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INSIDE

Long-term Controls on Eustatic and Epeirogenic Motions by Mantle Convection

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ABSTRACT

Computational geodynamics is leading to the synthesis of plate tectonics and mantle convection into a unified dynamic model. Coupled models of plates and thermal convection quantitatively show both eustatic and epeirogenic controls on long-term uplift and subsidence of Earth's surface from regional to global scales. Eustasy and epeirogeny can no longer be viewed as mutually exclusive hypotheses explaining continental stratigraphy—both arise with nearly equivalent amplitudes, but with complex phase offsets, by the same system of global convection. Dynamic models assist in the interpretation of the stratigraphic record, which has long been known to show that continents undergo both eustatic and epeirogenic motions.

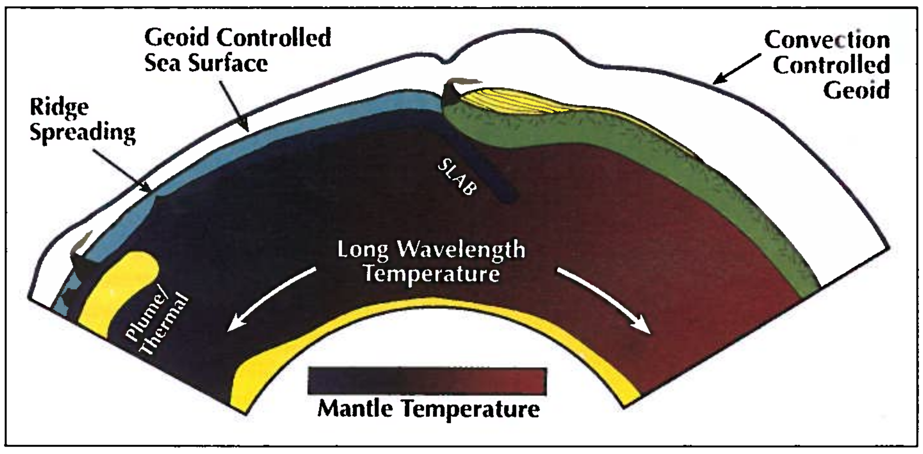


Figure 1. Summary diagram showing shallow and deep mantle convection controls on sea-level change and regional vertical motion discussed in the text. The influence of all mechanisms, except plume-lithosphere interactions, has been studied with dynamic models of plates, convection, and the geoid.

INTRODUCTION

"The explanation of the causes of transgression cycles in the history of the earth will represent one of the most important, but also one of the most difficult tasks of future geological and geophysical research." This statement is as true now as it was in 1929 when Alfred Wegener wrote these words in *The Origin of Oceans and Continents*. For although plate tectonics has been immensely successful at providing a kinematic framework of large-scale horizontal motions, it cannot explain vertical motions of continents. Stratigraphers have long appreciated the fundamental role that vertical motion must play in the development of the stratigraphic record of continental interiors (Sloss and Speed, 1974).

An entirely new frontier has opened in our effort to understand the causes of long-term sea-level fluctuations and the flooding of continental platforms by shallow seas. Over the past decade, the field of computational geodynamics has emerged, in which computer models of mantle convection are used in the interpretation of contemporaneous geophysical observations like seismic tomography and the geoid as well as of time-integrated observations from isotope geochemistry (see Davies and Richards, 1992, for a comprehensive review). We have now reached a point where we can use these techniques of computational geodynamics to make testable predictions of sea level and stratigraphy. The field of geodynamics is likely to benefit immensely from observational constraints on the time evolution of mantle dynamics from stratigraphy; this is particularly important, because traditional seismological and gravity observations do not provide any time-history constraints.

In the past decade, there have been important technical advances in our ability to understand mantle convection. From the perspective of craton and margin dynamics, these relevant advances range from the ability to partly simulate the dynamic interaction between tectonic plates and mantle convection (Gurnis, 1988; Weinstein et al., 1992) to the formulation of simple viscous flow models that allow us to calculate topography and geoid signatures from seismic anomalies in the mantle (Parsons and Daly, 1983; Richards and Hager, 1984). Here, I provide an overview of recent attempts at exploiting geodynamics to understand long-term controls on eustasy and epeirogeny (various mechanisms are summarized in Fig. 1). This paper is not intended to be a balanced review of sea-level change—the purpose is to highlight recent research at the boundary between sedimentary geology and geodynamics.

EUSTASY AND EPEIROGENY

No two concepts are probably as important for continental geology but so misunderstood as eustasy and epeirogeny. A eustatic sea-level rise is one that is globally uniform, whereas an epeirogenic motion is a broad, gradual rise of one continental region relative to another, or even the motion of an entire continent relative to others. Epeirogenic motions are unaccompanied by significant folding and faulting. Although seismic stratigraphy (Christie-Blick et al., 1990) has received widespread attention in recent years, it has never been clear if either mechanism of sea-level change can be tested directly by this method. The major problem with seismic stratigraphy is that the deposits studied are located on passive margins, where the lithosphere is thinned and thermally altered during rifting (Watts, 1982); so it is difficult to deconvolve deep mantle processes from shallow lithospheric ones.

The place to look for the influence of mantle convection on sea-level fluctuations is within vast sedimentary deposits covering the stable platforms of continents. Sedimentary geologists have long tried to determine if platform flooding can be explained solely by either eustasy or epeirogeny or if a combination of both processes is required. This problem was most clearly addressed by Bond (1978, 1979), who used a relative flooding–hypsometry technique. The difference in height between the sea surface and a continent can be determined from the intersection of the fraction of a continent covered by marine deposits with the continent's distribution of elevation vs. area (hypsometric curve). If there were only eustatic fluctuations, then at each geologic time each continent would have the same elevation difference. But Bond (1978, 1979) showed that the apparent sea level as seen by individual continents (North America, Africa, South America, Europe, Australia, and India) has differed by as much as an inferred eustatic signal since Early Cretaceous time (Fig. 2). Bond inferred a eustatic signal by noting that continents form distinct clusters—like the cluster of Australia, Europe, North and South America, and Europe during the Miocene (Fig. 2A)—and by making just four vertical translations since the Early Cretaceous, he showed that all the continents could be brought into clumps (Fig. 2B). These observations strongly suggest that distinct epeirogenic changes have been superimposed onto a clearly defined eustatic curve.

The large scatter between individual relative sea levels which we see in Figure 2 requires that the hypsometry of continents has changed (Bond, 1978). This means that either continental crust has thinned or thickened or that the continents have been tilted or vertically translated by mantle processes. Because sediments were laid down on flat, stable platforms, Bond suggested that changes in hypsometry were due to epeirogenic motions. An important aspect of the vertical motions evident in Figure 2 is that the amplitude of the regional epeirogenic motions are comparable to the amplitude of the inferred eustatic signal (both are about 100 to 200 m). As we will see, this near equality in the amplitude of eustatic and epeirogenic motions is what would be expected from a simple model of mantle convection.

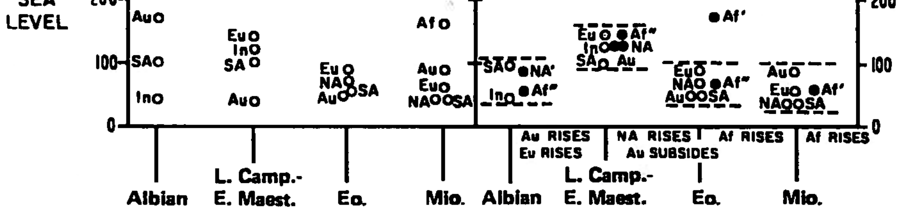


Figure 2. Sea-level elevations derived from the fraction of a continent flooded and its hypsometric curve. A: Uncorrected sea levels. B: Sea levels corrected by making individual vertical translations (corrected points indicated with primes). Reproduced from Bond (1976), with his permission.

Mantle Convection
continued on p. 144

Editor's Note:
This is the third article by a Packard fellow in earth science (see June 1991 and July 1991 issues of *GSA Today*). Each year the David and Lucile Packard Foundation awards 20 fellowships ($100,000 per year for five years) to promising young scientists and engineers working in fields less publicized than are high-energy physics, space, and medicine.
—Eldridge Moores

Mantle Convection
continued from p. 141

A most intriguing vertical motion evident in Figure 2 is that of Australia during the Cretaceous. The interior of Australia became flooded by nearly 50% between 125 and 115 Ma and then became progressively exposed between 100 and 70 Ma at a time when nearly all other continents reached their maximum Cretaceous flooding (Struckmeyer and Brown, 1990). Much of Australia must have vertically subsided by >100 m in the Early Cretaceous, but then must have been uplifted by hundreds of metres in the middle Cretaceous to counteract the effect of the eustatic rise in sea level. Because Australia did not undergo any significant faulting or folding during this time, the conclusion seems inescapable that the mantle pulled down and then pushed up this continent over a horizontal scale of thousands of kilometres.

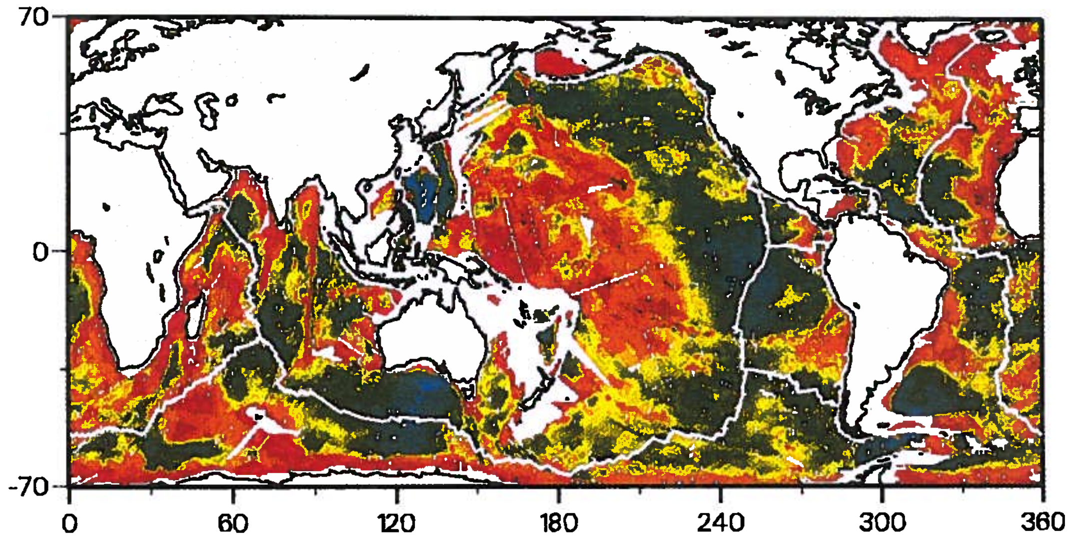


Figure 3. Residual topography obtained by removing the normal subsidence of the oceanic lithosphere. The topographically high areas are red and the low areas blue. The long-wavelength amplitude of this signal is 500 m. Figure courtesy of A. Cazenave.

DYNAMIC TOPOGRAPHY AND THE GEOID

Mantle convection controls continental vertical motion through dynamic topography. In a viscous medium, such as Earth's mantle (Cathles, 1975), flow is generated by internal mass anomalies (buoyancy forces). The flow transmits stress to the top of the mantle, where the vertical hydrostatic stress is balanced by the deflection of the interface, dynamic topography. Positive mass anomalies within the viscous mantle cause Earth's solid surface to be deflected downward. Dynamic topography often refers only to the topography generated by loads located deep beneath the lithosphere.

If mass anomalies within the mantle are known, then dynamic topography and the geoid can be computed from spherically symmetric viscous models of the mantle (Richards and Hager, 1984). The mass anomalies within the mantle have been inferred from body-wave (Dziewonski, 1984; Inoue et al., 1990) and surface-wave seismic tomography (Dziewonski and Woodhouse, 1987; Tanimoto, 1990). This technique shows that seismic anomalies drive a strong degree-two (i.e., a wavelength half the circumference of Earth) pattern in the geoid with ~100 m amplitude highs (mass excesses) located over Africa and the western Pacific—very similar to the observed long-wavelength nonhydrostatic geoid (Hager et al., 1985). Controlling this geoid are ~1-km-amplitude dynamic topography highs located again over Africa and the western Pacific. But do these large-scale topography anomalies really exist? Cazenave et al. (1989) has shown that when the subsidence caused by diffusive cooling of the lithosphere is removed from ocean bathymetry, a nearly identical pattern of global topography emerges (Fig. 3). This long-wavelength residual topography has been refined (Cazenave and Lago, 1991) and corroborated independently (Pribac, 1991).

The amplitude of sea-level change and the pattern of continental onlap associated with dynamic topography is not immediately obvious, because topography controls the geoid, which in turn controls the sea surface. Ignoring the geoid for the moment, it is quite clear that motion of continents relative to a topography undulation of ~1 km amplitude could play a dominant role in controlling the flooding of continents. But the ratio of geoid to dynamic topography (the admittance) must be considered when determining platform flooding (Gurnis, 1990a). Because admittances are small and positive for the longest wavelength mantle anomalies (Richards and Hager, 1984), continents will be relatively exposed over geoid highs and flooded over geoid lows (Fig. 4)—which is the reverse of what is expected without dynamic topography. With the small admittances, the geoid itself will have a relatively small effect on sea-level change, and if the continents do move over these observed 1 km undulations (Fig. 3), then the continents would flood by more than 75% (Gurnis, 1990a).

RIDGE SPREADING AND WHY SUBDUCTION CANNOT BE IGNORED

Since the acceptance of plate tectonics, variations in the rate of spreading of mid-ocean ridges have been thought to be the primary control on the Phanerozoic transgressions and regressions. According to this standard eustatic model, which was first proposed by Menard (1964), increased rates of plate spreading give rise to an increased volume of oceanic ridges, which in turn leads to a decreased volume of ocean basins. For a constant volume of water, continental platforms would flood during periods of increased spreading. Kominz (1984) has shown that the sea-level change computed from observed changes in the age of the oceanic lithosphere fits the post-Cretaceous inferred eustatic curve (Bond, 1978). But this model is incapable of explaining epeirogenic motions, which are as important as eustatic motions. The discrepancy may arise because the subduction of cold oceanic lithosphere into the mantle is ignored in the standard model (Hager, 1980; Gurnis, 1990b).

Limitations of the spreading-rate–sea-level hypothesis have been highlighted with convection calculations with an imposed oceanic plate (Gurnis, 1990b; Fig. 5). The convection models explicitly account for the effect of a slab returning to the deep interior. For example, when spreading rate is increased from 5 cm/yr to 7.5 cm/yr in the convection model (Fig. 6), sea level for the continental plate rises significantly faster than the rise predicted by the standard model, reaching a maximum 60 m.y. later, and finally falls to half the rise predicted from the standard model. The complex pattern of sea-level change is caused by changes in the thermal structure under plates: when plate spreading increases, cold fluid is dumped under the continent

Mantle Convection
continued on p. 145

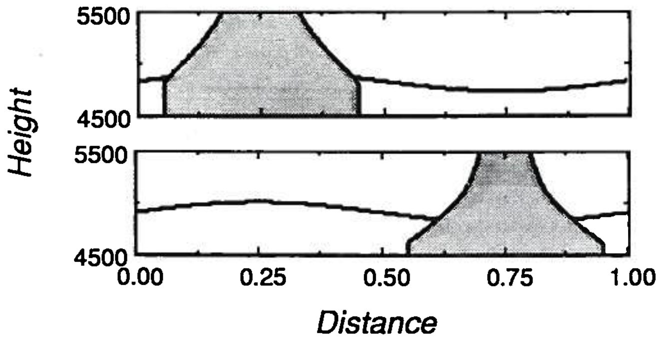


Figure 4. Total topography and sea surface for a one-dimensional continent passively moving over a dynamic topography undulation. The topography of the continent (shaded) is the result of isostatic topography (caused by crustal thickness variations), dynamic topography (with a 200 m amplitude), and sea-water loading. The continent becomes more flooded when positioned over a dynamic topography and geoid low (bottom). From Gurnis (1990a), reproduced from *Nature* by permission, copyright 1990 Macmillan Magazines Limited.

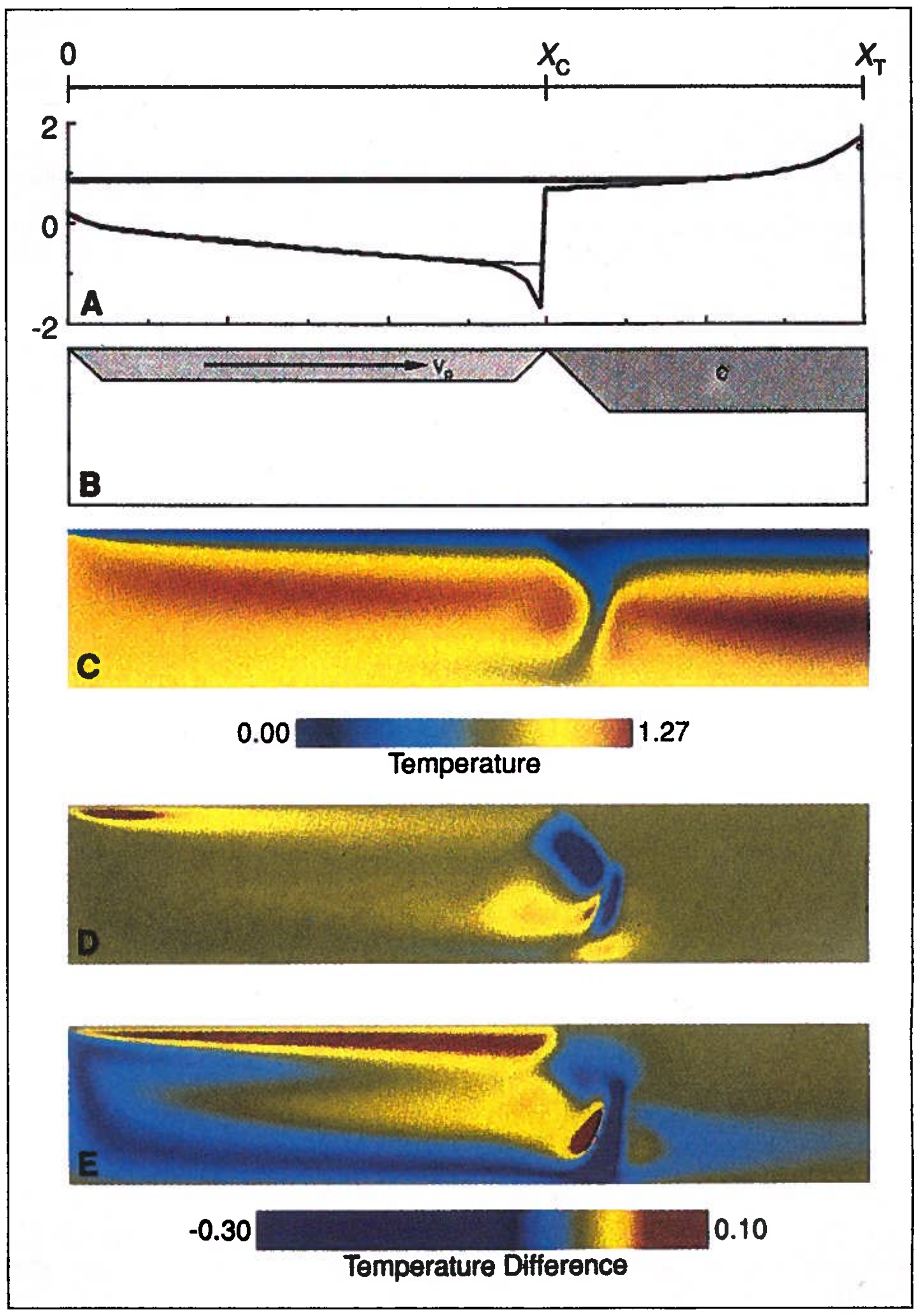


Figure 5. Convection model incorporating an oceanic and a continental plate kinematically. A: The total topography for the convection model at steady state. B: Schematic overview of model set-up showing the oceanic plate, which moves toward the right, and the stationary continental plate. C: The initial thermal structure. The temperature scale has been normalized by the constant basal temperature. D, E: Differential temperatures obtained by subtracting the temperature at time zero (the instant at which spreading increases) from the temperature after 10 m.y. (D) and after about 500 m.y. (E). The parts of the box that increase in temperature become red; those parts that cool become blue. Reproduced from Gurnis (1990c), copyright 1990 by the American Association for the Advancement of Science.

GSA Council Actions—Spring 1992

Council announces the following actions taken at its meeting on May 8, 1992, in Boulder, Colorado.

New Honorary Fellows

Yang Zun-yi
Department of Geology
China University of Geosciences
Xueyuan Road 29
Haidian, Beijing, 100083
Peoples Republic of China

Hans Füchtbauer
Geologisches Institut der Ruhr,
Universität Bochum
Universitätsstrasse 150
W-4630 Bochum 1, Germany

Medal and Award Recipients—1992

Penrose Medal
John F. Dewey
Department of Earth Sciences
University of Oxford
Parks Road
Oxford OX1 3PR, England

Day Medal
Susan W. Kieffer
Department of Geology
Arizona State University
Tempe, AZ 85287-1404

Donath Medal (Young Scientist Award)
John P. Grotzinger
Department of Earth and Planetary Sciences
Room 54-1014
Massachusetts Institute of Technology
Cambridge, MA 02139

GSA Distinguished Service Award
A. R. (Pete) Palmer
445 North Cedarbrook Road
Boulder, CO 80304

Archaeological Geology Division Award
Fekri A. Hassan
Department of Anthropology
Washington State University
Pullman, WA 99164-4910

Gilbert H. Cady Award (Coal Geology Division)
Tom L. Phillips
Department of Plant Biology
University of Illinois
505 South Goodwin Avenue
Urbana, IL 61801

E. B. Burwell, Jr., Award (Engineering Geology Division)
George A. Kiersch
4750 North Camino Luz
Tucson, AZ 85718

George P. Woollard Award (Geophysics Division)
Rob Van der Voo
Department of Geological Sciences
1006 C. C. Little Building
University of Michigan
Ann Arbor, MI 48109-1063

History of Geology Division Award
Michele L. Aldrich
American Association for the Advancement of Science
1333 H Street, N.W.
Washington, DC 20005-4792

O. E. Meinzer Award (Hydrogeology Division)
Craig M. Bethke
Department of Geology
245 Natural History Building
University of Illinois
1301 West Green Street
Urbana, IL 61801

G. K. Gilbert Award (Planetary Geology Division)
John A. Wood
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138

Kirk Bryan Award (Quaternary Geology and Geomorphology Division)
R. Dale Guthrie
Department of Biology and Landlife
Institute of Arctic Biology
Irving Building, Room 211
University of Alaska
Fairbanks, AK 99775

Structural Geology and Tectonics Division Career Contribution Award
John C. Crowell
Institute for Crustal Studies
University of California
Santa Barbara, CA 93106-1100 ■

Mantle Convection
continued from p. 144

(Fig. 5D), pulling the continent down and augmenting sea-level rise due to the shallowing ocean basin. But, as the age of the subducted plate decreases, the continent lifts and sea level falls. The models demonstrate that changes in mantle thermal structure occurring in response to spreading-rate changes cannot be ignored (Gurnis, 1990b). Furthermore, observed eustatic and epeirogenic effects are about equal in magnitude (Bond, 1978, 1979). The reason for this is apparently quite simple: eustatic fluctuations are generated by changes in the relative subsidence of the top thermal boundary layer of convection (the lithosphere), but these same changes in subsidence give rise directly to the dynamic topography fluctuations of a continent that overlies the subducted lithosphere. Thus, creation of a top thermal boundary layer and its injection into the interior is the simplest model of convection, and it directly predicts equivalent eustatic and epeirogenic effects (Gurnis, 1991a).

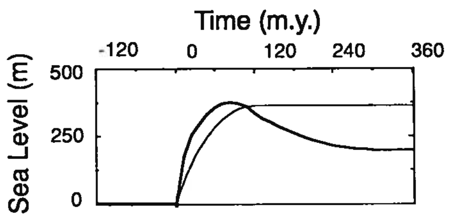


Figure 6. The sea-level curve that results from the convection model shown in Figure 5 (heavy line) compared to the sea-level curve expected from the standard spreading-rate hypothesis.

Details of the vertical motion associated with changes in slab configuration, with no eustatic fluctuations, have been explored in flow models with realistic viscosity variations (Gurnis, 1992). These models predict (Fig. 7) that during a Wilson cycle, dynamic topography resulting from slab subduction causes continental lithosphere to first rapidly subside following the start of subduction (Fig. 7A). As the dip of slab dynamically shallows, the continent will continue to subside, with a basin depocenter and forebulge migrating toward the continental interior (Fig. 7B). Finally, as the ocean basin closes, the continent will regionally uplift (Fig. 7C). The models show that the overriding continental plate can have apparent subsidence rates of up to 200 m/m.y., and they provide a simple explanation for the rapid subsidence of the eastern Laurentian margin which occurred in the mid-Ordovician before the development of the Taconic orogeny (Shanmugam and Lash, 1982). Excessive Cretaceous subsidence of the western interior seaway of North America (Bond, 1976; Cross and Pilger, 1978) is well explained by the second phase as the slab dynamically shallows (Fig. 7B). Finally, the uplift evident during the last phase is applicable to the Cenozoic uplift of western North America following the consumption of the Farallon plate (Damon, 1979; Mitrovica, et al., 1989). The models also predict a close spatial correlation between epeiric seas and subduction zones; generally, this may be the case for the Cretaceous (Bond, 1979), and even the enigmatic motion of Australia may be related to subduction (Veevers and Evans, 1973). At present there is a strong correlation between flooded continent and slabs in the western Pacific (Gurnis, 1991b).

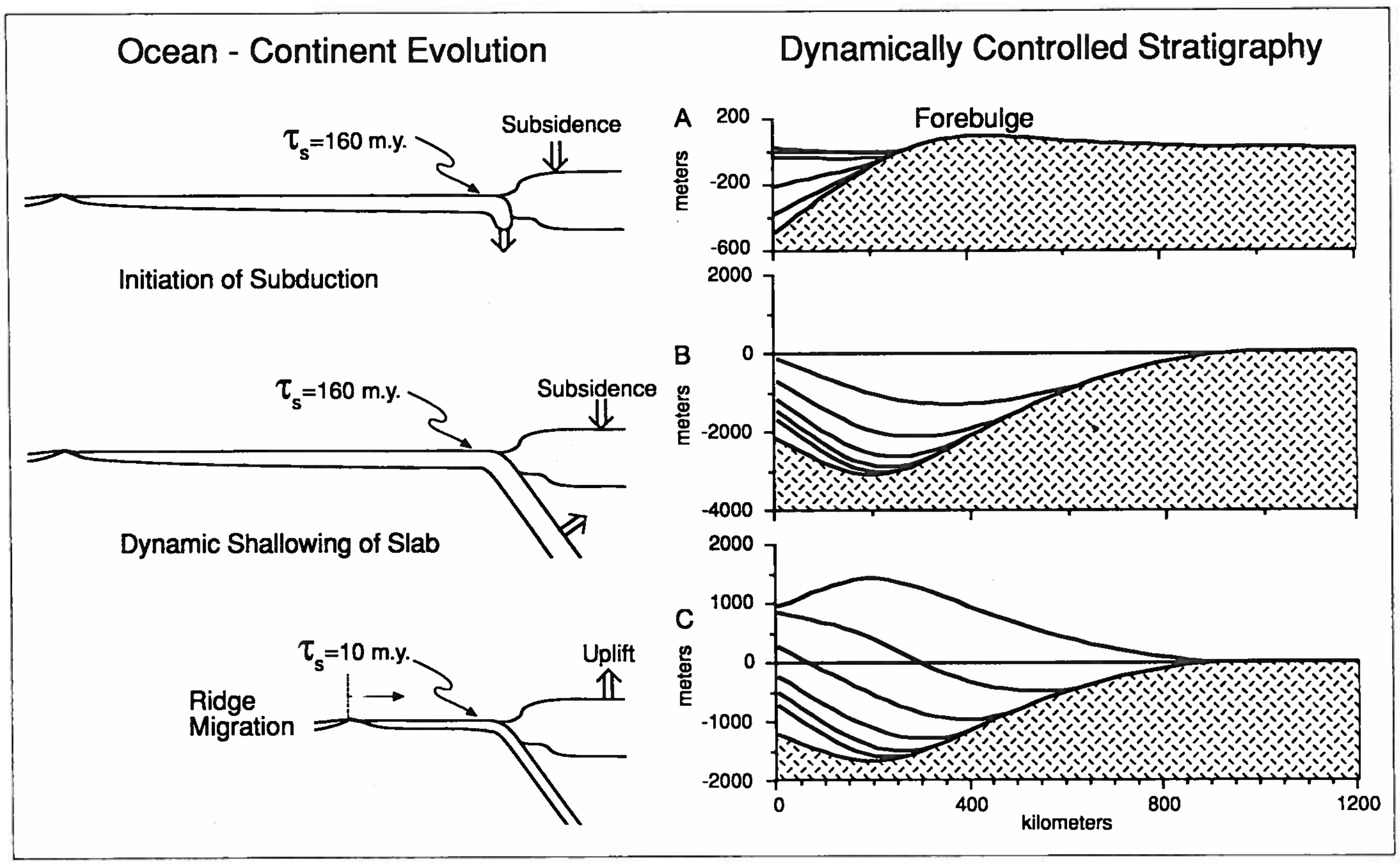


Figure 7. Left: The configuration of oceanic plate and slab during three stages in the evolution of a subduction zone. Right: The stratigraphy that results from subduction, computed from a finite-element model with realistic viscosity variations in the mantle. Thick solid lines on the right are chronostratigraphic surfaces; the line underlain by the stippling is the original land surface. The forebulge results from viscous flow in the mantle and not from the bending of the elastic lithosphere. During the first phase (A) chronostratigraphic surfaces are shown for a slab that successively deepens by 100 km . For a slab that descends at 5 cm/yr, these 100 km slab depth intervals correspond to 2 m.y. chronostratigraphic surfaces. During the second phase (B), the vertical distance between chronostratigraphic surfaces increases for each 10° decrease in slab dip. Reproduced from Gurnis (1992), copyright 1992 by the American Association for the Advancement of Science.

LARGE-SCALE MANTLE CONVECTION AND SUPERCONTINENTS

Bott (1964) was the first to suggest that thick continental lithosphere may inhibit cooling of the underlying mantle and generate large-scale mantle temperature anomalies which in turn cause continental drift. Anderson (1982) suggested that insulation under Pangea may have given rise to the long-wavelength geoid. The importance of insulation can easily be shown: if heat is added (per unit volume) throughout the depth of the mantle under a supercontinent at the same rate heat is being lost from the entire mantle, then the overlying supercontinent would have an uplift rate of ~5 to 10 m/m.y. A global pattern of dynamic topography with an amplitude of 500 m to 1 km could be generated in about 100 m.y.

Would continental fragments simply move with respect to these anomalies once they are generated via insulation? We can now address this question with fully dynamic models of plates

Mantle Convection
continued on p. 156

GSA Congressional Science Fellow Named for 1992–1993

Margaret Goud Collins has been selected as the seventh GSA Congressional Science Fellow. She will work as a special legislative assistant on the staff of a committee or Member of the U.S. Congress from September 1992 through August 1993.

As a Congressional Science Fellow, Goud Collins hopes to work on issues spanning science, education, the environment, and foreign relations, particularly with respect to developing countries. With the aim of strengthening local research and education capabilities in developing countries, her primary focus is to increase the involvement of the American scientific community in formulating and effecting environmental development aid.

Goud Collins received her Ph.D. in oceanography in 1987 from the Woods Hole Oceanographic Institution (WHOI)–MIT Joint Program in Oceanography. Her principal research interests are coastal processes, marine geology, and sediment transport. From 1988 to 1990, Goud Collins worked in Manila at the University of the Philippines Marine Science Institute, teaching and helping to set up graduate programs in marine geology and physical oceanography. She has been at WHOI since her return, investigating and instigating ways of increasing collaborative research between scientists in America and in developing countries. She also participated as a sedimentologist on Leg 134 of the Ocean Drilling Program. Goud Collins received her B.S. in geology from Stanford University in 1978.

The Fellowship

The Congressional Science Fellowship gives a geoscientist first-hand experience with the legislative process and the opportunity to view science policy issues from the lawmaker's perspective. At the same time, the fellow assists in the analysis of public policy issues by providing scientific and technical expertise.

Funded by GSA and by a grant from the U.S. Geological Survey, the fellowship is intended as a way to demonstrate the value of such science-government interaction, and to educate the earth science community about the need for informed involvement. The program places highly qualified, accomplished scientists with the offices of individual members of Congress or committees for a one-year assignment. Fellows perform in much the same way as regular staff members; they have the opportunity to be involved in varied legislative, oversight, and investigative activities. They offer their special knowledge, skills, and competence for the opportunity to acquire experience and the chance to contribute to the formulation of national policy. The GSA Congressional Fellow reports periodically to the GSA membership and to the USGS during the one-year period.

Requirements for the fellowship include exceptional competence in some area of the earth sciences, cognizance of a broad range of matters outside the fellow's particular area, and a strong interest in working on a range of public policy problems. Fellows attend a two-week orientation conducted by the American Association for the Advancement of Science.

Selection Committee

On the selection committee for the fellowship this year were Brian E. Tucker, Oyo-Pacific; William L. Fisher, Bureau of Economic Geology, University of Texas at Austin; Richard Witmer, USGS; and Craig M. Schiffries, AGI. ■

Mantle Convection

continued from p. 145

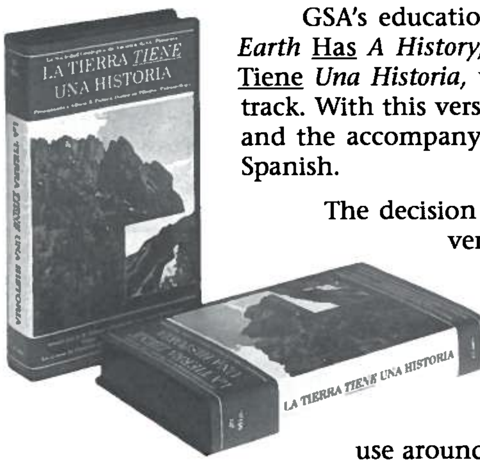
and convection (Gurnis, 1988). In a fully dynamic model of a nonsubducting plate interacting with convection, it was found that the continent remained stationary for an extended period as the temperature beneath the continent increased (Gurnis, 1990c; Fig. 8 here). During this period when the plate was stationary, the continent was uplifted and the sea regressed from the continent. The continent then rapidly moved horizontally away from the long-wavelength hot and topographically high area toward the cold and topographically low area. The continent moved downward during this rapid horizontal translation such that a transgression followed a pulse of rapid horizontal motion. Finally, the continent again settled over the cold area and the process was repeated. (The physics of subplate heating, horizontal motion, and sea-level change are particularly well illustrated in three-dimensional animations appearing on the video tape accompanying Gurnis, 1990c.) The models demonstrate that it is plausible for supercontinents to

Mantle Convection
continued on p. 157

La Tierra Tiene *Una Historia*—¡Ahora disponible en Español!

The Earth Has *A History* Now Available in Spanish

Jim Clark, GSA Marketing Manager



GSA's educational video and 16mm film *The Earth* Has *A History,* is now available as *La Tierra* Tiene *Una Historia,* with a Spanish-language audio track. With this version, the cover of the video case and the accompanying teacher's aid is supplied in Spanish.

The decision to produce a Spanish-language version was prompted by the success of this study module and by requests from educators in Mexico. The English-language version was introduced in late 1989, and nearly 2000 copies are now in use around the world. The video has been highly praised by educators, and it carries an attractive price tag ($25 list) for a 20-minute study module of this quality.

The video demonstrates, in simple terms, the principals of geologic time—or "deep" time—by literally walking the viewer *through* time, as reflected in the geology of the Flatirons area of the Rocky Mountain Front Range near Boulder, Colorado. It is recommended as an opening module for the geology section of earth-science courses or for a biology section on the record of life on Earth. It is "...an excellent resource for introducing the concept of geologic time; an opportunity for a super field trip without the hassle," according to Betty Wade Jones, presidential award winning earth-science teacher from Clements Junior High School, Prince George, Virginia.

It is our hope that the Spanish-language version will encourage use of the video in schools throughout Mexico and other Spanish-speaking countries, as well as in areas of the United States where Spanish is a predominant language.

The video—in English or Spanish—is now available in either VHS or BETA cassette style, and in the three most popular electronic formats: NTSC—the standard in the United States, Canada, Mexico, Japan, and 42 other countries; PAL—the standard in the United Kingdom, Australia, western Germany, and 61 others; and SECAM—the standard in France, eastern Germany, and 35 others. When ordering copies of the video, be sure to specify all three of these options.

(1) **Language:** English or Spanish
(2) **Cassette style:** VHS or BETA
(3) **Electronic format:** NTSC, PAL, or SECAM. (Few people are aware that different electronic formats exist. Tapes produced in one format and played on a player using another will be distorted or have no picture, and the sound will be garbled.)

If you are unsure which format you need, follow this rule: if your player successfully plays the video tapes commonly available in your country, ask us for the format that is standard in your country. We have a guide that lists all countries and the standards used in each, and we will supply the correct one.

If your player cannot successfully play video tapes available in your country, then you need to specify which format it uses. Your user's manual should state the format. If it does not, write to the manufacturer of the player, providing serial and model numbers, or consult a local electronics repair shop.

Copies of the video may be ordered from GSA Publication Sales, P.O. Box 9140, Boulder, CO 80301-9140, 1-800-472-1988—toll-free from the United States (outside Colorado) or (303) 447-2020. ■

Mantle Convection
continued from p. 156

break up and for the fragments to have little influence on the structure of long-wavelength thermal anomalies as they move horizontally—indeed, the continents seem to ride over a nearly immobile dynamic topography. Kominz and Bond (1991) suggested that rapid synchronous subsidence in marginal and interior basins of North America during middle Paleozoic time is consistent with the dynamic downwelling and compression that would affect continents as they assembled into a supercontinent.

These studies highlight a fundamental ambiguity in determining the causes of sea-level change. Because the average age of oceanic lithosphere decreases for tens of millions of years following supercontinent breakup (Heller and Angevine, 1985), we would expect the dynamic subsidence of continental fragments to be in phase with the eustatic sea-level rise associated with the decreased age of the sea floor (Gurnis, 1991a). In particular, even though an empirical correlation may occur between spreading rate and sea level, the sea level may not be primarily controlled by the "decreased volume" of the ocean basin—much of the change in sea level could be caused by dynamic subsidence. This was recognized earlier by Worsley et al., (1984) without the use of dynamic models.

SUMMARY AND FUTURE PROGRESS

The models reviewed here of mantle convection incorporating rudimentary oceanic and continental plates demonstrate that deep mantle convection can be a dominant control on long-term sea-level fluctuations. The oceanic lithosphere and in particular changes in the spreading rate of mid-ocean ridges are just one component of a globally coupled system. Changes in spreading lead directly to changes in the rate of subduction. Subduction can control the vertical motion and apparent sea level of the overriding continent. Longer term variations in spreading and continental insulation lead to the development of global scale variations in mantle temperature, and these fluctuations lead to changes in the relative height between one region and another elsewhere on the surface of Earth. A global scale undulation in dynamic topography, originally inferred from studies of the geoid but now observed directly, has an amplitude of about 1 km. Motion of the continents with respect to this topography could lead to the nearly complete flooding of platforms.

The major convection processes reviewed are summarized in Figure 1: ridge spreading, subduction, and the development of large-scale thermal anomalies. In comparison to dynamic topography, fluctuations in the geoid, which controls the sea surface, probably play only a small role in sea-level change. Mantle plumes, another important mode of mantle convection, may influence sea level via the impingement of a plume or diapir beneath the lithosphere, leading to the rapid dynamic uplift over a few thousand kilometres (Olson and Nam, 1986; Griffiths et al., 1989). The role of plumes has yet to be explicitly studied.

Unfortunately, the models of plates and convection have been illustrative rather than definitive. Enormous progress still must be made before we fully understand the interrelations between continental stratigraphy and mantle dynamics. Work must proceed in two areas. First, the modeled thermal convection drives dynamic topography and geoid fluctuations, and from these fluctuations we must make realistic predictions of the resulting sedimentary packages. Calculation of synthetic sequence stratigraphy resulting from plate bending and supracrustal loading is already well developed (see papers in Cross, 1990). Second, we need more realistic mantle convection models incorporating tectonic plates. For example, in the models with a nonsubducting plate and convection (e.g., Fig. 8), a realistic oceanic lithosphere now must be incorporated so that the relative importance of dynamic subsidence vs. spreading can be quantitatively explored. The dynamic balance between convection and oceanic and continental plates has been explored in other models (Gurnis and Hager, 1988), but these models incorporated plate margins in an ad hoc way. Recent progress with faults in viscous models of thermal convection (Zhong and Gurnis, 1992) will lead to much more realistic ocean-continent models. If we are to predict the three-dimensional pattern of stratigraphy and isopachs on a continent, then we must employ three-dimensional spherical models of convection with plates. Up to now, modeling of convection in spheres has been in isoviscous media without plates (e.g., Schubert, 1992), but with the rapid development of numerical algorithms, especially those for massively parallel supercomputers, spherical models with plates should be appearing within the next year.

The ability to model the dynamics of continental and oceanic plates, plate boundaries, and mantle convection will almost certainly lead to a new era of deciphering the ultimate causes of the longest term patterns in the sedimentary history of the continents. Inversion of continental stratigraphy may ultimately lead to important constraints on the evolution through time of mantle convection.

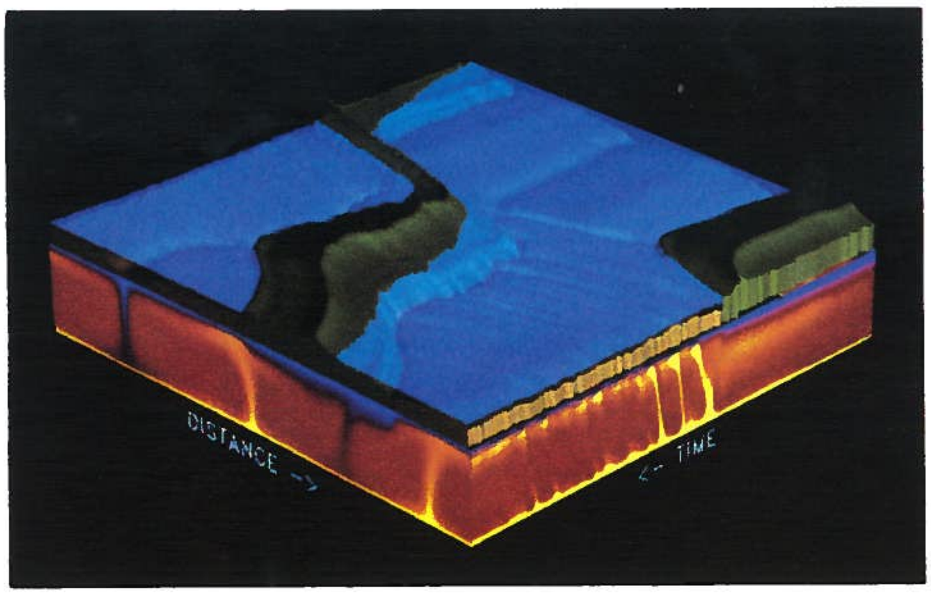


Figure 8. Three-dimensional visualization of a two-dimensional model of a nonsubduction continental plate interacting with thermal convection as a function of time. The front vertical face is the temperature field at the end of the simulation; yellow is hottest and blue is coldest. The side vertical face is the temperature field of a column that remains fixed relative to the center of mass of the system. From the back face toward the front face represents about 1 b.y. On the top surface the total topography and sea surface are displayed. One light illuminates the top from the upper right. The continental regions are green and the oceanic regions brown, and the water-surface is a transparent blue. At the start of the simulation, the continent is stationary and lies at the edges of the box (the model has periodic boundary conditions so that what flows out one side comes in the other). A third of the way through the progression of time, the continent rapidly moves horizontally and floods. Three-dimensional animations of this and other simulations can be found in Gurnis (1990c). Reproduced from Gurnis (1990c). Copyright 1990 by the American Geophysical Union.

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