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Crustal volumes of the continents and of oceanic and continental submarine plateaus

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Global topographic data and the assumption of Airy isostasy have been used to estimate the crustal volumes of the continents and the oceanic and continental submarine plateaus. The calculated crustal volumes are 7182×10^6 km³ for the continents, 242×10^6 km³ for continental submarine plateaus, and 369×10^6 km³ for oceanic plateaus. The Falkland Plateau and the Lord Howe Rise are the two largest continental submarine plateaus with volumes of 48×10^6 km³ and 47×10^6 km³, respectively. Total continental crustal volume is 7581×10^6 km³ (including the volume of continental sediments on the ocean floor 160×10^6 km³), in good agreement with previous estimates. Continental submarine plateaus on the seafloor comprise 3.2% of the total continental crustal volume. The largest oceanic plateaus in order of decreasing size are the Ontong-Java Plateau, the Kerguelen Plateau, the Caribbean, the Chagos Laccadive Ridge, the Ninetyeast Ridge, and the Mid-Pacific Mountains. Together they comprise 54% of the total anomalous crustal volume in oceanic plateaus. An upper bound to the continental crust addition rate by the accretion of oceanic plateaus is 3.7 km³/yr, a value that assumes accretion of all oceanic plateaus, with a total volume of 4.9% of the continental crustal volume, on a 100 Myr time scale. Even if a substantial fraction of the crustal volume in oceanic plateaus is subducted, accretion of oceanic plateaus could make a contribution to continental growth since the upper bound to the addition rate exceeds recent estimates of the island arc addition rate. Subduction of continental submarine plateaus with the oceanic lithosphere on a 100 Myr time scale gives an upper bound to the continental crustal subtraction rate of 2.4 km³/yr, much larger than recent estimates of crustal subtraction by subduction of seafloor sediments. Effective subduction of all oceanic plateaus implies equally effective subduction of continental submarine plateaus. A potentially important way to recycle continental crust back into the mantle may be the break off of small fragments from the continents, entrapment of the continental fragments in the seafloor, and subduction of the fragments with the oceanic lithosphere. This process may be occurring in the Mediterranean for Corsica and Sardinia.

1. Introduction

Major questions about past continental growth include identification of the physical mechanisms by which the crust separated from the mantle and accumulated into stable continental assemblages and the rate at which these processes operated (see e.g., [1–3]). The present volume of continental crustal material provides a boundary condition for models of continental growth. Yet, there are only approximate determinations of continental crustal volume. Reymer and Schubert [2] estimated the total volume of continental crustal material as 7.76×10^9 km³ (including 0.16×10^9 km³ of continental sediments in the ocean floor) based on an average thickness of the continental crust of 38 km [4] and an area of continental crust including

continental margins of 2×10^8 km². One purpose of the present paper is to make a more accurate inventory of the total volume of continental crust.

Continental crust is also found in the oceans, not only in the form of sediments, but also as submarine plateaus or rifted pieces of former continents [5]. For several reasons it is important to know the volume of this material. First, the crustal volume of these continental submarine plateaus contributes to the total inventory of continental crust. Second, if these pieces of continental crust are small enough to be subducted with the oceanic lithosphere, then this loss must be considered when calculating net continental growth.

Oceanic plateaus (areas of anomalously thick oceanic crust with age less than about 200 Myr) are a common feature of the ocean basins [6]). The

volumes of these oceanic plateaus also need careful determination because they represent potential additions to the continental crust if they are accreted to the continents instead of being subducted with the oceanic lithosphere [7].

Seafloor plateaus, whether oceanic or continental, can be buoyant enough to inhibit subduction. A present-day example is the Ontong-Java Plateau which is resisting subduction and thus modifying the active margin between the Pacific and Indian plates [8]. Another example is the Caribbean Plateau which resisted subduction with the Farallon plate [9,10]. However, smaller aseismic ridges such as the Emperor Seamount Chain may not have enough buoyancy to resist subduction; instead they produce a cusp in the axis of the trench [11]. Allochthonous terranes provide evidence that medium sized plateaus (e.g., the size of Shirshov Ridge and Agulhas Plateau) can resist subduction and become accreted to the continents [7]. These features provide an estimate of the minimum anomalous crustal volume required to inhibit subduction of otherwise negatively buoyant oceanic lithosphere.

For all the reasons stated above, we measure the volumes of both continental and oceanic plateaus on the seafloor in addition to determining the volume of the continents. We first describe how topographic data are used, along with the assumption of Airy isostasy, to infer crustal volumes. Studies of geoid heights and gravity anomalies over continents and plateaus suggest that the Airy model of local compensation is a good first approximation (e.g., [12,13]). We confirm this first-order model using seismic measurements of crustal thickness for oceanic and continental submarine plateaus as well as continents. One problem encountered in measuring the relative topography of a plateau or continent is the choice of a reference level. We developed two techniques for choosing the reference level. For seafloor plateaus the reference level is chosen as the most likely depth in a given area. For continents, seismic data are used to calibrate the crustal thickness at a prescribed reference level. Using these methods we estimate and tabulate the volumes of 54 seafloor plateaus and 10 continents. Finally, we explore the implications of these volume measurements for issues relating to the growth of continental crust as well as the subduction of buoyant plateaus.

2. Airy model for crustal volume measurements

Crustal volumes of continents and of continental and oceanic plateaus on the seafloor can be determined by integrating the crustal thickness over the area of the feature. For most features, however, crustal thickness information is not available in sufficient detail to perform this integration. Here we use elevation data along with the Airy compensation model (constrained by seismic refraction data) to estimate crustal thickness.

A diagram of the Airy compensation model is shown in Fig. 1. A uniform density crust is divided into 5 layers which float on the higher density mantle. Layer 1 lies above sea level, layer 2 lies between sea level and the normal seafloor depth (base depth) z_b, layer 3 corresponds to the thickness of normal oceanic crust, layer 4 is the compensating root for layer 2 and layer 5 is the compensating root for layer 1. The volumes of the 5 layers are determined individually and then added to give the total crustal volume.

To understand how the volume of each layer is calculated, consider a plateau on the seafloor where all of the topography lies below sea level. By
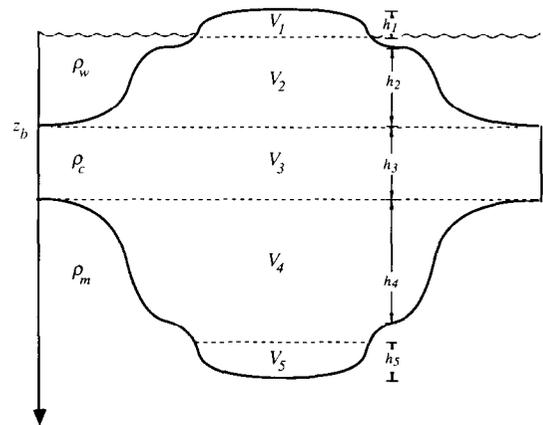
Fig. 1. Airy compensation model used to determine crustal thickness and crustal volume. The uniform density crust (ρ_c = 2800 kg/m^3) is divided into 5 layers which float on the higher density mantle (ρ_m = 3200 kg/m^3). The seawater has a density ρ_w of 1025 kg/m^3. Layer 1 lies above sea level, layer 2 lies between sea level and the normal seafloor depth (base depth) z_b, layer 3 corresponds to the thickness of normal oceanic crust, layer 4 is the compensating root for layer 2 and layer 5 is the compensating root for layer 1.

definition, the volumes of layers 1 and 5 are zero. The topography of the plateau above the normal seafloor depth (h_2) is isostatically compensated by a crustal root with a thickness of h_4. According to the Airy compensation model, the thickness of the crustal root is

$$h_4 = h_2 \frac{(\rho_c - \rho_w)}{(\rho_m - \rho_c)} \qquad (1)$$

where ρ_w (1025 kg/m^3) is the seawater density, ρ_c (2800 kg/m^3) is the crustal density and ρ_m (3200 kg/m^3) is the mantle density. The important parameter in determining h_4 is the density difference $\rho_m - \rho_c$; we discuss our choice of this quantity below. An assumption of this model is that the mantle beneath the crustal plateau has no anomalous compositional density variations. The validity of this assumption is also discussed below.

The total crustal volume of the plateau is the sum of the three volumes. The plateau volume V_2 is equal to the area of the plateau times the average height of the plateau above the normal seafloor depth. The volume of layer 3, V_3, is equal to the area of the plateau times the normal crustal thickness h_3. Seismic refraction studies [14] show that normal oceanic crust is about 6.5 km thick. Finally, using the Airy model, the volume of the crustal root is:

$$V_4 = V_2 \frac{(\rho_c - \rho_w)}{(\rho_m - \rho_c)} \qquad (2)$$

When a plateau or continent protrudes above sea level, layers 1 and 5 must also be included. Layer 5 is the crustal root needed to support the topography above sea level (layer 1). The thickness of layer 5 is:

$$h_5 = h_1 \frac{\rho_c}{(\rho_m - \rho_c)} \qquad (3)$$

and its volume is:

$$V_5 = V_1 \frac{\rho_c}{(\rho_m - \rho_c)} \qquad (4)$$

where V_1 is the area of the continent above sea level times the average elevation of the continent. The total crustal volume of a continent is then the sum of the five volumes shown in Fig. 1. Similarly,

the total crustal thickness h_t is the sum of the individual layer thicknesses:

$$h_t = \begin{cases} e\left[1 + \dfrac{\rho_c}{(\rho_m - \rho_c)}\right] \\ \qquad -z_b\left[1 + \dfrac{(\rho_c - \rho_w)}{(\rho_m - \rho_c)}\right] + h_3 \qquad e > 0 \\ (e - z_b)\left[1 + \dfrac{(\rho_c - \rho_w)}{(\rho_m - \rho_c)}\right] + h_3 \qquad e < 0 \end{cases}$$

where e is the elevation above sea level, z_b is the base depth and h_3 is the unknown thickness of the intermediate crustal layer. It should be pointed out that either z_b or h_3 (but not both) must be determined by using independent measurements of crustal thickness. While this model is straightforward, and volumes are simply calculated from the area of the feature and its average elevation, several complications arise when it is applied to real data.

3. Data analysis

The global elevation data base compiled by Heirtzler et al. [15] was used in our analysis. To reduce the number of computations, the 5-minute by 5-minute gridded data were averaged into 1/4° by 1/4° areas. Sixty-four elevated features of the Earth's topography were then selected and enclosed by polygons (Fig. 2). The boundaries of the areas were chosen to include a perimeter of deep seafloor. Ten of these regions are large continental areas (thick-lined in Fig. 2). The remaining 54 features are generally smaller and have little or no area above sea level (thin-lined polygons in Fig. 2). These oceanic features are categorized below as either oceanic plateaus, continental fragments, or thermal swells.

The major uncertainties in calculating the crustal volumes of these 64 features lie in determining the base depth z_b and the thickness of the intermediate crustal layer (layer 3). The technique that worked best for defining the base depth of the 54 smaller oceanic features did not yield accurate results for the larger continental areas. Therefore two techniques were used in our study. Measurements of the 54 submarine features are discussed first.
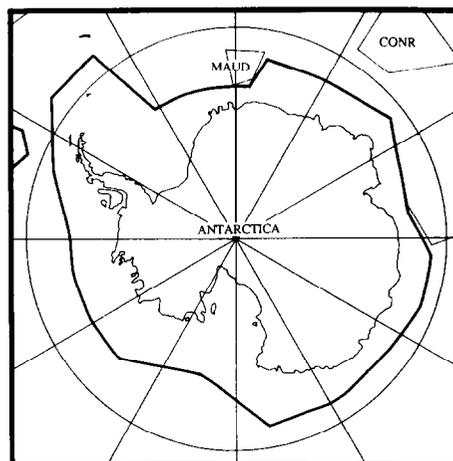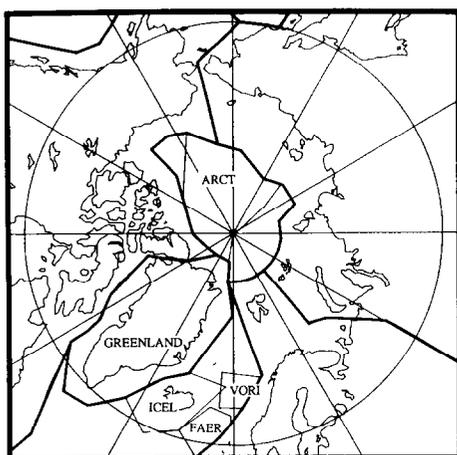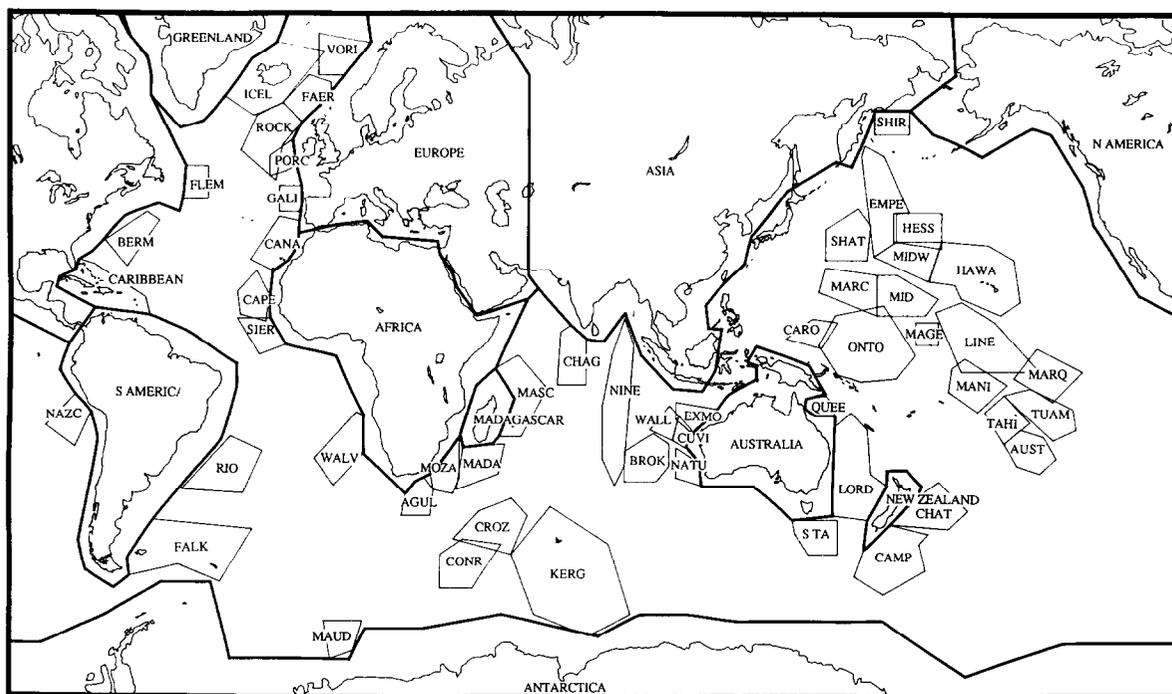
Fig. 2. Sixty-four elevated features of the Earth's topography are enclosed by polygons. Ten of the features are continental areas (thick-lined polygons) while the remaining 54 features (thin-lined polygons) are either oceanic plateaus (see Table 1), continental plateaus (see Table 2) or thermal swells (see Table 3). Plateaus are identified by the first 4 characters of their full names given in the tables.

3.1. Plateaus

The Shatsky Rise and Ontong-Java Plateau are used to illustrate the problem of defining the base depth for an oceanic region. For these areas we prescribed a number of base depths ranging from 2 to 7 km and calculated the total crustal volume for each depth. Results for the Shatsky Rise and Ontong-Java Plateau (Figs. 3a and 4a, respectively) show that the total crustal volume is very sensitive to the choice of the base depth. As the base depth is increased, both the area of the plateau and its average height above the base

Shatsky Rise

a

b
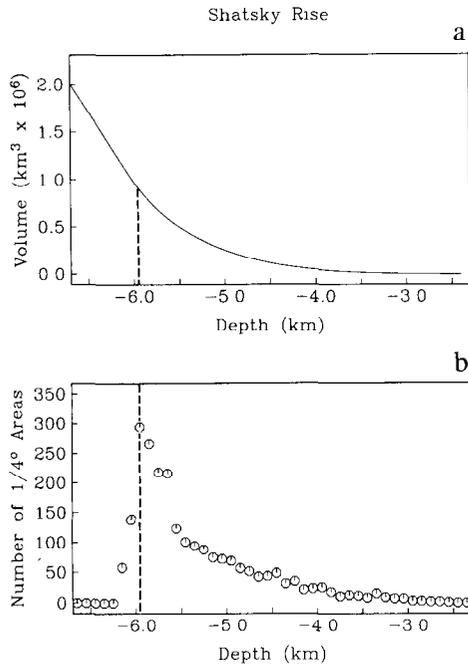
Fig. 3. (a) Total crustal volume of the Shatsky Rise calculated using base depths ranging between 7 km and 2 km. Plateau volume is sensitive to the base depth chosen. (b) Histogram showing the number of $1/4°$ by $1/4°$ areas in a 100 m elevation range versus elevation. The peak in the histogram, at a depth of 5.95 km, marks the base depth.

depth increase. Since the volumes of all three layers are proportional to the area or height, the total crustal volume of the Shatsky Rise increases by a factor of 2 when the base depth is increased from 5.5 to 6.0 km. Similarly, the total volume of the Ontong-Java Plateau increases by a factor of 1.5 when the base depth is increased from 4.5 to 5.0 km.

To define the base depth in an objective way, we made a histogram of the depths $(1/4° \times 1/4°$ areas) within the polygon containing each region. For the Shatsky Rise (Fig. 3b), the peak in the histogram occurs at a depth of 5.95 km. This depth is in good agreement with a base depth chosen visually from a bathymetric chart [16]. For the Ontong-Java Plateau, the peak in the histogram occurs at a depth of 4.65 km (Fig. 4b) which is also in good agreement with the seafloor depth surrounding the plateau. This technique of choosing the base depth works well because normal oceanic seafloor is quite flat while the topography of a plateau usually contains no large flat areas.

Therefore, even if the region of flat seafloor surrounding the plateau is small, it will still produce a peak in the histogram.

Another check of this base depth comes from the depth versus age relation [17]. The Shatsky Rise formed at a ridge-ridge-ridge triple junction between 144 and 116 Ma ago [18] while the seafloor surrounding the Shatsky Rise is about 135 Ma old [19]. The predicted seafloor depth for this area is 6.03 km. The peak in the histogram was only slightly less (5.95 km). While the origin of the Ontong-Java Plateau is not well understood, the age of the surrounding seafloor is roughly 140 Ma, corresponding to a predicted base depth of 6.06 km. In this case, the base depth measured with the histogram technique is only 4.65 km. In general, we find that the base depth derived from the histogram technique is systematically less than the depth predicted by the depth versus age relation. We do not completely understand why this systematic discrepancy occurs. However, the anomalously shallow seafloor surrounding plateaus could

Ontong Java

a

b
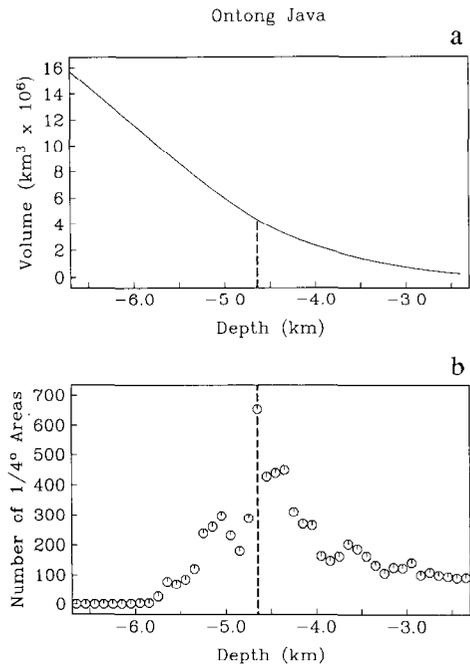
Fig. 4. (a) Total crustal volume of the Ontong-Java Plateau calculated using base depths ranging between 7 km and 2 km. Plateau volume is sensitive to the base depth chosen. (b) Histogram showing the number of $1/4°$ by $1/4°$ areas in a 100 m elevation range versus elevation. The peak in the histogram, at a depth of 4.65 km, marks the base depth.

be caused by anomalously low density mantle beneath and surrounding each plateau. As proposed in a number of studies [20–22] the extraction of melt from mantle during the formation of oceanic crust leaves a depleted upper mantle layer that is about 60 kg/m³ less dense than undepleted mantle. Oceanic plateaus are sites of excess crustal thickness (~ 13 km thicker than normal). Based on the calculations of Oxburgh and Parmentier [22] this would produce an extra thickness of depleted layer causing the lithosphere to float 650 m higher. This agreement with the observed depth anomaly of about 500 m suggests that the upper mantle beneath oceanic plateaus is indeed depleted. This extra buoyancy from the upper mantle does not influence our crustal thickness estimates, however, because the base depth was used rather than the depth predicted from the depth versus age relation.

To better understand how crustal thickness is related to oceanic plateau topography, we calibrated the Airy compensation model using crustal thicknesses determined from seismic refraction studies [4]. Four diverse areas having accurately determined crustal thicknesses were used (Lord Howe Rise [23]; Mascarene Plateau [24]; Ontong-Java Plateau [25]; and Shatsky Rise [26]). At the location of each seismic refraction measurement, we extracted the seafloor depth from the global elevation data base and subtracted from

it the base elevation determined from the histogram analysis. A plot of crustal thickness versus elevation above the base depth is shown in Fig. 5 for each of the 4 plateaus. At zero elevation, the crustal thickness is about 6.5 km in agreement with the crustal thickness of normal oceanic lithosphere [14]. This suggests that the histogram method of measuring base depth works quite well. Also shown in Fig. 5 is the crustal thickness versus elevation predicted by the Airy-compensation model for crustal densities of 2700 kg/m³, 2800 kg/m³ and 2900 kg/m³ and mantle density of 3200 kg/m³ (see equation (5)). As predicted by the simple Airy model, the seismically determined crustal thicknesses increase with increasing elevation above the base depth. The results suggest that best crustal density for the Airy model ranges between 2700 and 2900 kg/m³. As already noted, it is actually the density difference between the crust and mantle that controls the slope of the model (see equation (5)). The best density difference ranges between 500 and 300 kg/m³; we adopted a value of 400 kg/m³.

Based on the agreement between the base depth determined from the histogram method and the base depth predicted from the depth versus age relation as well as the agreement between the model crustal thickness at the base depth and the seismically determined thickness of normal crust, we applied the histogram technique to determine
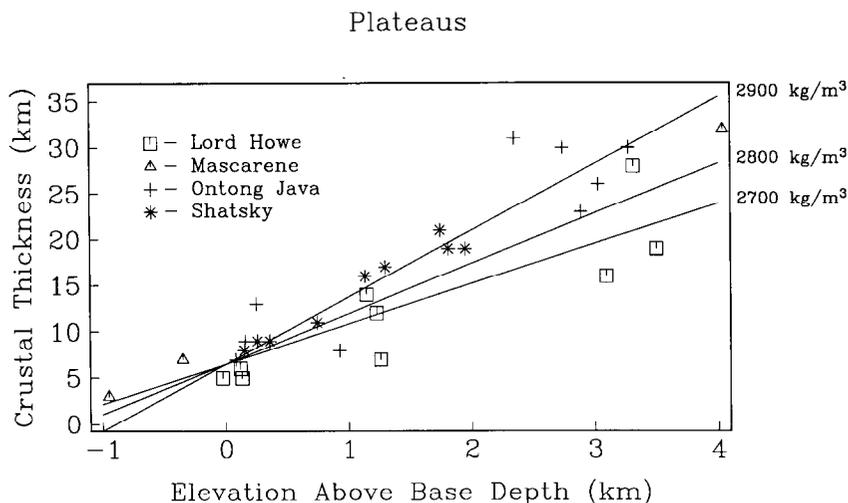
Plateaus

Fig. 5. Seismic refraction measurements (30) of crustal thickness versus elevation above base depth for two continental submarine plateaus (Lord Howe Rise and Mascarene Plateau) and two oceanic plateaus (Ontong-Java and Shatsky Rise). Predictions of the Airy compensation model are shown for crustal densities ranging from 2700 to 2900 kg/m³ and a mantle density of 3200 kg/m³.

TABEL 1
OCEANIC PLATEAUS

	LAT	LON	a_1 km² ×10⁶	a_2 km² ×10⁶	h_1 km	h_2 km	z_b km	age ma	z_{age} km	v_1 km³ ×10⁶	v_2 km³ ×10⁶	v_3 km³ ×10⁶	v_4 km³ ×10⁶	v_5 km³ ×10⁶	v_t km³ ×10⁶	h_t km
BROKEN RIDGE	30 S	97 E	.00	1.11	.00	.86	-4.55	70.	-5.35	.000	.955	7.210	4.236	.000	12.400	11.18
CARIBBEAN	20 N	85 W	.15	1.86	.23	2.27	-4.05	90.	-5.64	.035	4.212	12.063	18.690	.244	35.243	20.65
CAROLINE SEAMOUNTS	7 N	148 E	.00	.44	.00	1.14	-4.05	155.	-6.13	.000	.503	2.862	2.230	.000	5.595	12.71
CHAGOS LACCADIVE RIDGE	0 N	74 E	.00	1.69	.00	1.53	-5.05	75.	-5.43	.000	2.577	10.977	11.436	.000	24.991	14.80
CROZET PLATEAU	46 S	49 E	.00	.79	.00	1.01	-4.05	75.	-5.43	.000	.798	5.113	3.539	.000	9.449	12.01
EMPEROR SEAMOUNTS	42 N	171 E	.00	1.28	.00	.74	-5.75	100.	-5.75	.000	.941	8.308	4.175	.000	13.423	10.50
HESS RISE	36 N	179 W	.00	.80	.00	.90	-5.45	100.	-5.75	.000	.716	5.189	3.177	.000	9.081	11.38
ICELAND	64 N	18 W	.11	.86	.44	1.75	-2.85	25.	-4.25	.049	1.502	5.590	6.665	.345	14.151	19.54
KERGUELEN PLATEAU	54 S	74 E	.01	3.05	.12	1.50	-4.55	70.	-5.35	.001	4.570	19.797	20.278	.009	44.655	15.63
MADAGASCAR RIDGE	32 S	46 E	.00	1.10	.00	1.47	-5.05	80.	-5.50	.000	1.616	7.158	7.170	.000	15.944	14.48
MAGELLAN RISE	7 N	176 W	.00	.54	.00	.62	-5.95	140.	-6.06	.000	.335	3.514	1.486	.000	5.335	9.87
MANIHIKI PLATEAU	9 S	161 W	.00	1.21	.00	.79	-5.05	100.	-5.75	.000	.956	7.891	4.244	.000	13.092	10.78
MARCUS WAKE SEAMOUNTS	19 N	159 E	.00	1.52	.00	.67	-5.65	160.	-6.15	.000	1.022	9.868	4.537	.000	15.427	10.16
MAUD RISE	66 S	3 E	.00	.19	.00	1.13	-5.05	110.	-5.84	.000	.211	1.207	.935	.000	2.353	12.67
MID PACIFIC MOUNTAINS	18 N	178 E	.00	1.76	.00	1.05	-5.65	140.	-6.06	.000	1.846	11.430	8.193	.000	21.469	12.21
MOZAMBIQUE PLATEAU	32 S	35 E	.00	.66	.00	1.53	-5.05	120.	-5.93	.000	1.013	4.313	4.493	.000	9.819	14.80
NAZCA RIDGE	20 S	82 W	.00	.99	.00	.51	-4.55	30.	-4.42	.000	.507	6.407	2.251	.000	9.165	9.30
NINETYEAST RIDGE	13 S	88 E	.00	2.06	.00	.92	-4.55	60.	-5.17	.000	1.899	13.411	8.427	.000	23.738	11.50
ONTONG JAVA PLATEAU	4 N	165 E	.00	4.14	.00	1.06	-4.65	140.	-6.06	.000	4.369	26.918	19.389	.000	50.677	12.24
SHATSKY RISE	35 N	159 E	.00	1.24	.00	.73	-5.95	135.	-6.03	.000	.907	8.075	4.025	.000	13.007	10.47
WALLABY PLATEAU	20 S	103 E	.00	.41	.00	.66	-5.95	100.	-5.75	.000	.274	2.697	1.214	.000	4.185	10.08
WALVIS RIDGE	27 S	2 E	.00	1.44	.00	.87	-5.05	75.	-5.43	.000	1.259	9.378	5.587	.000	16.224	11.25
TOTALS			.276	29.135						.09	32.99	189.38	146.38	.60	369.42	

the base depths for the remaining 52 oceanic areas. Iceland was the only area for which the histogram method did not yield a reasonable base depth (i.e., only 0.15 km). Moreover, since Iceland straddles the Mid-Atlantic Ridge, the depth versus age method did not yield reasonable results either. For this area we chose the base depth (2.8 km) visually from the bathymetric chart. This rela-

tively low depth may result in an underestimate of the crustal volume of Iceland.

The results of the crustal volume calculations for each of the 54 oceanic areas are shown in Tables 1, 2 and 3, where we have attempted to categorize each feature. Table 1 lists oceanic plateaus that formed by igneous activity in existing seafloor. A fraction of these relatively young

TABLE 2
CONTINENTAL SUBMARINE PLATEAUS

	LAT	LON	a_1 km² ×10⁶	a_2 km² ×10⁶	h_1 km	h_2 km	z_b km	age ma	z_{age} km	v_1 km³ ×10⁶	v_2 km³ ×10⁶	v_3 km³ ×10⁶	v_4 km³ ×10⁶	v_5 km³ ×10⁶	v_t km³ ×10⁶	h_t km
AGULHAS PLATEAU	40 S	26 E	.00	.56	.00	1.03	-5.05	115.	-5.89	.000	.579	3.670	2.571	.000	6.821	12.08
ARCTIC RIDGES	85 N	130 W	.00	1.65	.00	1.26	-3.75	70.	-5.35	.000	2.084	10.726	9.247	.000	22.057	13.37
CAMPBELL PLATEAU	53 S	173 E	.00	1.16	.00	2.76	-5.15	80.	-5.50	.000	3.202	7.541	14.207	.000	24.950	21.50
CHATHAM RISE	42 S	176 W	.00	1.09	.00	1.99	-5.05	80.	-5.50	.000	2.171	7.080	9.634	.000	18.885	17.34
CUVIER PLATEAU	23 S	108 E	.00	.20	.00	.95	-5.05	120.	-5.93	.000	.192	1.308	.851	.000	2.351	11.68
EXMOUTH PLATEAU	19 S	113 E	.00	.59	.00	1.67	-5.55	130.	-6.00	.000	.995	3.863	4.415	.000	9.273	15.60
FAEROE BLOCK	62 N	8 W	.00	.32	.00	2.35	-3.55	55.	-5.07	.000	.762	2.111	3.383	.000	6.257	19.26
FALKLAND PLATEAU	51 S	44 W	.02	2.36	.12	2.53	-6.05	100.	-5.75	.002	5.971	15.329	26.496	.017	47.815	21.19
FLEMISH CAP	47 N	43 W	.00	.27	.00	1.26	-4.45	90.	-5.64	.000	.336	1.741	1.493	.000	3.570	13.33
GALICIA BANK	43 N	13 W	.00	.32	.00	.88	-5.35	90.	-5.64	.000	.282	2.091	1.251	.000	3.624	11.26
LORD HOWE RISE	31 S	163 E	.00	2.83	.00	1.87	-4.75	70.	-5.35	.000	5.295	18.369	23.499	.000	47.163	16.69
MASCARENE PLATEAU	12 S	58 E	0.00	1.52	.75	1.20	-4.05	65.	-5.26	.001	1.832	9.892	8.129	.008	19.861	19.06
NATURALISTE PLATEAU	32 S	110 E	.00	.31	.00	.74	-5.15	120.	-5.93	.000	.227	1.998	1.005	.000	3.230	10.51
PORCUPINE BANK	52 N	16 W	.00	.24	.00	1.65	-4.65	85.	-5.57	.000	.394	1.548	1.747	.000	3.689	15.49
QUEENSLAND PLATEAU	15 S	151 E	.00	.48	.00	1.98	-4.55	130.	-6.00	.000	.955	3.134	4.237	.000	8.325	17.27
ROCKALL PLATEAU	54 N	19 W	.00	.67	.00	1.45	-3.65	75.	-5.03	.000	.973	4.375	4.319	.000	9.668	14.36
SHIRSHOV RIDGE	58 N	173 E	.00	.15	.00	1.04	-3.65	100.	-5.75	.000	.151	.944	.672	.000	1.767	12.17
VORING PLATEAU	68 N	3 E	.00	.21	.00	.97	-3.55	50.	-4.97	.000	.207	1.391	.919	.000	2.518	11.76
TOTALS			.022	14.940						0.00	26.61	97.11	118.08	.02	241.82	

TABLE 3
THERMAL SWELLS

	LAT	LON	a_1 km² x10⁶	a_2 km² x10⁶	h_1 km	h_2 km	z_b km	age ma	z_{age} km	v_1 km³ x10⁶	v_2 km³ x10⁶
AUSTRAL SWELL	28 S	145 W	.00	.68	.00	.43	-4.55	60.	-5.17	.000	.290
BERMUDA RISE	33 N	62 W	.00	.79	.00	.36	-5.15	110.	-5.84	.000	.286
CANARY ISLANDS MADEIRA	32 N	18 W	0.00	.73	.25	.98	-4.45	115.	-5.89	0.000	.719
CAPE VERDE PLATEAU	18 N	25 W	.00	.97	.00	.84	-5.05	110.	-5.84	.000	.818
CONRAD RISE	54 S	43 E	.00	.45	.00	.61	-4.15	100.	-5.75	.000	.276
HAWAIIAN SWELL	23 N	162 W	.01	2.81	.85	.79	-5.35	90.	-5.64	.009	2.220
LINE SWELL	6 N	158 W	.00	2.95	.00	.56	-5.05	100.	-5.75	.000	1.657
MARQUESAS SWELL	6 S	139 W	.00	1.53	.00	.26	-4.55	60.	-5.17	.000	.401
MIDWAY SWELL	28 N	178 E	.00	.63	.00	.43	-5.25	100.	-5.75	.000	.272
RIO GRANDE RISE	32 S	34 W	.00	1.67	.00	.85	-4.95	85.	-5.57	.000	1.427
SIERRA LEONE	6 N	22 W	.00	.86	.00	.58	-4.85	85.	-5.57	.000	.496
S TASMAN RISE	49 S	149 E	.00	.57	.00	.77	-4.55	50.	-4.97	.000	.439
TAHITI SWELL	19 S	152 W	.00	.68	.00	.45	-4.55	85.	-5.57	.000	.303
TUAMOTU SWELL	18 S	142 W	.00	1.21	.00	.81	-4.05	55.	-5.07	.000	.975
TOTALS			.012	16.550						.01	10.58

features could eventually be added to the continents. Table 2 lists fragments of continental crust that for the most part are older than the surrounding seafloor. While they may become reattached to the continents, with a few exceptions they do not represent crustal material newly derived (within the last few hundred million years) from the mantle. From a review of the literature it is evident that not all authors would agree with our classification of these features as either oceanic plateaus or continental submarine plateaus, especially since many of the features are poorly sampled. Thus the reader may reclassify features as new data become available. Finally, Table 3 lists the thermal swells that are sometimes topped by large volcanoes. Since the topography of a thermal swell is not compensated by an increase in crustal thickness, the Airy compensation model does not apply to these features.

The name of each feature and its location are given in the first two columns of each table. The following 4 columns are the area of crust above sea level a_1, the area of crust above the base level a_2, the average height of the feature above sea level h_1, and the average height of the feature above the base level h_2. These quantities were calculated from the gridded topography data. The depth of the base level z_b was also derived from the topography data using the histogram method. For comparison purposes, the average age of the seafloor surrounding each feature [19] and the seafloor depth for that age [17] are given in columns 8 and 9. In some cases, such as the Broken Ridge, the seafloor age was significantly different on different sides of the plateau. In these cases we chose the younger age because it represents the time of the most recent reheating event. In 50 out of the 54 cases the base depth determined from the histogram method is less than the base depth predicted from the depth versus age relation. As noted above, this may indicate the presence of anomalously light mantle below and surrounding the plateaus.

Using the primary measurements of area and average height, we calculated the volumes of the 5 crustal layers for each area. The total crustal volume and the average total crustal thickness are given in the final two columns of the tables. It should be noted that the average crustal thickness h_t is significantly less than the maximum thickness of a feature because all thicknesses greater than 6.5 km are included in the average. Totals of the area and volume measurements are given in the last row of each table.

3.2. Continents

A slightly different technique was used to determine the total crustal volumes of the 10 continental areas. To avoid areas of thick sediment overlying oceanic crust, we defined the base depth of all continents to occur at 2.5 km. (We also tried base depths of 2.0 km and 3.0 km and found that the results were insensitive to the base depth.) With the base depth set to a prescribed constant,

Continents
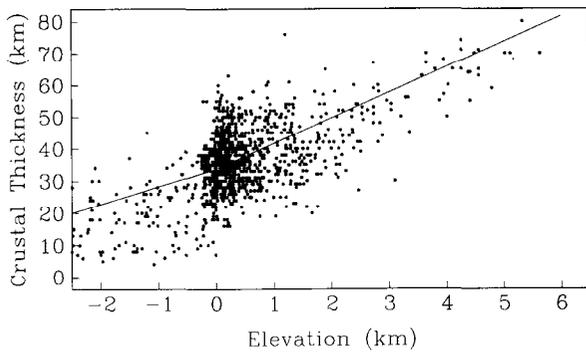
Fig. 6. Seismic refraction measurements (1350) of crustal thickness versus elevation. Measurements were selected from continental areas. Antarctica and Greenland data were not used. Best-fitting Airy compensation model (solid curve) has a base depth crustal thickness of 20 km. The RMS scatter about the model is 9.09 km.

the unknown parameter in equation (5) is the thickness h_3 of the intermediate crustal layer.

To determine this unknown parameter, we plotted crustal thickness determined from seismic refraction studies [4] versus elevation (Fig. 6). Data from all of the continental areas except Antarctica and Greenland were used. This resulted in 1350 crustal thickness measurements mostly from Asia, Europe and North America. As predicted by the Airy compensation model (equation (5)), crustal thickness increases with increasing elevation although there is a lot of scatter in the observed relationship. The unknown parameter h_3 was varied to minimize the RMS difference

between the crustal thickness data and the model. The best fitting model (RMS = 9.09 km) has a h_3 of 20 km. It should be noted that when the depth exceeds the base depth (e.g., on the stretched continental margins), the model predicts that the crustal thickness is less than 20 km. This model is shown as the solid curve in Fig. 6. The fit of the model is controlled mainly by the large number of data with elevations near zero. Since most continental areas have elevations in the range 0–1 km it is important that the model fits these data best. In addition to varying the parameter h_3, we also varied the mantle and crustal densities. The RMS-fit was relatively insensitive to the individual densities, but it did require a crust–mantle density contrast of about 400 kg/m^3. The underlying mantle density is assumed to be laterally homogeneous.

A systematic discrepancy between the crustal thickness predicted by the Airy model and the measured crustal thickness occurs for continental areas lying below sea level (e.g., the stretched continental margins). Many of the seismic refraction measurements show that the crust is less than 10 km thick (i.e., similar to oceanic crust), yet these areas are close to sea level. Since many studies have shown that passive continental margins are nearly in isostatic equilibrium (cf. [27]), we believe that some of the seismic measurements of crustal thickness are systematically low.

Using the base depth of 2.5 km and layer 3 crustal thickness of 20 km we calculated the volumes of the 10 continental areas (Table 4). Columns 2 and 3 are the areas of the continent

TABLE 4
CONTINENTS

	a_1 km^2 $\times 10^6$	a_2 km^2 $\times 10^6$	h_1 km	h_2 km	z_b km	v_1 km^3 $\times 10^6$	v_2 km^3 $\times 10^6$	v_3 km^3 $\times 10^6$	v_4 km^3 $\times 10^6$	v_5 km^3 $\times 10^6$	v_t km^3 $\times 10^6$	h_t km
ANTARCTICA*	12.7	17.9	2.15	2.30	-2.50	.0	41.1	358.0	182.4	68.4	649.9	37.87
AUSTRALIA	8.3	12.9	.30	2.33	-2.50	2.5	30.1	257.9	133.6	17.3	441.4	35.07
NEW ZEALAND	.3	1.1	.33	1.78	-2.50	.1	1.9	21.4	8.5	.6	32.5	32.29
ASIA	36.0	49.0	.95	2.37	-2.50	34.1	116.2	979.2	515.5	238.4	1883.2	40.48
EUROPE	16.3	22.8	.49	2.36	-2.50	7.9	53.8	456.3	238.6	55.3	811.9	36.70
AFRICA	29.2	33.1	.65	2.39	-2.50	19.0	79.1	662.2	350.9	133.0	1244.1	38.18
MADAGASCAR	.6	1.0	.57	1.99	-2.50	.3	2.0	20.3	9.0	2.3	34.0	35.38
GREENLAND*	2.2	3.7	1.72	2.18	-2.50	.0	8.1	74.2	35.9	9.5	127.8	36.16
N AMERICA	21.8	31.5	.63	2.35	-2.50	13.8	73.9	629.7	327.9	96.3	1141.6	37.81
S AMERICA	17.7	21.8	.59	2.39	-2.50	10.5	52.0	435.7	230.8	73.6	802.7	37.73
TOTALS	145.1	194.8				88.1	458.1	3895.0	2033.0	705.9	7180.2	

* – Calculations assume topography above sea level is ice.

above sea level and above the base level, respectively. The average height of each continent above sea level is given in column 4 followed by the average height of the continent above the base level. Since both Antarctica and Greenland are ice covered, they have large average elevations. In the volume calculations of these two areas, we assumed that all topography above sea level is composed of ice with density 980 kg/m^3. (Ice may also contribute to the topography below sea level.) Therefore their layer 1 crustal volumes are zero and their layer 5 volumes are calculated from (4) by replacing the crustal density in the numerator with the ice density and using the ice volume. The five volumes and total volume are given in columns 7–12 of Table 4. The average crustal thickness of the continents is given in the last column. Total areas and volumes are given in the last row of Table 4.

4. Discussion of results

4.1. Continents and continental submarine plateaus

The total volume of the continents 7180×10^6 km^3 (Table 4) is smaller than the value 7600×10^6 km^3 estimated by Reymer and Schubert [2] from the area of the continents (including continental margins) and the average thickness of the continental crust of 38 km reported by Soller et al. [4]. If we add the volume of the crust in continental submarine plateaus 242×10^6 km^3 (Table 2) to the volume of the continents, we obtain a continental crustal volume of 7422×10^6 km^3. By including the volume of continental sediments on the ocean floor 160×10^6 km^3 [2], we arrive at the total continental crustal volume presently at the Earth's surface 7582×10^6 km^3. This is close to the estimate of 7760×10^6 km^3 by Reymer and Schubert [2]. Continental plateaus on the seafloor comprise 3.2% of the total continental crustal volume; continental sediments contribute only 2.1% to the total continental crustal volume.

The continents in decreasing order of volume are Asia, Africa, North America, Europe, South America, Antarctica, Australia, Greenland, Madagascar and New Zealand (Table 4). Europe and South America are nearly equal in volume, as are New Zealand and Madagascar. The Falkland Plateau and the Lord Howe Rise are the two largest continental submarine plateaus with volumes of 48×10^6 km^3 and 47×10^6 km^3, respectively (Table 2). The next largest continental plateaus, in decreasing order of volume, are the Campbell Plateau, the Arctic Ridges, the Mascarene Plateau, and the Chatham Rise. These six plateaus constitute 75% of the continental crustal volume on the seafloor.

Subduction of all the continental submarine plateaus with the oceanic lithosphere on a 100 Myr time scale gives an upper bound to the continental crustal subtraction rate of 2.4 km^3/yr. Undoubtedly, a number of the continental submarine plateaus may be too large to be subducted, particularly the six plateaus mentioned above [28]. Even if only 25% of the continental crust in the seafloor could be subducted, the resulting subtraction rate of 0.6 km^3/yr is equivalent to the total yearly subtraction attributed to subducted sediments [1,2]. A potentially important route for returning continental crust to the mantle may be the break off of small fragments from the continents, entrapment of the continental fragments in the seafloor, and subduction of the fragments with the oceanic lithosphere. This process may be occurring now in the Mediterranean for Corsica and Sardinia.

4.2. Oceanic plateaus

The total crustal volume of the 22 oceanic plateaus investigated here is 369×10^6 km^3 (Table 1). Oceanic plateaus contain about 50% more crustal volume than do the continental plateaus trapped in the seafloor. The largest oceanic plateaus in order of decreasing volume are the Ontong-Java Plateau, the Kerguelen Plateau, the Caribbean, the Chagos Laccadive Ridge, the Ninetyeast Ridge, and the Mid-Pacific Mountains. These five plateaus constitute 54% of the total crustal volume in all oceanic plateaus.

The anomalous crustal volume in all oceanic plateaus equals 4.9% of the total continental crustal volume. Accretion of all oceanic plateaus to the continents on a time scale of 100 Myr gives an upper bound to the continental addition rate of 3.7 km^3/yr. This can be compared to the average continental crustal addition rate due to the accretion of island arcs which has been estimated by Reymer and Schubert [2] to be 1.1 km^3/yr. Accretion of island arcs is generally accepted as the

main mechanism responsible for the growth of continents. However if only the upper part of island arcs are added to the continents then the island arc addition rate will be less than 1 km^3/yr, which is the minimum rate required to account for constancy of freeboard [29]. This low addition rate severely exacerbates the problem of rapid growth of certain Precambrian terranes by island arc addition [30,31]. Even if a substantial fraction of the crustal volume in oceanic plateaus is subducted, accretion of oceanic plateaus can make a nontrivial contribution to continental growth.

Reymer and Schubert [2] considered oceanic intraplate volcanism as a source of addition to the continental crust, but they estimated this addition rate as only 0.2 km^3/yr. We believe this to be an underestimate since they considered only Kerguelen, Hawaii and Iceland and they did not include the anomalous crustal volume in the compensating roots of the islands. Burke and Sengor [32] concluded that while "slivers" of oceanic plateaus are contained in the world's mountain belts, oceanic plateaus do not contribute significant volumes of material to the continents. However, nearly 10^5 km^3 of the Angayuchan terrane in Central Alaska has been recently recognized as the upper skin (3–4 km thick) of a long-lived (200 Myr) oceanic plateau [33]. Moreover, large seamounts having tholeiitic pillow basalts (0.25 × 10^6 km^3) have been found embedded in the continental crust along the west coast of North America [34,35]. Perhaps other terranes in the continents will be recognized as having oceanic plateau (or seamount) origin. For example, Hoffman and Ranalli [36] have suggested that greenstone belts in Archean terranes may contain the upper part of thickened Archean oceanic crust. Though this thickened crust may have been global and not concentrated in plateaus, the processes involved in addition of anomalously thick oceanic crust to the continents may be similar. When crustal thickness exceeds about 15 km, a low viscosity, ductile layer develops just above the crust/mantle boundary that could act as a weakness for detaching the crust from the mantle.

It is difficult to contemplate the ultimate subduction of the Ontong-Java Plateau and the Caribbean since these features have already resisted subduction (see below). If large oceanic plateaus are indeed subducted, then so should continental submarine plateaus, making the sub-

duction of these fragments the major mechanism of continental subtraction. It is possible that only the upper parts of the large oceanic plateaus could be tectonically emplaced in the continents [33,36–38]. Even in this case, the amount of added crust would be substantial since the crust should be sheared off at the weak lower ductile layer which occurs at depths greater than 15 km. In any event, the measurement of oceanic plateau volumes sets an upper limit to the continental crustal addition rate by these features.

While small oceanic islands can be subducted [28], the larger oceanic plateaus might be sufficiently buoyant to resist subduction. Indeed, the Ontong-Java Plateau is known to have interfered with the subduction of the Pacific plate beneath the Indian plate [8] and the Caribbean plateau has resisted subduction with the Farallon plate [10]. The volumes of the Ontong-Java Plateau and Caribbean Plateau (50.7 × 10^6 km^3 and 35.2 × 10^6 km^3 respectively) thus provide an estimate of the minimum anomalous crustal volume required to make the oceanic lithosphere too buoyant to subduct. Only the Kerguelen Plateau among the oceanic plateaus and the Falkland Plateau and the Lord Howe Rise among the continental submarine plateaus have comparable crustal volumes, though several other plateaus with volumes in excess of about 20 × 10^6 km^3 may be buoyant enough to inhibit subduction. While an anomalous crustal volume smaller than about 35 × 10^6 km^3 could inhibit subduction, especially if the plateau were on very young seafloor (young, hot lithosphere is more buoyant than old lithosphere), it is unlikely that a volume more than about a factor of two smaller would be effective in slowing or halting subduction. Indeed, the subduction of the Emperor Seamounts (volume 13.4 × 10^6 km^3, Table 1) [11] and the Nazca Ridge (volume 9.2 × 10^6 km^3, Table 1) [7] supports this speculation. Even though these features were not buoyant enough to prevent subduction, they may have locally modified the geometry of the subducted slab. For example, the Nazca Ridge is the southern boundary of the flat slab region beneath South America [7] and the Emperor Seamounts meet the Aleutians at a cusp in that arc [11]. Probably, it is not simply the total anomalous crustal volume that determines the consequences for subduction, but the distribution of that volume as well; the
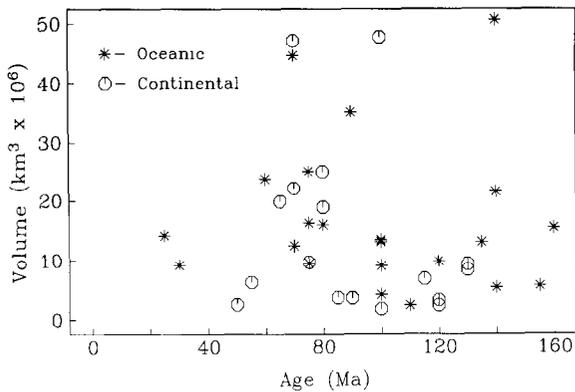
Fig. 7. Volumes of oceanic plateaus (asterisks) and continental submarine plateaus (octagons) versus the average age of the seafloor surrounding each feature.

cross-section of the crustal volume in a plane parallel to the strike of the trench should be an important parameter [28].

As a final point of interest we examined how the volumes of oceanic plateaus and continental submarine plateaus are distributed with respect to the age of the seafloor surrounding each feature (Fig. 7). For oceanic plateaus, the age of the surrounding seafloor is greater than or equal to the age of the plateau. The age of continental submarine plateaus, however, is generally much greater than the surrounding seafloor age which marks the time when the fragment rifted from the parent continent. The results show that most of the large oceanic and continental submarine plateaus (volume $> 20 \times 10^6$ km^3) have surrounding seafloor ages greater than about 60 Myr. The smaller features are more randomly distributed with age. The most notable, present-day examples of oceanic and continental submarine plateau formation are Iceland and Baja California (the rifting of Baja is not yet complete), respectively. Because most of the large features are on old seafloor, they will either be subducted in the next 100 Myr or they will partially resist subduction and eventually become accreted to a continent. While oceanic plateaus and continental submarine plateaus are geologically distinct, they have equal buoyancy per volume of crust. Thus, effective subduction of all oceanic plateaus implies equally effective subduction of continental submarine plateaus.

4.3. Thermal swells

The oceanic swells listed in Table 3 are thermally compensated by anomalously hot mantle within and beneath the oceanic lithosphere [13]. The volumes of these features above the depth of normal seafloor are of interest because they are related to the volumes of anomalously hot mantle at depth. The anomalous swell volume is listed as V_2 in Table 3. The total volume of thermal swells above the depth of normal seafloor is 10.6×10^6 km^3. The largest swells, in decreasing order of volume, are the Hawaiian Swell, the Line Swell, and the Rio Grande Rise which together comprise 50% of the total anomalous swell volume. The Airy compensation model applied to the plateaus is not relevant to the thermal swells, and it is beyond the scope of this paper to explore the consequences of our measurements for thermal compensation models of the swells.

The distinction between thermal swell and oceanic plateau is made on the basis of the characteristic geoid/topography ratios [13] and is independent of the occurrence of active hotspot volcanism; thermal compensation of anomalous seafloor topography does not require active volcanism. Some thermal swells have anomalous crustal volumes associated with volcanic and magmatic activity. We have not attempted to separate the anomalous topography due to volcanism from the thermal swell topography because it is beyond the scope of this investigation. In any case, the anomalous crustal volumes of the volcanoes above thermal swells are relatively small.

Acknowledgements

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