Latest pulse of Earth:
Evidence for a mid-Cretaceous superplume

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ABSTRACT

A calculation of Earth's ocean crustal budget for the past 150 m.y. reveals a 50% to 75% increase in ocean crust formation rate between 120 and 80 Ma. This "pulse" in ocean crust production is seen both in spreading-rate increases from ocean ridges and in the age distribution of oceanic plateaus. It is primarily a Pacific Ocean phenomenon with an abrupt onset, and peak production rates occurred between 120 and 100 Ma. The pulse decreased in intensity from 100 to 80 Ma, and at 80 Ma rates dropped significantly. There was a continued decrease from 80 to 30 Ma with a secondary peak near the Cretaceous/Tertiary boundary at 65 Ma. For the past 30 m.y., ocean crust has formed at a nearly steady rate. Because the pulse is seen primarily in Pacific oceanic plateau and ridge production, and coincides with the long Cretaceous interval of normal magnetic polarity, I interpret it as a "superplume" that originated at about 125 Ma near the core/mantle boundary, rose by convection through the entire mantle, and erupted beneath the mid-Cretaceous Pacific basin. The present-day South Pacific "superswell" under Tahiti is probably the nearly exhausted remnant of the original upwelling. How this superplume stopped magnetic field reversals for 41 m.y. is a matter of speculation, but it probably involved significant alteration of the temperature structure at the core/mantle boundary and the convective behavior of the outer core.

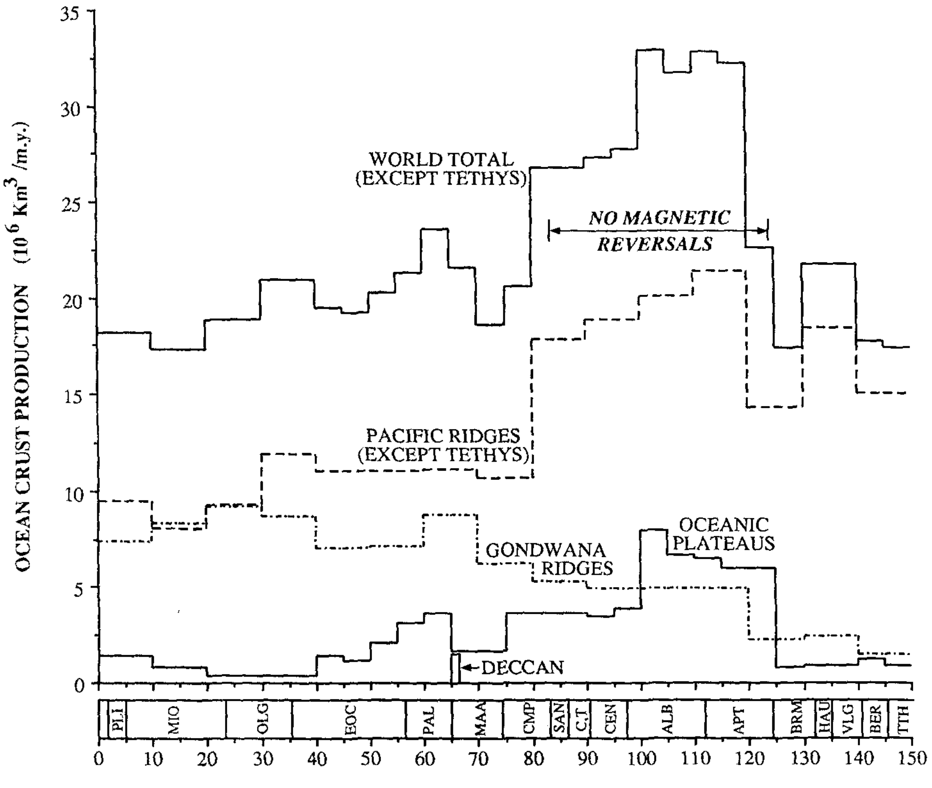

Figure 1. World oceanic crust production for past 150 m.y. partitioned into Pacific ridges, Gondwana ridges (Atlantic and Indian oceans), and oceanic plateaus that sum to world total. Deccan Traps volume shown for comparison with continental flood basalts. Each point on these noncumulative histograms represents volume of ocean crust produced in 1 m.y. "No magnetic reversals" represents long Cretaceous interval of normal polarity enclosed by magnetic anomalies 34 to M0. Geologic time scale from Harland et al. (1990).

INTRODUCTION AND METHODS

Earth is a huge heat engine, fueled mainly by the decay of the radioactive isotopes of potassium, uranium, and thorium and by release of the heat of crystallization at the inner/outer core boundary. The heat from this engine is dissipated mainly during the formation of oceanic crust in the world's ocean basins. It is generally assumed that this heat energy is produced at a nearly constant rate. However, the constancy of heat-energy dissipation has been a source of speculation for decades (Holmes, 1965), and an episodically "pulsating" Earth could account for mountain-building episodes, climatic extremes, eustatic sea-level fluctuations, and abnormal accumulations of petroleum. The most recent of these pulses can now be confirmed and quantified as a 50% to 75% increase in oceanic-crust production during mid-Cretaceous time. The initial suggestion (Larson and Pitman, 1972) of a mid-Cretaceous spreading pulse was speculative, but new evidence on magnetic lineation mapping, magnetic reversal stratigraphic calibration, and ocean-crustal dating allow a more quantitative calculation of Earth's ocean-crustal budget for the past 150 m.y. The sources of error in this calculation are still finite but are substantially reduced by recent studies. One source of error, the biostratigraphic calibration of the mid- to Late Cretaceous magnetic reversal time scale, is virtually eliminated. The magnetic reversal stratigraphy of the Late Cretaceous at Gubbio, Italy (Alvarez et al., 1977), places the upper end of the long Cretaceous interval of normal magnetic polarity (magnetic anomaly 34) at the Santonian/Campanian boundary, whereas the lower end (magnetic anomaly M0) is placed with equal certainty in the early Aptian in other Italian sections (Lowrie et al., 1980), and by Deep Sea Drilling Project (DSDP) Hole 417D it is placed in the western North Atlantic Keathley magnetic lineation sequence (Miles and Orr, 1979).

New magnetic anomaly studies were summarized on world maps of basement age by Larson et al. (1985) and of magnetic lineations by Cande et al. (1989). Whereas many detailed areas remain for future analysis, the world-wide distribution of magnetic lineations is, in the main, well known. Working versions of these charts and various tectonic models were used by Kominz (1984, Table 1) to compile tables of ridge crest lengths vs. spreading rates for the eventual purpose of calculating sea-level variations. I have used her tables to calculate the rate of mid-ocean ridge crust production as a function of time for the past 150 m.y. (Fig. 1), although I have recalibrated her spreading rates using the most recently available magnetic reversal time scale (Harland et al., 1990). This is simply a matter of summing the products of ridge-crest lengths times the revised spreading rates times the 6.5 km thickness of normal ocean crust (Shor et al., 1970). The result is a calculation of the dominant igneous process on Earth for the past 150 m.y., so it is important to define its limitations.

First, single spreading-rate averages are assigned to entire plate boundaries for 10 m.y. intervals, and plateau ages are averaged to 5 m.y. intervals so that the eventual result is a histogram of total production of ocean crust at 5 m.y. increments for the past 150 m.y. Second, there is no allowance for variation of crustal thickness as a function of spreading rate or age. This is probably reasonable for total crustal thickness (Shor et al., 1970), although variations do occur in the layer 2 velocity structure as a function of age (Houtz and Ewing, 1976). Third, the radiometric calibration of geologic time prior to 100 Ma is poorly known. The critical issue here is the length of the long interval of normal magnetic polarity in the mid-Cretaceous, because the crustal production pulse coincides with it. The end of the long normal interval at the Santonian/Campanian boundary is well dated at 83 Ma (Harland et al., 1982, 1990). However, the beginning of the long normal interval in the early Aptian is poorly known. Previous time scales (Harland et al., 1982; Kent and Gradstein, 1986) list 118 Ma, and the latest time scale (Harland et al., 1990) lists 124 Ma, although the different dates result from different manipulations of virtually the same data. These ages result in 35 m.y. and 41 m.y., respectively, for the length of the Cretaceous normal interval, and they imply about 25% slower spreading rates during the Cretaceous normal period relative to adjacent time intervals when the Harland et al. (1990) time scale is used. I have used the Harland et al. (1990) time scale in my calculations because it is the most conservative approach to studying a potential pulse in ocean crustal production in the mid-Cretaceous.

There are large assumptions in the calculation of Pacific ridge volume that probably never can be verified, but they must be utilized if such a worldwide calculation is made. All Pacific ridge calculations for the time prior to about 50–60 Ma require the assumption of symmetric spreading, because the eastern flanks of all the older Pacific ridge systems have been subducted beneath the Americas (Fig. 2). Furthermore, two "auxiliary" ridges exist in the Pacific ridge calculation (the Farallon-Phoenix and Farallon-Kula ridges) that were used by Kominz (1984) as geometrical necessities to complete the Magellan Rise and Shatsky Rise triple junctions of the western Pacific lineation patterns. Although there is little doubt of their former existence, and the two remaining "arms" of each system can be used to calculate spreading rates, the lack of any other remaining evidence makes it difficult to estimate their ridge lengths.

I did not include Tethyan ridge lengths and spreading rates in this calculation because all the evidence has been subducted beneath Asia. Most workers, including Kominz (1984), assume that the Tethyan seaway contained spreading ridges; however, there is no objective way to estimate quantitatively their crustal formation rates, if they existed. Thus, my results will be minimum rates, especially for Mesozoic and early Cenozoic time.

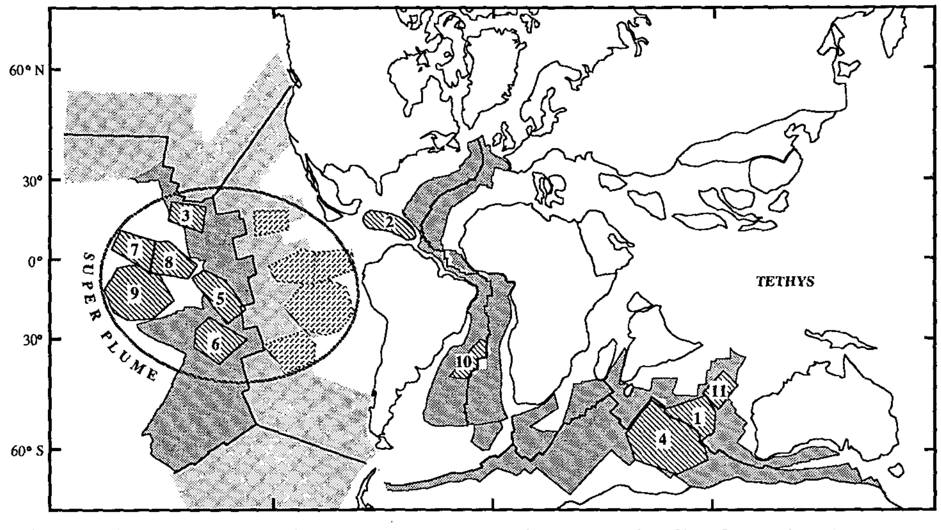

Figure 2. World reconstruction at magnetic anomaly 34 time (83 Ma, Santonian/Campanian boundary) showing ocean crust that has been created during mid-Cretaceous pulse between magnetic anomalies 34 and M0. Reconstruction is adapted from Scotese et al. (1988); ocean-crust isochrons from Larson et al. (1985) were used. Striped polygons indicate schematic outlines of oceanic plateaus of same age (125–80 Ma) from Schubert and Sandwell (1989). Light stipple indicates ocean crust and oceanic plateaus that have been subducted. Ellipse, in south-central Pacific, encloses probable area affected by mid-Cretaceous superplume. Numbers refer to plateaus listed in Table 1.

The other significant components of oceanic crust formed in the past 150 m.y. are the oceanic plateaus, such as the Ontong-Java and Kerguelen plateaus. To calculate oceanic-plateau production as a function of geologic time, I have assumed that the age of the oldest sediment overlying basalt which has been recovered by scientific ocean drilling or the age of dredged rocks represents the age of the individual plateau, except for exposed plateaus such as Iceland (Table 1). These assumptions will yield minimum ages for these features, but the plateaus were probably built quickly by flood basalts fed by massive dike-intrusion centers. These dates were then combined with oceanic plateau volumes estimated by Schubert and Sandwell (1989), using ocean-plateau topography and the assumption of Airy isostasy. I used volumes compiled in Schubert and Sandwell's (1990) Table 1 (Oceanic Plateaus), except that I recalculated the Caribbean volume to include only the Colombia and Venezuela basins, and the Beata Ridge: I also added volumes for the Line Islands and the Rio Grande Rise. The technique of topography and Airy isostasy to estimate crustal thickness (or depth to Moho) was shown to be quite accurate over large plateaus where seismic refraction data exist (e.g., Ontong-Java Plateau and Shatsky Rise). Oceanic plateau volumes are underestimated for plateaus created at spreading ridges because their normal ocean-crust thickness of 6.5 km was assigned to the ridge histograms. This is because Kominz's (1984) tables include those ridge-crest segments as finite ridge lengths.

As will be seen below, it is likely that the mid-Cretaceous oceanic plateaus in the western Pacific were formed by the upwelling of a very large plume of mantle material that erupted beneath the Pacific basin onto the Pacific and Farallon plates. Thus, I have included potential symmetric twin plateaus that would have formed on the Farallon plate by doubling the sizes of the western Pacific plateaus that formed on the Pacific plate. The Line Islands are excluded from this doubling because they are close to the same size and age of the Caribbean basin, which is probably the only Farallon plate plateau to have survived subduction intact.

RESULTS

The results of the calculations are shown in the histograms in Figure 1. Ocean crustal production from ridges is partitioned into Pacific and Gondwana (Atlantic and Indian oceans) ridges, and oceanic plateaus are shown separately. The "world total" is the sum of the lower three curves, excluding Tethys. The Deccan Traps (Courtillot et al., 1987; White and McKenzie, 1989) at 65 Ma are shown for comparison of a well-known continental flood-basalt sequence, but are not included in the world total. Clearly, a pulse of ocean crustal production appears between 120 and 80 Ma in the world total that is predominantly the result of contributions from the Pacific ridges and Pacific oceanic plateaus. Maximum spreading rates calculated for individual ridges during the Cretaceous pulse are about 17 cm/yr. This is, perhaps coincidentally, about the same as the present world-maximum spreading rates observed at the Pacific-Nazca ridge. Thus, individual ridges did not spread abnormally rapidly in the mid-Cretaceous, but average rates on the Pacific ridges were clearly higher.

The onset of the mid-Cretaceous episode is sudden and is seen in all three components (Pacific ridges, Gondwana ridges, and oceanic plateaus) of the world total. The general shapes of the histograms for "world total" and "oceanic plateau" production are very similar. The mid-Cretaceous pulse peaked soon after its onset (between 120 and 100 Ma), after which it continued with reduced intensity from 100 to 80 Ma. This decay is partially the result of end-on ridge subduction in the Pacific as opposed to spreading-rate variations that cannot be measured during the long Cretaceous normal polarity interval. However, the oceanic plateau volumes also decay in the same fashion. After 80 Ma, the world total and oceanic plateau production continued to decline until about 30 Ma; a secondary peak occurred near the Cretaceous/Tertiary boundary at 65 to 60 Ma. This subsidiary pulse is mainly a result of increased production rates in the Gondwana ridge system and oceanic plateaus (Fig. 1). In particular, it results from the fast spreading rates on the Indian Ocean ridge system associated with the breakup of Madagascar and India that also resulted in the Chagos-Laccadives, the Madagascar Ridge, and the Deccan Traps flood basalts.

There is no evidence in Figure 1 for the hiatus in mid-Cretaceous volcanism from 95 to 80 Ma reported by Rea and Vallier (1983). Their proposed hiatus was centered on the Turonian and Coniacian stages, now thought to total only 4 m.y., from 90.5 to 86.5 Ma (Harland et al., 1990). Thus, a very short hiatus may exist during these stages that is averaged out by the histogram intervals in Figure 1.

TABLE 1. OCEANIC PLATEAU AGES AND VOLUMES

Oceanic plateau	Age (Biostratigraphy)	Age (Ma)	Volume ($10^6 Km^3$)	References
Broken Ridge-1	>Turonian=Kerguelen	90-110	5.19*	ODP 754
Caribbean-2	Turonian-Campanian	75-90	20.41	DSDP 146, 149, 150, 152, 153
Caroline Seamounts	Miocene-Pleistocene	1-10	5.60	Keating et al. (1984)
Chagos Laccadives	early Paleocene-early Eocene	50-60	14.01*	ODP 707, 712, 713, 715
Crozet Plateau	<Anomaly 31	<65	9.45	Cande et al. (1989)
Emperor Seamounts	Maastrichtian-Eocene	40-70	13.42	DSDP 192, 308, 430, 431, 432, 433
Hess Rise-3	late Aptian-early Cenomanian	95-115	7.78*+	DSDP 465, 466, 310
Iceland	Miocene-Holocene	0-20	8.56*	Moorbath et al. (1968)
Kerguelen Plateau-4	Albian-early Turonian	90-110	24.86*	ODP 738, 748, 750
Line Islands-5	Santonian-Campanian	75-85	10.01*	DSDP 165, 315, 316
Madagascar Ridge	Paleocene	55-65	15.94	DSDP 246, 247
Magellan Rise	Jurassic/Cretaceous boundary	140-150	3.64*+	DSDP 167
Manihiki Plateau-6	Aptian	115-125	10.40*+	DSDP 317
Marcus Wake Smts.-7	Albian-Cenomanian	90-115	30.85+	Sager and Pringle (1988)
Maud Rise	late Campanian-early Maast.	70-75	2.35	ODP 690
Mid Pacific Mtns.-8	Barremian-Campanian	75-130	42.94+	Hamilton (1956); DSDP 313, 463, 171
Mozambique Plateau	Neocomian	130-145	5.51*	DSDP 249
Nazca Ridge	<Anomaly 18	<40	9.17	Cande et al. (1989)
Ninetyeast Ridge	early Campanian-Eocene	40-85	23.74	DSDP 217, 216, 215, 214; ODP 756, 757, 758
Ontong Java Plat.-9	Aptian-Albian	100-125	101.35+	DSDP 288, 289; ODP 803, 807
Rio Grande Rise-10	Coniacian	85-90	7.76*	DSDP 516
Shatsky Rise	Anomalies M10- M21 Jurassic/Cretaceous boundary	130-150	9.86*+	DSDP 49, 50, 306
Wallaby Plateau-11	<Australia/India breakup	110-125	1.49*	Cande et al. (1989)
Walvis Ridge	late Campanian-Maast.	65-75	6.85	DSDP 525, 527, 528

Note: Ages are mainly from the oldest sediment ages at the base of Deep Sea Drilling Project (DSDP) or Ocean Drilling Program (ODP) drill sites, from dredged rocks, or from tectonic associations with other features of known age (e.g., Broken Ridge=Kerguelen Plateau). Individual DSDP and ODP drill sites are not referenced in full except for the most recent sites, ODP 803 and 807 (Leg 130 Shipboard Scientific Party, 1990), but their ages can be found in the Site Chapter for each site in the Initial reports of the Deep Sea Drilling Project and in the Proceedings of the Ocean Drilling Program. Plateau volumes derived from Schubert and Sandwell (1989). Numbered plateaus are shown in Figure 2.

*Volumes reduced from their total plateau volumes by removing a 6.5 km thickness of normal oceanic crust because these plateaus formed at spreading ridges.

+Volumes doubled to account for potential twin plateaus on the Farallon plate that have been subducted.

By 30 Ma, the world total and oceanic-plateau production rates had nearly leveled off at about the same rates seen prior to the mid-Cretaceous pulse, although it must be remembered that the exclusion of a potential Tethys ridge system may underestimate Early Cretaceous and Late Jurassic rates. During the past 30 m.y., Pacific ridge output approximated Gondwana ridge output, while world total and oceanic plateau formation rates remained constant.

INTERPRETATION

The mid-Cretaceous pulse in ocean-crust formation is evidenced mainly in Pacific ridge and Pacific oceanic plateau production, began relatively suddenly at 120–125 Ma, and decreased over a long period to about 70 Ma. Spreading rates during the Cretaceous lie within the present-day range, although average Pacific rates were higher. Present-day variation in spreading rates is mainly a function of the availability or absence of long subducting slabs to provide driving forces for rapid spreading. Thus, it is possible that subduction-zone initiation or rearrangement in the Mesozoic Pacific is responsible for the pulse. However, what we know of Mesozoic subduction from the geologic record of the rim of the Pacific basin is that subduction has been generally continuous since the Jurassic, at least in the American Cordillera and in Japan. It is also unlikely that increased driving forces from subduction could explain the synchronous onset of oceanic plateau formation. Thus, I doubt that changes in subduction-zone driving forces in the Mesozoic Pacific caused the pulse. I have not included flood basalts associated with continental breakups in the compilation of oceanic plateaus. Such flood basalts might result from decompression melting during extension, whereas the oceanic plateaus of the Pacific formed far from continents and resulted from deeper mantle sources. The Pacific oceanic plateaus are thickened areas of oceanic crust that resulted from an abnormally high degree of melting of mantle material. This higher degree of melting requires higher temperatures (McKenzie and Bickle, 1988) that imply deeper source levels in the mantle. The source material must also rise quickly and approximately adiabatically to the lithosphere in order to retain most of its original heat for massive upper-mantle melting.

The pulse in both total production and oceanic-plateau building correlates closely with the long period of normal magnetic polarity in the mid-Cretaceous, and the coincident onset of both these phenomena is especially striking. As discussed above, the Cretaceous normal interval began in the early Aptian (125 Ma), as did the massive episode of Cretaceous plateau building that continued in its initial intensity through most of the Albian (to 100 Ma) and with reduced intensity to 80 Ma. The magnetic field began to reverse polarity, eventually ending the Cretaceous normal interval at 83 Ma. The only Pacific plateaus with older ages (Shatsky and Magellan rises) are associated with magnetic lineation triple junctions of the same age as those plateaus.

Because the initiation and duration of the mid-Cretaceous pulse coincide so closely with the initiation and duration of the long interval of normal magnetic polarity, it follows logically that the heat source for the pulse was near the core/mantle boundary. Heat extraction from just above the core/mantle boundary could significantly alter the temperature gradient at that depth. This could increase convection in the outer core that would alter the magnetic reversal frequency. Thus, following general suggestions by Vogt (1975) and Sheridan (1983), I propose that a "superplume" originated about 125 Ma just above the core/mantle boundary, rose by convection through the entire mantle, and erupted beneath the mid-Cretaceous Pacific basin (Fig. 2). The present-day South Pacific "superswell" probably marks its location, as proposed by McNutt and Fischer (1987). However, consideration of Figures 1 and 2 here suggests that the present-day superswell is probably the nearly exhausted remnant of the mid-Cretaceous upwelling, rather than a present-day analogue.

The suggestion that a large area of the Farallon plate was also affected by the superplume (Fig. 2) is a restatement of the hypothesis of Schlanger et al. (1981), who called for widespread mid-Cretaceous volcanism in this area. They cited the Caribbean basin as part of this volcanism and abundant evidence for other Cretaceous plateaus. These plateaus were mostly subducted beneath western North and Central America, and their obducted remains now extend from northern California to Panama. I also note that Hess Rise, the Line Islands, and the Manihiki Plateau (oceanic rises 3, 5, and 6 in Fig. 2) all have ages concordant with those of the surrounding oceanic crust, indicating that they were created at or near the Pacific/Farallon plate boundary. It is unlikely that such a large phenomenon as the superplume would have erupted beneath just the Pacific flank of this system, and symmetry about the spreading ridge is assumed for lack of evidence to the contrary. The minimum dimensions of this mantle upwelling were about 6000 × 10000 km, and the present-day South Pacific superswell lies close to its center.

The ability of the superplume to stop magnetic field reversals probably involved significant alteration of the temperature structure just above the core/mantle boundary through removal of heat and lowermost mantle material. This increased the convective activity of the outer core in a way that locked the dipole field into a long period of uniform polarity. Then in time (41 m.y., in this case), the preexisting temperatures and temperature gradients reestablished themselves, and dipole field reversals proceeded as before (Larson, unpublished).

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ACKNOWLEDGMENTS

This project would not have been possible without the 20 years of ongoing efforts by scientific ocean drilling to date oceanic crust worldwide. I thank L. J. Abrams, D. Anderson, M. A. Arthur, R. T. Bird, R. S. Detrick, E. Erba, M. Kominz, W. C. Pitman III, J.-G. Schilling, H. Sigurdsson, and R.S.J. Sparks and the late S. O. Schlanger for discussions and reviews.

Manuscript received September 4, 1990
Revised manuscript received December 17, 1990
Manuscript accepted December 27, 1990

Printed in U.S.A.