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Quantitative bedrock geology of Brazil

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[1] We quantitatively analyze the area-age distribution of sedimentary, igneous, metamorphic, and ultramafic bedrock on the basis of data from the digital geologic map of Brazil, published as a GIS map by the Brazilian Geological Survey. Bedrock units exclusively encompassing sedimentary rocks, igneous rocks, or metamorphic rocks cover 40.4%, 31.5%, and 17.7%, respectively, of the total bedrock area. These numbers have to be considered minimum estimates of the areal abundance of sedimentary, igneous, and metamorphic bedrock because polygons defined by mixed lithologies cover ~8.5–9.5% of the total bedrock area. These mixed units are sedimentary rocks with igneous and/or metamorphic contributions (1.4%), metamorphic rocks with sedimentary contributions (1.2%), metamorphic rocks with igneous contributions (1.5%), igneous rocks with sedimentary and/or metamorphic contributions (4.4%), and ultramafic units with sedimentary, igneous, and/or metamorphic contributions (~1–2%). The average ages of major lithologic units, weighted according to bedrock area, are as follows: sedimentary rocks (average stratigraphic age of 248 ± 5 [1σ] Myr; median stratigraphic age of 87.5 Myr), igneous rocks (1153 ± 13 [1σ] Myr), metamorphic rocks (1678 ± 30 [1σ] Myr), and ultramafic rocks (~1227 ± 25 [1σ] Myr). The average bedrock age of Brazil is 946 ± 7 [1σ] Myr. The range in lithologic composition and age structure of the various bedrock units reflects the complex tectonic makeup of Brazil that ranges from Neogene sedimentary cover in the Amazon Basin to Precambrian cratons (Guyana and Brazilian shields) and Transamazonian greenstone belts. The average spatial resolution of the data is 232 km^2 $polygon^{-1}$ and is sufficient to perform area-age analyses of individual river drainage basins larger than ~5,000 km^2.

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1. Introduction

[2] We are extending our previous investigations of bedrock composition in the conterminous United States of America [*Peucker-Ehrenbrink and Miller*, 2002], Alaska and Canada [*Peucker-Ehrenbrink and Miller*, 2003], and East and Southeast Asia [*Peucker-Ehrenbrink and Miller*, 2003] to

Brazil in an attempt to improve global estimates of the lithologic composition and age distribution of bedrock using modern geographic information system technology and digital geologic maps.

[3] Here, we quantitatively investigate a modern compilation of digital bedrock maps of Brazil at a scale of 1:2,500,000 [*Bizzi et al.*, 2001]. The area includes parts of the eastern drainage of the Andes, the majority of the Amazon basin, the highlands north and south of that basins, as well as drainage basins along the eastern seaboard of Brazil. The data set is of particular interest as the area includes most of the Amazon drainage basin for which a wealth of hydrochemical data exists [e.g., *Stallard and Edmond*, 1983; *Gaillardet et al.*, 1997; *Seyler et al.*, 2003]. The Amazon ranks first among the world's rivers in runoff (~15% of the world's total) and supplies the majority of freshwater and fluvial detritus to the central Atlantic [*Milliman et al.*, 1995; *Meybeck and Ragu*, 1996].

2. Data

[4] The Brazilian Geological Survey has made the geologic map of Brazil available in digital format at a scale of 1:2,500,000. The cartographic data were obtained by generalizing the International Maps of the World at a scale of 1:1,000,000 as edited by the IBGE (Fundaçao Instituto Brasileiro de Geographia e Estatistica). The digital version covering 8,340,538 km^2 of bedrock consists of 36,002 polygons (~232 km^2 $polygon^{-1}$, on average) containing information on age and lithology, grouped into 1235 unique lithostratigraphic units. An even higher resolution map at a scale of 1:1,000,000, not evaluated as part of this study, was recently published as a set of 46 maps and 41 CDs [*Schobbenhaus et al.*, 2004]. It provides spatial data on ~3200 different lithologic units. The 1:2,500,000 map evaluated in this study is the highest resolution digital map analyzed by us thus far (Figure 1). The geologic data is complex, in that lithologies are grouped into lithotype (Litotipo 1 and Litotipo 2) units that do not necessarily clearly separate sedimentary, intrusive, extrusive, metamorphic and ultramafic units into separate polygons. Several examples show the complexity of the data: Unit NdI (1.0 to 1.75 Ma) is made up of two polygons covering 29 km^2 of laterite (sedimentary rock). Similarly well defined is unit NPmi (541 to 1000 Ma) that comprises 79 polygons covering 12,958 km^2 of schist (metamorphic rock). Finally, unit K1_beta_ce (97 to 135 Ma) includes 21 polygons with a total area of 9,503 km^2 of basaltic bedrock (igneous rock). These three ideal cases stand in stark contrast to many units that are lithologically diverse. For instance, unit A3ph (2801 to 3200 Ma) contains dominant (Litotipo 1) metagraywacke, basic and ultrabasic volcanic rocks as well as schist, and minor (Litotipo 2) lithologies that include chert, conglomerates, metapelites, metatuffs, quartzites, and felsic volcanic rocks. The first lithotype unit (=Litotipo 1) is classified as metamorphic and igneous rock, whereas the second lithotype (=Litotipo 2) is classified as sedimentary, metamorphic and igneous rock. Together, this unit (A3ph) comprises 3 polygons with a total area of 2150 km^2. These complexities in the definition of polygons with respect to lithology make quantitative analysis of the Brazil data much more challenging than the GIS data sets previously analyzed by us [*Peucker-Ehrenbrink and Miller*, 2002, 2003, 2004].

3. Methods

[5] The methods used are very similar to those used in our previous studies [*Peucker-Ehrenbrink and Miller*, 2002, 2003, 2004]. Digital data sources for the bedrock data (1:2,500,000) used as well as relevant projection parameters are summarized in an auxiliary material[1] data file (Text S1). The digital cartographic data are generalized from International Maps of the World with a scale of 1:1,000,000. These maps have been edited by the IBGE (Fundaçao Instituto Brasileiro de Geografia e Estatistica). We have grouped the data into 8 classes (Sedimentary, igneous and/or metamorphic rocks; Sedimentary rocks; Metamorphic and sedimentary rocks; Metamorphic and igneous rocks; Metamorphic rocks; Igneous, sedimentary and/or metamorphic rocks; Igneous rocks; Ultramafic rocks), three of which are major classes (Sedimentary rocks; Metamorphic rocks; Igneous rocks). Classes with mixed lithologies (e.g., Sedimentary, igneous and/or metamorphic rocks, encompassing 633 polygons that cover 1.4% of the total bedrock area) do not contribute significantly to the total bedrock area. However, these lithologically mixed units make an unequivocal assignment of all polygons to specific lithologic units impossible. For this reason we could not unequivocally distinguish between volcanic and intrusive igneous rocks. In addition, our attempt to

[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GC001505.

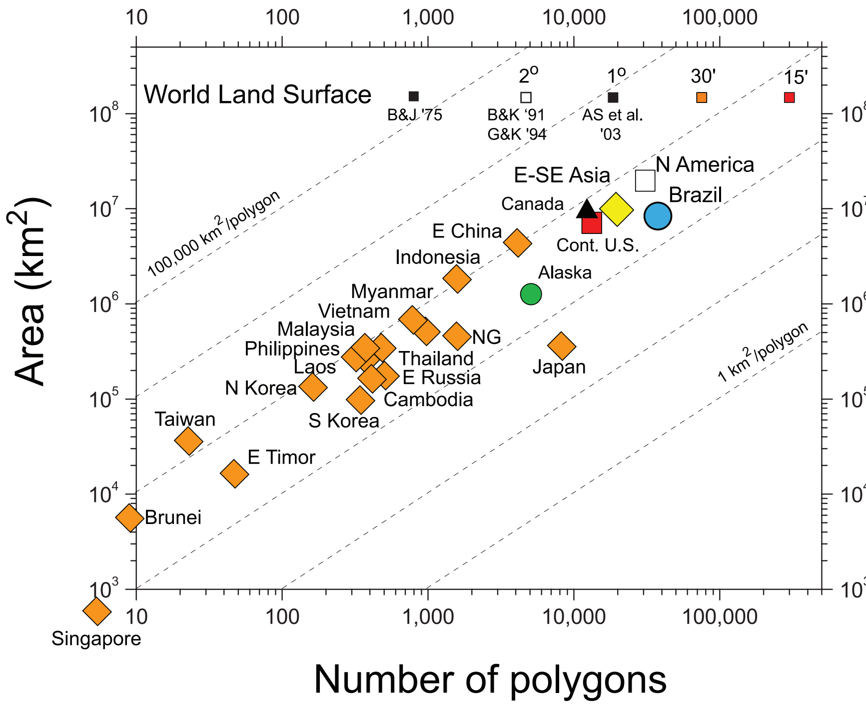

Figure 1. Spatial resolution (average area of a polygon in km^2) of digital bedrock maps for Brazil (blue circle) in comparison to data for East and Southeast Asia (yellow diamond) and the 18 countries in East and Southeast Asia (orange diamonds), Canada (black triangle), Alaska (green circle), the conterminous United States of America (red square), and North America without Mexico (open white square, calculated as the weighted sum of the conterminous U.S., Alaska, and Canada). Dotted lines are lines of equal resolution. Characteristic resolutions of some global assessments of bedrock geology are shown as small black and white squares. These range from coarse resolution of work by *Blatt and Jones* [1975] (black square labeled B&J '75) that is equivalent to a resolution of ~100,000 km^2 polygon^{-1}, estimates by *Bluth and Kump* [1991] (white square labeled B&K '91) and *Gibbs and Kump* [1994] (white square labeled G&K '94) that are based on 2 degree digitizations of maps compiled by *Ronov* [1989] and collaborators, to the most recent global assessment by *Amiotte Suchet et al.* [2003] (black square labeled AS et al. '03) with a resolution of slightly better than 10,000 km^2 polygon^{-1}.

quantify the areal extent of ultramafic bedrock only resulted in reasonable upper and lower limits.

4. Results and Discussion

[6] The results are shown in Table 1. Auxiliary material Table S1 shows abbreviated rock description (LITOTIPO 1 and 2), rock classification (CLASSE 1 and 2), and abbreviated lithologic unit (SIGLA_UNID). Upper (IDADE_MAX) and lower (IDADE_MIN) age boundaries with uncertainties (ERRO_MAXI, ERRO_MINI), number of polygons (COUNT) and bedrock area (SQ KM) are also listed. Total calculated bedrock area of Brazil is 8,340,538 km^2, of which 3,366,525 km^2, or 40.4%, is classified as sedimentary bedrock (Figure 2). This has to be viewed as a lower limit because other lithologic units also contain minor contributions from sedimentary rocks (116,719 km^2, or 1.4%, is classified as sedimentary, igneous and/or metamorphic bedrock; 97,383 km^2, or 1.2%, is classified as metamorphic and sedimentary bedrock; 366,641 km^2, or 4.4%, is classified as igneous, sedimentary and/or metamorphic bedrock). An upper limit of 3,947,268 km^2, or 47.3%, of sedimentary bedrock can be calculated by including these minor contributions. Igneous rocks cover at least 2,629,702 km^2, or 31.5%, of the total surface area. This should be considered a minimum value because some of the units with mixed lithologies contain minor amounts of igneous rocks (Sedimentary, igneous and metamorphic rocks, 116,719 km^2, or 1.4%; Metamorphic and igneous rocks, 124,778 km^2, or 1.5%; Igneous, sedimentary and/or metamorphic bedrock, 366,641 km^2, or 4.4%; Ultramafic rocks, 163,837 km^2, or 2.0%). Including all these contributions in an upper estimate of the extent of igneous bedrock yields 3,401,676 km^2, or 40.8%

Table 1. Quantitative Bedrock Geology of Brazil

Parameter	Value
Map date	2001
Map scale	1:2,500,000
Total area, km^2	8,340,538
Number of unique lithologic units	1235
Number of polygons	36,002
Average area per polygon, i.e., spatial resolution, km^2	232
Sediments, km^2	3,366,525
Number of polygons (unique lithologic units)	7,822 (275)
Percent of total bedrock area	40.4
Area-weighted average age, Myr	248 ± 5
Median age, Myr	87.5
Sediments, igneous and/or metamorphic rocks, km^2	116,719
Number of polygons (unique lithologic units)	633 (59)
Percent of total bedrock area	1.4
Area-weighted average age, Myr	1362 ± 36
Igneous rocks, km^2	2,629,702
Number of polygons (unique lithologic units)	17,217 (351)
Percent of total bedrock area	31.5
Area-weighted average age, Myr	1153 ± 13
Igneous, sedimentary and/or metamorphic rocks, km^2	366,641
Number of polygons (unique lithologic units)	1880 (44)
Percent of total bedrock area	4.4
Area-weighted average age, Myr	2023 ± 13
Ultramafic rocks, km^2	163,837
Number of polygons (unique lithologic units)	1097 (66)
Percent of total bedrock area	2.0
Area-weighted average age, Myr	1227 ± 22
Metamorphic rocks, km^2	1,474,953
Number of polygons (unique lithologic units)	6445 (382)
Percent of total bedrock area	17.7
Area-weighted average age, Myr	1678 ± 30
Metamorphic, sedimentary rocks, km^2	97,383
Number of polygons (unique lithologic units)	387 (27)
Percent of total bedrock area	1.2
Area-weighted average age, Myr	2585 ± 33
Metamorphic, igneous rocks, km^2	124,778
Number of polygons (unique lithologic units)	521 (31)
Percent of total bedrock area	1.5
Area-weighted average age, Myr	1531 ± 117

of the total bedrock area. Metamorphic rocks comprise at least 1,474,953 km^2, or 17.7% of the Brazilian bedrock. If all lithologic classes that contain some metamorphic lithologies are included in the tally (i.e., 116,719 km^2, or 1.4% sedimentary, igneous and/or metamorphic bedrock; 97,383 km^2, or 1.2% metamorphic and sedimentary bedrock; 124,778 km^2, or 1.5% metamorphic and igneous bedrock; 366,641 km^2, or 4.4% igneous, sedimentary and/or metamorphic bedrock; and 163,837 km^2, or 2.0% ultramafic bedrock that includes igneous and metamorphic lithologies), metamorphic bedrock covers at most 2,344,311 km^2, or 28.1% of the Brazil. Given these complexities, normalized relative (to 100%; see Figure 2) areal abundances range from 40.1%–45.1% (sedimentary rocks), 35.1%–35.2% (igneous rocks), to 19.8%–24.2% (metamorphic rocks). An estimate of the abundance of ultramafic rocks has been computed by summing all units (Litotipo 1 = lithotype 1 only) that contain ultramafic lithologies. According to this estimate, ultramafic rocks cover less than 163,837 km^2, or 2.0% of the total bedrock. A more conservative estimate that includes only those lithotypes (Litotipo 1) that mention ultramafic lithologies prominently (but rarely contain exclusively ultramafic bedrock), reduces the areal coverage to about half of the above estimate. Units that include minor amounts of ultramafic lithologies (Litotipo 2 = lithotype 2) have not been included in these estimates. We propose that the latter, more conservative estimate (~1% of the bedrock

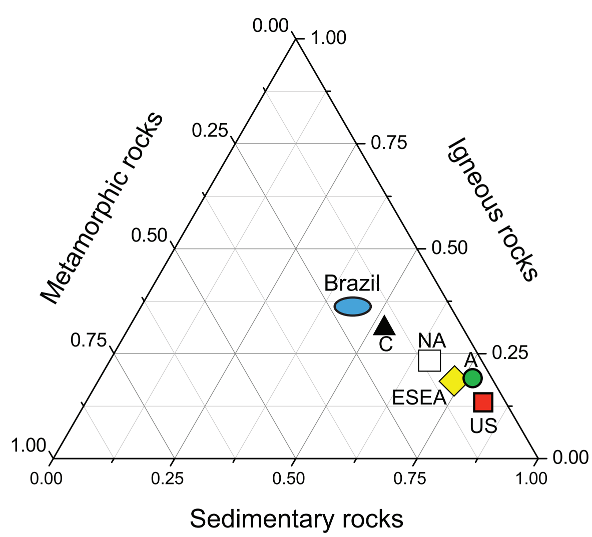

Figure 2. Relative abundances (normalized to 100%) of sedimentary, metamorphic, and igneous bedrock in Brazil (blue oval, representing uncertainty in area coverage that is mainly due to uncertainties in the areal extent of sedimentary [40.7%–45.1%] and metamorphic [19.8%–24.2%] rocks) compared to similar data for East and Southeast Asia (yellow diamond labeled ESEA), Alaska (green circle labeled A), Canada (black triangle labeled C), the conterminous United States of America (red square labeled US), and North America without Mexico (white square labeled NA).

area) is a more realistic estimate of the abundance of ultramafic rocks in Brazil. Absolute and relative area coverages of individual lithologic classes are tabulated in Table S1 together with the number of polygons and average ages, weighted according to bedrock area.

[7] Further sub-classification of volcanic, plutonic and metamorphic rocks is virtually impossible. This is caused by the summation of various lithologies, ranging from sedimentary to metamorphic, into the same lithotype unit. In this respect the bedrock GIS data for Brazil is very different from data sets previously analyzed by us.

[8] The spatial resolution of the bedrock data varies from 149 km^2 $polygon^{-1}$ for ultramafic units to 430 km^2 $polygon^{-1}$ for sedimentary units (see Table 1). The average spatial resolution of 232 km^2 $polygon^{-1}$ for the entire data set is similar to that of Alaska (297 km^2 $polygon^{-1}$ [*Peucker-Ehrenbrink and Miller*, 2003]), and higher than that of east and Southeast Asia (490 km^2 $polygon^{-1}$ [*Peucker-Ehrenbrink and Miller*, 2004]), the conterminous U.S. (602 km^2 $polygon^{-1}$ [*Peucker-Ehrenbrink and Miller*, 2002]) and Canada (801 km^2 $polygon^{-1}$ [*Peucker-Ehrenbrink and Miller*, 2003]). The resolution is comparable to that of a ~7–8 arc minute gridded map, and is thus more than an order of magnitude higher than the most recent global compilation of bedrock geology [*Amiotte Suchet et al.*, 2003], and more than two orders of magnitude more detailed than the global compilation by *Bluth and Kump* [1991] and *Gibbs and Kump* [1994] that are based on paleogeologic reconstructions by Ronov and coworkers [e.g., *Ronov*, 1989].

[9] Average ages (Table 1), weighted according to bedrock area, range from 248 ± 5 Myr for sedimentary rocks, 1153 ± 13 Myr for igneous rocks, ~1227 ± 25 Myr for ultramafic rocks, to 1678 ± 30 Myr for metamorphic rocks. Uncertainties were determined with a Monte Carlo simulation with 1000 runs and are reported at the 1 σ level. Average ages of mixed lithologic units range from 1362 ± 36 Myr for sedimentary, igneous and/or metamorphic rocks, 1531 ± 117 Myr for metamorphic and igneous rocks, 2023 ± 13 Myr for igneous, sedimentary and/or metamorphic rocks, to 2585 ± 33 Myr for metamorphic and sedimentary rocks.

[10] Data for sedimentary bedrock (7,822 polygons) were used to plot cumulative surface area for each time period mapped, normalized to 100% (Figure 3). Rather than redefining ages according to the newest international geologic timescale (GTS2004, [*Gradstein et al.*, 2004]) we use minimum and maximum ages given by the compilers of the digital GIS map. We emphasize that lower and upper age estimates are given for all polygons (i.e., no undated units). The average duration of ~7.5 Myr of all Phanerozoic units is significantly shorter than the average duration of ~35 Myr for Phanerozoic units in the 1:2,500,000 GIS data for the conterminous U.S., and even more significantly shorter than those of Alaska, Canada [*Peucker-Ehrenbrink and Miller*, 2003], and east and Southeast Asia [*Peucker-Ehrenbrink and Miller*, 2004]. Even the average duration of all Phanerozoic and Precambrian units in Brazil of 27 Myr is shorter than the average duration of Phanerozoic units alone in the conterminous U.S. data set, highlighting the high temporal resolution of the Brazil data. This higher temporal resolution implies a smaller uncertainty in the calculated area-age relationships compared to previous data sets [*Peucker-Ehrenbrink and Miller*, 2002, 2003, 2004].

[11] The half-area age, defined as the age for which half the area is younger and half is older (see Figure 3) of different bedrock units can be determined from cumulative age-area curves. We have calculated such a curve for sedimentary bedrock and calculate a median age of 88 Myr. This age was derived by linearly extrapolating between the two data points closest to the half-area age (i.e., 58.6% coverage at 66 Ma versus 46.6% coverage at 96 Ma). As discussed previously [*Peucker-Ehrenbrink and Miller*, 2003] the median age is a good measure of the average age of bedrock only if the area-age relationship is linear. As this is generally not the case the average age of each unit, weighted by bedrock area, is a more accurate estimate of the average lithologic age (see above). The median (half-area) ages are generally younger than the weighted average ages (i.e., downward concave age-area curves) due to the combined effects of erosion and cannibalistic recycling (sediments) as well as preferential burial of older units [e.g., *Gregor*, 1968; *Gilluly*, 1969; *Garrels and Mackenzie*, 1969; *Blatt and Jones*, 1975].

[12] Some of the most notable features of the area-age curve of sedimentary bedrock is the dearth of Jurassic and Triassic units (~150–250 Ma) as well as Mississippian and Late and Middle Devonian sedimentary bedrock (330–410 Ma). The former is

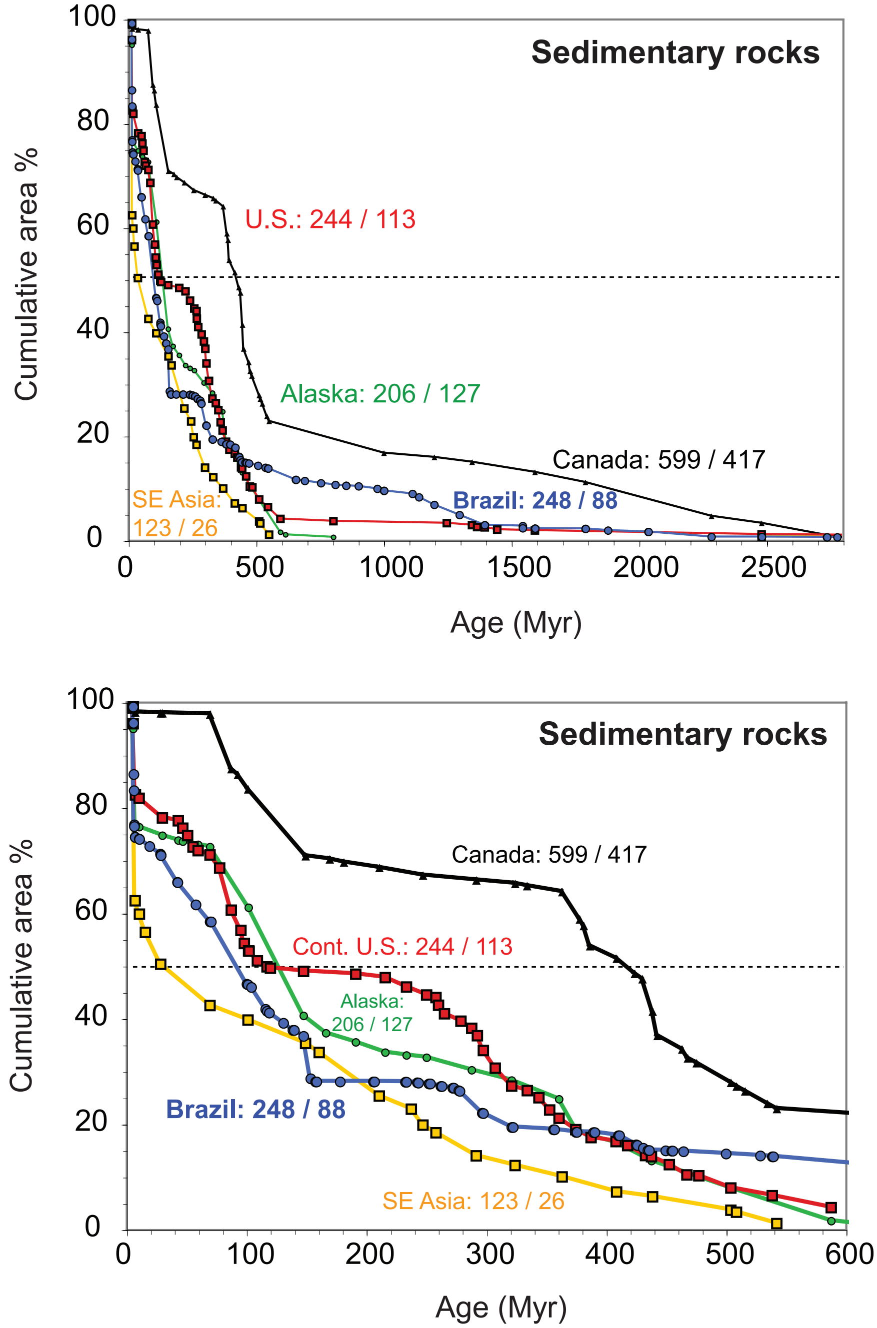

Figure 3. Cumulative area-age distribution of sedimentary rocks from (top) 0-2800 Ma and (bottom) 0-600 Ma. Numbers indicate average age weighted according to area (first number) and half-area age (second number). The hatched horizontal line marks 50% cumulative area (intersects with area-age curves correspond to half-area ages). Symbols: Canada, black triangles [*Peucker-Ehrenbrink and Miller*, 2003]; conterminous U.S., red rectangles [*Peucker-Ehrenbrink and Miller*, 2002]; Alaska, green circles [*Peucker-Ehrenbrink and Miller*, 2003]; SE Asia, orange squares [*Peucker-Ehrenbrink and Miller*, 2004]; Brazil, blue circles with thick line (this study).

caused by the stabilization of the Brazilian platform during the Permo-Triassic and the predominance of extensional tectonics, block rotations and continental graben filling (extensional volcanism) with only rare marine influences. The latter reflects incorporation of early to middle Paleozoic strata in intracratonic basins surrounding Precambrian cores that now exist as elongated, tightly folded belts with limited areal exposure of Devonian and early Carboniferous sedimentary strata [*Martin*, 1976].

5. Summary

[13] The data reflect the lithologic composition and age distribution of the continental bedrock in Brazil at unprecedented temporal and spatial resolution. We are not aware of any published bedrock data for Brazil that could be used as a reference for comparison. Data on bedrock geology can be used to estimate the chemical composition of the eroding continental crust, an important input parameter in models of global geochemical cycles [e.g., *Bluth and Kump*, 1991; *Amiotte Suchet and Probst*, 1995; *Amiotte Suchet et al.*, 2003]. In addition, a refined understanding of area-age distributions of continental rocks is a prerequisite for improving models of sedimentary recycling rates though time [e.g., *Blatt and Jones*, 1975].

[14] We intend to use this data in conjunction with digital maps of major river basins to quantitatively evaluate the link between bedrock geology and the chemical and isotopic composition of the dissolved and particulate load of major rivers. At a statistically meaningful coverage of at least 20 polygons per drainage basin, the average spatial resolution of the bedrock data for Brazil (232 km^2 polygon^{-1}) is sufficient for performing analyses of bedrock distribution of river basins larger than ~5,000 km^2. Such an analysis will lead to a more quantitative understanding of the influence of bedrock geology on the chemical and isotopic composition of continental runoff as well as the driving forces of change in marine isotope records on long timescales.

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[15] We acknowledge the Brazilian Geological Survey as the source of the digital bedrock data. We thank an anonymous reviewer and editor Vincent Salters for their comments. B.P.E. acknowledges financial support from the U.S. National Science Foundation (NSF-EAR-0125873) and the Woods Hole Oceanographic Institution.

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