NASA

Technical Memorandum **79669**

Emergence of the Continents

Herbert Frey

(NASA-TM-79669) EMERGENCE OF THE CONTINENTS N79-16475
(NASA) 17 p HC A02/MF A01 CSCI 08F

Unclas
G3/46 13567

NOVEMBER 1978

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

EMERGENCE OF THE CONTINENTS

Herbert Frey

Geophysics Branch
NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

and

Astronomy Program
University of Maryland
College Park, Maryland 20742

submitted to Origins of Life

ABSTRACT

If early degassing of the Earth produced a global ocean several km deep overlying a global sialic crust, then late heavy bombardment of that crust by basin forming impacting bodies would have produced topography such that by 4 billion years ago dry "continental" landmasses would stand above sea level. From extrapolation of lunar crater statistics, at least 50% of an original global crust on the Earth would have been converted into basins averaging 4 km deep after isostatic adjustment. These basins formed the sink into which such a global ocean would drain. If the ocean was initially 2 km deep, then approximately 50% of the early Earth would have stood above sea level when the late heavy bombardment came to a close.

INTRODUCTION

The nature of the earliest crust of the Earth is a subject of intense debate. Uncertainties on the nature and extent of crustal materials result from the scarcity of geologic data prior to 3.5 billion years ago. Yet this is the very time frame in which so much of what is present on the Earth today began. Not the least of these is the origin of life. While only the existence of water is probably required for the formation of the first organisms, subsequent evolution probably depended critically on the nature of the Archaean environment. This paper addresses one of the most fundamental aspects of that environment: the existence of dry land and water on the early Earth.

Hargraves has suggested a model for the primitive Earth that included a global sea roughly 2 km deep overlying a sialic crust. In this theory the "emergence" of continental masses from the global ocean is delayed until 1.7-2.3 billion years ago, or to the late Precambrian, depending on the data used to infer the appearance of dry land. Comparative planetary studies suggest instead that emergence of dry continental masses occurred by at latest 4 billion years ago, even if the primordial Earth was originally covered by a global sea.

IMPACTS AND EARLY CRUSTAL STRUCTURE

The enormous activity of the Earth has been very efficient at removing very ancient rocks; it is therefore extremely hard to construct a detailed theory of the Archaean crust of the Earth from terrestrial data alone. Constraints on such theories are available from comparative planetary data, when allowance is made for the different sizes, masses and bulk compositions involved. This is especially true for the early cratering effects, which are much more fully preserved in the highland crusts of the smaller terrestrial planets, and which are almost negligibly present on the Earth. Recently, dynamical modeling of planetesimal distributions (Wetherill, 1975) have been incorporated into the establishment of cratering chronologies for the inner solar system by Hartmann (1977). These have important implications for the Earth, whose early history must also have been affected by the late stage heavy bombardment which is largely responsible for the Moon's crustal structure (Frey, 1977a,b).

Comparative planetary data suggests the Earth's original differentiation produced a global crust of intermediate composition; the present day continents may represent redifferentiated remnants of the primordial crust (Lowman, 1976, 1978). Likewise, terrestrial data has been interpreted by Shaw (1972, 1976) and Hargraves (1976) as also implying an original global sialic crust. How then was some 60% of such an original global low density crust converted into the higher density "oceanic" crust which dominates the Earth's surface today? Plate tectonic processes, which generate oceanic crust today, are inadequate because of the difficulty in subducting sialic lithosphere once this formed (McKenzie, 1973; Molnar and Gray, 1979). This is especially true for the early Earth, when thickness of the lithosphere was undoubtably less than today. Rather it may be argued that "oceanic" crust must have been present before the onset of plate tectonic activity, which may have been effective early in Earth history (McKenzie and Weiss, 1975; Burke et al., 1976). A plausible mechanism for producing an early crustal dichotomy superficially similar to the present one is through basin-forming impact bombardment (Frey, 1977b) which appears to have been widespread in the inner solar system until 4 billion years ago (Murray et al., 1975). The crustal dichotomies of the Moon, Mercury and Mars (older low density highlands, younger higher density maria) can be traced to this bombardment. The Earth could not have escaped this bombardment regardless of whether it was due to late stage accretional sweep-up (Wetherill, 1976) or to a special flux of objects (Chapman, 1976).

Scaling from the observed number of lunar impact basins (a minimum number) provides a lower limit to the number of such basins which formed on the Earth (Frey, 1977b). When both the greater velocity of impact (which affects crater diameter) and the much greater gravitational collecting area of the Earth (which affects the number of impacts per unit area) are considered, at least 50% of an assumed original global crust on the Earth would have been converted into large basins. By 4 billion years ago more than 60 craters with diameters exceeding 1000 km would have formed. It is even possible that the Earth sustained impacts which produced a few extremely large basins, more than 4000 km across (Frey, 1978).

The major effects of such a basin-forming impact bombardment on an original andesitic crust some 20 km thick would have included the following:

a. Establishment of a topographic dichotomy. Though initially deeper, the basins would adjust isostatically over several thousand years, leaving floors some 4 km below basin rims (Frey, 1977a).

b. Localization of basaltic flooding in the basin floor. Excavation of a 1000 km wide impact basin would induce pressure-release partial melting below the basin. Basaltic lavas from a peridotite or pyrolite mantle would rise rapidly through the badly fractured lithosphere below the basin, erupting onto the basin floor in times short compared with the isostatic adjustment (Frey, 1977b).

c. Complex thermal effects. Penetration to deeper, hotter layers would tend to steepen thermal gradients across the newly exposed surface layer as it cooled by radiation. This would have stirred whatever convection must have existed in the early asthenosphere of the Earth below the basin (McKenzie and Weiss, 1976). This may have been partially offset by heat deposited in the basin by the impact itself (Safronov, 1978; Dence et al., 1977). Note, however, that Green (1975) has argued that some ancient Archaean rocks require exceptionally high geothermal gradients.

EFFECTS ON SEA LEVEL

If the early Earth had already degassed enough water so that the original crust was covered by 2 km of water (Hargraves, 1976), then the formation of such large impact basins had another important effect: the lowering of sea level. The cumulative effect of converting an increasing percentage of the Earth's surface into basins roughly 4 km deep would eventually drain the water and expose the higher topography of the basin rims. Figure 1 shows this effect. The cumulative volume of basins increases linearly with the percentage of the Earth's surface converted into basins. For simplicity, all basins are assumed to have an adjusted depth of 4 km, although this is only an average value. The volume of water minus the volume of basins decreases at the same rate; these curves cross at 0.25 of the Earth's surface converted into basins. At this point the cumulative volume of basins formed equals half the volume of the proposed original global ocean, and sea level has dropped from 2 to 1 km, as shown by the short dashed curve. Given that impacts which are capable of producing a basin 1000 km across also produce rim relief of at least 1 km (Pike, 1967), some highland basin rims are already emergent when basins cover only 25% of the Earth surface. If 50% of the Earth's surface was ultimately converted into basins 4 km deep, sea level would have dropped to about the original crustal radius of the Earth, leaving nearly one half of the surface (at least slightly) above sea level.

A cartoon version of the lowering of sea level is plotted in Figure 2. The net effect of the basin-forming bombardment is to drain the water of the original global ocean, if it existed, into deep basins, exposing as dry land the continental "highland" crust. In Hargraves (1976) model true continental crust requires much longer to thicken and emerge from below the sea. The redistribution of sialic crust by impact accomplishes this emergence long before 2.3 billion years ago, which is the earliest date suggested by Hargraves.

DISCUSSION

The implications of the emergence of dry continental crust are many. While not required for the origin of life, dry land was certainly important in the subsequent evolution of life on this planet. All mammals on Earth, including marine mammals, are derived from land-dwelling reptilian stock

(McAlestar, 1968). Although this occurred quite late in the history of the Earth, earlier evolution may also have been influenced by the exposure of dry highlands through basin-forming impacts. As shown in Figure 3, a late forming basin whose rim is thrust above sea level should erode rapidly due to the highly fractured nature of the rim rocks. Giant sedimentary deltas should have formed quickly, producing early analogs to the shallow continental shelves of today. These may have been conducive shallow water environments for the evolution of early photosynthetic lifeforms. The transport of crustal sediments into the basins may have provided important concentrations of minerals there, as may the eruptions of basalts in the basin floors.

The model of continental emergence by basin-forming impacts says nothing directly about the degassing history of the Earth. It is not clear that a global ocean did exist 4 billion years ago, though most modern theories favor early catastrophic degassing of the Earth (Fanale, 1971). Rather the above analysis demonstrates the utility of comparative planetary studies in constraining models of the early Earth. If there was an original global ocean covering a global sialic crust, then dry continental masses existed by 4 billion years ago, due to the late basin-forming bombardment. If water was degassed more slowly over time, then the large mare-type basins already existing by 4 billion years ago provided natural sinks into which that water would drain. The early crustal evolution of the Earth was significantly affected by large, late forming impacts, but appreciation of the magnitude and implications of those effects requires the data and perspective that can only be provided by comparative planetary studies (Frey, 1978).

ACKNOWLEDGEMENTS

This paper is based on a presentation made at the 4th College Park Colloquium on Chemical Evolution--Limits of Life, October 20-23, 1978. I would like to thank Cyril Ponnamparuma for the opportunity to address that meeting. I am also grateful for the encouragement of and fruitful discussions with Paul Lowman and Michael A'Hearn. This work was supported by NASA Grant NGL-21-002-033.

REFERENCES

Burke, K., J.F. Dewey and W.S.F. Kidd (1976), Dominance of Horizontal Movements, Arc and Microcontinental Collisions During the Later Permobile Regime. In The Earth History of the Earth (B.F. Windley, Ed.), pp. 113-130.

Chapman, C.R. (1976), Chronology of Terrestrial Planet Evolution: The Evidence from Mercury. Icarus, 28, 523 536.

Dence, M.R., R.A.F. Grieve and P.B. Robertson (1977), Terrestrial Impact Structures: Principle Characteristics and Energy Considerations. In Impact and Explosion Cratering (D.J. Rodey, R.O. Pepin and R.B. Merrill, Ed.). pp.247-275.

Fanale, F. (1971), A Case for Catastrophic Early Degassing of the Earth. Chem. Geol. 8, 79-105.

Frey, H. (1977a), Crustal Evolution in the Early Earth: Basin-Forming Impacts, Crustal Dichotomy and Plate Tectonics. Ph.D. Thesis, University of Maryland.

Frey, H. (1977b), Origin of the Earth's Ocean Basins. Icarus, 32, 235-250.

Frey, H. (1978), Crustal Evolution in the Early Earth: The Role of Major Impacts. Paper presented at special symposium "Comparative Planetary Evolution: Implications for the Proto-Archaean," 91st Meeting Geol. Soc. Am., Abstracts with Programs, 10, 404.

Green, D.H. (1975), Genesis of Archaean Peridotitic Magmas and Constraints on Archaean Geothermal Gradients and Tectonics. Geology, 3, 15-18.

Hargraves, R.B. (1976), Precambrian Geologic Evolution. Science, 193, 363.

Hartmann, W.K. (1977), Relative Crater Production Rates on Planets. Icarus, 31, 260-276.

Lowman, P.D. (1976), Crustal Evolution in Silicate Planets: Implications for the Origin of Continents. J. Geol., 84, 1-26.

Lowman, P.D. (1978), Crustal Evolution in the Silicate Planets. Naturwissenshaften, 65, 117-124.

McAlestar, A.L. (1968), History of Life (Prentice Hall).

McKenzie, D. (1973), Speculations on the Consequences and Causes of Plate Motions. In Plate Tectonics and Geomagnetic Reversals (Freeman & Company), 447-469.

McKenzie, D. and N. Weiss (1975), Speculations on the Thermal and Tectonic History of the Earth, Geophys. J. Roy. Astron. Soc., 42, 131-174.

Molnar, P. and D. Gray (1979), Subduction of Continental Lithosphere: Some Constraints and Uncertainties. Geology, 7, 58-62.

Murray, B.C., R.G. Strom, N.J. Trask and D.E. Gault (1975), Surface History of Mercury: Implications for Terrestrial Planets. J. Geophys. Res., 80, 2508-2514.

Pike, R.J. (1967), Schroeter's Rule and the Modification of Lunar Crater Morphology. J. Geophys. Res., 72, 2099-2106.

Safronov, V.S. (1978), The Heating of the Earth During its Formation, Icarus, 33, 3-12.

Shaw, D.M. (1972), Development of the Early Continental Crust. Part 1. Use of Trace Element Distribution Coefficient Models for the Proto-Archaean Crust. Con. J. Earth Sci., 9, 1577-1595.

Shaw, D.M. (1976), Development of the Early Continental Crust. Part. Pre-archean, Proto-archean and Later Eras. In The Early History of the Earth (B.F. Windley, Ed.), pp. 33-53 (Wiley).

Wetherill, G.W. (1975), Late Heavy Bombardment of the Moon and Terrestrial Planets. Proc. Lun. Sci. Conf., 6, 1539-1561.

Wetherill, G.W. (1976), Comments on the paper by C.R. Chapman: Chronology of Terrestrial Planet Evolution--The Evidence from Mercury. Icarus, 28, 537-542.

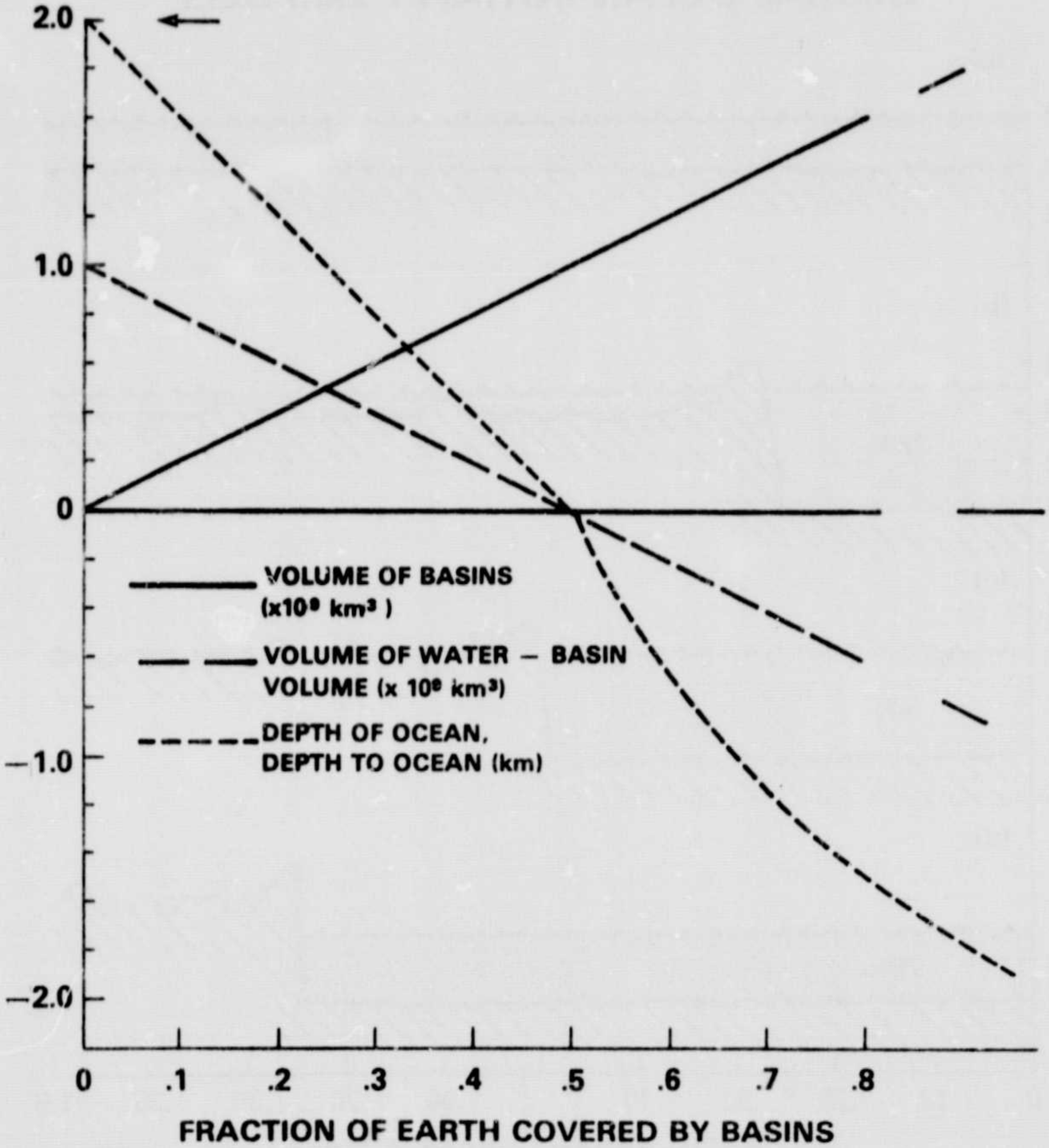
FIGURE CAPTIONS:

Figure 1: Change in cumulative basin volume (solid line), water volume - basin volume (long dashes) and depth of ocean (short dashes) versus fraction of Earth surface converted into basins. An initial global sea level of 2 km depth has been assumed (1). The mean depth of basins (after isostatic adjustment) is taken as 4 km (4).

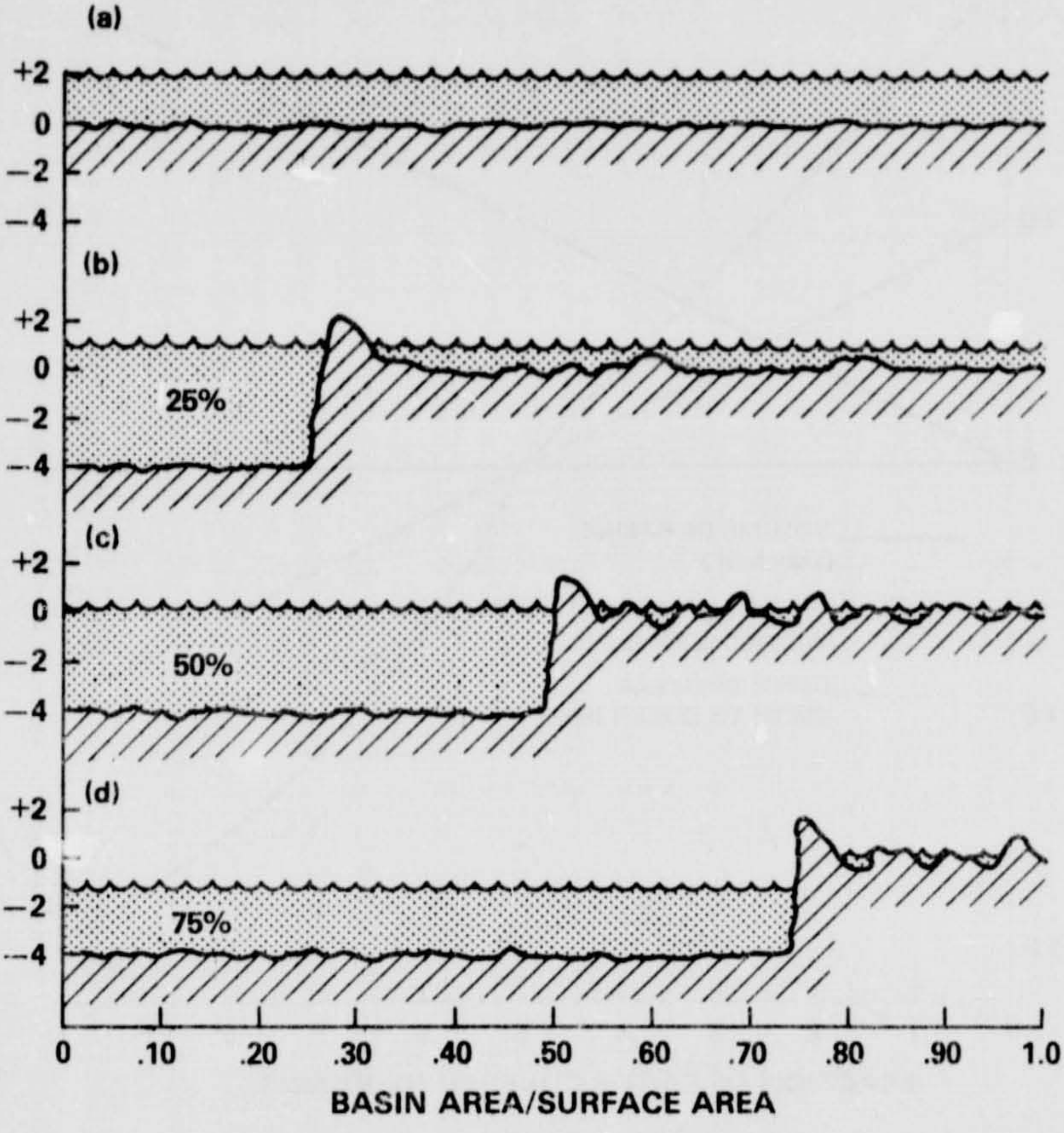
Figure 2: Change in sea level as the percentage of Earth surface converted into basins increases. Allowing for relief caused by impact basin formation, some basin rims emerge when only 25% of the surface has been converted into basins (b). When 50% of the surface has been turned into basins, mean sea level equals original crustal radius (c), causing approximately one-half of the surface to be dry land.

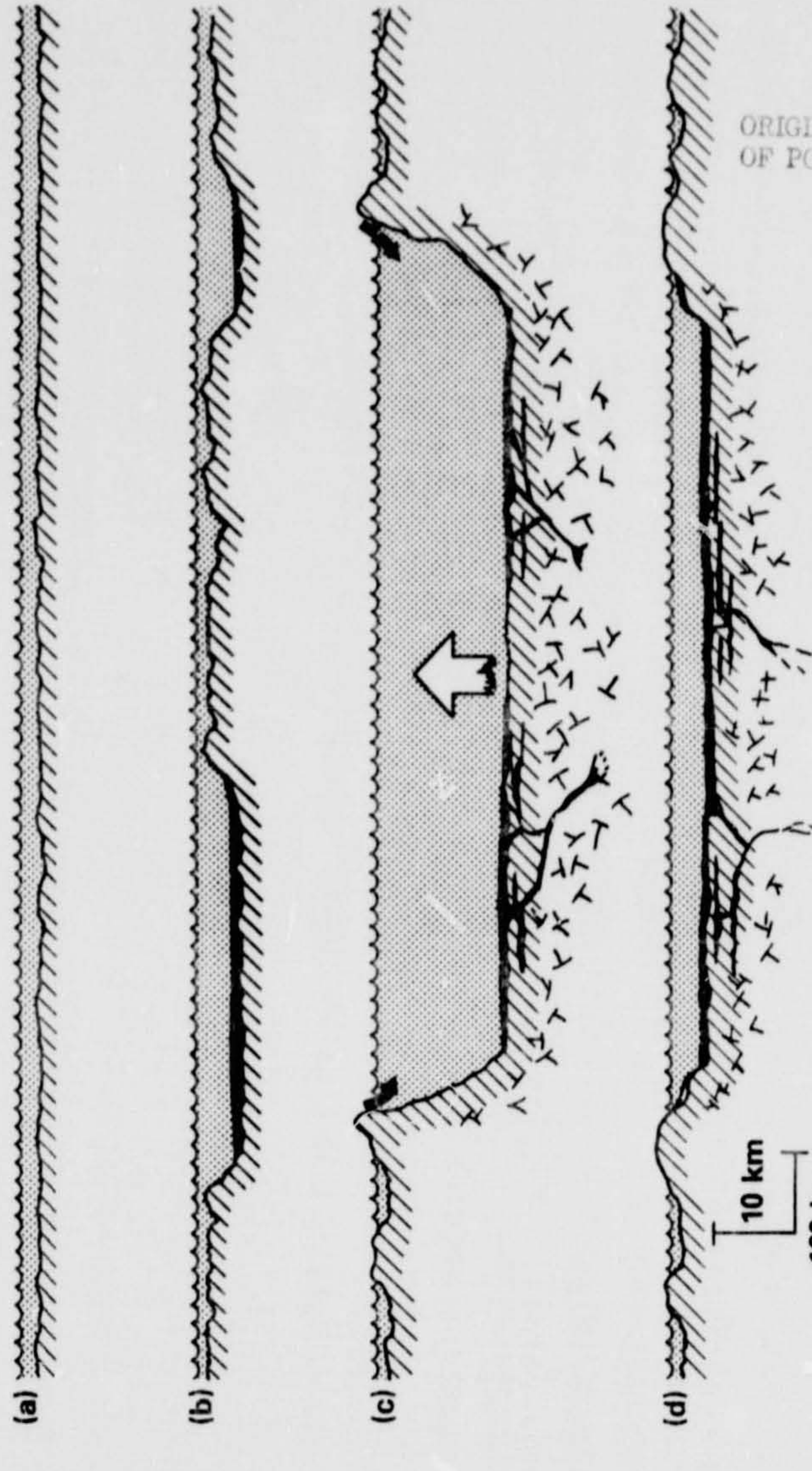
Figure 3: Lowering of sea level (a,b) exposes basin rims to rapid erosion (c), creating large sedimentary fans (d) as basin floor adjusts upward isostatically. Flooding of basin floor by basalt rapidly follows impact (c,d).

CHANGE IN MEAN SEA LEVEL



GLOBAL OCEAN INITIALLY 2km DEEP




(a)
(b)
(c)
(d)
10 km
100 km