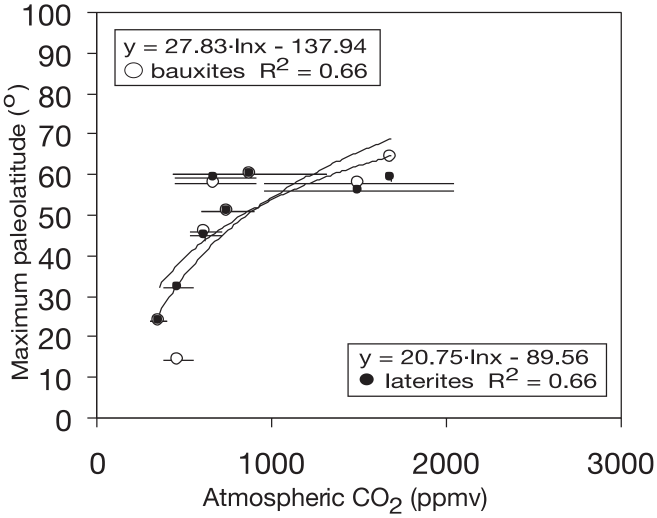

FIG. 9. Relationship between past atmospheric carbon dioxide (ppmv, from fossil plant stomatal index: Retallack, 2009) and maximum paleolatitude (north or south) of laterites and bauxites represented by at least 10 occurrences (Table 1).

bauxites and generate 38,000 to 75,000 ppmv $CO_2$ in their deeply weathered soils (Brook et al., 1983). The lower value may be close to the minimum required for bauxitization and lateritization.

Mechanisms for transient paleoclimatic extremes may include catastrophic outburst of greenhouse gases, such as methane and carbon dioxide, caused by meteorite impact or volcanic eruptions. Evidence for such carbon injection into the atmosphere comes from marked excursions in carbon isotopic values of organic matter and carbonate requiring orders of magnitude more gigatons of isotopically light carbon than can reasonably be obtained from any other source (Jahren et al., 2001; Retallack and Krull, 2006). This isotopic evidence is inconsistent with alternative explanation that greenhouse spikes were produced by constructive interference of Milankovitch rhythms (Kemp et al., 2005). Methane outbursts, rapidly oxidized to carbon dioxide, from intrusion of coal seams and carbonaceous shales by flood basalt feeder dikes, have been proposed for basal Eocene (55 Ma), Aptian (125 Ma), Toarcian (125 Ma), basal Triassic (252 Ma), and basal Late Permian (260 Ma) paleoclimatic fluctuations (Retallack and Jahren, 2008).

Meteorite impact at the Cretaceous-Tertiary boundary was also associated with a massive injection of carbon into the atmosphere (Arens and Jahren, 2000), which took 50 k.y. to be removed by precipitation and titrated by soil (Retallack, 2004a). The decalcification of aridland soils (Retallack, 2009) and spread of lateritic and bauxitic weathering to high paleolatitudes (Fig. 9) represents a last defense against these global acidification events, returning the climate system to its former state.

## Implications for Exploration

Paleoclimatic fluctuations defined by the time series of laterites and bauxites (Figs. 5, 6) are best suited to an event stratigraphic exploration strategy for iron and aluminum ores in sedimentary rocks and paleosol sequences. Productive stratigraphic levels were created at specific times of past paleoclimatic fluctuations (Table 1), which turn out to be very favorable (Lagerstätten or "mother lodes") for bauxitic and lateritic ores, as well as for exceptional fossil preservation (Bottjer et al., 2002). There are 42 such times over the course of the past 300 million years (Fig. 6C), and their recognition requires geological age control at the level of a biostratigraphic zone, or approximately ± four million years (Gradstein et al., 2004).

Furthermore, productive ores of laterite and bauxite tend to be concentrated during these times at major geological unconformities, which can be identified by seismic survey (Ansari and Shrotri, 1989), electrical resistance tomography, or ground-penetrating radar (Beauvais et al., 2004). Iron and aluminum duricrusts form dense and radioactive horizons, which are easily identified and characterized by gamma ray (Batista et al., 2008) and magnetic susceptibility surveys (Uchida et al., 1999). The problem of exploration for aluminum and iron ores is not so much one of finding laterites and bauxites, which are widespread, but finding special circumstances where the ancient weathering has enhanced metal abundance of a banded iron formation (Spier et al., 2006), or nickel-bearing serpentinite or peridotite (Gaudin et al., 2005). Laterites with economic concentrations of nickel, gold, niobium, and phosphorus are also very dependent on particular parent materials with these elements (Freyssinet et al., 2005). Laterites and bauxites themselves are not dependent on parent material, as is indicated by laterites developed on very iron-poor quartz sandstone near Sydney, Australia (Hunt et al., 1977), and bauxites on very pure coral limestones (Bárdossy,

TABLE 1. Extreme Paleolatitudes of Bauxites and Laterites and Atmospheric $CO_2$

| Ma | Bauxites (°) | Laterites (°) | $CO_2$ (ppmv) | Bauxite example | Laterite example | References |
|---|---|---|---|---|---|---|
| 2 | 24 ± 0.02 | 24 ± 002 | 355 ± 50 | Esama, Malagasy | Esama, Malagasy | Bárdossy and Aleva (1990) |
| 11 | 14 ± 0.1 | 32 ± 0.1 | 468 ± 86 | Ratnagiri, India | Mount Tabor, Australia | Kumar (1986), Li and Vasconselos (2002) |
| 16 | 51 ± 5 | 51 ± 5 | 754 ± 153 | Kassel, Germany | Kassel, Germany | Schwarz (1997) |
| 35 | 60 ± 0.4 | 60 ± 0.4 | 875 ± 439 | Chadobets, Russia | Chadobets, Russia | Bárdossy and Aleva (1990) |
| 48 | 58 ± 0.6 | 56 ± 0.6 | 1501 ± 545 | Cooma, Australia | Bungonia, Australia | A, Retallack (2008) |
| 55 | 58 ± 0.7 | 59 ± 0.7 | 678 ± 230 | Cooma, Australia | Clarendon, Australia | Firman (1994), Retallack (2008) |
| 65 | 64 ± 0.9 | 59 ± 0.9 | 1689 ± 2 | St Leonards, Australia | Chowilla, Australia | Matthews (1983), Firman (1994) |
| 100 | 46 ± 1.6 | 45 ± 1.6 | 623 ± 91 | Arkalyk, Russia | St Cloud, Minnesota | Bárdossy (1982), Setterholm and Morey (1995) |

Note: Paleolatitudes derived using Point-Tracker© program of Paleomap (by C. Scotese) from modern latitude and longitude with 95% uncertainty from Scotese (2004): past $CO_2$ inferred from stomatal index of fossil *Ginkgo* leaves with standard deviation error (Retallack, 2001, 2002, 2009)

1982). Such observations support the idea that many laterites and bauxites are substantially derived from eolian dust (Brimhall et al., 1991).

Comparable event stratigraphic approaches have long been used in the exploration for sedimentary uranium and copper ores. The guiding idea is that some horizons are unusually productive because of transient paleoclimatic extremes. The Copper Sandstones of Russia (Bogdanov and Feoktistov, 1982), and Kupferschiefer of Germany (Wedepohl and Rentzsch, 2006), for example, fall on one of the paleoclimatic events (end-Guadalupian, 260 Ma) recognized here. Uranium roll ores of North America's Shinarump (early Late Triassic 230 Ma) and Morrison Formations (Late Jurassic, 150 Ma: Sanford, 1994) also fall on paleoclimatic events recognized here. Both laterites and bauxites are associated with unusually deep weathering profiles from which these metals are extensively leached. Copper bound by organic ligands in groundwater would then be fixed by anaerobic microbial activity in marine and lacustrine anoxic zones. Uranium transported as soluble uranyl in groundwater would be fixed in chemically reducing pockets of fluvial deposits (Sanford, 1994). Such events of exceptional mineral mobilization may have delivered unusual enrichments to suitable traps. Prospecting for these ores may benefit from compilations of laterite and bauxite time series that are even more detailed than those of Figures 5 and 6.

## Conclusions

Laterites and bauxites show an uneven distribution through time, consistent with evidence from time series of other paleosols and of carbon dioxide (Retallack, 2009) that indicate paleoclimatic events of intense weathering lasting for geologically short intervals (<100 ka). During these events, bauxite and laterite formation extended from their modern distribution, between the tropics of Cancer and Capricorn (Fig. 7), to areas near the Arctic and Antarctic Circles (Fig. 8). The cause of these paleoclimatic anomalies may have been greenhouse gas outbursts, because there is independent carbon isotope (Jahren et al., 2001; Retallack and Krull, 2006) and *Ginkgo* stomatal index (Retallack, 2002, 2009) evidence for elevated methane and carbon dioxide levels during bauxitization and lateritization events. Each of these events varied in the magnitude of greenhouse gas levels and in poleward extension of laterites and bauxites (Fig. 9). The source of greenhouse gases may have been meteorite impact or flood basalt-related intrusion of coals and carbonaceous shales (Retallack and Jahren, 2008), because the events were short-lived, with rapid onset and slow recovery. Recovery from these greenhouse crises was, in part, due to photosynthetic fixation and burial of carbon, but carbon also was consumed by enhanced silicate weathering (Berner, 2005). The soil itself was a last line of defense for titration of carbonic and other acids, particularly at times such as the Cretaceous-Tertiary and Permian-Triassic boundaries, when the carbon cycle crisis involved profound mass extinction (Retallack, 2004b). These greenhouse events of the past not only have consequences for distribution of lateritic and bauxitic iron and aluminum ores, but also for ores of uranium and copper, which would have been mobilized to a great extent during episodes of deep weathering.

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