ABSTRACT
A compilation of lithosphere consumed globally in the past 180 m.y. reveals that the equivalent of the surface area of Earth has descended into the mantle, producing "lithospheric graveyards." Not uniformly distributed, this subducted lithosphere lies concentrated in areas of cold mantle that correspond to gross mantle heterogeneities delineated by seismic tomography and the geoid and inversely related to the global distribution of hotspots. Some convergent margins (e.g., North American continent) show subducted lithosphere distributed over a large region beneath the land mass while others (e.g., eastern Eurasia) show an accumulation of up to 18 subducted lithospheric thicknesses in a narrow region. Differences in the net gravitational distribution result from displacements of trenches (assumed nearest fixed to the overriding plate) over the margins: North America, South America, Africa, and southeastern Eurasia each advanced toward and perpendicular to their trenches by approximately 400, 300, 2700, and 1000 km, respectively between 140 Ma and the present. In contrast, eastern Eurasia (near Japan) first retreated by approximately 1200 km until 80 Ma and then advanced an equivalent distance to the present.

Net convergence at selected subduction zones also shows variability: in the past 150 m.y., approximately 13,000 km of lithosphere has been consumed into the Japan and western North American trench systems, whereas approximately 8000 km under the central Andes and Himalayan regions, and about 1000 km of convergence was accommodated by the western Alps. Such extreme differences in kinematic histories may help explain contrasting orogenic styles. It appears that a large amount of convergence is not a necessary condition for orogeny (western Alps) nor is it sufficient (eastern Eurasia), whereas significant trench advance may be both necessary and sufficient, especially when the plate interaction involves at least one continent.

Previous workers have shown that a decrease in global spreading rates (hence increasing the geometry and spreading history of ridges for the past 80 m.y.) is the primary cause of a volume decrease in mid-ocean ridges and is consistent with a corresponding lowering of eustatic sea level during this time interval. We present an extension of this hypothesis to the past 180 m.y. by using our rates of global lithosphere consumption to estimate the total volume of spreading and calculate the inferred changes in mid-ocean ridge volumes. Changes in global spreading rates do not affect the age distribution within the oceans instantaneously, because it takes a finite amount of time for significant amounts of oceanic crust to be replaced: an approximate 30 m.y. lag time is noted between first-order changes in global spreading rates and eustatic sea level. A simple model predicts that eustatic sea level using global spreading rates is in good agreement with the observed sea level curve, especially after 120 Ma.

A noted misfit in predicted and observed eustatic sea level prior to 120 Ma may indicate a long period of slow global spreading before 120 Ma. This may reflect rising mantle temperatures, consistent with a recently proposed dynamic-convection model.

INTRODUCTION
Continued refinement of relative plate motions within the fixed-hotspot reference frame allows global subduction parameters to be estimated. Of prime interest is the area of lithosphere subducted annually (presented in km²/year) and the locations of this subducted lithosphere (referred to as lithospheric graveyards; Fig. 1). As proposed by Chase (1979), Chase and Sprowl (1983), and Richards et al. (1988), large regions containing previously subducted lithosphere should correlate with large-scale mantle heterogeneities. The relation between locations of subducted lithosphere and mantle heterogeneity was tested by Richards and Engelnedt (1992) and is reviewed here.

Also of interest is the kinematic character of subduction zones in both the hotspot reference frame and in total convergence at plate boundaries. The distribution of lithospheric graveyards is a direct result of the prebreakup configuration of the subduction zones encircling Pangaea, the subsequent migration of these convergent boundaries, and the net convergence at these boundaries. We selected five convergence zones and calculated the displacements over the hotspots of the overriding plates perpendicular to their boundaries and linear consumption of lithosphere descending into the mantle. Given this no-net-rotational contraction, calculation for the global accretion rate at oceanic ridges provides the opportunity to estimate the capacity of the world's oceans to hold sea water. Previous attempts were based on knowing the lengths and spreading histories of ridge systems (e.g., Pitman, 1976; Komizu, 1987) and covered the time period since 80 Ma. Our work is dependent upon knowing the geometry and plate interaction history of subduction zones, and we extend the analysis back to 180 Ma. Both methods share severe uncertainties that increase as the time of interest is expanded. The methods presented here are preferred since the history of subduction is probably more completely recorded in the geologic record than past geometries of largely missing oceanic crust.

GLOBAL SUBDUCTION PARAMETERS
Finite rotations describing relative motions in the various ocean basins and between plates and hotspots given in Table 1, along with their sources, have been calibrated to the time scale of Kent and Gradstein (1996). It is beyond the scope of this paper to critically evaluate all sources of uncertainties in the model. Uncertainties grow with increasing spreading history. Such results that prior to about 150 Ma are highly speculative. Sources for errors in inferred spreading histories between Pacific and African hotspots, plate-to-hotspot motions (especially Subduction continued on p. 94
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prior to 120 Ma), plate-to-plate dis- placements, plate geometries (with the possibility of missing entire plates, most notably during the early history of the Tethys), and the magnetic time scale. We examined with colleagues in- member reconstructions and found a qualitative estimate for uncertainty in time-integrated motions to be about 20% at 100 Ma and 40% at 180 Ma. To obtain amounts of subducted lithosphere, subduction zones were assigned to an overriding plate, digi- tized at their present locations and reconstructed to their former positions in a fixed-hotspot reference frame at 30 m.y. intervals. It was assumed that these convergence zones remained fixed relative to their overriding plates: we acknowledge that back-arc spreading and trench-polarity reversals intro- duce additional errors into the results. Critical decisions made about the loca- tion of the intersecting plates were based primarily on the locations of plate boundaries within the oceans and to a lesser extent on known geo- logic histories. Stage poles of 5 m.y.

DISTRIBUTION OF LITHOSPHERIC GATEWAYS

Differences in gravestayd size are the result of the 180 Ma location and subse- quent migration of the overriding plate relative to the mantle, with the total plate consumed at trenches. To investigate these relationships, two kine- matics were used to study selected sites: the total component of displacement over the mantle normal to plate boundaries (Fig. 3), and the total amount of plate consumed (Fig. 3). For these analyses, we have restricted the treatment to selected sites of poorly determined reconstructions for the earlier record. Positive values in Fig- ure 3 represent plate areas of overriding plates advancing in the direc- tion of their boundaries; negative values show retreat. Likewise, positive and negative slopes along the curves in Figure 2 represent rates of advance and retreat, respectively. To examine the Figure 3, concordant components of subduction relative to the overriding plates (North America, South America, Eurasia, and Africa) were calculated by using the plate boundary azimuths given in the caption. For these interaction histories are summarized in the caption for Figure 3. Figures 1, 2, and 3 show the fol- lowing patterns: both North America and South America advanced large dis- tances toward their trench (Fig. 1, 2), thereby distributing subducted litho- sphere beneath their land masses (Fig. 1), North America more so than South America. In contrast, Eurasia first re- treated from the Japan Trench (between about 150 and 90 Ma) and then ad- vanced to create the largest gravestayd seen globally, a ratio of subducted plate to Earth surface area (within the dark blue area near Japan). North America and Eurasia (near Japan) each consumed approximately 1300 linear km of plate (Fig. 3). Near the Himalayan suture, Eurasia advanced trenchward approximately 1000 km between 150 and 75 Ma and then re- mained stationary (Fig. 2). In total plate consumed, Eurasia (near the Himalayan suture) and South America are similar (about 8000 km) but differ in their times of major convergence (see the pre—50 Ma curves in Fig. 3). Quite different is the kinematic his- tory of Africa (near the Zambezi) where approximately 2200 km of northward trench advance is seen since 100 Ma. Eurasia also moves northward but at a slower rate, result- ing in a minimum of convergence for the sites studied (about 1000 km).
cient to explain the lower mantle degree-2 seismic velocity structure as well as the geoid. Thus, they hypothe-
sized that the amount and location of lithosphere subducted over the past 100-200 m.y. might explain the ob-
served large-scale structure of convec-
tion. This assumes, implicitly, that mid-ocean ridges are passive structures and that mantle heterogeneity is pri-
marily the result of subduction. This hypothesis was supported by Richards

Figure 4 (from top to bottom) shows the general agreement found between the largest wavelengths (10,000-20,000 km) of the time-inte-
grated flux of subducted slabs since 120 Ma, lower mantle seismic struc-
ture, residual geoid, and global hotspot distribution. The main conclusion of Richards and Engelnbront (1992) was that there is a dynamically reasonable relation between plate tectonics and large-scale mantle convection—the deep mantle is cold where there has been subduction. Implicit in this work is the assumption that horizontal mo-
tions in the deep mantle are much slower than in the upper mantle. This is justified by the fact that hotspots, which presumably result from deep mantle plumes, exhibit relative motions that are much slower than relative plate motions. Therefore, we feel justified in ignoring horizontal motions of sub-
ducted slabs after they enter the lower mantle, although they probably con-
tinue to descend (nearly vertically).

ACCRETION RATES AND SEA LEVEL

During periods of rapid seafloor spreading, young (hot) ocean floor dis-
places older (cold) parts of the seafloor, causing the volume of the world's ocean basins to decrease (Pitman, 1978). Gur-
nis (1990) has questioned this relation by pointing out that the effect of in-
creased spreading rates is to increase the amount of cold lithosphere injected into the mantle, significantly changing the deep thermal structure under oceans and continents. Increased injection of cold lithosphere reduces the volume of sublithospheric mantle, causing the volume of the ocean basins to increase, most notably when subduction occurs within the ocean basins.

The primary difference between the dynamic-convection model (Gurnis, 1990) and the lithosphere-subduction model (Pitman, 1978) occurs about 100 m.y. after a signifi-
cant change in spreading from steady spreading rates (Fig. 2) to Gurnis, 1990). Hager (1980) presented a dynamical model in which sea level could either rise or fall with increased spreading. If lithospheric slabs are primarily in-
jected into mantle beneath the oceans, the overlying plate is pulled down, which increases the volume of the oceans and lowers sea level: if slabs are primarily subducted beneath continents, the local effect is to pull down the continent and locally produce a sea-level rise. Sea level will rise or fall according to increased or decreased spreading only when subcontinental and suboceanic mantles are cooled equally by subducted lithosphere (Hager, 1980). We will return to these discussions after presenting our attempt to model sea level using only the litho-
spheric-subduction model.

Previous estimates for the effect of variations in global spreading rates (e.g., Pitman, 1978; Komnin, 1987) have focused on knowing the lengths and spreading rates of all the world's ridge systems. In contrast, the method used here infers spreading rates from global subduction rates. Global spreading rates were derived by summing the total area of subducted lithosphere through 5 m.y. time intervals (Fig. 5). Interestingly, the grand total of sub-
ducted lithosphere (area under curve in Fig. 5) is approximately 525 x 10^6 km^2, nearly equal to the surface area of Earth. Included in Figure 5 is eustatic sea level (Haq et al., 1987) averaged through a 10 m.y. running window. Note the approximate 30 m.y. lag time between greatest accretion rate and highest sea level (dashed line in Fig. 5).

Pitman (1978) and Komnin (1987) have demonstrated the importance that spreading rates have in regard to changes in sea level by estimating the lengths and spreading rates of ridges, calculating ridge bathymetry from the age-depth relation (Scatter et al., 1971; Prons and Scatter, 1977), and interpre-
ting corresponding volume changes assuming they knew the shape and size of the ocean basins being filled or drained. General agreement between their work and estimates of eustatic sea level from seismic stratigraphy (e.g., Vail et al., 1977; Haq et al., 1987) sup-
pport a causal relation. Komnin (1987) presented the most complete analysis of these relations to date, analyzed sources of error, produced several reconstruction stages estimating rise and fall, and showed that the primary cause of a decrease in ridge volume since the Late Cretaceous was a decrease in spreading rates. Komnin (1987) noted that ridges within the Pacific basin dominate the results; sev-
eral important discrepancies in ridge geometries exist between Komnin's (1987) work and our own (Engelnbront et al., 1984, 1985). Whereas the work of Komnin (1987) was an excellent attempt at a difficult problem, some improvements are possible given that there are new reconstructions available for nearly all plate pairs and improved reconstructions for the hotspot refer-
ence frame. Moreover, by reconstruc-
tion of the subduction history, we are able to extend the analysis back to 180 Ma. Results back to 120 Ma are reason-
able (Fig. 6). An agreement (Fig. 6) is seen between 180 and 120 Ma, pre-
sumably due either to our inability to decipher earlier plate displacements or to processes involved in the dynamic-
 conversion model.

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Figure 4. Comparison (from top to bottom) of spherical harmonic components (l = 2,3) of time-integrated flux of subducted slabs since 120 Ma calculated in the hotspot fixed reference frame (Richards and Engelnbront, 1992), lower mantle seismic velocity model of Olszewski (1984) (corrected for hydrostatic figure: Nakajouga, 1982) and upper mantle slabs (Hager, 1984); and hotspot distribution (Richards et al., 1988).

Figure 5. Subduction rate vs. time (upper curve) and the eustatic sea-level curve of Haq et al. (1987). Both curves have been smoothed with a 10 m.y. running window. Dashed curve shows approximately 30 m.y. lag time between maximum spreading rates and highest sea level.
Subduction continued on p. 95

We analyzed the effect that changes in global sea-level rise has and are applicable to earlier times, the misfit in our model prior to 120 Ma is consistent with the dynamic-convective model. Put more optimistically, the pre-120 Ma increase in eustatic sea level suggests that spreading rates were slow for the time period prior to 130 Ma and possibly as far back as 125 Ma. Agreement (at least since 120 Ma) between first-order changes in eustatic sea level and predicted changes using simple assumptions about the overall area distribution of lithosphere entering trenches correlates with global spreading rates is encouraging.

SUMMARY

Since 180 Ma, the area of plate (primarily oceanic) now buried in the mantle is approximately equal to the surface area of Earth. Subducted lithosphere is concentrated in regions (lithospheric graveyard), and these regions correlate gross mantle heterogeneity—the mantle is colder where plate is buried.

More than 13,000 km of convergence has occurred at the Japan Trench and western North America since 150 Ma. Approximately 8000 km has descended beneath the central American plate and the Andes, and an additional 5000 km of convergence is seen for the western Alps.

With regard to motions of the overriding plates relative to the hotspots (the component orthogonal to their boundary), North and South America show a net advance (primarily westward) of about 3000 km. South America, near the Himalayan sutures, has advanced about 1000 km (southward) with most of this displacement occurring after 75 Ma. Although no net orthogonal motion is observed for the Japan Trench, retreat of this trench about 1000 km (eastward) between 150 and 90 Ma was followed by an equivalent advance (westward). Africa, near the western Alps, shows approximately 2200 km of steady trenchward advance (northward). Thus, each of these regions of convergence displays a unique kinematic history. It appears that a significant amount of advance of the overriding plates toward their convergent boundaries is both a necessary and sufficient condition for large-scale uniform uplift and orogeny.

Finally, the pattern of global spreading rates and the ridge ridges is consistent with a first-order eustatic sea-level curve (120-150 Ma) that is stronger the area model for the area distribution within the world’s ocean basins is assumed (lithospheric age vs. convergence model). The amount of plate subducted as a function of its age appears directly related to the orogeny pattern. Effects of the dynamic-convective model of Gurnis (1990) may be recorded in the steady rise of eustatic sea level between 180 and 120 Ma and imply a long history of slow spreading prior to 120 Ma.

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