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PHANEROZOIC TRANSGRESSIONS AND REGRESSIONS ON THE CONTINENTS: A QUANTITATIVE APPROACH BASED ON AREAS FLOODED BY THE SEA AND AREAS OF MARINE AND CONTINENTAL DEPOSITION

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ABSTRACT. Analysis of the areas of major tectonic units of the continents flooded by the sea during the Phanerozoic shows that there have been three major cycles of transgression and regression corresponding to the Caledonian, Hercynian, and Alpine orogenic cycles. Approximately equal areas of the platforms and geosynclinal regions have been flooded synchronously, but seas occupied only small areas of the orogenic belts. The areas of the Laurasian continental blocks flooded were more extensive than those of the Gondwanan blocks, even though the latter have an overall greater area. The flooding histories of individual cratons show notable exceptions to the global history of transgressions and regressions.

In terms of proportions of the area flooded, the platform regions average about 20 percent, the geosynclinal regions about 80 percent, and the orogenic belts about 20 percent in the Paleozoic, and 10 percent in the Mesozoic and Cenozoic. There has been a decline in the proportion of the area of marine versus continental sedimentation throughout the Phanerozoic on the continental platforms and in orogenic belts. A similar decline has occurred in the geosynclinal regions but only during the later Mesozoic and Cenozoic.

The overall pattern of flooding of the continents during the Cenozoic corresponds well with the general trend of the eustatic curve of Vail, Mitchum, and Thompson (1977). Continental uplift and subsidence calculated from the volumes of sediments eroded and deposited also correlate with the changing areas of the continents flooded by transgressing and regressing seas.

INTRODUCTION

This paper presents estimates of the areas of the platforms, geosynclines, and orogenic zones as well as the total areas of the continental blocks covered by the sea during transgressions and regressions. The estimates cover all the continents except Antarctica and all the geological record from Early Cambrian through Pliocene. Also included are estimates of the areas of marine and continental sedimentation at each of the major stages of geological evolution. Finally, the chronology of marine transgressions and regressions is compared to vertical motions of the continental crust and changes in eustatic sealevel.

The estimates have been made by measuring the marine and land areas on the continents and volumetric calculations of the major types of sedimentary rocks shown on the series of global lithological-paleogeographical maps compiled by Ronov, Khain, and Seslavinsky (1984) for the Paleozoic and by Ronov, Khain, and Balukhovsky (1989) for the Mesozoic and Cenozoic. The maps were compiled from literature and other data sources for regional geological studies of structure, stratigraphy, lithology, paleogeography, and paleoenvironments cited by Ronov, Khain, and Seslavinsky (1984) and by Ronov, Khain, and Balukhovsky (1989). The paleogeography, shorelines, elevation of the land areas, and depths of water are based on interpretation of the surviving geologic record exposed in outcrop and preserved in the subsurface. Ronov, Khain, and Seslavinsky (1984) and Ronov, Khain, and Balukhovsky (1989) took into account whether the strata were deposited under marine or continental conditions and estimated the relative elevation of the areas of erosion from the grain-size of the sediments derived from them. The original data are based on descriptions of many thousands of outcrop and borehole sections. The maps cover 28 stratigraphic intervals covering each of the epochs of the Phanerozoic. The reliability of the maps is not the same in all regions. It decreases with geologic age. The reliability also decreases from platforms to geosynclines and from the northern to the southern hemisphere within each map.

The continents are divided into three major categories of tectonic unit: platforms, geosynclines, and orogenic zones. Table 1[2] shows the areas of regions of erosion, regions of sedimentation, areas covered by seas, and areas covered by seas as a percentage of the total area for each category of tectonic unit. The analysis excludes the Antarctic and a few other areas that are poorly known. It should be noted that the Quaternary is not included in table 1, and that the area of continents shown as flooded on the Pliocene map of Ronov, Khain, and Balukhovsky (1989) is much less than the area flooded at present because of the lower sealevel at the time chosen for the paleogeographic reconstruction.

FLOODING OF THE CONTINENTS

As shown in figure 1, the data demonstrate regular changes of area covered by the sea (from expansion to abrupt reduction) in the course of major tectonic cycles. The major geocratic and thalassocratic episodes in the geological history of the Earth recognized by Ronov (1968) are evident.

At present, as during the times of sealevel high stand of the Quaternary, the world ocean, including epicontinental and marginal seas, covers 361 × 10^6 km^2, corresponding to 71 percent of the Earth's surface. Seen from the perspective of geological history, this area is minimal. The contemporary epoch should be identified as geocratic, characterized by regression from elevated continents. Ancient geocratic epochs correspond to the final stages of tectonic cycles: Early Cambrian, which corresponds to the boundary between the Baikalian and Caledonian Cycles; Late Silurian-Early Devonian, which corresponds to the boundary between the Caledonian and Hercynian Cycles; the Late Permian-Middle Triassic, which corresponds to the boundary between the Hercynian and Alpine Cycles. The Pliocene-Quaternary falls at the boundary between the Alpine and a future cycle. Figure 1 shows the successive increase in amplitude of regressions during the Phanerozoic to the extreme geocratic condition represented by the present. The middle stages of the tectonic cycles correspond to thalassocratic episodes of earth history. The areas of the continents flooded by marine transgressions were increased as a result of subsidence of the continents or shallowing of the ocean floor. The thalassocratic epochs of the Phanerozoic are the Middle Ordovician, the Middle Devonian, and the Late Cretaceous. The areas flooded decrease from the Caledonian to the Alpine cycle. Thus one common trend in the areal measurements is that the areas of the continents covered by the sea has successively decreased from the Early Paleozoic to Present. The reduction of marine area has been about 40×10^6 km^2.

Figure 2 shows the areas of the major categories of tectonic units of the continents flooded by the sea at different times. The largest areas flooded are on the platforms, and the next largest are the geosynclinal regions. The transgressions and regressions affecting these areas correspond to the overall continental flooding episodes shown in figure 1. A second common trend of the areal measurements is that the transgressions and regressions on platforms and in geosynclinal regions are synchronous. Figure 2 also shows that the smallest areas flooded are in the orogenic regions, and here transgressions and regressions do not repeat the pattern of figure 1.

Table 2 and figure 3 summarize the data in terms of the Laurasian (Russian, Siberian, Chinese, and North American) and Gondwanan (African, Arabian, South American, Australian, Indian) platforms. Transgressions and regressions on both groups of platforms are synchronous. The synchronism is very close for the Hercynian and Alpine Cycles and differs only slightly in the Caledonian cycle, when a regression on the Gondwanan platforms corresponds to the time of maximum trangression on the Laurasian platforms. There is, however, the marked difference that the areas covered by the seas on the Laurasian platforms are much more extensive than those on the Gondwanan platforms. This relation is consistent even though the total area of Gondwanan platforms is larger than that of the Laurasian platforms.

Figure 4 compares the areas of flooding on individual platforms. As has been noted by Yanshin (1973) there is considerable asynchroniety in the development of transgressions and regressions on the different

TABLE 1

Transgressions and regressions of seas on continents and their main tectonic units during the Phanerozoic

STRATIGRAPHIC INTERVAL	DURATION OF INTERVAL (MY)	MAIN TECTONIC UNITS OF CONTINENTS	REGIONS OF EROSION (10^6 km^2)	REGIONS OF SEDIMENTATION (10^6 km^2)	AREAS COVERED BY SEAS (10^6 km^2)	AREAS COVERED BY SEAS AS % OF THE TOTAL AREA OF TECTONIC UNIT
PLIOCENE (N_2)	5.3 - 1.6 = 3.7	PLATFORMS	73.40	21.44	4.45	5
		GEOSYNCLINES	1.32	1.58	0.99	34
		OROGENIC BELTS	21.23	14.23	1.91	5
		WHOLE CONTINENT	95.95	37.25	7.35	5
MIOCENE (N_1)	23.7 - 5.3 = 18.4	PLATFORMS	74.55	20.14	6.53	7
		GEOSYNCLINES	0.74	2.13	2.10	73
		OROGENIC BELTS	20.47	14.64	4.30	12
		WHOLE CONTINENT	95.76	36.91	12.93	10
OLIGOCENE (₽$_3$)	36.6 - 23.7 = 12.9	PLATFORMS	77.80	17.71	5.85	6
		GEOSYNCLINES	1.76	3.91	3.58	63
		OROGENIC BELTS	21.26	9.23	2.76	9
		WHOLE CONTINENT	100.82	30.85	12.19	9
EOCENE (₽$_2$)	57.8 - 36.6 = 21.2	PLATFORMS	75.35	24.31	14.67	15
		GEOSYNCLINES	2.27	7.95	7.18	70
		OROGENIC BELTS	14.73	8.00	2.19	10
		WHOLE CONTINENT	92.35	40.26	24.04	18
PALEOCENE (₽$_1$)	66.4 - 57.8 = 8.8	PLATFORMS	77.37	20.32	12.35	13
		GEOSYNCLINES	3.82	6.13	6.03	61
		OROGENIC BELTS	19.06	5.86	1.87	7
		WHOLE CONTINENT	100.20	32.31	20.25	15
LATE CRETACEOUS (K_2)	97.5 - 66.4 = 31.1	PLATFORMS	56.90	41.76	22.41	23
		GEOSYNCLINES	1.37	16.82	14.53	80
		OROGENIC BELTS	9.28	7.45	1.81	11
		WHOLE CONTINENT	67.55	66.03	38.72	29
EARLY CRETACEOUS (K_1)	144 - 97.5 = 46.3	PLATFORMS	59.77	40.06	17.04	17
		GEOSYNCLINES	3.55	18.76	15.12	70
		OROGENIC BELTS	9.59	7.06	0.78	5
		WHOLE CONTINENT	72.91	65.88	33.54	24

LATE JURASSIC (J_3)	163 - 144 = 19	PLATFORMS	74.30	25.15	16.82	17
		GEOSYNCLINES	4.91	16.05	14.10	67
		OROGENIC BELTS	8.13	4.12	1.44	12
		WHOLE CONTINENT	87.34	45.32	32.36	24
MIDDLE JURASSIC (J_2)	187 - 163 = 24	PLATFORMS	75.08	25.47	14.83	15
		GEOSYNCLINES	2.29	12.76	12.49	83
		OROGENIC BELTS	11.54	6.04	1.40	8
		WHOLE CONTINENT	88.91	44.27	28.79	22
EARLY JURASSIC (J_1)	208 - 187 = 21	PLATFORMS	79.85	22.97	11.40	11
		GEOSYNCLINES	1.54	10.93	10.86	87
		OROGENIC BELTS	10.85	5.73	1.35	8
		WHOLE CONTINENT	92.24	39.63	23.61	18
LATE TRIASSIC (T_3)	230 - 208 = 22	PLATFORMS	78.75	23.53	10.44	9
		GEOSYNCLINES	1.56	13.63	13.27	87
		OROGENIC BELTS	9.81	3.63	0.50	4
		WHOLE CONTINENT	90.12	40.79	24.21	18
MIDDLE TRIASSIC (T_2)	240 - 230 = 10	PLATFORMS	82.01	17.95	10.65	11
		GEOSYNCLINES	1.69	11.57	11.36	86
		OROGENIC BELTS	23.19	1.77	0.69	5
		WHOLE CONTINENT	96.89	31.29	22.70	18
EARLY TRIASSIC (T_1)	245 - 240 = 5	PLATFORMS	79.57	24.73	11.49	11
		GEOSYNCLINES	1.94	10.22	9.96	82
		OROGENIC BELTS	10.52	1.65	0.07	1
		WHOLE CONTINENT	92.03	36.60	21.52	17
LATE PERMIAN (P_2)	258 - 245 = 13	PLATFORMS	75.61	19.34	11.55	12
		GEOSYNCLINES	1.07	9.23	8.94	86
		OROGENIC BELTS	14.58	4.88	1.81	9
		WHOLE CONTINENT	91.26	33.45	22.30	18
EARLY PERMIAN (P_1)	286 -258 = 28	PLATFORMS	68.88	24.70	13.96	15
		GEOSYNCLINES	0.98	9.36	9.18	89
		OROGENIC BELTS	13.07	7.73	4.02	19
		WHOLE CONTINENT	82.93	41.79	27.16	22

TABLE 1

(continued)

STRATIGRAPHIC INTERVAL	DURATION OF INTERVAL (MY)	MAIN TECTONIC UNITS OF CONTINENTS	REGIONS OF EROSION (10^6 km^2)	REGIONS OF SEDIMENTATION (10^6 km^2)	AREAS COVERED BY SEAS (10^6 km^2)	AREAS COVERED BY SEAS AS % OF THE TOTAL AREA OF TECTONIC UNIT
LATE & MIDDLE CARBONIFEROUS (C_{3+2})	320 -286 = 34	PLATFORMS	68.26	28.04	16.69	17
		GEOSYNCLINES	1.02	9.66	9.46	89
		OROGENIC BELTS	11.53	8.81	5.36	26
		WHOLE CONTINENT	80.81	46.51	31.51	25
EARLY CARBONIFEROUS (MISSISSIPPIAN) (C_1)	360 - 320 = 40	PLATFORMS	71.91	20.99	15.92	17
		GEOSYNCLINES	2.38	17.63	17.28	86
		OROGENIC BELTS	8.67	4.03	2.36	19
		WHOLE CONTINENT	82.96	42.65	35.46	28
LATE DEVONIAN (D_3)	374 - 360 = 14	PLATFORMS	67.65	25.39	21.80	23
		GEOSYNCLINES	2.50	18.55	17.99	85
		OROGENIC BELTS	7.32	4.10	2.23	19
		WHOLE CONTINENT	77.47	48.04	42.02	33
MIDDLE DEVONIAN (D_2)	387 - 374 = 13	PLATFORMS	68.75	26.17	24.23	25
		GEOSYNCLINES	1.83	18.82	18.43	89
		OROGENIC BELTS	7.49	3.57	2.04	18
		WHOLE CONTINENT	78.17	48.56	44.70	35
EARLY DEVONIAN (D_1)	408 - 387 = 21	PLATFORMS	74.53	16.90	14.51	16
		GEOSYNCLINES	2.39	17.48	17.29	87
		OROGENIC BELTS	6.94	4.18	2.45	22
		WHOLE CONTINENT	83.86	38.56	34.25	28
LATE SILURIAN (S_2)	421 - 408 = 13	PLATFORMS	72.74	22.29	17.65	19
		GEOSYNCLINES	2.89	15.24	14.93	82
		OROGENIC BELTS	8.16	2.12	1.65	16
		WHOLE CONTINENT	83.79	39.65	34.23	28
EARLY SILURIAN (S_1)	438 - 421 = 17	PLATFORMS	66.75	28.38	27.56	29
		GEOSYNCLINES	2.92	17.08	16.82	84
		OROGENIC BELTS	4.70	2.13	1.71	25
		WHOLE CONTINENT	74.37	47.59	46.09	38

LATE ORDOVICIAN (O_3)	458 -438 = 20	PLATFORMS	69.49	26.85	22.50	23
		GEOSYNCLINES	3.84	18.52	18.24	82
		OROGENIC BELTS	2.14	0.33	0.27	11
		WHOLE CONTINENT	75.47	45.70	41.01	34
MIDDLE ORDOVICIAN (O_2)	478 - 458 = 20	PLATFORMS	69.28	27.90	27.44	26
		GEOSYNCLINES	2.46	19.78	19.51	88
		OROGENIC BELTS	1.40	0.41	0.26	14
		WHOLE CONTINENT	73.14	48.09	47.21	39
EARLY ORDOVICIAN (O_1)	505 - 478 = 27	PLATFORMS	70.26	25.40	24.65	26
		GEOSYNCLINES	2.38	18.32	18.32	88
		OROGENIC BELTS	1.21	0.46	0.38	23
		WHOLE CONTINENT	73.85	44.18	43.35	37
LATE CAMBRIAN ($€_3$)	520 - 505 = 15	PLATFORMS	66.54	24.43	22.93	25
		GEOSYNCLINES	2.67	15.61	15.46	84
		OROGENIC BELTS	6.02	0.92	0.46	7
		WHOLE CONTINENT	75.23	40.96	38.85	33
MIDDLE CAMBRIAN ($€_2$)	540 - 520 = 20	PLATFORMS	66.77	25.65	22.17	24
		GEOSYNCLINES	2.01	14.47	14.41	87
		OROGENIC BELTS	6.76	1.03	0.45	6
		WHOLE CONTINENT	75.54	41.15	37.03	32
EARLY CAMBRIAN ($€_1$)	570 - 540 = 530	PLATFORMS	55.78	22.94	18.23	23
		GEOSYNCLINES	1.78	13.96	13.86	88
		OROGENIC BELTS	15.87	1.76	1.28	7
		WHOLE CONTINENT	73.43	38.66	33.37	30

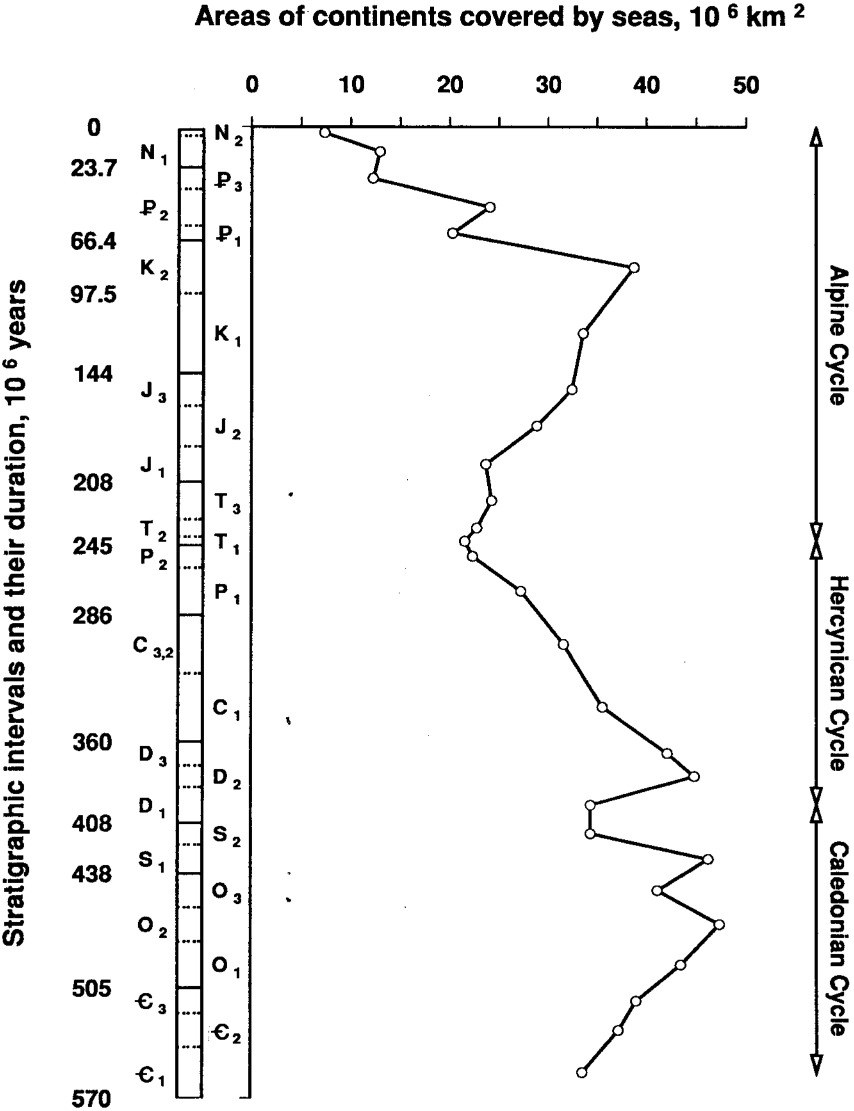

Fig. 1. Transgressions and regressions of the seas on the continents during the Phanerozoic.

platforms. The synchroniety of transgressions and regressions on platforms and in geosynclinal regions apparent in the global data suggests that there are global rhythms that result from periodic increase and decline of tectonic activity. The global rhythms dominate the evolution of

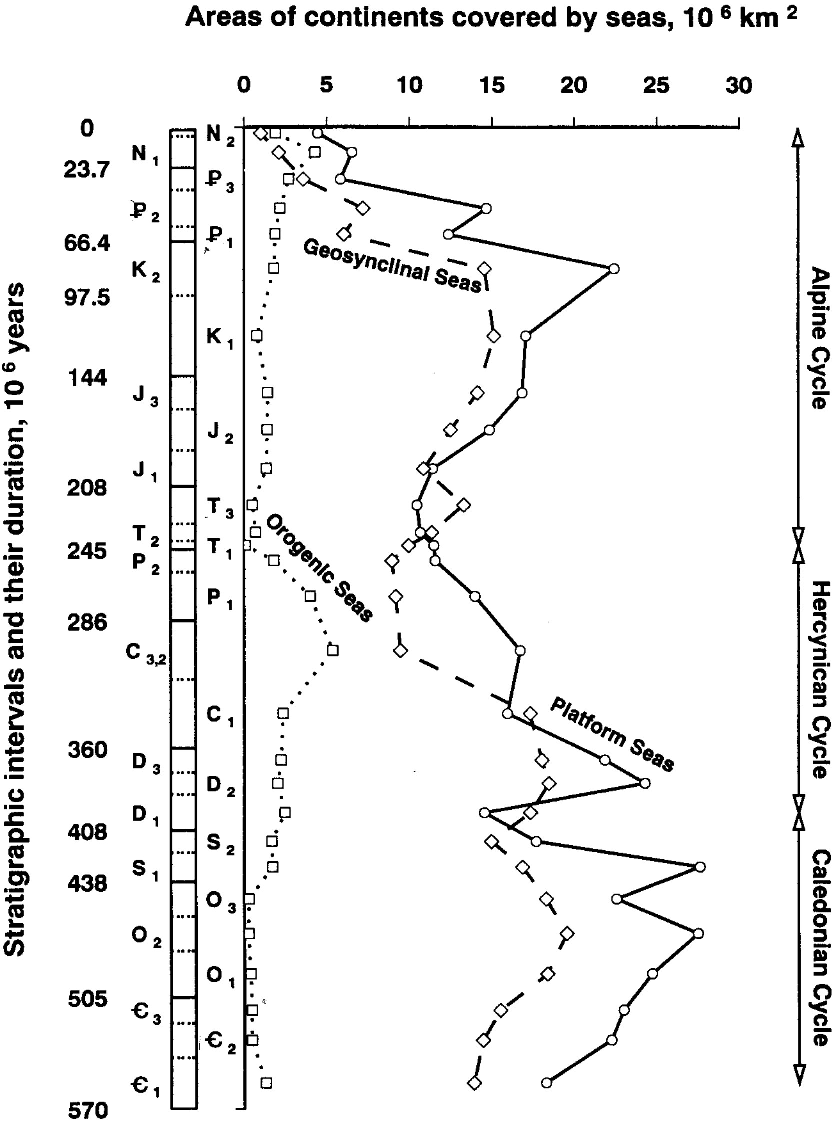

Fig. 2. Transgressions and regressions of the seas over platforms, geosynclines, and orogenic belts during the Phanerozoic.

vast lithospheric regions (Ronov, Khain, and Balukhovsky, 1976), such as Laurasia and Gondwana, as shown in figure 3. The global rhythms are apparent in the supercontinental aggregations, although there is a much more noisy signal in the data from individual platforms.

TABLE 2

Transgressions and regressions of the seas on Laurasian and Gondwanan platforms during the Phanerozoic

STRATIGRAPHIC INTERVAL	DURATION OF INTERVAL (MY)	GROUPS OF PLATFORMS	REGIONS OF EROSION (10^6 km^2)	REGIONS OF SEDIMENTATION (10^6 km^2)	AREAS COVERED BY SEAS (10^6 km^2)	AREAS COVERED BY SEAS AS % OF THE TOTAL AREA OF TECTONIC UNIT
PLIOCENE (N_2)	5.3 - 1.6 = 3.7	LAURASIAN	31.80	8.63	2.69	7
		GONDWANAN	41.60	12.81	1.76	3
MIOCENE (N_1)	23.7 - 5.3 = 18.4	LAURASIAN	32.14	7.93	3.79	9
		GONDWANAN	42.41	12.21	2.74	5
OLIGOCENE ($₽_3$)	36.6 - 23.7 = 12.9	LAURASIAN	30.92	9.20	4.42	11
		GONDWANAN	46.88	8.51	1.43	3
EOCENE ($₽_2$)	57.8 - 36.6 = 21.2	LAURASIAN	32.51	11.93	9.42	21
		GONDWANAN	42.84	12.38	5.25	9
PALEOCENE ($₽_1$)	66.4 - 57.8 = 8.8	LAURASIAN	32.22	9.89	7.81	18
		GONDWANAN	45.10	10.43	4.54	8
LATE CRETACEOUS (K_2)	97.5 - 66.4 = 31.1	LAURASIAN	23.16	31.64	14.04	26
		GONDWANAN	33.74	10.12	8.37	19
EARLY CRETACEOUS (K_1)	144 - 97.5 = 46.3	LAURASIAN	28.65	19.52	10.91	23
		GONDWANAN	31.13	20.54	6.13	12
LATE JURASSIC (J_3)	163 - 144 = 19	LAURASIAN	27.35	16.25	13.17	30
		GONDWANAN	46.95	8.90	3.65	6
MIDDLE JURASSIC (J_2)	187 - 163 = 24	LAURASIAN	27.17	17.48	11.11	25
		GONDWANAN	47.91	7.99	3.72	7
EARLY JURASSIC (J_1)	208 - 187 = 21	LAURASIAN	31.48	15.58	8.29	18
		GONDWANAN	48.37	7.39	3.11	6
LATE TRIASSIC (T_3)	230 - 208 = 22	LAURASIAN	30.71	16.06	8.24	18
		GONDWANAN	48.04	7.47	2.20	4
MIDDLE TRIASSIC (T_2)	240 - 230 = 10	LAURASIAN	33.87	12.50	9.17	20
		GONDWANAN	48.14	5.45	1.48	3
EARLY TRIASSIC (T_1)	245 - 240 = 5	LAURASIAN	31.43	18.30	10.60	21
		GONDWANAN	48.14	6.43	0.89	2

LATE PERMIAN (P_2)	258 - 245 = 13	LAURASIAN	30.21	13.12	9.03	21
		GONDWANAN	45.40	6.22	2.52	5
EARLY PERMIAN (P_1)	286 -258 = 28	LAURASIAN	18.37	13.73	10.47	33
		GONDWANAN	40.51	10.97	3.49	7
LATE & MIDDLE CARBONIFEROUS (C_{3+2})	320 -286 = 34	LAURASIAN	27.03	14.42	10.86	26
		GONDWANAN	41.23	13.58	5.83	11
EARLY CARBONIFEROUS (C_1)	360 - 320 = 40	LAURASIAN	26.05	13.56	11.53	29
		GONDWANAN	45.86	7.43	4.39	8
LATE DEVONIAN (D_3)	374 - 360 = 14	LAURASIAN	24.96	15.85	14.76	36
		GONDWANAN	42.69	9.54	7.04	13
MIDDLE DEVONIAN (D_2)	387 - 374 = 13	LAURASIAN	26.96	14.66	13.48	32
		GONDWANAN	41.79	11.51	10.75	20
EARLY DEVONIAN (D_1)	408 - 387 = 21	LAURASIAN	31.99	7.73	6.65	17
		GONDWANAN	42.54	9.17	7.86	15
LATE SILURIAN (S_2)	421 - 408 = 13	LAURASIAN	30.85	10.71	9.35	22
		GONDWANAN	41.89	11.58	8.30	15
EARLY SILURIAN (S_1)	438 - 421 = 17	LAURASIAN	26.04	16.26	15.81	37
		GONDWANAN	40.71	12.12	11.75	22
LATE ORDOVICIAN (O_3)	458 -438 = 20	LAURASIAN	25.09	18.35	17.9	41
		GONDWANAN	44.40	8.50	4.60	9
MIDDLE ORDOVICIAN (O_2)	478 - 458 = 20	LAURASIAN	24.89	20.06	19.90	44
		GONDWANAN	44.39	7.84	7.54	14
EARLY ORDOVICIAN (O_1)	505 - 478 = 27	LAURASIAN	24.74	18.41	18.41	43
		GONDWANAN	45.52	6.99	6.24	12
LATE CAMBRIAN (€$_3$)	520 - 505 = 15	LAURASIAN	24.53	18.27	17.36	41
		GONDWANAN	42.01	6.16	5.57	12
MIDDLE CAMBRIAN (€$_2$)	540 - 520 = 20	LAURASIAN	22.73	19.90	17.54	41
		GONDWANAN	44.04	5.75	4.63	6
EARLY CAMBRIAN (€$_1$)	570 - 540 = 530	LAURASIAN	22.00	17.37	14.56	37
		GONDWANAN	33.29	5.57	3.67	9

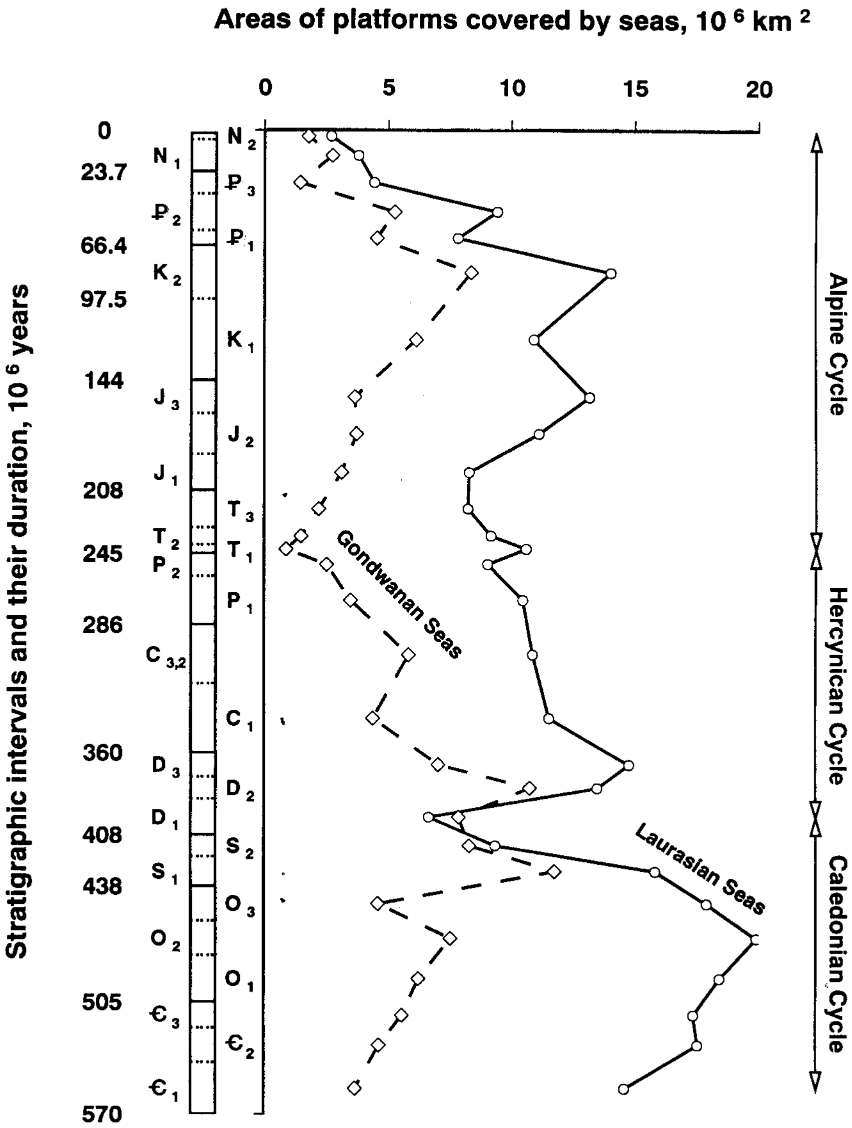

Fig. 3. Transgressions and regressions of the seas on Laurasian and Gondwanan platforms during the Phanerozoic.

PROPORTIONS OF THE CONTINENTS FLOODED

Figure 5 shows the proportion of the total area of the continents covered by the sea. The flooded areas of the continents range between 5 and 40 percent of the total continental area. Most of the continental blocks have been land throughout the entire Phanerozoic. The general

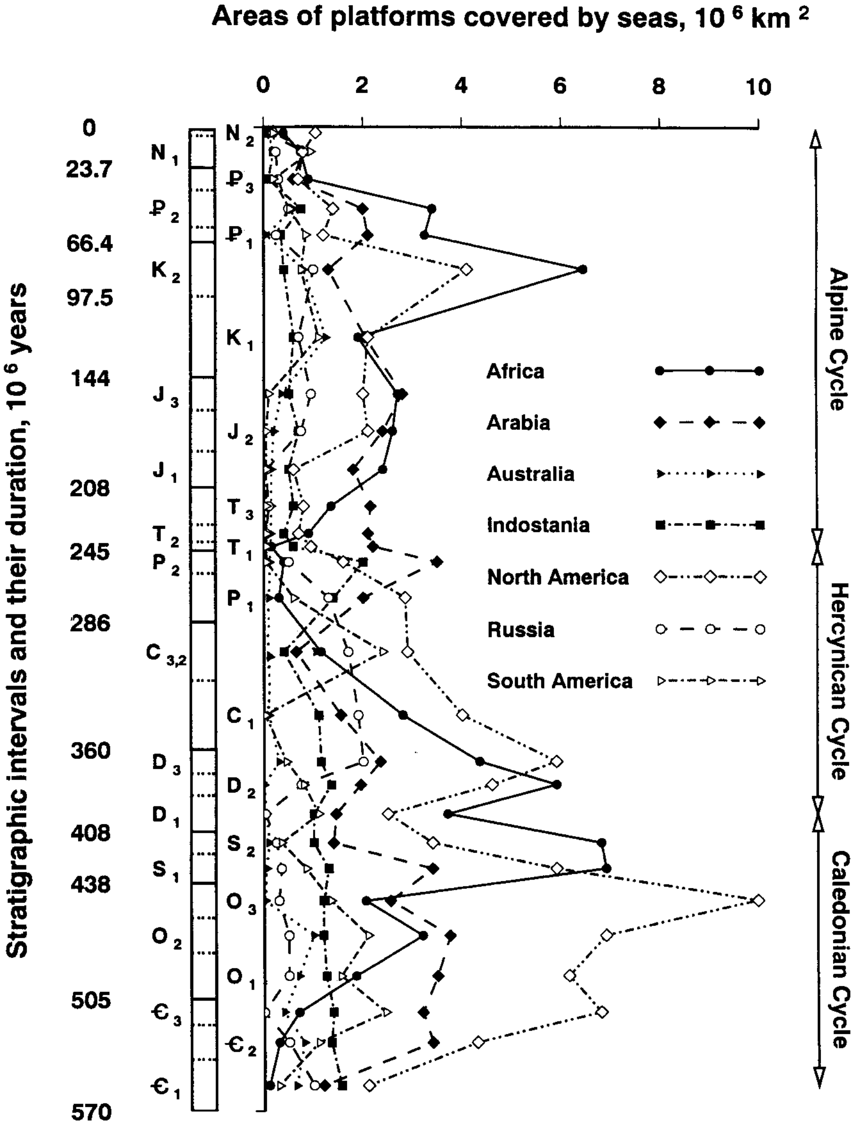

Fig. 4. Transgressions and regressions of the seas on the major cratonic platforms during the Phanerozoic.

trend toward increase of land area on the continental blocks through the Phanerozoic is again apparent.

The stable (platform) and mobile (geosynclines and orogenic belts) regions of the continents have had very different land/sea distributions. The land area greatly predominates on the platforms, as shown in figure

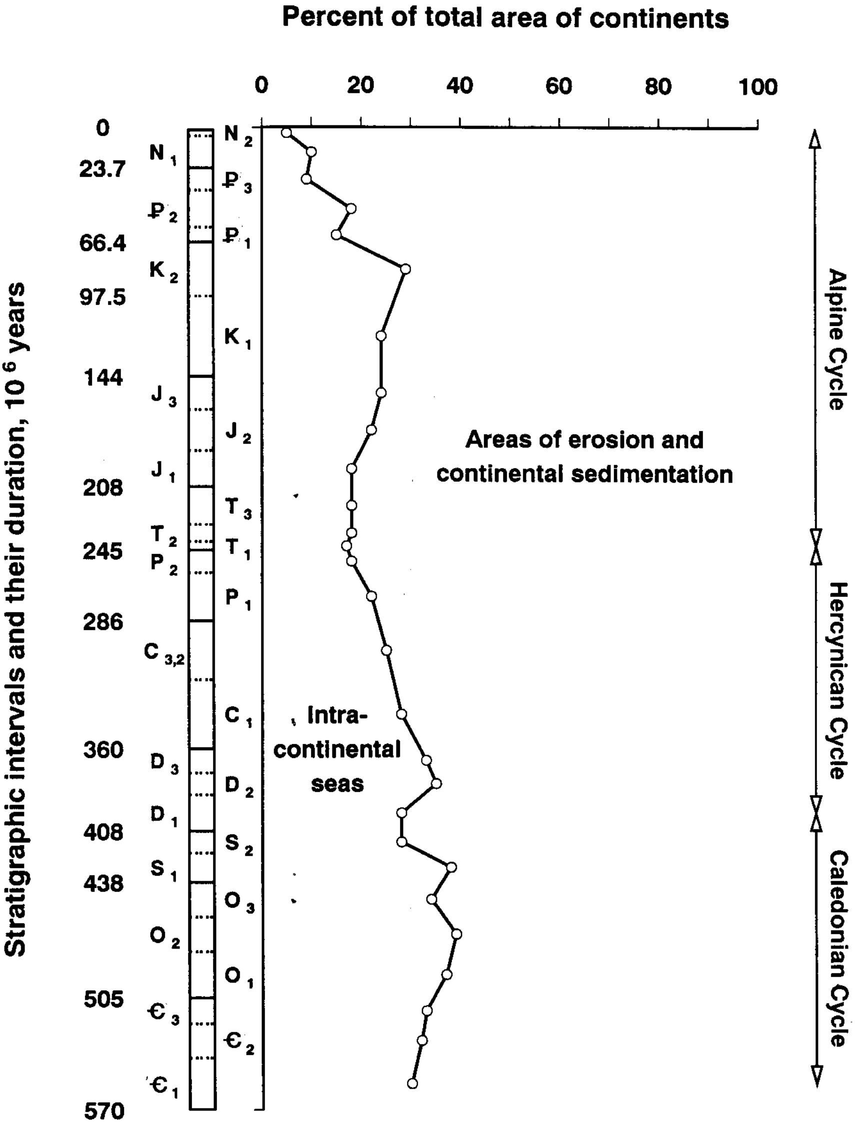

Fig. 5. Distribution of land (including areas of continental sedimentation) and sea as a percentage of the total area of the continents during the Phanerozoic.

6. On the platforms the marine areas generally did not exceed a quarter of the total area; the flooding ranged from 5 to 30 percent. In contrast, the geosynclines are characterized by a dominance of marine conditions. Paleozoic seas covered up to 90 percent of the total area of the geosyn-

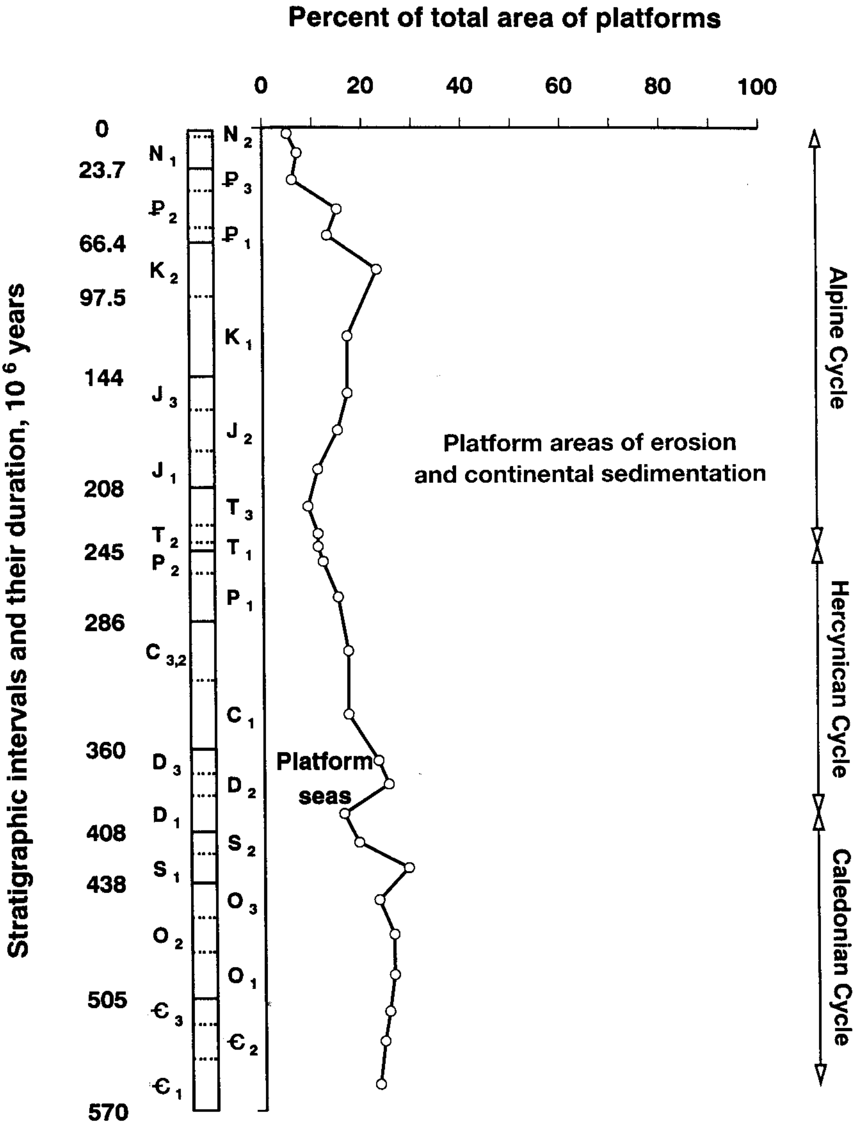

Fig. 6. Distribution of land (including areas of continental sedimentation) and sea as a percentage of the area of the continental platforms during the Phanerozoic.

clines, as shown in figure 7. Only in the Late Mesozoic and the Cenozoic did the marine area of the geosynclinal regions decrease significantly. The largest regressions were in the Early Cretaceous and Pliocene. As shown in figure 8, the marine areas in the orogenic belts were very