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Quantitative bedrock geology of east and Southeast Asia (Brunei, Cambodia, eastern and southeastern China, East Timor, Indonesia, Japan, Laos, Malaysia, Myanmar, North Korea, Papua New Guinea, Philippines, far-eastern Russia, Singapore, South Korea, Taiwan, Thailand, Vietnam)

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[1] We quantitatively analyze the area-age distribution of sedimentary, igneous and metamorphic bedrock based on data from the most recent digital geologic maps of East and Southeast Asia (*Coordinating Committee for Coastal and Offshore Geosciences Programmes in East and Southeast Asia (CCOP) and the Geologic Survey of Japan*, 1997; 1:2,000,000), published as Digital Geoscience Map G-2 by the Geological Survey of Japan. Sedimentary rocks, volcanic rocks, plutonic rocks, ultramafic rocks and metamorphic rocks cover 73.3%, 8.5%, 8.8%, 0.9%, and 8.6% of the surface area, respectively. The average ages of major lithologic units, weighted according to bedrock area, are as follows: sedimentary rocks (average stratigraphic age of 123 Myr/median age of 26 Myr), volcanic rocks (84 Myr/20 Myr), intrusive rocks (278 Myr/195 Myr), ultramafic rocks (unknown) and metamorphic rocks (1465 Myr/1118 Myr). The variability in lithologic composition and age structure of individual countries reflects the complex tectonic makeup of this region that ranges from Precambrian cratons (e.g., northeast China and North Korea) to Mesozoic-Cenozoic active margins (e.g., Japan, the Philippines, Indonesia and New Guinea). The spatial resolution of the data varies from 44 km^2 per polygon (Japan) to 1659 km^2 per polygon (Taiwan) and is, on average (490 km^2/polygon), similar to our previous analyses of the United States of America and Canada. The temporal and spatial resolution is sufficiently high to perform age-area analyses of individual river basins larger than $\sim$10,000 km^2 and to quantitatively evaluate the relationship between bedrock geology and river chemistry. As many rivers draining tropical, mountainous islands of East and Southeast Asia have a disproportionate effect on the dissolved and particulate load delivered to the world oceans, bedrock geology in such river drainage basins disproportionately affect ocean chemistry.

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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] and Alaska and Canada [*Peucker-Ehrenbrink and Miller*, 2003] to east and Southeast Asia 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. One of our goals is to quantify bedrock geology of major river basins and investigate its relation to the chemical composition of continental runoff. The premise is that the relative abundance of various rock types strongly affects river chemistry of a given drainage basin [e.g., *Reeder et al.*, 1972; *Stallard and Edmond*, 1983; *Amiotte Suchet et al.*, 2003]. The lithologic-paleogeographic maps compiled by Ronov and colleagues at fairly coarse spatial resolution (e.g., *Ronov* [1989] and literature cited in *Peucker-Ehrenbrink and Miller* [2003]) lack sufficient details for investigations of individual river drainage basins and do not yet provide coverage for the Quaternary.

[3] Here we quantitatively investigate a modern compilation of bedrock maps of east and Southeast Asia at a scale of 1:2,000,000. The area includes highstanding tropical islands such as Borneo, Celebes, Java, New Guinea, the Philippines and Sumatra that are of great importance to the global input of particulate and dissolved matter to the ocean, because high rainfall and relief as well as the predominance of easily erodable lithologies (volcanic rocks, young sediments) lead to disproportionately (relative to area) high dissolved and particulate riverine fluxes into the northeastern Indian and western Pacific Oceans [e.g., *Meybeck and Ragu*, 1996; *Milliman and Meade*, 1983; *Milliman and Syvitski*, 1992; *Milliman et al.*, 1995].

2. Data

[4] The Coordinating Committee for Coastal and Offshore Geoscience Programmes in east and Southeast Asia (CCOP) and the Geological Survey of Japan have made the geologic map of east and Southeast Asia available in digital format (Digital Geoscience Map G-2). This map shows bedrock geology of east and Southeast Asia at a scale of 1:2,000,000. Ten of the eleven CCOP member countries participated in this project (Cambodia, China, Indonesia, Japan, Republic of Korea, Malaysia, Papua New Guinea, The Philippines, Thailand and Vietnam) and coverage for additional countries was digitized from available geologic maps (Brunei, East Timor, Laos, Myanmar, North Korea, Russia, Singapore, Taiwan). The digital version consists of 19,724 polygons containing information on age and lithology (~490 km^2 per polygon, on average), grouped into 163 lithostratigraphic units plus two unidentified units as well as one unit for water (e.g., lakes, large river deltas).

3. Methods

[5] The methods used are very similar to those used in our previous studies [*Peucker-Ehrenbrink and Miller*, 2002, 2003]. Digital data sources for the bedrock data (1:2,000,000) and the country polygon data (nominally 1:15,000,000) used as well as relevant projection parameters are summarized in an auxiliary material data Table 1 (ASCII format). Overlaying the smaller scale country map onto the larger scale geologic bedrock map resulted in minor inaccuracies along some country borders.

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Table 1 (Representative Sample). Area-Age Information of Bedrock in 18 Countries in East and Southeast Asia[a] (The full Table 1 is available in the HTML version of this article at http://www.g-cubed.org)

Major Lithologic Units	Number of Polygons	Area (km^2)	Average Age (Myr)	Median Age (Myr)	Area (%) Per Major Lithology	Area (%) of Total Area	Major/Minor Lithologic Units	Units	Brunei	Cambodia	China	E Timor	Indonesia	Japan
Volcanic rocks	1217	251001	122	147	31.77	2.6	Felsic	% area		18.61	37.37	12.2	5.59	23.92
	244	94253	126	212	11.93	0.98	Felsic/Intermediate	% area		10.87	14.72	64.95	12.34	
	176	87507	139	163	11.08	0.91	Intermediate	% area		14.59	15.88	15.2	15.78	
	244	151438	7	1	19.17	1.57	Interm/Mafic	% area			0.2	7.58	62.79	
	1768	205911	64	9	26.06	2.13	Mafic	% area		55.92	31.83	0.07	3.49	48.96
	558	26970	3		3.41	0.28	Unknown	% area						27.12
						8.46	all volcanic rocks	% area		11.72	6.93	18.43	10.11	27.98
			84	20			Average age	Myr		105	149	114	15	27
Plutonic rocks	2620	781559	279	197	91.47	8.09	Felsic	% area		93.04	96.49	56.71	83.58	93.69
	289	32286	271	137	3.78	0.33	Felsic/Intermediate	% area				41.56	15.78	
	122	16727	293	180	1.96	0.17	Intermediate	% area			2.58	0.4	0.22	
	70	11859	17		1.39	0.12	Interm/Mafic	% area		2.05		1.33	0.42	
	418	11815	499	182	1.38	0.12	Mafic	% area			0.94			6.31
	7	190	349		0.02	0	Unknown	% area		4.91				
						8.85	all plutonic rocks	% area		1.41	11.34	5.62	4.7	11.29
			278	195			Average age	Myr		157	361	143	109	102
Ultramafic rocks	526	85105			100	0.88	all	% area		0	0	0	1.77	0.52
							Average age	Myr						
Sedimentary rocks	10079	7073070	123	26	100	73.25	all	% area	100	84.6	69.95	63.46	80.43	56.23
							Average age	Myr	8	48	176	19	32	56
Metamorphic rocks	630	361149	1112	861	43.69	3.74	Low grade	% area		58.79	50.05		0.01	
	586	367727	1808	1576	44.49	3.81	Intermediate	% area			43.54	93.9	80.83	100
	66	44537	2606	2790	5.39	0.46	High grade	% area		41.21	6.41			
	104	53173	529	354	6.43	0.55	Unknown	% area			0	6.1	19.17	
						8.56	all metamor. rocks	% area		2.27	11.79	12.49	3	3.99
			1465	1118			Average age	Myr		1149	1686	212	281	267
						Sum of all	Average age	Myr	8	81	373	68	41	62
						19724	All polygons	number	9	499	4032	44	1455	7977
						9656277	Total area	km^2	5713	182106	4110343	14294	1811568	354150
						19131	Dated polygons	number	9	495	4029	44	1416	7779
						9559879	Dated area	km^2	5713	181979	4110243	14294	1779561	352298
							Dated polygons	%	100	99.2	99.93	100	97.32	97.52
							Dated area	%	100	99.93	100	100	98.23	99.48
						490	Resolution	km^2/Poly	635	365	1019	325	1245	44

[a] Average (weighted by area) ages and median (50% area coverage) ages are given in million years for major lithologic units in each country. Area coverage is given in square kilometer and percent of total area for major and minor lithologic units in each country. Number of polygons (total as well as age dated), area covered (total as well as age dated) and average (weighted by area) ages are also given for the entire area of east and Southeast Asia as well as for major and minor bedrock units.

For example, this procedure created minor bedrock coverage for three countries, Mongolia (1599 km^2), India (4712 km^2), and Bangladesh (460 km^2), for which no bedrock data were compiled in the original bedrock map. We therefore assigned the Mongolian bedrock to China, and Indian and Bangladeshi bedrock to Myanmar.

4. Results and Discussion

[6] The results are shown in auxiliary material[1] Table 2 and Table 1 together with an abbreviated rock description. Upper and lower age boundaries [*Harland et al.*, 1990; *Lumbers and Card*, 1991; Cambrian-Precambrian boundary at 544 Ma] and duration are also listed. Total calculated bedrock area of east and Southeast Asia is 9,656,277 km^2, of which 7,073,070 km^2, or 73.2%, is sedimentary bedrock (Figure 2). Igneous rocks cover 18.2% (8.5% volcanic rocks, 8.8% plutonic rocks, 0.9% ultramafic rocks) of the total surface area. These should be considered minimum values because some of the sedimentary units contain minor amounts of igneous rocks (e.g., volcanic ash, dikes and sills). Metamorphic rocks comprise 8.6% of the bedrock. It should be noted that low and medium grade metamorphic rocks, not mapped as metamorphic rocks by the United States Geological Survey (USGS) and the Canadian Geological Survey in North America, have been mapped as metamorphic rocks in east and Southeast Asia. Such regional differences in bedrock classification will complicate future comparison between digital data sets for different world regions. Water (major code 230) covers 0.14% of the total surface area. No information is available for 0.0016% of the surface area (major codes 0 and 996). Relative area coverage for individual countries is tabulated in Table 1, together with the average and median ages weighted according to bedrock area.

[7] Further subclassification of volcanic, plutonic and metamorphic rocks (see Table 1) shows that volcanic bedrock is dominated by Mesozoic felsic and Cenozoic mafic volcanic rocks in nearly equal proportions. In contrast, Mesozoic to Paleozoic felsic plutonic rocks by far dominate plutonic bedrock (>90%). Low grade and medium grade metamorphic rocks of mostly Precambrian age dominate metamorphic bedrock in nearly equal proportions (~45%), whereas predominantly Archean high-grade metamorphic rocks constitute a minor percentage (~5%) of all metamorphic rocks. Table 1 also shows the relative area coverage of various bedrock units broken down for each country.

[8] The spatial resolution of the data varies from 44 km^2 per polygon in Japan to 1659 km^2 per polygon in Taiwan (see Figure 1 and Table 1). On average, the spatial resolution of 490 km^2 $polygon^{-1}$ for east and Southeast Asia is similar to that of the conterminous U.S. (602 km^2 $polygon^{-1}$ [*Peucker-Ehrenbrink and Miller*, 2002]), Alaska (297 km^2 $polygon^{-1}$ [*Peucker-Ehrenbrink and Miller*, 2003]) and Canada (801 km^2 $polygon^{-1}$ [*Peucker-Ehrenbrink and Miller*, 2003]). This resolution is comparable to that of a ~15 arc minute gridded map and is at least one order of magnitude higher than the most recent global compilation of bedrock geology [*Amiotte-Suchet et al.*, 2003] and nearly 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] Data for sedimentary bedrock (10,079 polygons), volcanic rocks (4207 polygons), plutonic rocks (3526 polygons), ultramafic rocks (526 polygons) and metamorphic rocks (1386 polygons) were used to plot normalized cumulative surface area for each time period mapped (Figure 3). Area values of undifferentiated units such as "Jurassic and Cretaceous" were divided according to duration (km^2 Myr^{-1}) among the subunits. The *Harland et al.* [1990] (Cambrian-Precambrian boundary modified to 544 Ma) and *Lumbers and Card* [1991] timescales were used to define ages of upper and lower bounds for each unit. The temporal resolution of the data is lower (generally at the subperiod level) than comparable data for the conterminous U.S. (generally at the Epoch level). The average duration of ~84 Myr for all Phanerozoic units in the data set is thus significantly longer than average duration of

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gc/2003GC000619.

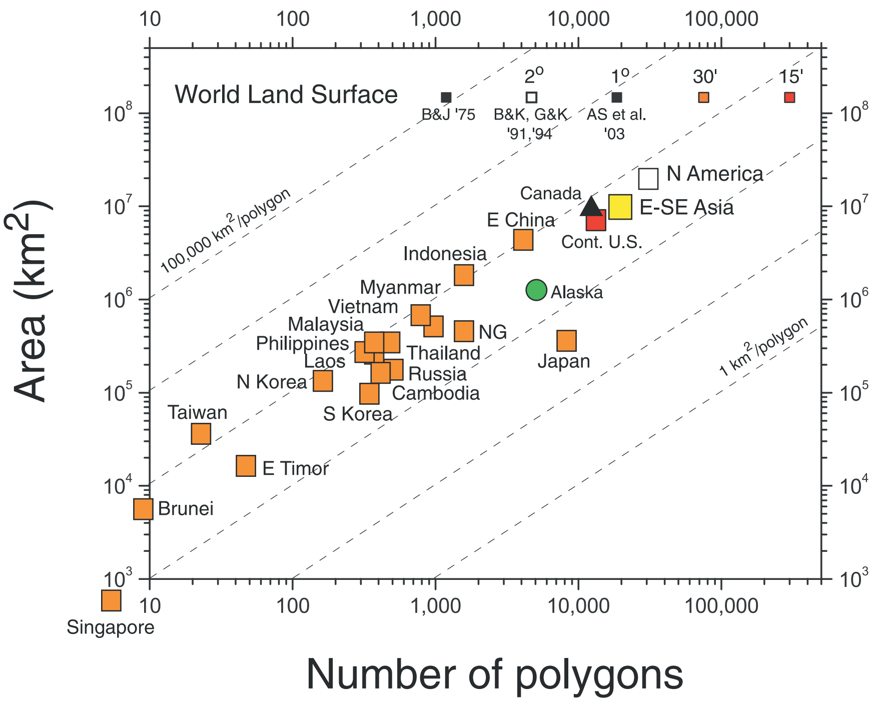

Figure 1. Spatial resolution (average area of a polygon in km^2) of digital bedrock maps for east and Southeast Asia (yellow square) as well as 18 countries in east and Southeast Asia (orange squares) in comparison to Canada (black triangle), Alaska (green circle), the conterminous United States of America (red square), and North America without Mexico (open white square). Dotted lines are lines of equal resolution. Characteristic resolutions of some global assessments of bedrock geology are shown as small squares. These range from coarse resolution of work by *Blatt and Jones* [1975] that is equivalent to a resolution of ~100,000 km^2 per polygon, to the most recent assessment by *Amiotte Suchet et al.* [2003] with a resolution of slightly better than 10,000 km^2 per polygon.

~35 Myr for Phanerozoic units in the data set for the conterminous U.S., but comparable to those of Alaska and Canada [*Peucker-Ehrenbrink and Miller*, 2003]. The coarser temporal resolution of the east and Southeast Asia data implies a larger uncertainty in the calculated area-age relationships compared to the data set for the conterminous U.S. [*Peucker-Ehrenbrink and Miller*, 2002]. It should be noted, however, that 99% of the bedrock area (97% of all bedrock polygons) have been dated.

[10] The median ages (i.e., half-area age, see Figure 3 and Table 1) of the four major lithologic groups are as follows: sedimentary bedrock (26 Myr), volcanic rocks (20 Myr), plutonic rocks (195 Myr) and metamorphic rocks (1118 Myr). Owing to the lack of data, the median age of ultramafic rocks in east and Southeast Asia cannot be calculated. 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 age of each unit should be weighted by bedrock area to calculate a weighted average age. The weighted average ages of the four major lithologic units in east and Southeast Asia are as follows: sedimentary bedrock (123 Myr), volcanic rocks (84 Myr), plutonic rocks (278 Myr) and metamorphic rocks (1465 Myr). Additional weighted average and half-area ages for lithologic subunits (e.g., felsic volcanic rocks, intermediate volcanic rocks, mafic volcanic rocks) are listed in Table 1. The median (half-area) ages are generally younger than the weighted average ages. This reflects the fact that cumulative area-age curves generally have a concave downward shape, a consequence of the preferential exposure of young rocks due to decreasing survival probability of geologic units with increasing age due to erosion

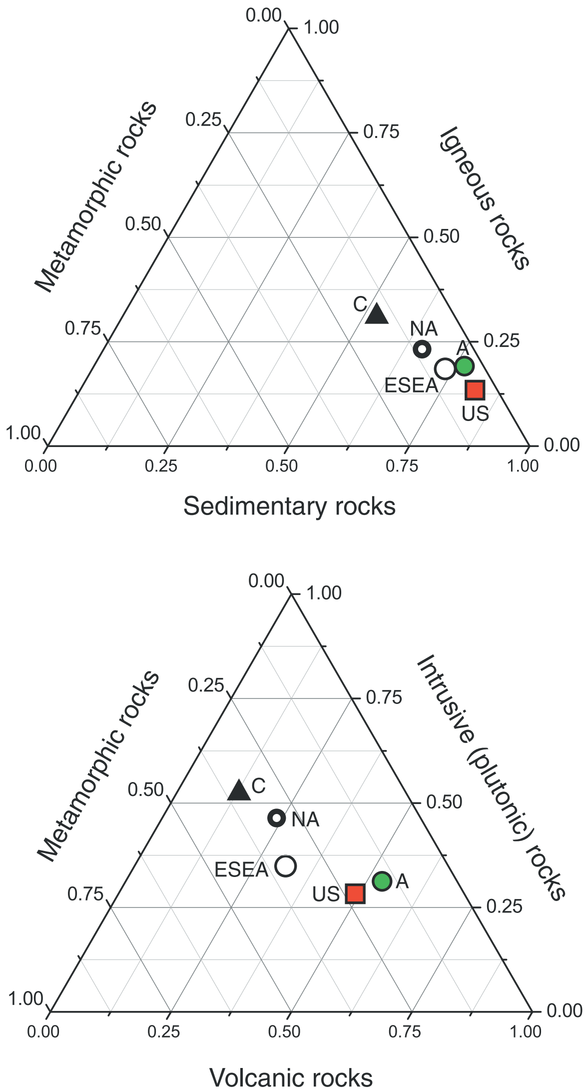

Figure 2. Relative abundances (normalized to 100%) of sedimentary, metamorphic and igneous bedrock (top panel) and intrusive (plutonic), volcanic, and metamorphic bedrock (bottom panel) in east and Southeast Asia (large white circle) in comparison to Alaska (green circle), Canada (black triangle), the conterminous United States of America (red squares) and North America without Mexico (thick black-rimmed circle).

and/or burial of older units [e.g., *Gregor*, 1968; *Garrels and McKenzie*, 1969; *Blatt and Jones*, 1975]. Only in the special case of linear cumulative area-age curves are weighted average ages and median (half-area) ages identical.

[11] The lithologic composition and age distribution of bedrock in individual countries varies widely and reflects the complex tectonic evolution of east and Southeast Asia. For instance, the extremes in the weighted average age spectrum, North Korea (1542 Myr) on the one hand and the Philippines and New Guinea (33 Myr) on the other hand, reflect the influence of the Precambrian North China craton on the geology and North Korea and the young, active margin influence on the geology of the Philippine archipelago and New Guinea. This tectonic contrast is also visible in the

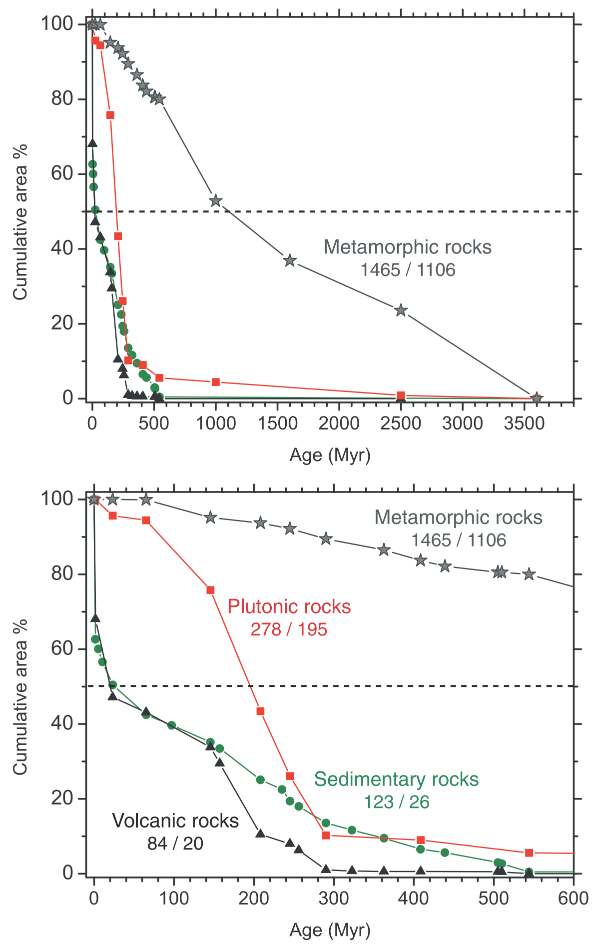

Figure 3. Cumulative area-age distribution of sedimentary rocks (green circles), volcanic rocks (black triangles), plutonic rocks excluding ultramafic rocks (red squares), and metamorphic rocks (gray stars) from 0–3900 Ma (top panel) and 0–600 Ma (bottom panel). Numbers below each lithology indicate average ages weighted according to lithology (first number) and median (i.e., half-area) ages (second number). The hatched horizontal line marks 50% cumulative area (intersects with area-age curves correspond to median ages). Stratigraphic ages are based on *Harland et al.* [1990] as well as *Lumbers and Card* [1991] for the Precambrian.

lithologic composition of bedrock in individual countries. Metamorphic rocks of predominantly Precambrian age make up more than half of the bedrock area in North Korea, whereas subduction-related volcanic and plutonic rocks comprise nearly 40% of the bedrock area in Japan. (See Table 1 for further details).

5. Summary

[12] The data reflect the lithologic composition and age distribution of the continental bedrock in east and Southeast Asia at an unprecedented temporal and spatial resolution. We are not aware of any published bedrock data for east and Southeast Asia that could be used as a reference for comparison. In general, such data 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].

[13] As outlined in the introduction, 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 east and Southeast Asia (490 km^2 polygon^{-1}) is sufficient for performing analyses of bedrock distribution of river basins larger than ~10,000 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 and the driving forces of change in marine isotope records on long timescales.

Acknowledgment

[14] We acknowledge the CCOP and the Geologic Survey of Japan as the source of the digital bedrock data (Digital Geoscience Map G-2). We are deeply indebted to Joel Bandibas (Geological Survey of Japan) for correcting missing polygons in the original digital data set, for supplying the appropriate datum information and for electronically transferring useable ArcInfo files. Financial support was provided through the U.S. National Science Foundation (NSF-EAR-0125873) to BPE. This is WHOI contribution No. 11,046.

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