Subsidence of the Scotian Basin:

A Theoretical Model

by

Robin C. Mann

Submitted in partial fulfillment of
the requirements for the degree of
Honours Bachelor of Science

Dalhousie University

Halifax, Nova Scotia

Distribution License

DalSpace requires agreement to this non-exclusive distribution license before your item can appear on DalSpace.

NON-EXCLUSIVE DISTRIBUTION LICENSE

You (the author(s) or copyright owner) grant to Dalhousie University the non-exclusive right to reproduce and distribute your submission worldwide in any medium.

You agree that Dalhousie University may, without changing the content, reformat the submission for the purpose of preservation.

You also agree that Dalhousie University may keep more than one copy of this submission for purposes of security, back-up and preservation.

You agree that the submission is your original work, and that you have the right to grant the rights contained in this license. You also agree that your submission does not, to the best of your knowledge, infringe upon anyone's copyright.

If the submission contains material for which you do not hold copyright, you agree that you have obtained the unrestricted permission of the copyright owner to grant Dalhousie University the rights required by this license, and that such third-party owned material is clearly identified and acknowledged within the text or content of the submission.

If the submission is based upon work that has been sponsored or supported by an agency or organization other than Dalhousie University, you assert that you have fulfilled any right of review or other obligations required by such contract or agreement.

Dalhousie University will clearly identify your name(s) as the author(s) or owner(s) of the submission, and will not make any alteration to the content of the files that you have submitted.

If you have questions regarding this license please contact the repository manager at dalspace@dal.ca.

Grant the distribution license by signing and dating below.

______________________________ ______________________________

Name of signatory Date

TABLE OF CONTENTS

Abstract

The development of a continental margin basin such as the Scotian Basin depends on various factors, exponential thermal contraction, sedimentary loading and the physical properties of the lithosphere underlying the basin.

From recent studies of the Scotian Basin it is concluded that the Basin has subsided exponentially with time with an exponential time constant of 50 m.y. to 60 m.y. in the western half of the Basin and 70 to 80 m.y. in the eastern half, since the final breaking apart of Africa and North America (160 to 170 m.y. ago). Sedimentation has also played an important role in the subsidence history of the Scotian Basin. During early stages of basin development sedimentation was rapid and constant. Later it gradually slowed and the Basin became an area of deep marine sedimentation (approximately 70 m.y. to 40 m.y. b.p.). Sedimentation rates then increased refilling the basin to its present shelf environment.

The modelling of a basin representing regional isostatic adjustment in a simplified Scotian Basin was done in three stages. First, the point load response of a viscoelastic plate (simulating the lithosphere) was found. Second, convolutions were evaluated representing a square load. Finally, the square loads were applied to a 500 x 500 km grid representing the Scotian Basin. The viscoelastic plate used to simulate the lithosphere underlying the Basin had varying flexural rigidities and viscous time constants. The best results were

obtained when the flexural rigidity was taken as 10^{25} n.m. and the viscous time constant was 10^5 to 10^6 yrs. Sediment influx into the oceanic side of the theoretical Basin was kept at a constant 1000 meters per 20 m.yrs., a reasonable approximation to the observed sedimentation rates. Sediment influx onto the continental margin was assumed to be just sufficient to fill the subsiding area.

The model results obtained for a 160 m.y. time history gave a close approximation of the sediment accumulation in the Scotian Basin. We suggest minor improvements that would give model results that more closely represent subsidence in the Scotian Basin.

List of Figures

PAGE

List of Tables

Acknowledgements

I would like to thank, and am greatly indebted to, my supervisor Dr. C. Beaumont for his useful guidance and patience throughout all phases of this study. I would also like to thank Kathie Beaumont for her many hours spent at the computer centre punching the data used in this study.

I am also indebted to Bedford Institute of Oceanography, especially Dr. L. Jansa, Dr. L. King and Mr. J. Wade for their cooperation and assistance during the collecting of the oil company data from their files.

Lastly, I would like to thank Patty Burke for her time spent running some of the computer programs, but especially for her encouragement that was needed to complete this study.

Part of this study was funded by Earth Physics Branch contract number 06SU23235-6-1033.

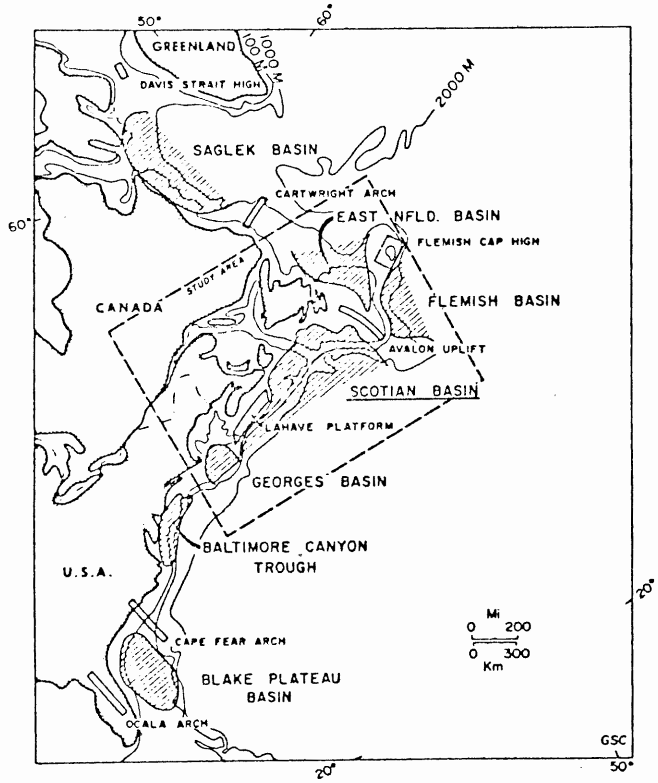
Introduction

The continental margin of Atlantic Canada has been developing since the final rifting of Africa from North America, 160 to 170 m.y. ago (Jansa *et al.*, 1975). The development of Atlantic Canada's continental margin, in particular the Scotian Basin (Figure 1), is thought to be the result of three main processes: 1) thermal uplift and erosion prior to rifting of Africa and North America followed by thermal contraction resulting in the initial subsidence of the Scotian Basin as described by Sleep (1971); 2) transform faulting at the eastern end of the Scotian Basin as discussed by King *et al.* (1975); and finally, 3) the contemporaneous formation of the thick sedimentary sequence in the Scotian Basin to form the continental shelf, slope and rise. The formation of the thick sedimentary sequence, exceeding 10 km in some places, has been controlled in part at the eastern end of the basin by transform faulting and by subsidence resulting from thermal contraction throughout.

Since there is a thick sedimentary sequence in the Scotian Basin the history of development of the Basin must depend on the process of isostatic adjustment and consequently on the response characteristics of the lithosphere to a sedimentary load that increases with time. Therefore, in any model describing the subsidence of the Scotian Basin, the physical properties of the lithosphere must be examined.

The major physical properties are:

Figure 1: Index map showing Mesozoic and Cenozoic depocenters. The Scotian Basin is in the blocked off area.



50°
60°
GREENLAND
1000 M
DAVIS STRAIT HIGH
2000 M
SAGLEK BASIN
CARTWRIGHT ARCH
EAST NFLD. BASIN
FLEMISH CAP HIGH
CANADA
STUDY AREA
FLEMISH BASIN
AVALON UPLIFT
SCOTIAN BASIN
LAHAVE PLATFORM
GEORGES BASIN
BALTIMORE CANYON
TROUGH
U.S.A.
Mi
0 200
0 300
Km
CAPE FEAR ARCH
BLAKE PLATEAU
BASIN
OCALA ARCH
GSC
20°
50°

i) The magnitude of the load in the Basin as a function of time, calculated by using an approximate sediment density and observed sedimentary accumulation during set time intervals.

ii) The viscous relaxation time constant that characterizes the viscous properties of the lithosphere, if the lithosphere is approximated by a viscoelastic plate.

iii) The flexural rigidity of the lithosphere, which characterizes the elastic properties as opposed to the above viscous properties.

iv) The density and mobility of the asthenosphere laying below the lithosphere and under the developing basin.

Using the above physical parameters, a theoretical subsidence model was developed that predicts the lithospheric response to the sedimentary loading process. The accumulation of sediment predicted by the model was then compared with observations to determine whether the model develops in accordance with observations (in the case described here the model represents a simplified Scotian Basin).

Well data obtained by Shell Canada Ltd. and Amoco Canada Petroleum Company Ltd. while drilling structures in preliminary oil exploration in the Scotian Basin and on its flanks was used to determine a general subsidence history for comparison with the theoretical model. The well data used from both the Scotian Shelf (drilled by Shell) and Grand Banks (Amoco) was obtained from wells drilled on salt domes and other related possible oil trap structures, so the subsidence history of the basin is not determined as accurately as if the drilling were not biased to anticlinal structures. Errors also arise because corrections for paleobathymetry and compaction were not made. However, only a general history and record of sediment accumulation is required for our comparison.

The model calculated the lithospheric response to sediment loading as well as the sediment accumulation at various set times. The continental margin basin was developed in two halves, determining sediment accumulations on the shelf as well as oceanic accumulations.

The final step in the modelling of the continental margin is to allow the basin to subside exponentially, thereby simulating thermal contraction. This process allows additional sediment to accumulate followed by isostatic adjustment and should give a more realistic model of basin development on the continental margin than using thermal contraction theory alone. Our main problem was to determine the relative amounts of sediment that accumulated due to thermal contraction and due to isostatic adjustment of the viscoelastic lithosphere. Our second problem was to estimate the viscous and elastic properties of the lithosphere from a comparison of model predictions and observations.

Section I

Formation of Atlantic Type Continental Margins

Plate Tectonics:

One of the major features of passively subsiding (or "Atlantic type") continental margins is the great accumulation of sediment that is present on the shelf and rise. When these were first discovered off the American and European coasts they seemed to present no real problem to any of the existing theories. Many early authorities (Johnson, 1919) regarded them as rubbish piles supplied from the continents and built outward into the ocean. Today, we know differently. If this great thickness of sediment had been built out from the continent, the older rocks would have been overlapped by younger ones and could not appear near the edge of the continental shelf. This is not the case on Georges Bank for example. Here, older Cretaceous rocks extending to the continental edge, overlain by Tertiary sediments, are outcroping on the edge of the Georges Bank shelf. If the sediments had just been built outward from the coast the Tertiary sediments would overlap the Cretaceous sediments and they would not be exposed. From work done over the last two decades it has been found that in many places the sediments lie almost horizontally in basins which are far below the level of the deep sea floor (Bullard,1975). The bedding extends in some cases nearly to the continental edge. The rocks under the rise, slope and shelf are typical of continental material and not part of the ocean floor, therefore, methods have to be derived to explain how the continental basin is formed.

A simple view of continental margin development, compatible with the ideas of Plate Tectonics, is that a rift forms within the continent followed by spreading, basaltic lavas fill the gap, and a new ocean floor is gradually formed (Bullard, 1965). As time passes the hot lithosphere forming the ocean floor near the separated continental margins will cool and contract and the sea floor will subside (Figure 2).

The continental splitting takes the form of a rift valley (or graben) which would contain freshwater or saline lakes in its early form much like the Rhine Graben or East African Rift (Bullard, 1975). As widening of the rift continues a point is reached where the continental crust has thinned enough that the production of oceanic crust can begin. This should be thought of as a gradational process. The continent within the graben is first intruded by the basaltic lavas but later when spreading is sufficiently advanced the new crust is formed solely from intrusive and extrusive magmas. Now there are two separate continents split by an embryo ocean and each bordered by a part of a rift valley floored by rocks similar to those of the continent (Bullard, 1975). The process has created marginal depressions in which continental sediments are deposited. The newly formed basin is bounded on the continental side by a fault which has a large throw and on the oceanic side by an ocean floor sloping gently upward towards the ridge.

However, this simple model has ignored three important additional processes that determine the nature of subsidence and the formation of a deep

Figure 2: Formation of continental margin from tectonic theory.

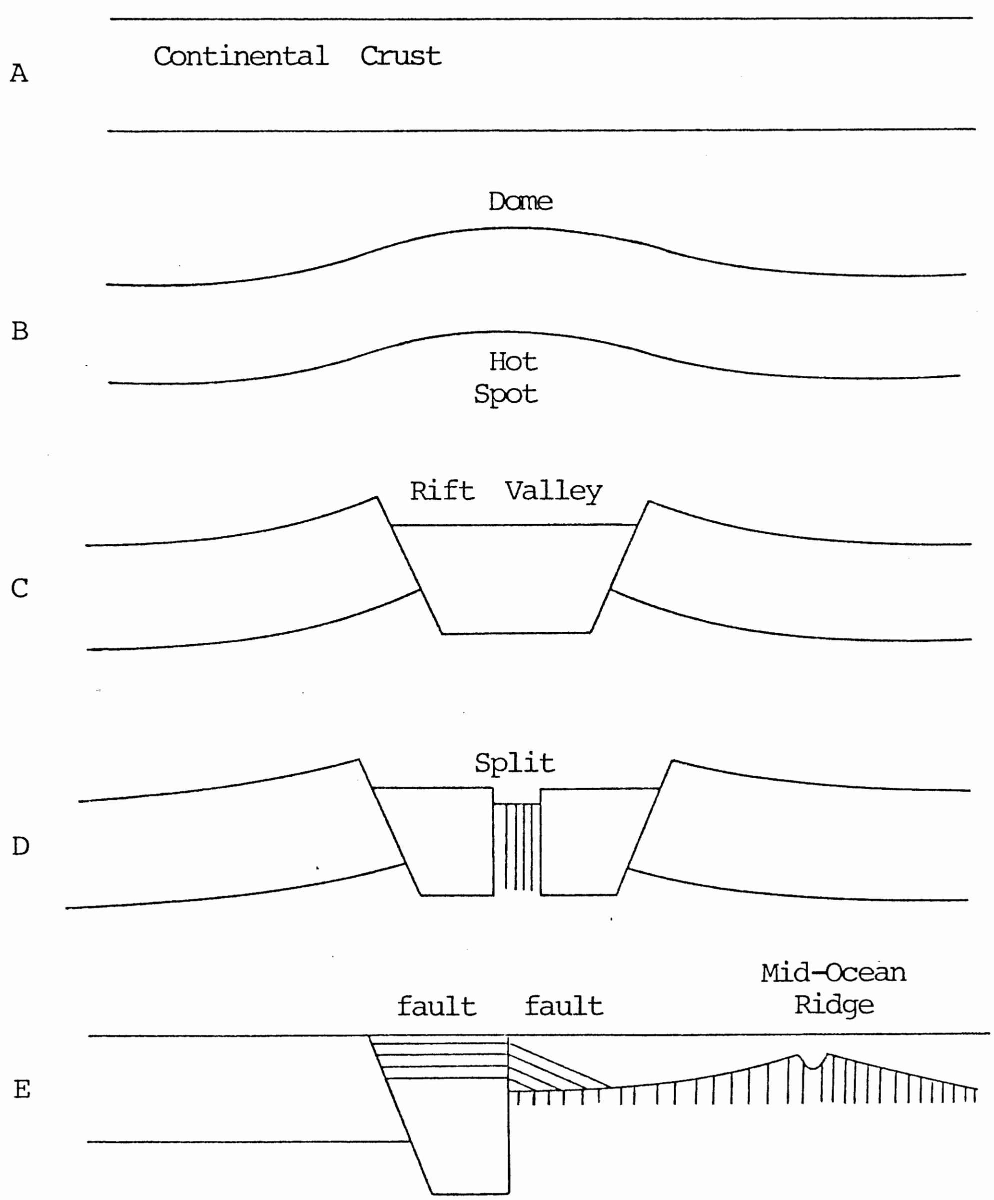
a) Continent breaks up

b) Continental crust domed

c) Formation of rift valley

d) Final splitting of continents

e) Seafloor and shelf subside, sediments from the continent accumulate on the shelf and spill over onto the ocean floor. (After Bullard, 1975.)


A
Continental Crust
Dome
B
Hot
Spot
Rift Valley
C
Split
D
Mid-Ocean
Ridge
fault
fault
E

sedimentary basin (King *et al.*,1975).

a) During the initial rifting phase the heat associated with the intrusives has caused thermal expansion and uplift of 'hog's backs' adjacent to the rift and these are subsequently eroded.

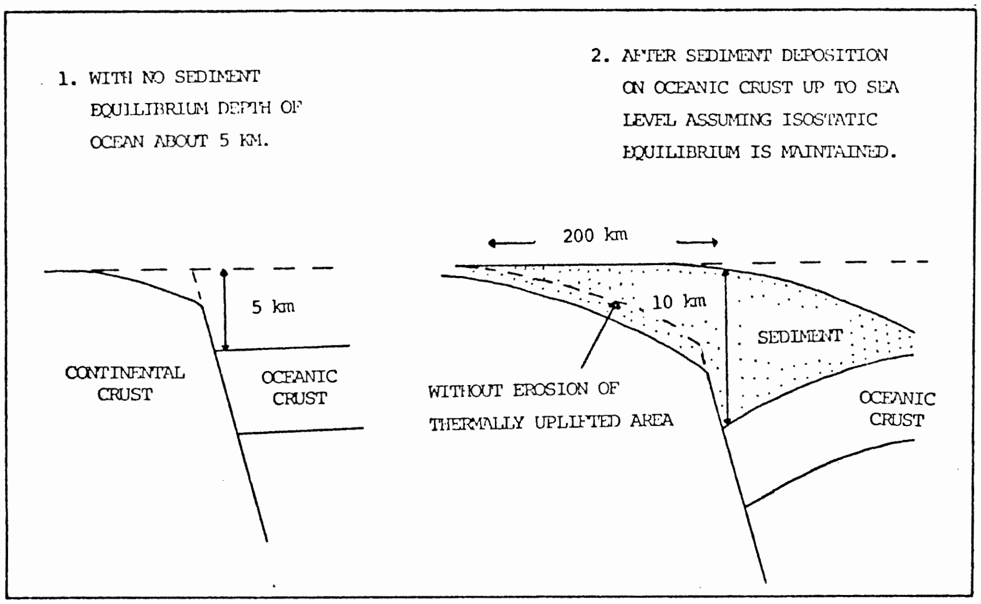
b) The region is further depressed by sedimentary loading along the continental margin (Figure 3).

The continental margin which has been uplifted as a result of rifting should subside exponentially with time (Sleep,1971) and return to a level lower than its original height by the amount of crust eroded. A time constant has been calculated for this process and is approximately 50 million years (Sleep, 1969).

At first, the eroded material which has been removed from the uplifted area of the rift drains mainly toward the continent (King *et al.*, 1975), but as erosion continues to level the rifted section of the crust to sea level the flow direction reverses and the sediment is deposited on the margin (Figure 3). The sediment gradually fills the marginal depression and causes the area to further subside due to sedimentary loading and isostatic adjustment.

This is a very simple model of the uplift, erosion and subsidence that occurred on the eastern continental margin of North America following rifting at about 170 m.y. (Jansa, 1975). The actual processes are much more complex and many more factors should be taken into account if a detailed

Figure 3: Diagram illustrating the sediment loading effect, after uplift and initial subsidence (After King *et al.*, 1975)



1. WITH NO SEDIMENT EQUILIBRIUM DEPTH OF OCEAN ABOUT 5 KM.
2. AFTER SEDIMENT DEPOSITION ON OCEANIC CRUST UP TO SEA LEVEL ASSUMING ISOSTATIC EQUILIBRIUM IS MAINTAINED.
5 km
CONTINENTAL CRUST
OCEANIC CRUST
200 km
10 km
SEDIMENT
WITHOUT EROSION OF THERMALLY UPLIFTED AREA
OCEANIC CRUST

description is required. For example, erosion will attack the positive topographic feature created by the rifting. This erosion is roughly comparable to the rate of subsidence such that the entire uplifted area is not eroded (Sleep, 1971). A second opposing effect to subsidence as a result of erosion is isostatic rebound. Over 6000 meters of material will have to be eroded for example to reduce the elevation by only 1500 meters (King _et al._, 1975).

Sleep (1971) has obtained estimates (using equations 1a and 1b) of the displacements caused by the erosion of highlands or filling basins with sediment, using point-wise isostasy. The amount of sediment which accumulates eventually is given by:

$$S = -f_s U \qquad (1a)$$

$$f_s = \rho_m / (\rho_m - \rho_s) \qquad (1b)$$

S is the thickness of sediment

U is uplift of a point in the basement

f is the isostatic amplification factor

ρ is density

s, m, c are subscripts referring to sediment, mantle and crust

As the sediment is eroded and deposited into the basin it causes sedimentary loading of the area. Using gravity studies and estimates of the Earth's lithospheric strength it can be shown that as a first approximation isostatic equilibrium is maintained throughout erosion and sedimentation if the process is occurring over an area several times the dimension of the lithospheric thickness (King *et al.*, 1975).

The system is in equilibrium if the sediment which displaces the lower density sea water causes subsidence of the lithosphere as fast as it accumulates. Isostatic equilibrium is maintained if the mass per unit area in a column down to the depth of compensation remains constant. For example, if a 5 km deep basin were to be filled with sediment it would accommodate 10 to 12 km of sediment if the lithosphere responds in a point-wise isostatic compensation. Toward the edge of the basin point-wise isostasy does not occur and the rate of sediment accumulation may be dictated by the bending properties of the lithosphere.

Quantitative Theory of Subsidence

Thermal expansion and contraction have been the most favoured theories to explain uplift and subsidence of the Earth's surface even though other theories have been put forward.

Hsü (1965), for example, suggested a two stage phase change process for the uplift, erosion and subsidence model. Stage 1: A decrease in mantle density causing uplift which has been attributed to a phase change in the upper mantle. Stage 2: An increase in mantle density causing subsidence. Subsidence will occur below pre-uplifted levels if erosion has taken place. This increase in mantle density is attributed to a reversals of the phase change postulated for the uplift stage.

The problem with this theory is that the lithospheric expansion, resulting from a possible mantle density change, will not give enough uplift, as has been observed and calculated for various examples such as the Rhine Graben. Therefore, the most widely accepted theory for uplift and subsidence is the thermal expansion model.

The uplift of the lithosphere is an isostatic response caused by a thermal anomaly below the lithosphere which in turn causes the lithosphere to expand. The thermal expansion initially causes uplift, but as the edges of the continent are removed from the thermal anomaly there is thermal contraction or subsidence (Sleep, 1971). The amount of uplift which is caused by isostatically compensated thermal expansion is given by Sleep's (1971) equation:

$$U = \alpha \int_{o}^{c} Tdz = (2\ \alpha\ c/\pi)\ g(x)\ \text{odd} \sum_{1}^{\infty} (A_n/n)\ \exp\ (-a_n t) \qquad (2a)$$

where α = volume coefficient of thermal expansion

a = crustal thickness

c = horizontal distance

T(Z) = temperature as a function of depth(Z) within the lithosphere

g(x) = temperature distribution as a function of horizontal distance x.

The even terms in the Fourier series expansion are not required becuase the uplift is an even function. The fundamental (n = 1) is therefore the dominant term since the first odd overtone attenuates 9 times faster than the fundamental (Sleep, 1971). Equation 2a therefore reduces approximately to Vogt and Ostenso's (1967) equation $U = u_o(x)\ \exp\ (-at)$, where u is the initial uplift, x is the horizontal distance across the uplifted area, a is the reciprocal time constant and t is time. The fundamental conclusion is that subsidence is an exponential function of time.

When a continental margin is formed, if it merely expanded and then contracted, no sediments would accumulate and the lithosphere would return to its original height. The amount of sediment that can accumulate as the basin subsides is dictated by the erosion that occurred during uplift. Therefore change in the elevation (E) with respect to preuplifted levels is given by the change due to thermal contraction, $dE/dt = -a\ E_o\ \exp\ (-at)$, and the law of erosion with time and elevation. Foucher and Le Pichon (1972) used a law of the type -kE where k^{-1} is the erosion time constant. Isostatic movements also have to be taken into account because as material is eroded the lithosphere will move up. Sleep (1971) has defined an isostatic multiplying factor $f_e = \rho_m/(\rho_m - \rho_c)$ where ρ_c and ρ_m are crustal and mantle densities. Sleep also defines D as the total denudation by erosion from t = 0 to time T when the elevation has been reduced to zero. Therefore, Foucher and Le Pichon (1972) get for the change in elevation with time:

$$dE/dt = -a\ E_o \exp(-at) - kE/\int_c \qquad (3)$$

and:

$$E = (E_o/(-a\int_c + k))\ \ (k \exp(-k/\int_e t)\ -a\int_c \exp(-at)) \qquad (4)$$

$$T = (\int_c/(-a\int_c + k))\ \ \log(k/a\int_c) \qquad (5)$$

$$D = (k\int_c E_o/(-a\int_c + k))\ (\exp(-aT) - \exp(-k/\int_c T)) \qquad (6)$$

Therefore, if the thermal time constant (a^{-1}) is taken as 80 m.y., that for an oceanic plate, an erosion constant (k^{-1}) is needed to be of the order 5 to 10 m.y. (Le Pichon _et al_., 1973). Thus, for an initial uplift of 1.5 km Le Pichon (1973) has calculated that the total erosion will be approximately 6 km over 100 to 200 m.y. which will result in the formation of a thick sedimentary basin.

The sediment accumulation, or thickness, for isostatically compensated thermal contraction with a unlimited sediment supply has also been calculated by Sleep (1971). The main problem found in these calculations was knowing the initial sedimentary accumulation at the time t_o. Sleep has eliminated this difficulty by normalizing the depth of other horizons to the depth of the horizon formed at the time t_o. Thus, the normalization of the formations can be calculated by Sleep's (1971) equation:

$$(h_p/h_x)_o = (\exp(a(p-x)) - \exp(-ax))/(1-\exp(-ax)) \quad (7)$$

where:

h - depth to formation

x - absolute age of standard formation

p - absolute age of specific formation

x,p - subscripts for both formations

o - subscript indicating no secondary effects

Continental Margins off the East Coast of Canada

Two major centers for sediment accumulation off the east coast of Canada are the Scotian Basin and the East Newfoundland Basin. They have both been receiving sediment since the Late Triassic and have accumulated 10 to 12 km of material in places (Jansa et al., 1975).

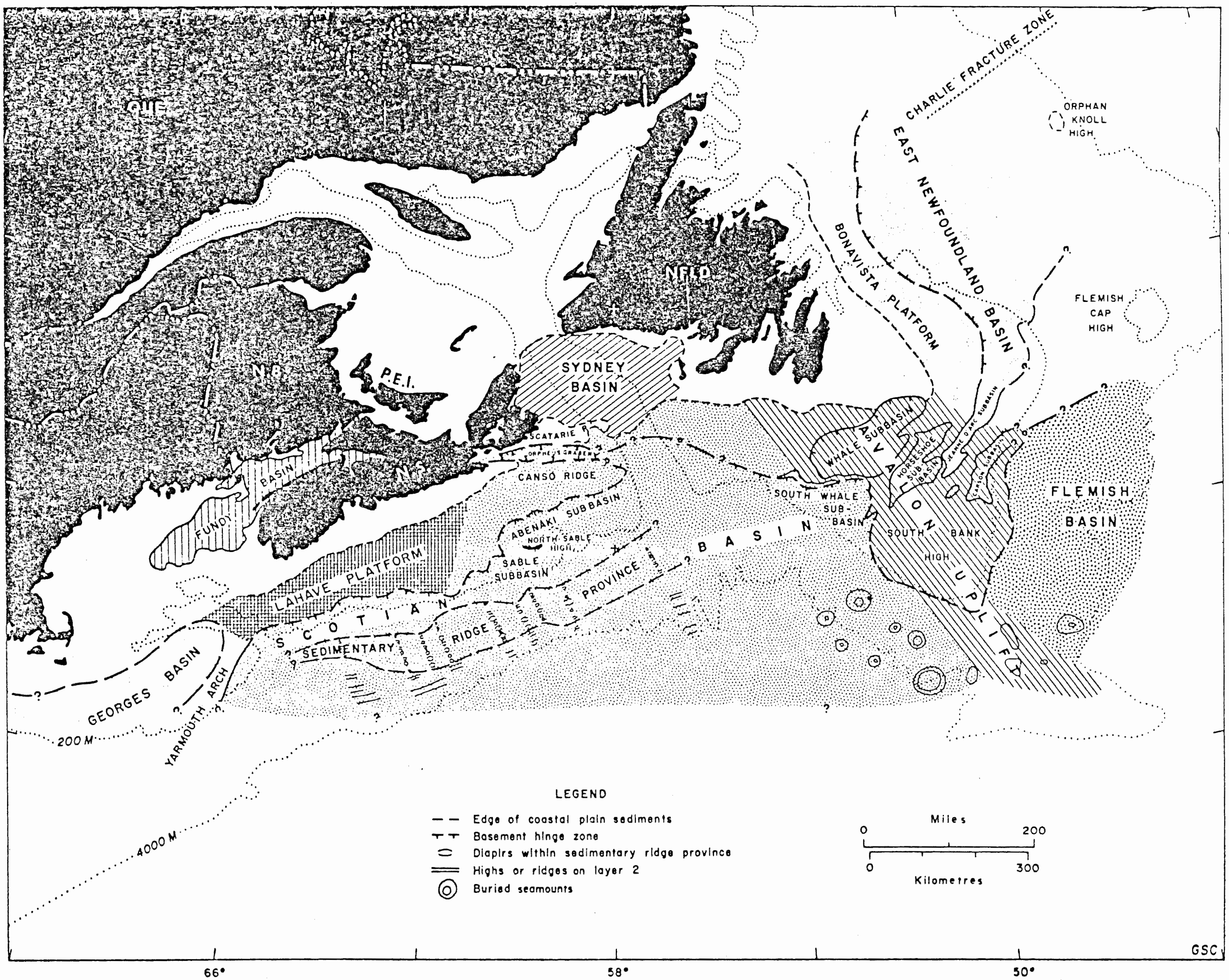
Sedimentation off the east coast has continued since the Paleozoic, but since we are mainly looking at the mechanism of subsidence on the continental margin, the only sediment accumulations that are relevant are those since the last rifting of Africa and North America, which occurred approximately 160 to 170 m.y. ago (Jansa et al., 1975).

The area of continental margin that will be discussed here is mainly the Scotian Basin and to a minor extent the East Newfoundland Basin. The Scotian Basin covers the eastern section of the Scotian shelf (Figure 4), the western Grand Banks and Laurentian channel, and the continental slope and off all these areas (Jansa et al., 1975). The Scotian Basin is flanked to the north by the Nova Scotia and Newfoundland uplands as well as the Sydney Basin. To the northwest it is bordered by the broad stable Lahave Platform and bordered by the Avalon Uplift to the east.

The Scotian Basin has been subdivided into four smaller sub-basins according to minor tectonic features (Figure 4). These sub-basins are referred to by Jansa (1975) as the Opheus Graben, Abenaki, Sable, and South Whale Basins.

The continental margin off Canada's east coast is believed to have

Figure 4: Location of the Scotian Basin, its subdivisions and tectonic elements (Jansa *et al*., 1975).


74°
66°
58°
50°
42°
48°
40°
QUE
NFLD
N.B.
P.E.I.
N.S.
CHARLIE FRACTURE ZONE
ORPHAN KNOLL HIGH
EAST NEWFOUNDLAND BASIN
BONAVISTA PLATFORM
FLEMISH CAP HIGH
SYDNEY BASIN
SCATARIE R.
CANSO RIDGE
FUNDY BASIN
ABENAKI SUBBASIN
NORTH SABLE HIGH
SABLE SUBBASIN
LAHAVE PLATFORM
SCOTIAN BASIN
SCOTIAN SEDIMENTARY RIDGE PROVINCE
WHALE SUBBASIN
HORSESHOE SUB BASIN
SOUTH WHALE SUB-BASIN
SOUTH BANK HIGH
AVALON UPLIFT
FLEMISH BASIN
GEORGES BASIN
YARMOUTH ARCH
200 M
4000 M
LEGEND
Edge of coastal plain sediments
Basement hinge zone
Diapirs within sedimentary ridge province
Highs or ridges on layer 2
Buried seamounts
Miles
0
200
0
300
Kilometres
GSC

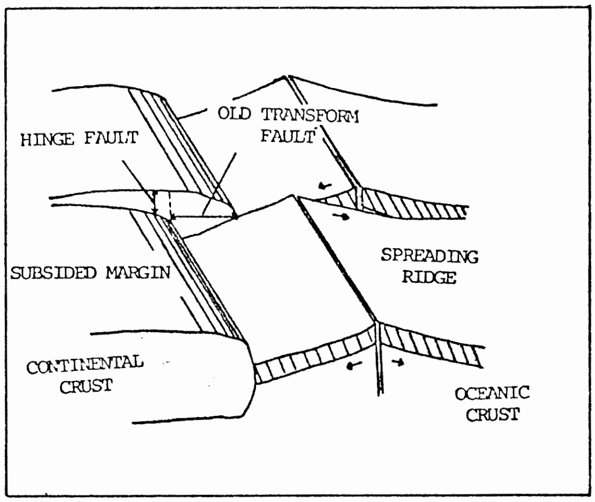
been developed in two distinct ways (King et al., 1975), consequently the complicated sub-basins within the major Scotian Basin. The development of the Scotian Basin is a result of rifting and thermal contraction as discussed earlier, and also as a result of transform faulting. Figure 5 shows these two mechanisms, the rifting followed by contraction and the offset of the fracture zone.

The amount of subsidence of both continental and newly formed oceanic crust across the rifted zone should theoretically be the same as they are both coupled to each other (King et al., 1975). Conversely, the continental and oceanic lithosphere across the transform fault will be decoupled as a result of the faulting and the subsidence rates across this margin will be different (Figure 5). Along the transform margin a hinge fault will also result as the rifted portion of the margin subsides. This hinge fault will occur along the transform fault, going into the continent (Le Pichon et al., 1972).

The result of this differential subsidence and hinge faulting in the Scotian Basin is the formation of the Orpheus sub-basin (King et al., 1975). The other sub-basins in the Scotian Basin just seem to be a result of the rifting, erosion and subsidence that has taken place.

The offset rifted portions of the east coast (Figure 15) seem to behave in the same manner, but there are some striking differences in structural characteristics across the transform margin. The diapiric structures which are so evident on the rifted margin off Nova Scotia are not found in the southern margin of the Grand Banks (across the transform margin). Jansa

Figure 5: Formation of a sedimentary basin with transform faulted margin, as proposed for the Scotian Basin. (After King *et al.*, 1975.)


OLD TRANSFORM
FAULT
HINGE FAULT
SUBSIDED MARGIN
SPREADING
RIDGE
CONTINENTAL
CRUST
OCEANIC
CRUST

(1975) has suggested that during the early stages of opening there was a narrow sea along the rifted margin off Nova Scotia. Restricted circulation in this sea formed evaporites, but to the north of the transform margin the continents had not yet separated as they were just sliding past each other. Therefore only evaporite deposition occurred to the southwest of the transform margin which later formed the typical diapirs on the margin off Nova Scotia.

A second structural characteristic which differs across the faulted margin is the basement topography (King *et al.*, 1975). Along the rifted margin the basement slopes relatively gently, in a similar manner to that of a typical ocean basin. While along the transform margin south of the Grand Banks the topography is described as having a rigorous relief which in some cases is as much as 4 km (King *et al.*, 1975).

With the separating of the African Plate from the North American Plate, and the resultant rifting and thermal contraction causing subsidence, the sediment influx into the Scotian Basin and Whale sub-basin was quite significant in the formation of these basins. The basement rocks of the Scotian Basin (rocks which were present in the area before the final break up of Africa and North America) are mainly continental sediments of the Cambro-Ordovician Meguma Group (Schenk, 1971). Intruded in places in the Meguma are granite plutons, the same as those found in Nova Scotia, for example the South Mountain Batholith (Jansa *et al.*, 1975).

Since separation and rifting took place approximately 160 to 170 m.y.

ago only post mid-Jurassic sedimentation in the area of the Scotian Basin is relevant to its subsidence and formation. In a gross scale sedimentation is complete in the Scotian Basin from the Jurassic through the Tertiary with only a minor hiatus in Berriasian - Valanginian times (136 to 124 m.y.) recognized in three wells (Gradstein et al., 1975). This minor hiatus at the western end of the Scotian Basin along with the thinning of the sediments during the Lower Cretaceous seems to be the only interruption in sedimentation in the Basin itself.

To the east of the Scotian Basin two unconformities have been recognized (Gradstein, 1975), these are both thought to be a result of tectonic activity under the Avalon Uplift. Jansa (1975) has also suggested an angular unconformity on the Canso Ridge to the north and an unconformity on the LaHave Platform to the northwest. During the Early Cretaceous all of these areas are thought to represent times of erosion when they were all positive topographic features (Jansa et al., 1975).

With the emergence of the Canso Ridge, LaHave Platform, and Avalon Uplift, the sedimentation around the Early Cretaceous Scotian Basin, described by Jansa (1975), was dominantly a sandstone sequence which grades laterally into a shale away from the source (Missisauga Sandstones and Merrill Canyon Shales). After the deposition of these two formations there was a regional transgression which commenced in the Aptian (106 m.y.) and not concluded until the Cenomanian - Turonian (88 to 94 m.y.) During this time Jansa (1975) suggests that the sedimentation was mainly terrigenous with carbonates being deposited as the transgression reached its maximum.

The transgression was followed in the Late Oligocene (31 m.y.) by a regional regression which increased the amount of coarse clastic material being deposited in the basin because of the emergence of peripheral areas (Jansa et al., 1975). The regression was terminated in the Late Pliocene as glacial and periglacial conditions existed across the emergent areas surrounding the basin.

As mentioned earlier, one of the striking structural characteristics of the Scotian Basin is the presence of salt diapirs. From the seismic data the growth of the diapirs seems to have been periodic during the Early Cretaceous, Late Cretaceous and Tertiary (Jansa et al., 1975). The origin of the diapirs is thought by Jansa and Wade (1975) to be related to over burden load on thick Triassic-Jurassic salt as well as on under-watered Verrill Canyon shales.

Quaternary and recent deposition has mainly been glacial drift and is distributed across the whole basin. The sedimentation is greatest in the area of the Laurentian Fan indicating a northwest movement of the Tertiary depocenter from the LaHave Platform (Jansa et al., 1975).

Section II

Theory of Isostatic Adjustment of Atlantic Type Continental Margins

Isostasy:

Isostasy, or isostatic adjustment, is one of the major factors governing how a basin subsides and how much it subsides. Isostatic compensation of the Earth's crust is the adjustment of the crust to maintain equilibrium among units of varying mass and density, excess mass above is balanced by a deficit of mass below and vice versa. That is to say, as stated earlier, that when sediment of higher density than sea water is deposited in the basin it causes the basin to subside. Subsidence results from the displacement of high density mantle material so as to keep the same mass per unit area over the entire region in a column down to the center of the Earth.

There are two major theories on isostasy. Airy isostasy and Pratt isostasy. Pratt isostasy postulates an equilibrium of crustal blocks of varying density, thus the topographically lower basins would be underlain by higher density material than the topographically higher units and the depth of the lithosphere would be constant.

Airy isostasy states that there is an equilibrium of crustal blocks of the same density but of different sizes. Thus, the topographically lower basins would be of the same density as other crustal blocks but would have less mass and shallower roots. However, if the basin was full of sediment its roots would be deeper.

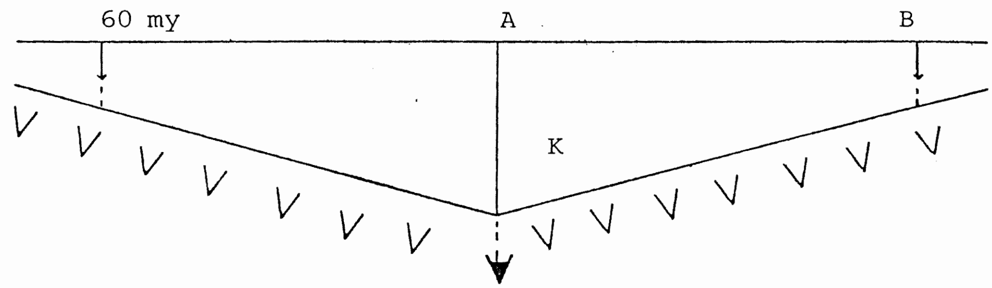
From these two definitions of how isostasy works it seems reasonable in our case to accept the latter model which fits the data and observations more closely.

One of the main complications is that regional isostatic equilibrium is modified by the finite strength of the lithosphere. Sleep (1971) illustrates this idea as follows: If an area is subsiding and a greater amount of subsidence occurs at one point, for example station A (Figure 6), than at a nearby station B, then the loading at A will drag B further down than it normally would have gone had isostasy been pointwise. Also station A will not subside as much as it would have, due to a buoying effect caused by B.

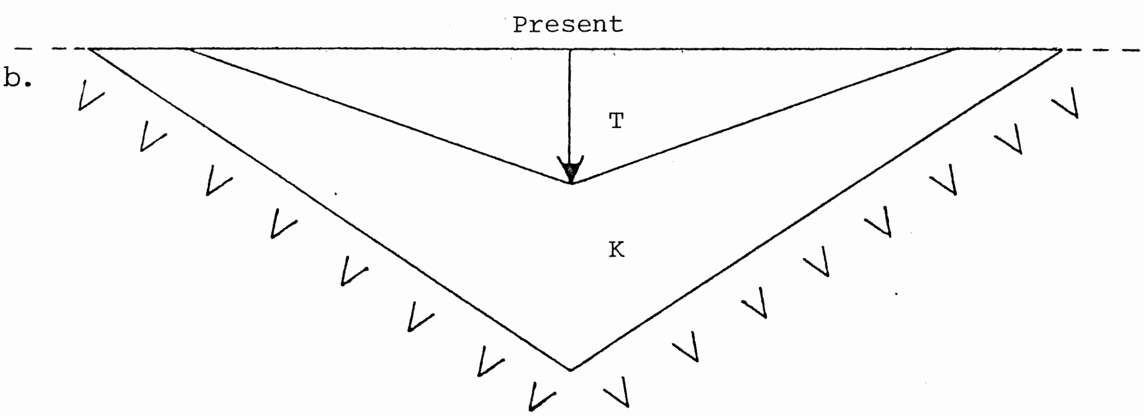
In the model developed in this study it is the finite strength of the lithosphere which allows us to develop a continental margin basin. The weight of sediment which is deposited on the ocean floor drags down the nearby continental shelf causing a initial depression to form which in turn will be filled with sediment causing an increase in the subsidence. Also, the area of the ocean floor where initial sedimentary loading takes place will be buoyed upwards by the continental shelf.

Figure 6: Schematic diagrams show effect of regional isostasy on subsidence. More subsidence occurred at point A than at point B (top diagram). Point A is buoyed up and point B is dragged down the amount indicated by the dashed lines. (After Sleep, 1976).

a.



b.



Model of the Response of a Viscoelastic Lithosphere to Surface Loads

Subsidence of the continental part of a continental margin a basin is thought to depend primarily on the thermal contraction phase in the uplift, erosion and subsidence model put forward by Sleep (1971). The mathematical aspects of this model, discussed earlier, show that subsidence decays exponentially with time. Any deviations from this decay are attributed to eustatic changes in sea level and variations in sedimentary influx.

It can be seen from the subsidence curves for the Scotian Basin (Appendix I) that some closely follow an exponential curve while most deviate to varying extents from the exponential fit curve. Therefore, there must be other major features governing the formation of the Scotian Basin in addition to thermal contraction. Since the sediment in the Scotian Basin has been reported to exceed 10 km (King _et al_., 1975), it is reasonable to examine the role that sedimentary loading has played in the formation of the Scotian Basin.

The problem is therefore to develop a model that examines the response of a viscoelastic plate that simulates the Earth's lithosphere, to a distributed load on its surface. The distributed load represents the influx of sediment into the thermally contracting basin which in the case of the Scotian Basin will result in up to 10 km of sediment being deposited over 160 to 170 myrs.

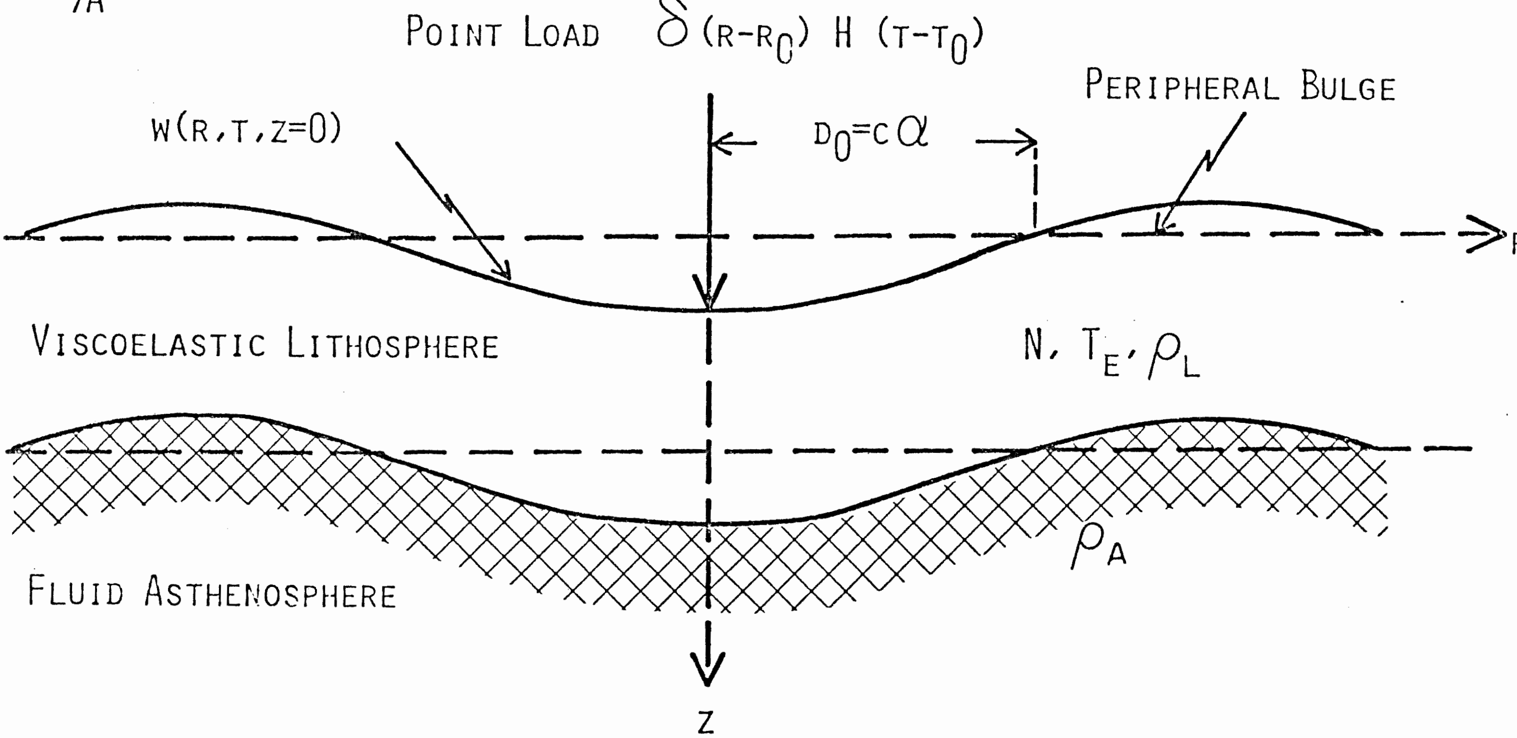
The development of the model was broken into two parts by three

Figure 7a: Diagram showing response of a viscoelastic plate to a point load $\delta(R-R_o)\ H\ (T-T_o)$

7b: Diagram showing response of a viscoelastic plate to a distributed load $L(R,\ \theta)$.

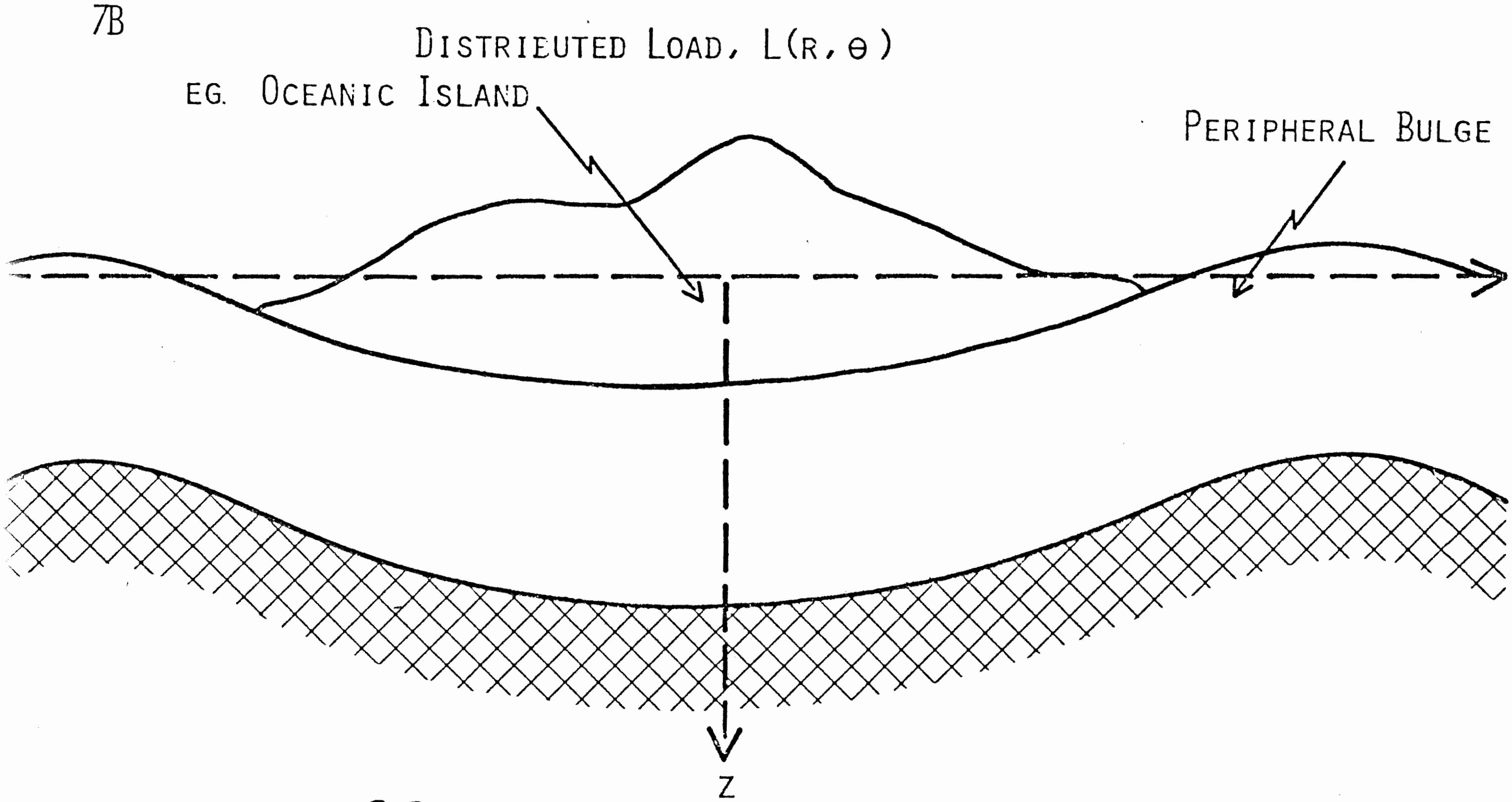
Point Load Response of a Viscoelastic Beam

7A



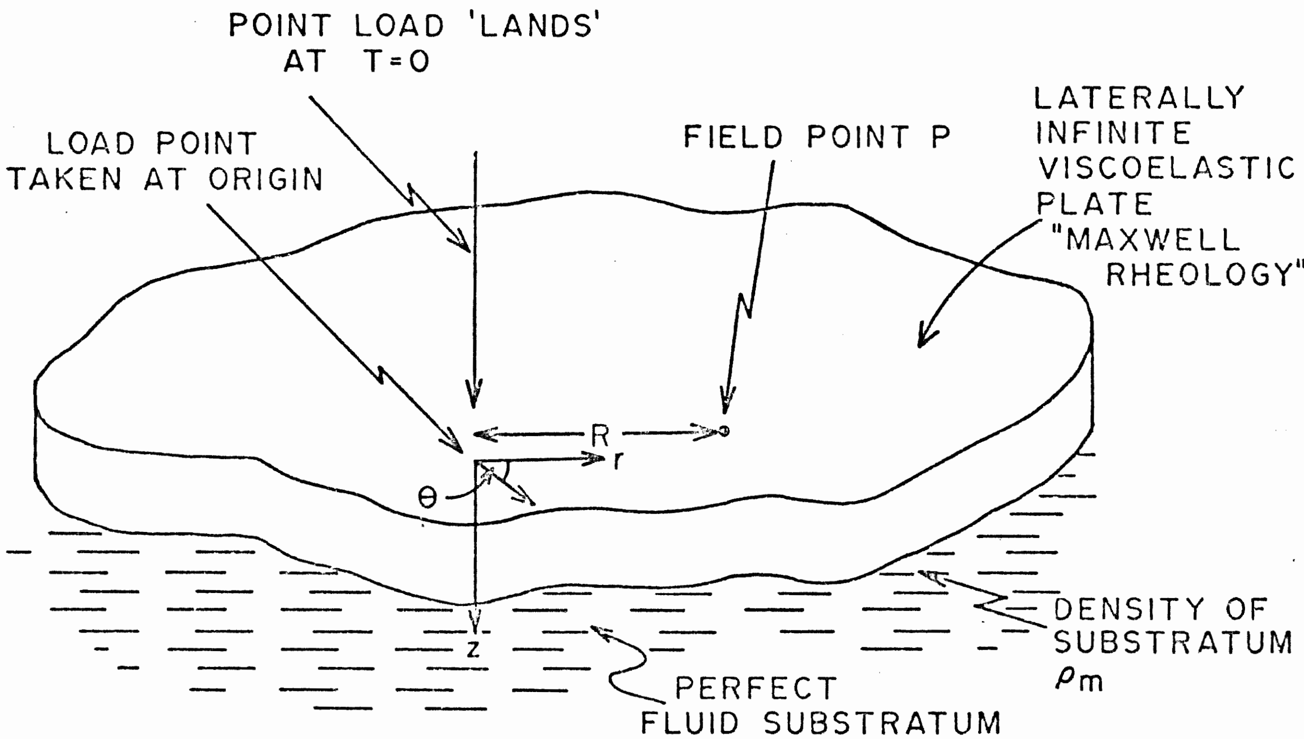
Distributed Load Response of a Viscoelastic Beam

7B



$$W(R,\ \theta\ ,Z{=}0) = \iint_{R,\theta} W(R-R_0,\ T,\ Z{=}0)\ L(R,\theta)\ R\,dR\,d\theta$$

Figure 8: The viscoelastic plate used in ROMVPLA. Cylindrical coordinates (r, Θ, Z) were used.


POINT LOAD 'LANDS'
AT T=0
LOAD POINT
TAKEN AT ORIGIN
FIELD POINT P
LATERALLY
INFINITE
VISCOELASTIC
PLATE
"MAXWELL
RHEOLOGY"
R
r
θ
z
DENSITY OF
SUBSTRATUM
ρm
PERFECT
FLUID SUBSTRATUM

main computer programs and closely parallels the model developed by Beaumont for cratonic basins. The first part is to calculate the response of the viscoelastic plate to a point load (Figure 7a), and the second part is to apply these results to the more realistic response of a viscoelastic plate to a distributed load (Figure 7b).

In the first part of the model, the point load response was calculated using the program ROMVPLA (an acronym for Romberg integration of the viscous plate problem). Here, very simply, the problem is to find the vertical (Z) displacement, W (r, t), of all surface points P(r), distance r from the origin, due to a point load of mass 1 kg, that is applied at the origin, r = 0, at time t = 0 and remains for all time. As seen in Figure 8, cylindrical coordinates (r, Θ, z) were used because the point load is symmetrical with respect to Θ, thus, the spatial solution for Z = 0, the surface, is only a function of distance from the point load (r). The load, represented mathematically by $\delta(r-r_o)\ H(t-t_o)$ where r_o and t_o are taken as zero, is applied to the viscoelastic plate. The vertical displacements W are a function of both r and t because of the viscous nature of the plate. The solution for a purely elastic plate would be that at t = 0. From the form of W(r, t) we can observe that there is a central region which is depressed, surrounded by an upward peripheral bulge. As time continues, the central depression deepens and the peripheral bulge migrates inward so that at time t = ∞ there is an infinitely deep and infinitely narrow hole. This, of course, is not physically realistic but correct results are obtained when the Heaviside Green Functions (the functions formed by ROMVPLA) are convolved with a physically meaningful distributed load.

ROMVPLA determines the displacement functions W(r, t) by evaluating the integral

$$W(r, t) = \frac{P_o}{2\pi \gamma_s} \int_o^\infty \left(\left(\frac{t_e}{t_\xi} - 1 \right) e^{-t/t_\xi} + 1 \right) J_o(\xi r) \xi \, d\xi$$

with $t_\xi = [1 + \frac{\alpha^4}{4} \xi^4] t_e$

The integral contains the following constants which are properties of the plate and substratum

$$\gamma_s = \rho_m g$$

where - ρ_m is the density of the substratum (mantle)

- g is the acceleration due to gravity

Since SI units are used g is approximately 9.8 m/s^2, ρ_m is approximately 3.4 x 10^3 kgm/m^3 and γ_s is approximately 3.34 x 10^4 kg/m^2s^2.

In the integral t_e is the relaxation time characterizing the viscous plate properties, and is assumed to be from 10^4 to 10^6 years. P_o is the magnitude of the point load and α is the Flexural Parameter of the plate which characterizes the elastic properties of the plate. α is related to the flexural ridigity, N by:

$$\alpha^4 = 4N/\gamma_s$$

α is proportional to the distance from the origin to the edge of the depression (Figure 9) when t = 0.

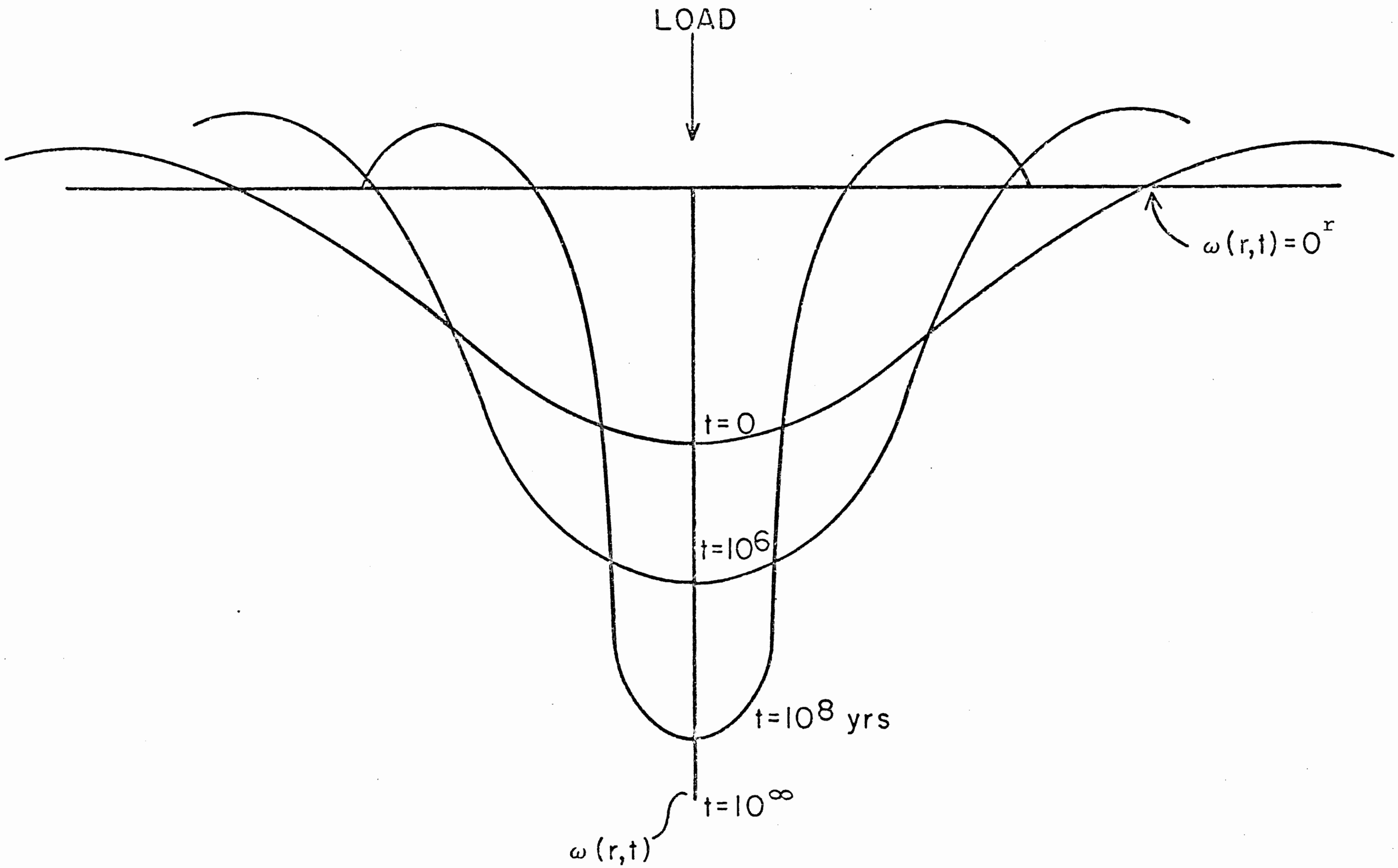
In the cases taken here N was 10^{24}, 10^{25} or 10^{26} newton meters, γ_s was 3.335×10^4 kg/m^{2}s^2, the magnitude of the point load was 1 kgm, the integral was evaluated over 68 spatial points (from 0 to 1200 km) and 35 different time values were used (from 0 to 500 million years).

From ROMVPLA a series of Green functions are produced (displacement versus distance from the origin for various times), these are presented graphically in appendix II.

The next program in the series of three is INTSQ (an acronym for integration of viscoelastic Green functions over a square), which takes the Green functions produced for a point load in ROMVPLA and convolves them over a square to produce the square load response functions (Figure 10). The size of the squares used was 50 by 50 km and the convolution evaluated by dividing the square into 50 by 50 units.

The convolution was done over a grid of 10 squares by 10 squares, 100 in all or an area 500 by 500 km. The output of INTSQ is a response function that gives the vertical displacement at the center of each grid square due to a 1 kgm load on any other grid square in terms of the distance from the loaded square to the grid square (Figure 10). A set of response functions were determined that describe the amount of downward displacement through time of each square of the 500 km by 500 km grid due to a load of 1 kgm on any of the grid squares.

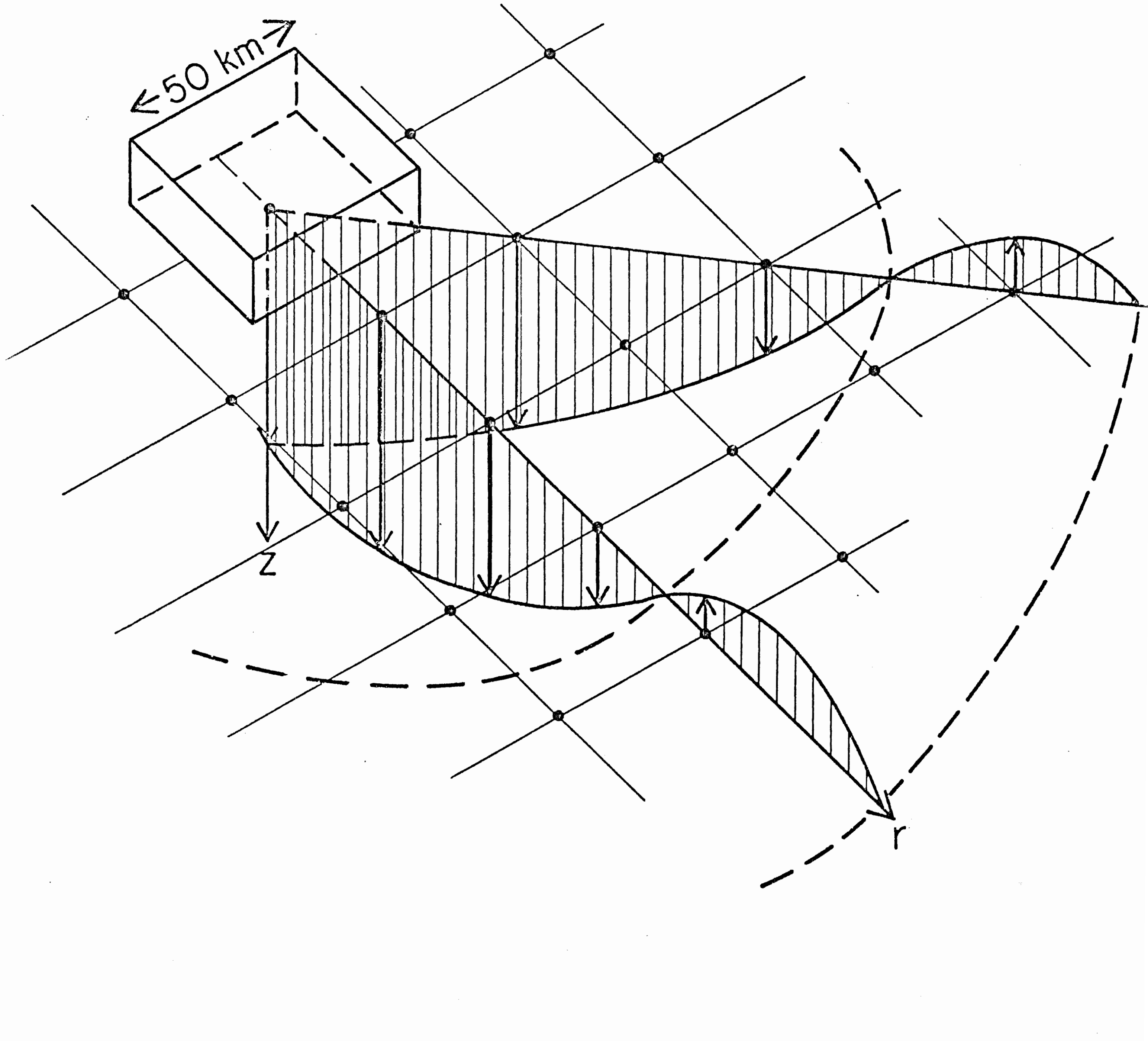
Figure 9: Response of a viscoelastic plate to a point load. Depression showed at different times (t).



LOAD
ω (r,t) = 0r
t=0
t=106
t=108 yrs
t=10∞
ω (r,t)

Figure 10: Response of a viscoelastic plate to a square load over an area. Subsidence or uplift observed at centers of all grid squares.

Response of Viscoelastic Plate to Square Load



The final program in the series of three is CONVOL, and this program develops the basin for the required time increments. The program divides the area (10 by 10 squares, each square being 50 km on each side) into two halves, an oceanic half and a continental half (Figure 13). When the program is run a specific amount of sediment is added to the oceanic side of the basin at the beginning of each time interval and allowed to subside for a specified length of time. In effect the program is working with 50 squares (half the grid), loading one square at a time using the results from INTSQ and adding the results of these separate loadings together. In CONVOL a 1 kgm mass is not used as in INTSQ but the result is scaled by the mass of sediment which is initially deposited on that one square.

After all 50 squares have been loaded on the oceanic side of the area they will cause subsidence through time. Therefore, the area is left to subside for a specified length of time (in the case used here time increments of 20 m.y. were used, up to 180 m.y.). Since the oceanic half of the area is uniformly loaded it will subside approximately uniformly, and the continental half of the basin will be dragged downwards by the subsiding oceanic half.

The next step in the program is to fill the continental half of the area in a manner that simulates the outward growth of a continental shelf. The program fills the continental half of the area with sediment to sea level. This results in further subsidence due to the loading effect, the oceanic side also being dragged downwards due to this increased load. The program then fills the area again after the next time step is reached as a further void is produced on the continental half of the area due to the viscoelastic relazation subsidence as a result of loading. The basin is then allowed to subside again for the same time interval, refilled and so on until the area comes to isostatic equilibrium with a full basin after 20 m.y. The program prints out the results of subsidence and sediment accumulation on the continental side and the amount of further subsidence on the oceanic side.

The program next adds at the end of the 20 m.y. another movement in exponential subsidence, and the process is repeated to the end of the next time interval. This process is then repeated nine times with an interval of 20 m.y. between each time step, resulting in a basin 160 m.y. old (0 m.y. is time step number one).

The final step in the creation of the theoretical continental margin basin is the incorporation of the exponential thermal contraction factor into the subsidence of both the oceanic and continental halves of the basin. This was done using Sleep's (1971) model with a time constant of 50 m.y. for both oceanic and continental sides of the area.

Figure 11: Flow chart showing the steps in CONVOL and how it fills the basin and lets it subside.

Flow Chart for Calculations of Basin Subsidence

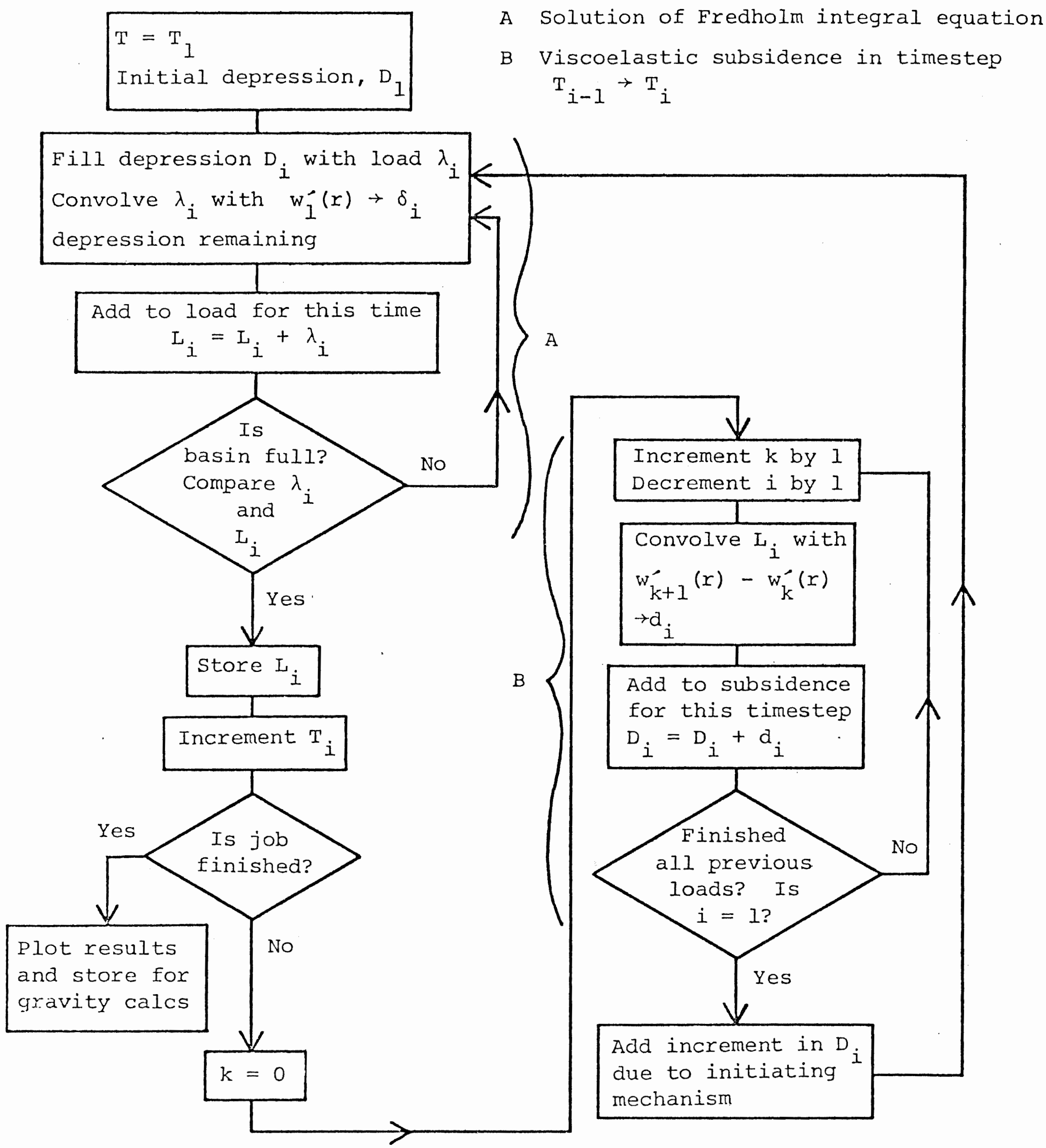
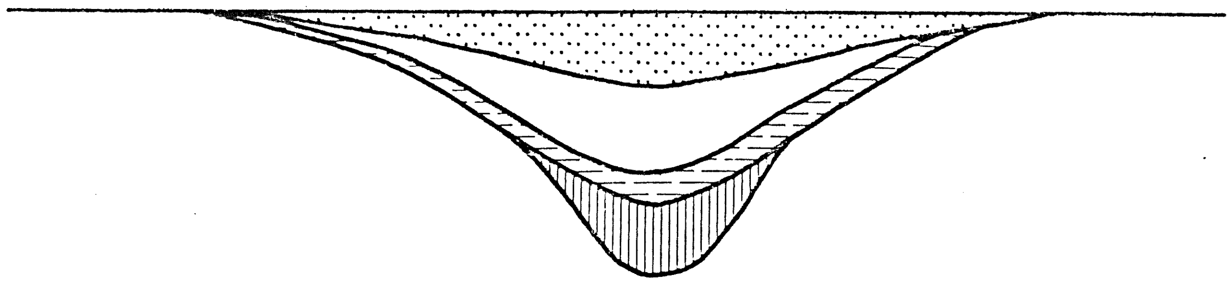
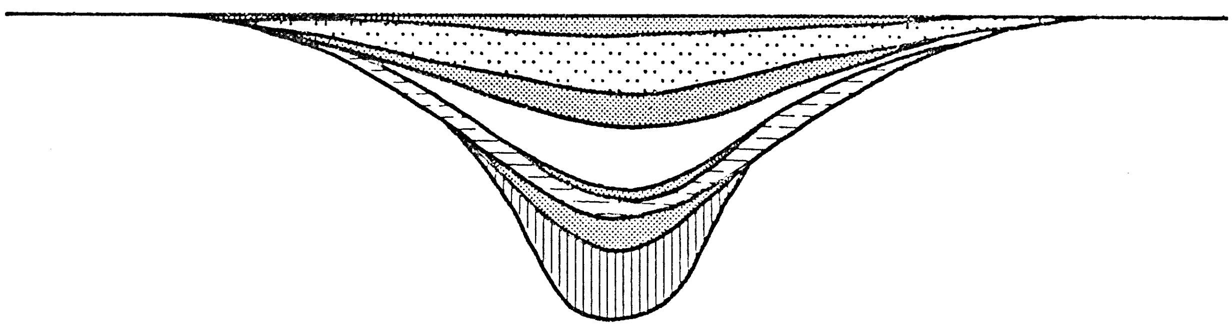


Figure 12: Development of a continental basin using CONVOL for two time steps. T = 4, basin has been filled, the basin then sits until T = 5 and a depression develops over this time due to viscoelastic relaxation. The basin is then filled at T = 5 taking into account further subsidence due to increased load.

T = T_4



T = T_5



T = T_5

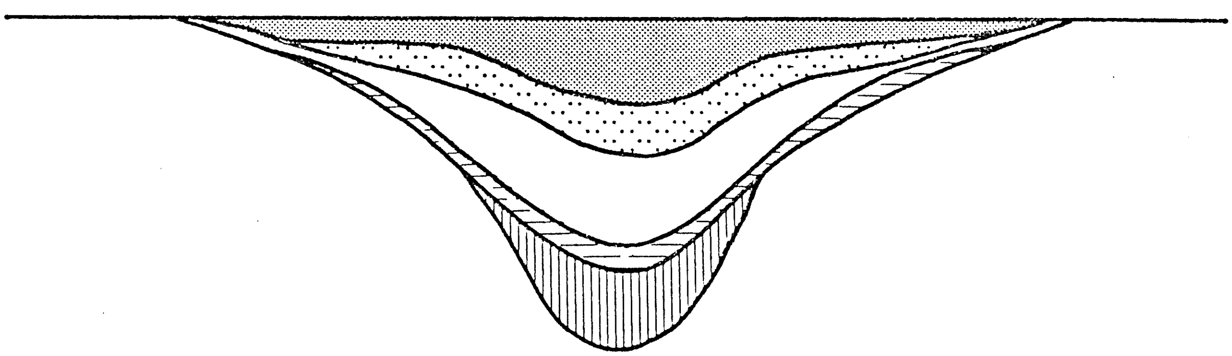
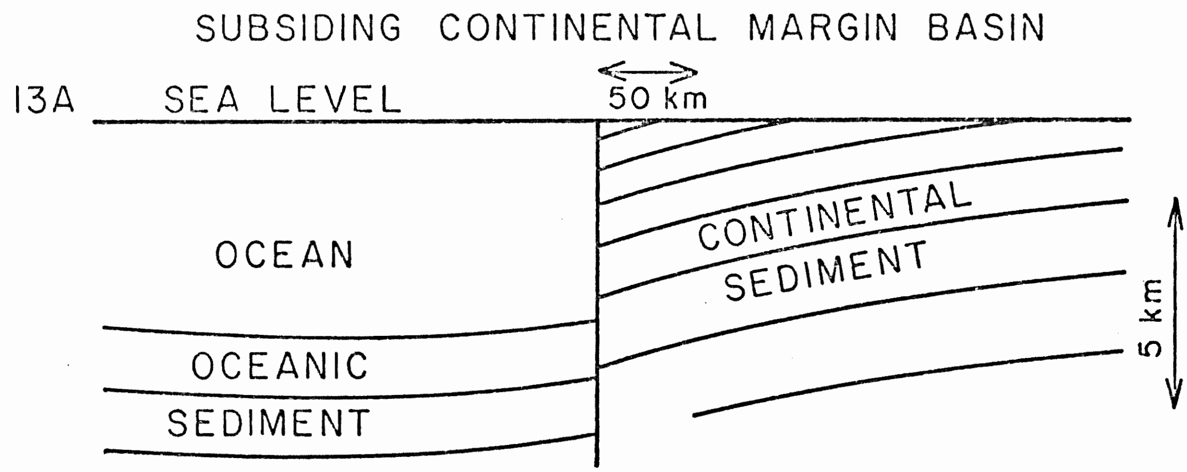
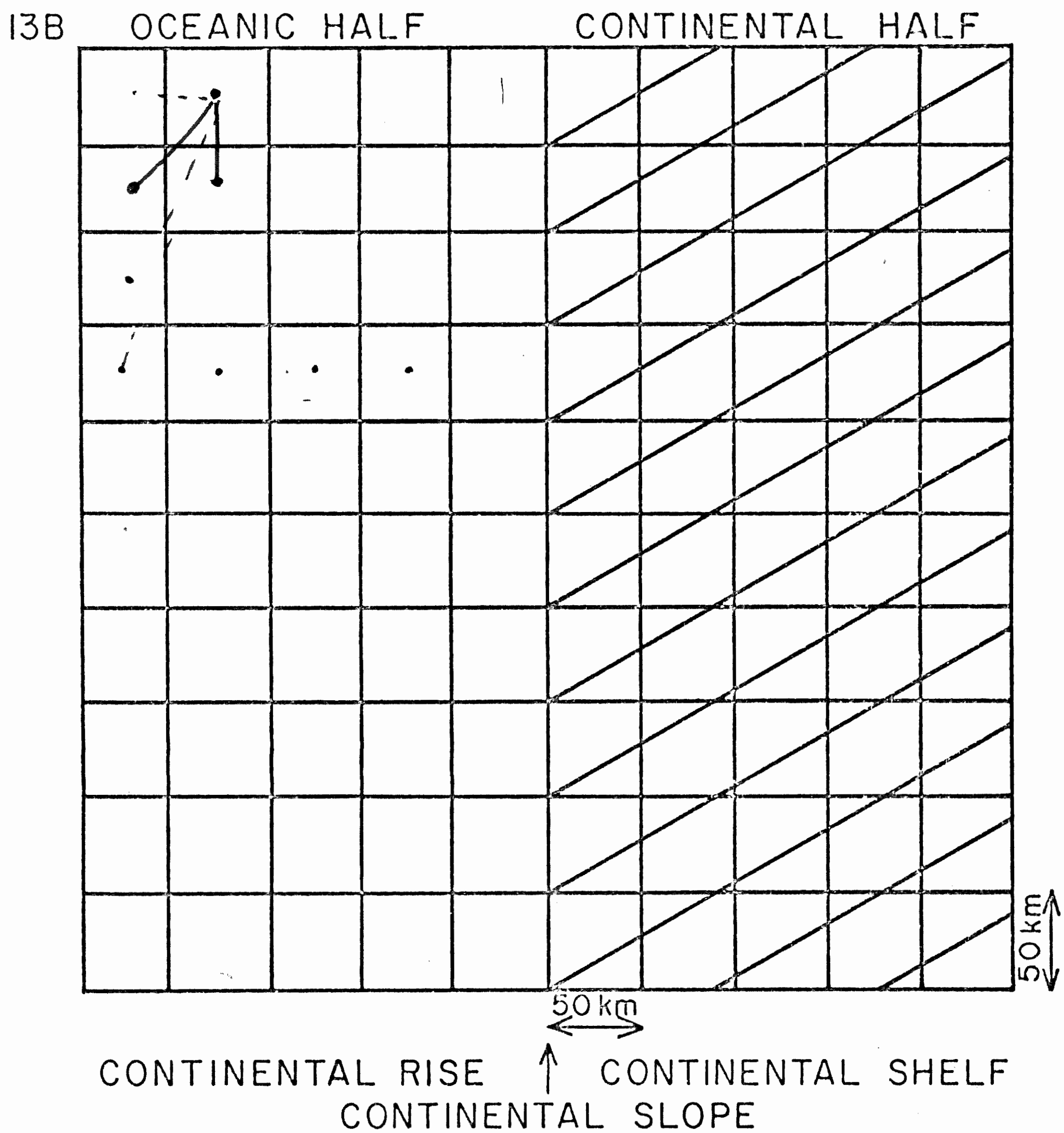


Figure 13a: Cross section of modeled theoretical basin, with oceanic half on the left and continental on the right. Thickness of sediment layers on the oceanic half is 1000 m which have been deposited over a period of 20 m.y. Thickness of sediment layers on the continental half depends on subsidence rates. Each layer on the continental half also took 20 m.y. to deposit.

13b: Plan view of theoretical basin showing the grid squares used.


SUBSIDING CONTINENTAL MARGIN BASIN
13A
SEA LEVEL
50 km
OCEAN
CONTINENTAL
SEDIMENT
5 km
OCEANIC
SEDIMENT


13B
OCEANIC HALF
CONTINENTAL HALF
50 km
50 km
CONTINENTAL RISE
CONTINENTAL SHELF
CONTINENTAL SLOPE

Section III

Subsidence History of the Scotian Basin - Observations

The amount of subsidence in an area during a given time may be calculated from measurement of the amount of sediment accumulated in the area during that period, and the paleo-water depth (Gradstein et al., 1975). Subsidence may occur without sediment accumulation, therefore, total subsidence is equal to the sum of the change in paleo-water depth and the thickness of sediment accumulated during the period.

In this study the subsidence history of the Scotian Basin was determined by using 20 wells drilled by two oil companies. Wells used (Table 1) were drilled by Shell Canada Ltd. (10 used) on the Scotian Basin and by Amoco Canada Petroleum Company Ltd. (9 used) on the Grand Banks. Also one well drilled by Elf Petroleum Ltd. was used on the Grand Banks. The radiometric time scales used were from Holmes (1959) for the Jurassic through to the Recent. Only a general subsidence history at each location in the Scotian Basin is observed because of inaccurancies in the time scale, measurement of age and determination of water depths.

Shell wells were selected for the Scotian Shelf and mainly Amoco wells were used for the Grand Banks in order to retain a consistent interpretation of the paleontological data. The subsidence curves obtained from both the Scotian Shelf and Grand Banks are presented in Appendix I.

To a first approximation, the subsidence curves from the well data when plotted in the form of absolute age against depth from sea level

Table 1: Oil company wells drilled on the continental shelf of southeastern Atlantic Canada, used in this study.

Scotian Shelf

Well	Latitude (N) °	Latitude (N) '	Longitude (W) °	Longitude (W) '
Shell Mohawk B-93	45	42	64	44
Shell Oneida O-25	43	20	61	30
Shell Triumph P-50	43	40	59	45
Shell-Mobil-Tetco Eagle D-21	43	50	59	34
Shell Primrose N-50	43	59	59	04
Shell Missisauga H-54	44	23	59	23
Shell Sauk A-57	44	20	58	30
Shell Chippewa G-67	44	40	58	30
Shell Demascota G-32	43	50	60	45
Shell Wyandot E-53	45	00	59	15

Grand Banks

Wells	Latitude (N) °	'	Longitude (W) °	'
Amoco-Imp-Skelly Razorbill F-54	45	13	52	08
Amoco-Imp-Skelly Sandpiper J-77	45	37	51	41
Amoco-Imp-Skelly Osprey G-84	44	43	49	27
Amoco-Imp-Skelly-Bl Egret K-36	46	25	48	50
Amoco-Imp A-1 Bittern M-62	44	42	51	10
Amoco-Imp-Skelly Brant P-87	44	17	52	42
Amoco-Imp Petral A-62	44	51	52	54
Amoco-IOE-A-1 Gannet 0-54	45	04	52	38
Elf Hermine E-94	45	30	54	15
Amoco-IOE Puffin B-90	44	39	53	42

follow Sleep's (1971) model that predicts exponentially decreasing subsidence with time. Superimposed on each of the subsidence curves is also an exponential subsidence curve. This curve was calculated by taking known points (with respect to age and depth) in the well data and fitting a 'best fit exponential curve' to these points in a least squares sense. The exponential curve was calculated by the program EXPFIT (Appendix III), that was given to us by J.Sweeney of the Earth Physics Branch, Ottawa. A mean time constant for the Scotian Shelf subsidence is approximately 60 m.y. $\pm$ 25 m.y. A mean was also calculated for the Grand Banks, and here the time constant was approximately 90 m.y. $\pm$ 56 m.y. If well Razorbill F-54 were omitted from the mean value, it would then be a more reasonable 67.5 m.y. $\pm$ 34 m.y. Both of these values are higher than those obtained by Renwick (1973), who obtained a value of 50 m.y. for the Scotian Shelf and 65 m.y. for the Grand Banks. However, he had far fewer wells available to examine, for example, only one was available on the Grand Banks for his study. The reason for this difference may also be due to the fact that the values used here have not been normalized or corrected for compaction but rather represent a fit to the absolute depths from the revised well data.

It is believed that the two sides of the Scotian Basin have developed in different ways as outlined earlier (Section I), therefore we will subdivide the basin into an east half represented by the Grand Banks wells and a west half represented by Scotian Shelf wells.

In the western half of the Scotian Basin sedimentation rates were greatest during the Jurassic and lower to middle Cretaceous and gradually

Table 2: Exponential time constant values for subsidence curves from wells used in this study. Average time constant at bottom of table calculated by taking arithmetic mean of well time constants.

Scotian Shelf

Well		Exponential Time Constant From EXPFIT (m.yrs)
Shell Mohawk	B-93	101.0
Shell Oneida	O-25	19.0
Shell Triumph	P-50	79.9
Shell-Mobil-Tetco Eagle	D-21	48.5
Shell Primrose	N-50	66.1
Shell Missisauga	H-54	55.9
Shell Sauk	A-57	98.0
Shell Chippewa	G-67	37.8
Shell Demascota	G-32	60.6
Shell Wyandot	E-53	61.5

Average time constant - 62.8

Grand Banks

Well		Exponential Time Constant From EXPFIT (m.yrs)
Amoco-Imp-Skelly Razorbill	F-54	223.0
Amoco-Imp-Skelly Sandpiper	J-77	25.7
Amoco-Imp-Skelly Osprey	G-84	63.5
Amoco-Imp-Skelly Egret	K-36	83.0
Amoco-Imp A-1 Bittern	M-62	78.3
Amoco-Imp-Skelly Brant	P-87	138.8
Amoco-Imp Petral	A-62	104.5
Amoco-IOE-A-1 Gannet	0-54	43.0
Amoco-IOE Puffin	B-90	53.5
Elf Hermine	E-94	84.7

Average time constant - 89.8

decreased until recent times. Peak sedimentation rates seem to have occurred during Albian to Aptian times when sedimentation rates were as high as 17.3 cm per 1000 yrs (Eagle D-21). Since we are trying to estimate subsidence, we must correct the observed depth for the paleobathymetry at the time when the sediments were deposited. Jansa et al. (1975) believe that sedimentation occurred in a shallow water, deltaic environment. Therefore, errors incurred in ignoring a paleobathymetric correction will be small in comparison with the overall subsidence.

In the Late Cretaceous and Tertiary, sedimentation slowed considerably in all of the Scotian Shelf wells. The average sedimentation rate was only 2.0 cm per 1000 years. Also, during this time it can be seen from the well logs (Appendix IA) that the sediment being deposited was deeper water sediment, which makes the subsidence estimates dependent upon accurate bathymetric knowledge. The decrease in sedimentation and the increase in paleobathymetry was accompanied by the establishment of a widespread open marine condition during the Late Cretaceous, thus diminishing sediment influx and making the conditions of sedimentation more pelagic (Gradstein et al., 1975).

Paleobathymetric curves are presented on six of the subsidence curves following the same procedure as Gradstein (1975). Data on paleobathymetry for the other curves was unavailable at the time of this study.

The data from the eastern end of the basin, on the Grand Banks (Appendix IB) demonstrates that the subsidence rates were not as great as those observed in the western section of the Scotian Basin. In a majority of the wells subsidence rates vary between 12 cm to 0 cm per 1000 yrs. with an average of approximately 2.25 cm per 1000 yrs. during the Jurassic and Cretaceous. Lower Cretaceous sediments are largely missing at the eastern end of the Scotian Basin but with the development of open marine conditions in the Late Cretaceous sedimentation and subsidence rates increased.

In the Early Tertiary subsidence was rapid (a good example is Puffin B-90) on the Grand Banks as can be seen by comparison with wells within the Scotian Basin. Wells to the north show a more uniform subsidence rate (Bittern M-62 and Gannet 0-54). The result of the rapid subsidence during the Eocene, Oligocene and Miocene was the establishment of shallow marine conditions at the eastern end of the Scotian Basin (Gradstein et al., 1975). Therefore, recent subsidence can be directly related to sediment accumulation with little regard to bathymetry.

A comparison of all 20 subsidence curves used in this study demonstrates that subsidence and sedimentation occurred rapidly during the early stages of development of the Scotian Basin (Jurassic to Middle Cretaceous). Subsidence then gradually slowed followed by a major upsurge at the eastern end of the Basin during the Early to Middle Tertiary. This has been attributed by Gradstein et al. (1975) as a local tilting effect of the shelf's edge causing increased subsidence.

Subsidence and sedimentary accumulation continued in the Middle to Late Tertiary but the rate of subsidence was slow as deep water marine conditions prevailed and sediment influx was small. In the Middle Eocene sedimentation increased with subsidence continuing at a progressively slowing rate, therefore, by the Middle Miocene shallow marine conditions were present in the Scotian Basin.

Model Application to the East Coast

Results for this study were obtained by modelling a subsiding continental margin basin using the three computer programs described in Section II. The programs model a subsiding basin in an attempt to describe the formation of continental margins of the Atlantic type, with only a few modifications from one basin to another. In this study, as mentioned earlier, the model generates only a simplified Scotian Basin and evidence from observations was also simplified to make the model tractable. Only a simplified Scotian Basin could be used in this study because the model designed is in general very simple and needs further refinements before it can simulate a more complex basin.

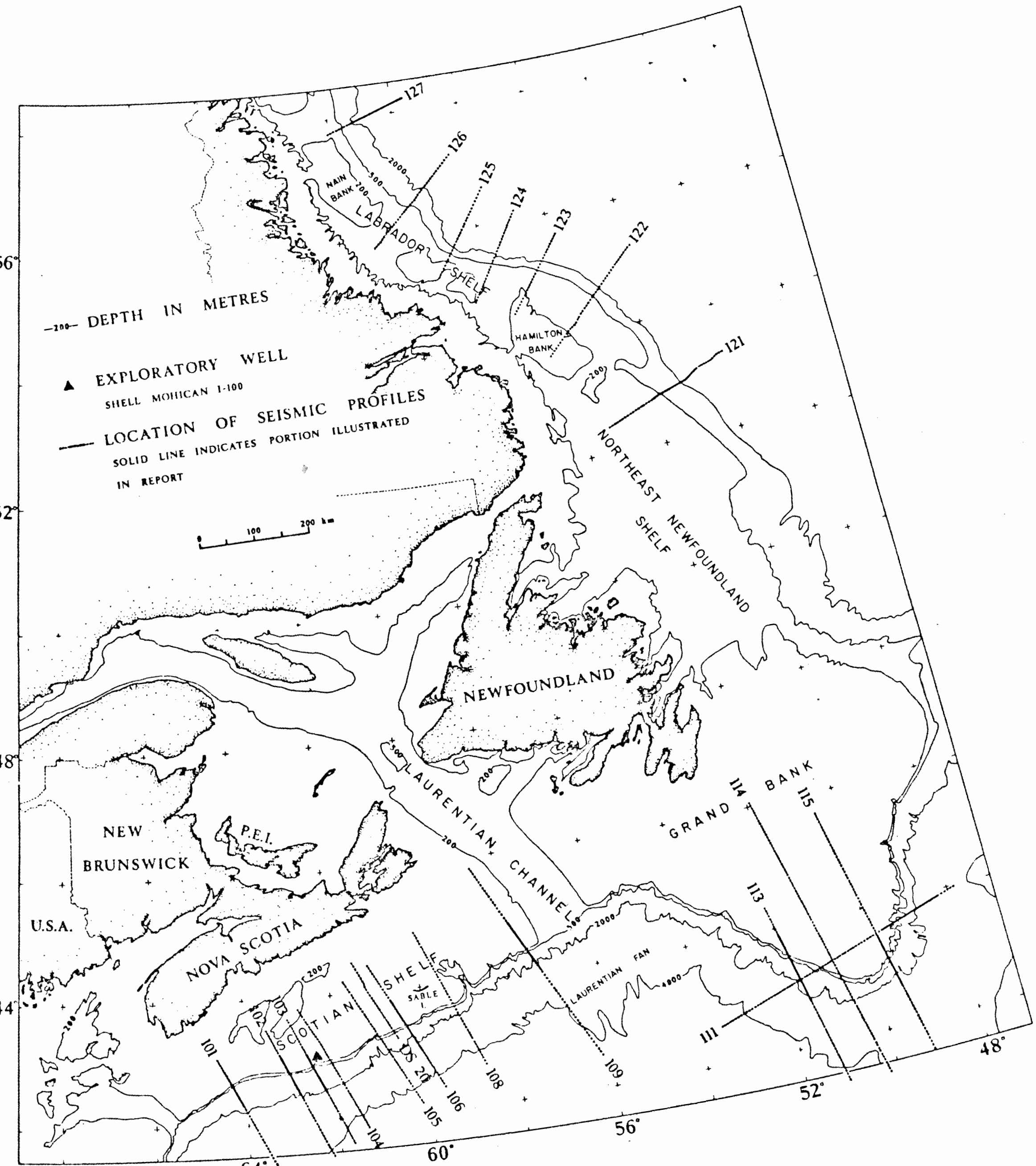
Prior to making these modifications in the model, the theoretical predictions of the simple model are needed as a guide to the extent of modification and the requirements needed to simulate a more realistic sedimentary basin. In this study the first step was completed by calculating a model for a simplified basin and attempting to correlate the results with those obtained from observations of the general subsidence history of the Scotian Basin.

The model developed here was done, as stated in Section II, over a 500 km by 500 km area split down the center into oceanic and continental halves. The oceanic half was initially loaded with sediment and the resulting immediate elastic subsidence calculated. Immediate subsidence on the continental side was filled with sediments until isostatic equilibrium was reached. Therefore, the first information required was an estimate of the amount of sediment that was deposited on the oceanic half of the area as a function of time.

To determine the amount of sediment on the continental rise off the Scotian Shelf (the area that parallels the oceanic half of the theoretical model) seismic results were used. The results used (Figure 14) were in themselves speculative and many approximations and assumptions made (King and Wade, personal communication). Depth to the top of the Jurassic was obtained (Wade, personal communication), and from Figure 15 (showing the depth to basement) the thickness of the Jurassic sediments was determined (approximately 1600 meters) on the continental rise. Next, the thickness of the Cretaceous and Tertiary-Quaternary layers were calculated using thickness ratios in seismic lines 101, 103 (Figure 12). These thicknesses averaged to 2250 meters and 4500 meters respectively. These thicknesses were then divided by the length of time they represent and multiplied by 20 m.y. to determine the amount of sediment deposited over one 20 m.y. time step in the model. The result was an average sedimentation rate of 1000 m per 20 m.y. on the continental rise and beyond. Therefore, in the program 1000 meters of sediment was added to the oceanic side at the beginning of each time step to simulate the amount of sediment accumulated during the same time off the Scotian Shelf.

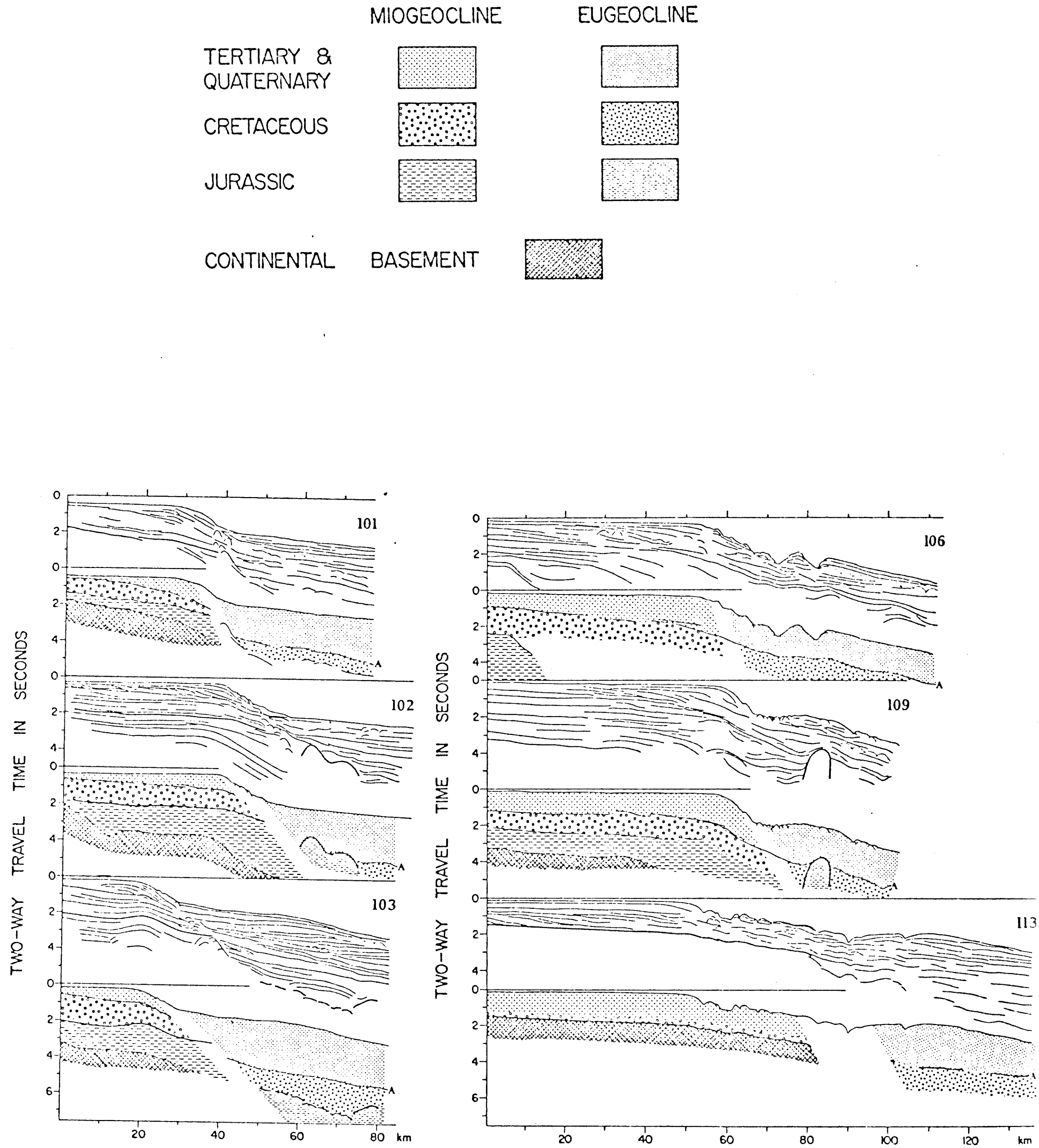
The next assumption was in calculating the load that this sediment exerted on each one of the grid squares in the oceanic half of the basin. A simple 2.4 g/cm^3 was used for the density of the

Figure 14a: Location of seismic lines used to determine sediment thickness. (Courtesy of Dr. L. King.)



DEPTH IN METRES
EXPLORATORY WELL
SHELL MOHICAN I-100
LOCATION OF SEISMIC PROFILES
SOLID LINE INDICATES PORTION ILLUSTRATED IN REPORT
0 100 200 km
LABRADOR SHELF
NAIN BANK
HAMILTON BANK
NORTHEAST NEWFOUNDLAND SHELF
NEWFOUNDLAND
LAURENTIAN CHANNEL
GRAND BANK
NEW BRUNSWICK
P.E.I.
NOVA SCOTIA
U.S.A.
SCOTIAN SHELF
SABLE I.
LAURENTIAN FAN
101
103
104
105
106
108
109
111
113
114
115
121
122
123
124
125
126
127
DS 20
56°
52°
48°
44°
68°
64°
60°
56°
52°
48°

Figure 14b: Seismic lines used to determine sediment thickness on the continental rise. (Courtesy of Dr. L. King.)

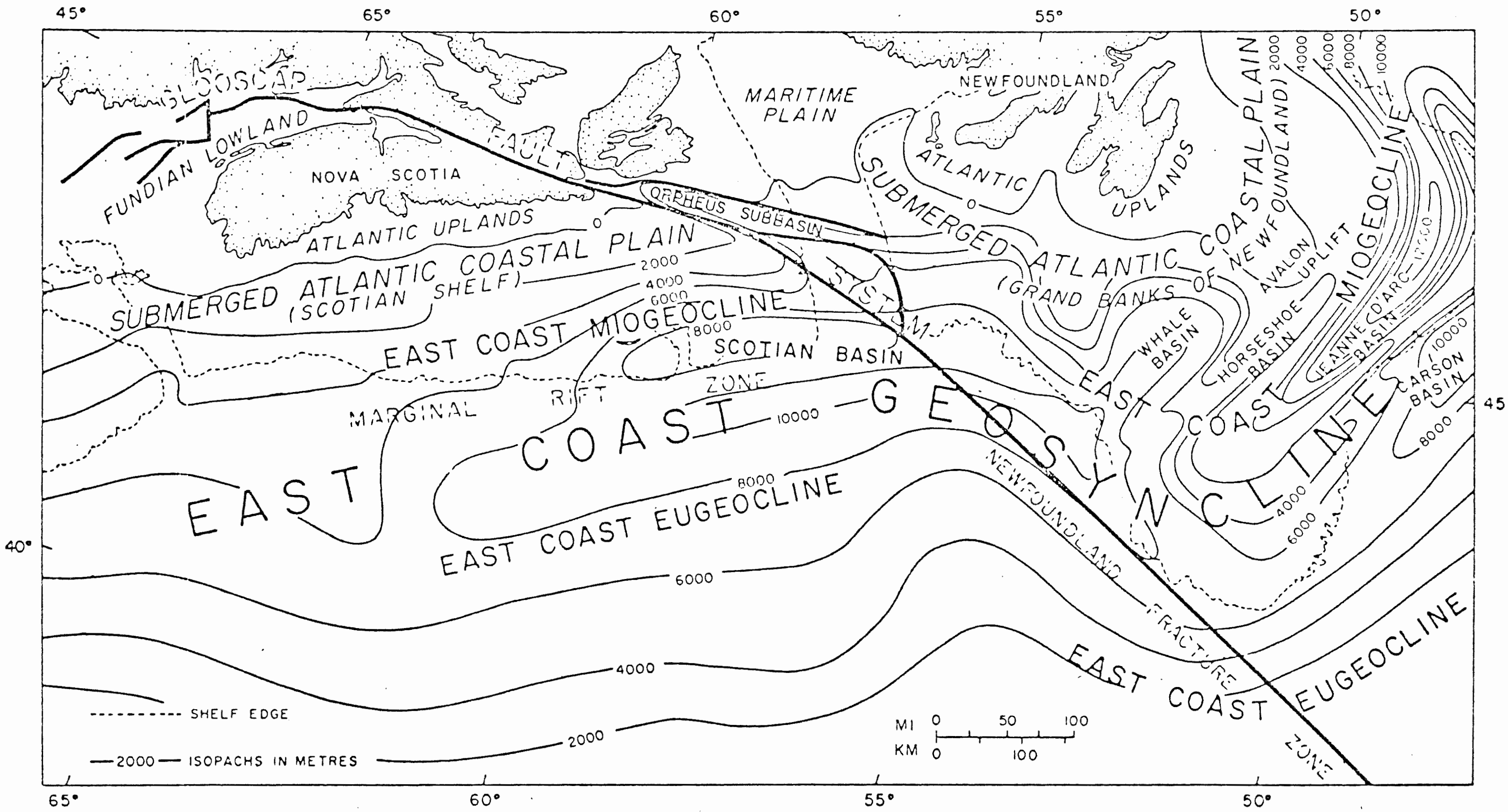

MIOGEOCLINE
EUGEOCLINE
TERTIARY & QUATERNARY
CRETACEOUS
JURASSIC
CONTINENTAL BASEMENT
TWO-WAY TRAVEL TIME IN SECONDS
101
102
103
106
109
113
km

sediment on both the oceanic and continental side of the margin. This figure was used as it is the approximate density of recently deposited sediment in the Scotian Basin. Refinements in this value can be made It should be remembered that this is a first order model.

As can be seen from Figure 13a, showing a cross-section through the theoretical basin, that the boundary between the ocean half and continental half of the margin is represented by a vertical line. To develop the basin more realistically, the sediment would be sloping seaward and not truncated by a vertical barrier, but this simplification is not so far from being correct as the shelf-rise boundary is fairly steep. The minor change in the results would be the increased subsidence on the oceanic side of the dividing line due to the increased sediment forming the continental slope. Progradation of the shelf sediments could be included if we knew the volume of available sediment and the slope stability.

Other minor simplifications that were made were that a sufficient sediment supply was available at all times to fill the basin on the continental side to the edge of the shelf. In reality, as can be seen from the general subsidence curves (Appendix I), sedimentation rates fluctuate in the Scotian Basin with time, but in the time spans used in this study the rates can be averaged. Also variations in paleo-bathymetry must be taken into account, these were plotted on a few of the Scotian Basin wells but data was not available for all wells. In the model the effect of changes in bathymetry can be simulated by

Figure 15: Isopach map showing sediment thickness to basement. Also showing transform fault truncating the Scotian Basin. (After King, 1975.)



GLOOSCAP
FUNDIAN LOWLAND
NOVA SCOTIA
FAULT
ATLANTIC UPLANDS
SUBMERGED ATLANTIC COASTAL PLAIN
(SCOTIAN SHELF)
ORPHEUS SUBBASIN
MARITIME PLAIN
NEWFOUNDLAND
ATLANTIC UPLANDS
SUBMERGED ATLANTIC COASTAL PLAIN OF NEWFOUNDLAND
(GRAND BANKS)
EAST COAST MIOGEOCLINE
SCOTIAN BASIN
MARGINAL RIFT ZONE
SYSTEM
EAST COAST GEOSYNCLINE
EAST COAST EUGEOCLINE
WHALE BASIN
HORSESHOE BASIN
AVALON UPLIFT
JEANNE D'ARC BASIN
CARSON BASIN
NEWFOUNDLAND FRACTURE ZONE
SHELF EDGE
2000 ISOPACHS IN METRES
MI 0 50 100
KM 0 100

reducing the sediment supply to the area but letting it continue to subside, but this was not taken into account in this study.

The final assumption made was to add a thermal contraction of the lithosphere on the continental shelf side. This was added to the effect of sedimentary loading, Sleep's (1971) time constant of 50 m.y. for exponential subsidence was used. Results obtained from unnormalized and uncorrected data for the Scotian Basin in this study suggests a slightly higher time constant of 60 m.y., but since the well data was uncorrected the lower value was taken. The pre-exponential term defining the total eventual depth of the basin was assumed to be constant over the entire basin. However, if the initiation process for subsidence is uplift erosion followed by thermal contraction causing subsidence the final depth will not be the same over the entire area, but will change as distance from the rifted boundary increases. Therefore, in a more complex model the pre-exponential of the subsidence would decrease away from the margin toward the continent.

As stated earlier, the model used here was time stepped forward for a period of 160 m.y. (approximate age of the Scotian Basin) with each time step being 20 m.yrs. The results of the theoretical model are presented in Figures 16 to 19, showing model results for four locations, three on the continent side and one of the oceanic side, plus subsidence curves for these locations. Three models were run; a) Taking the flexural rigidity to be 10^{25} newton meters (n.m.) and the viscous time constant as 10^{4} yrs.

b) Flexural rigidity of 10^{25} n.m. and viscous time constant of 10^{5} yrs.

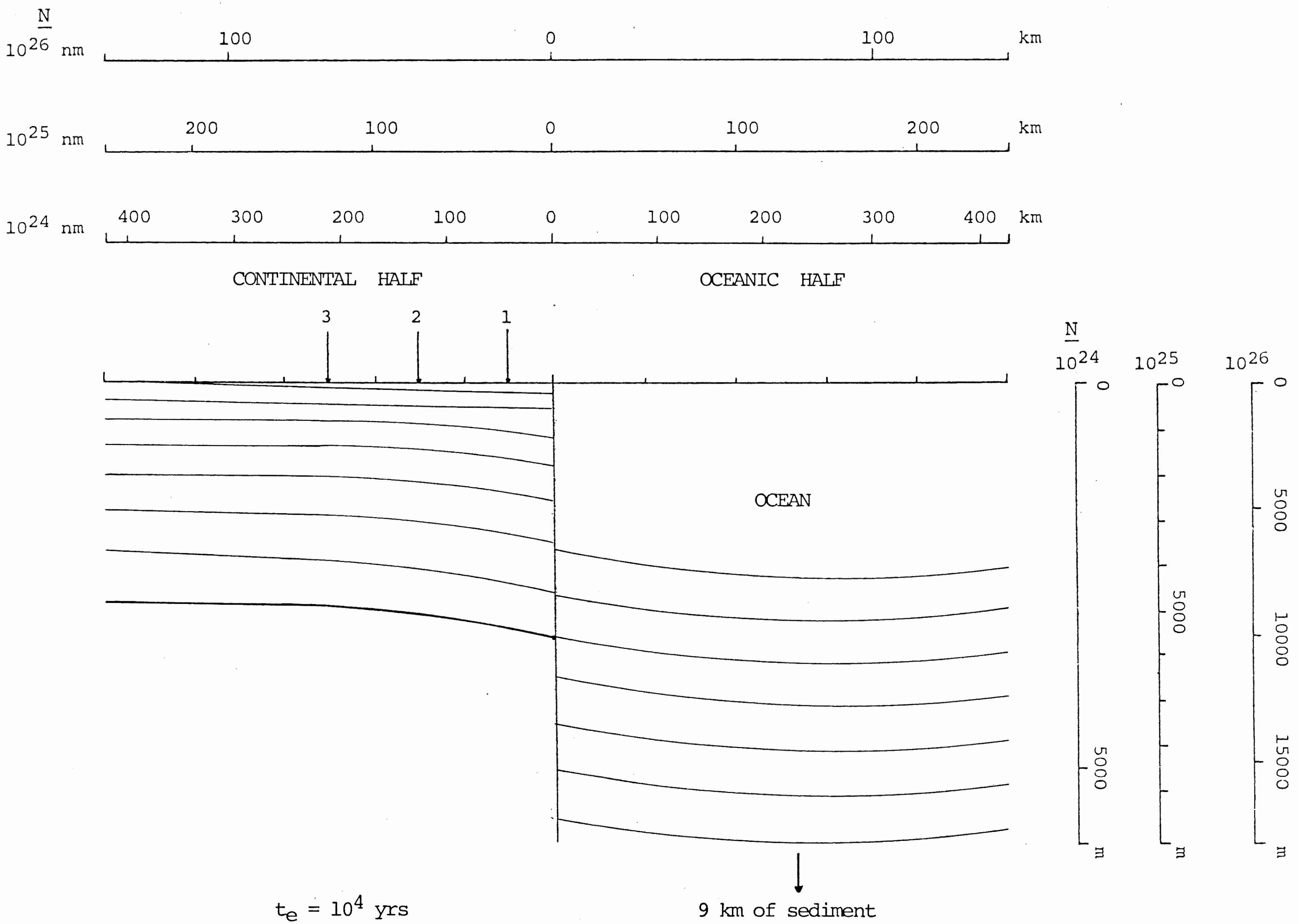
c) Flexural rigidity of 10^{25} n.m. and viscous time constant of 10^{6} yrs.

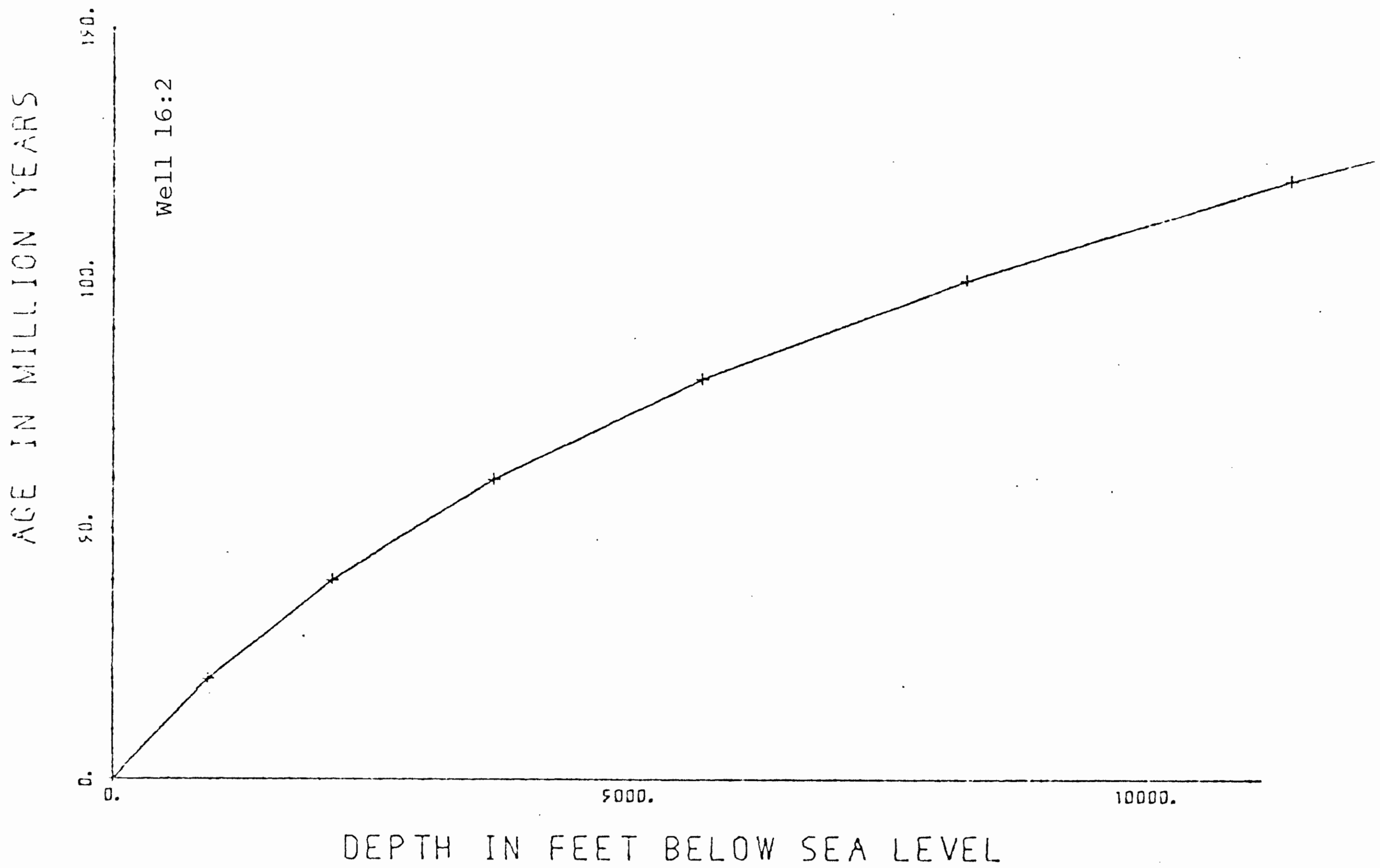
It can be noted from the cross-sections (Figures 16, 17 and 18) of the theoretical basin that a change in the flexural rigidity only changes the spatial scale of the cross sections and not their shape. Therefore, results for a different value of N can be obtained, merely by scaling as we have indicated.

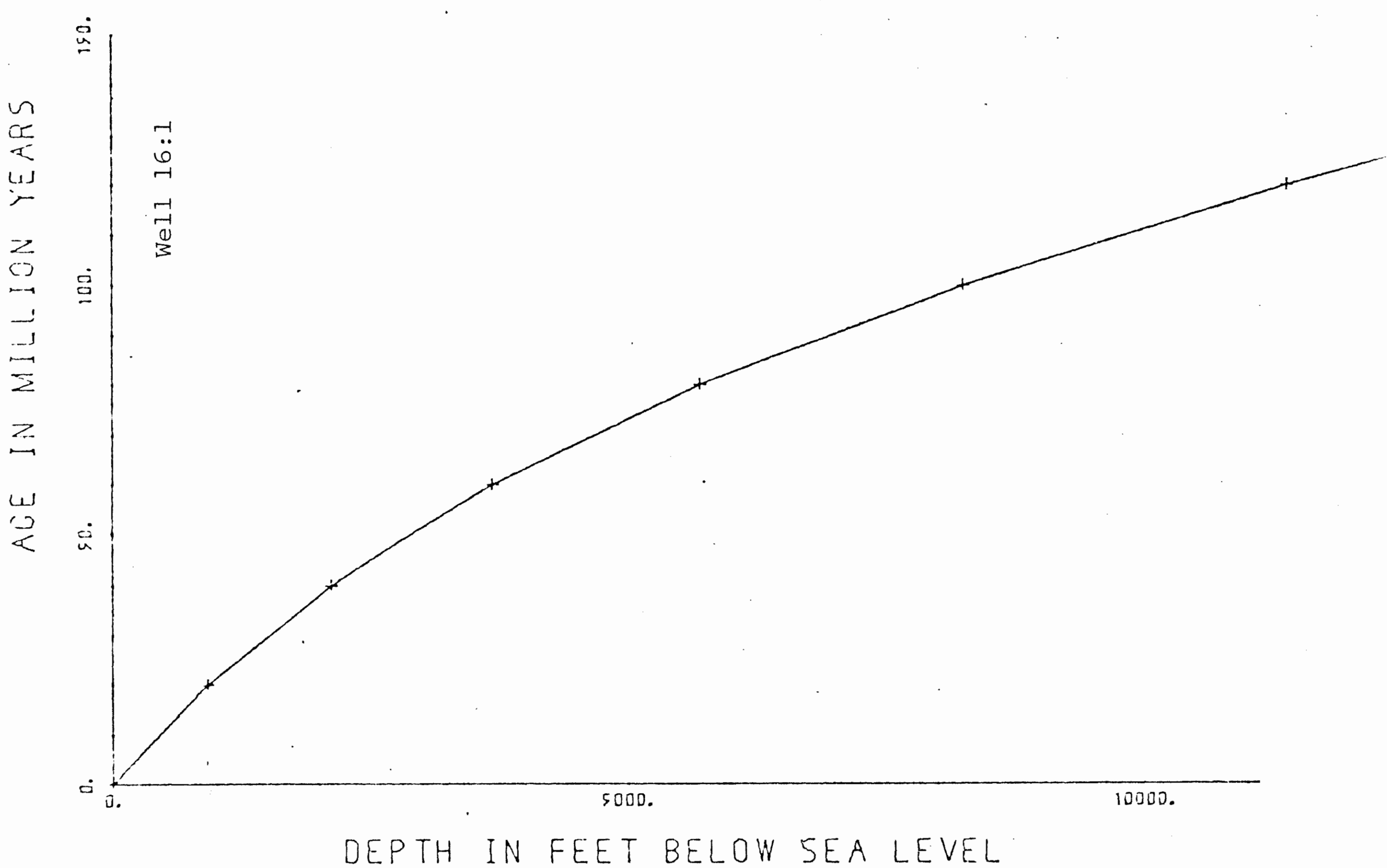
In the first run of the model, subsidence was calculated using a flexural rigidity of 10^{25} n.m. and a viscous time constant of 10^{5} yrs. but not adding the exponential subsidence. This model gave results on how the basin subsided purely as a result of sedimentary loading (Figure 19). The total amount of subsidence after 160 m.y. at the predicted by this model is 2 km which in the case of the Scotian Basin is much too small. The model results do, however, show decreasing subsidence rates away from the continental margin as is observed (Figure 17). The reason the subsidence curves 75 km and 125 km landward from the edge of the margin become positive after a certain length of time is due to the migration of the peripheral bulge toward the center of the basin, and this causes the uplift.

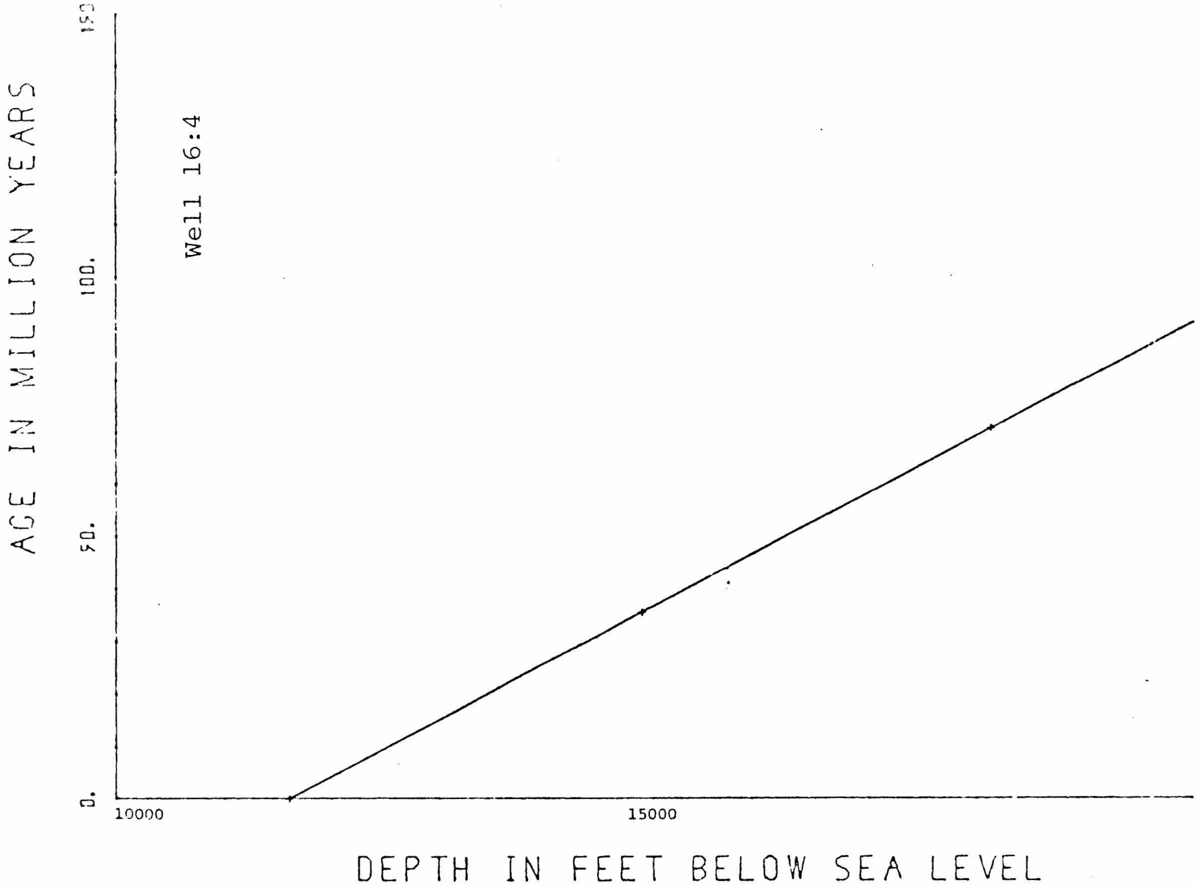
Next the effect of exponential subsidence as a result of thermal contraction was taken into account, and the results calculated in all

Figure 16: Cross section of theoretical basin using $N = 10^{25}$ n.m., $t_e = 10^4$ yrs. The following subsidence curves Figures 16(i), 16(ii), 16(iii), and 16(iv) are taken from plotting age against depth at theoretical wells 16:1, 16:2; 16:3, and 16:4. This cross section may be used for any N, only the scale has to be changed.


N
10^26 nm
100
0
100
km
10^25 nm
200
100
0
100
200
km
10^24 nm
400
300
200
100
0
100
200
300
400
km
CONTINENTAL HALF
OCEANIC HALF
3
2
1
OCEAN
N
10^24
10^25
10^26
0
5000
m
0
5000
m
0
5000
10000
15000
m
t_e = 10^4 yrs
9 km of sediment


Well 16:2
AGE IN MILLION YEARS
0.
50.
100.
150.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL


Well 16:1
AGE IN MILLION YEARS
0.
50.
100.
150.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL


AGE IN MILLION YEARS
Well 16:4
100.
50.
0.
10000
15000
DEPTH IN FEET BELOW SEA LEVEL

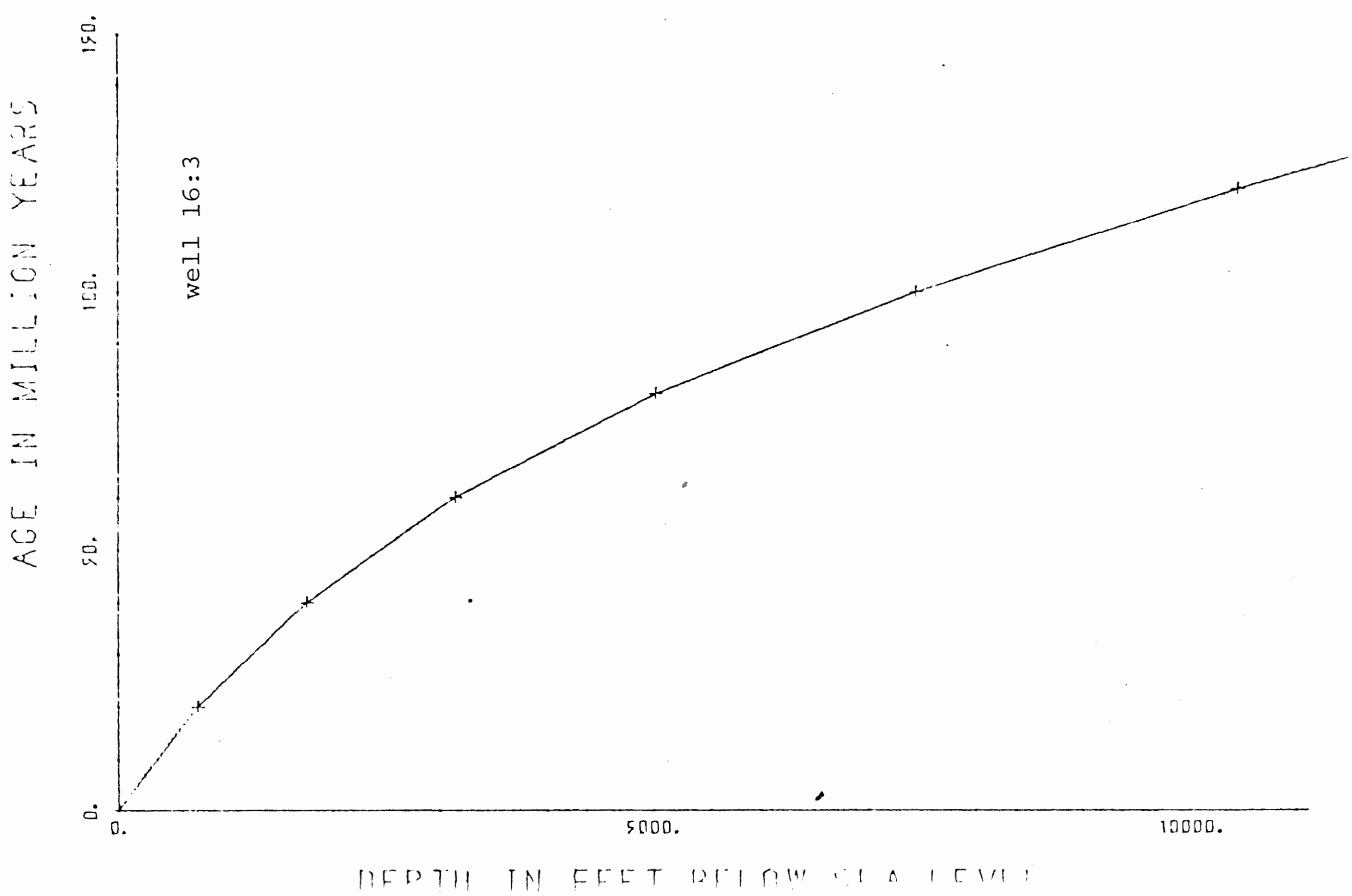

AGE IN MILLION YEARS
well 16:3
150.
100.
50.
0.
0.
5000.
10000.

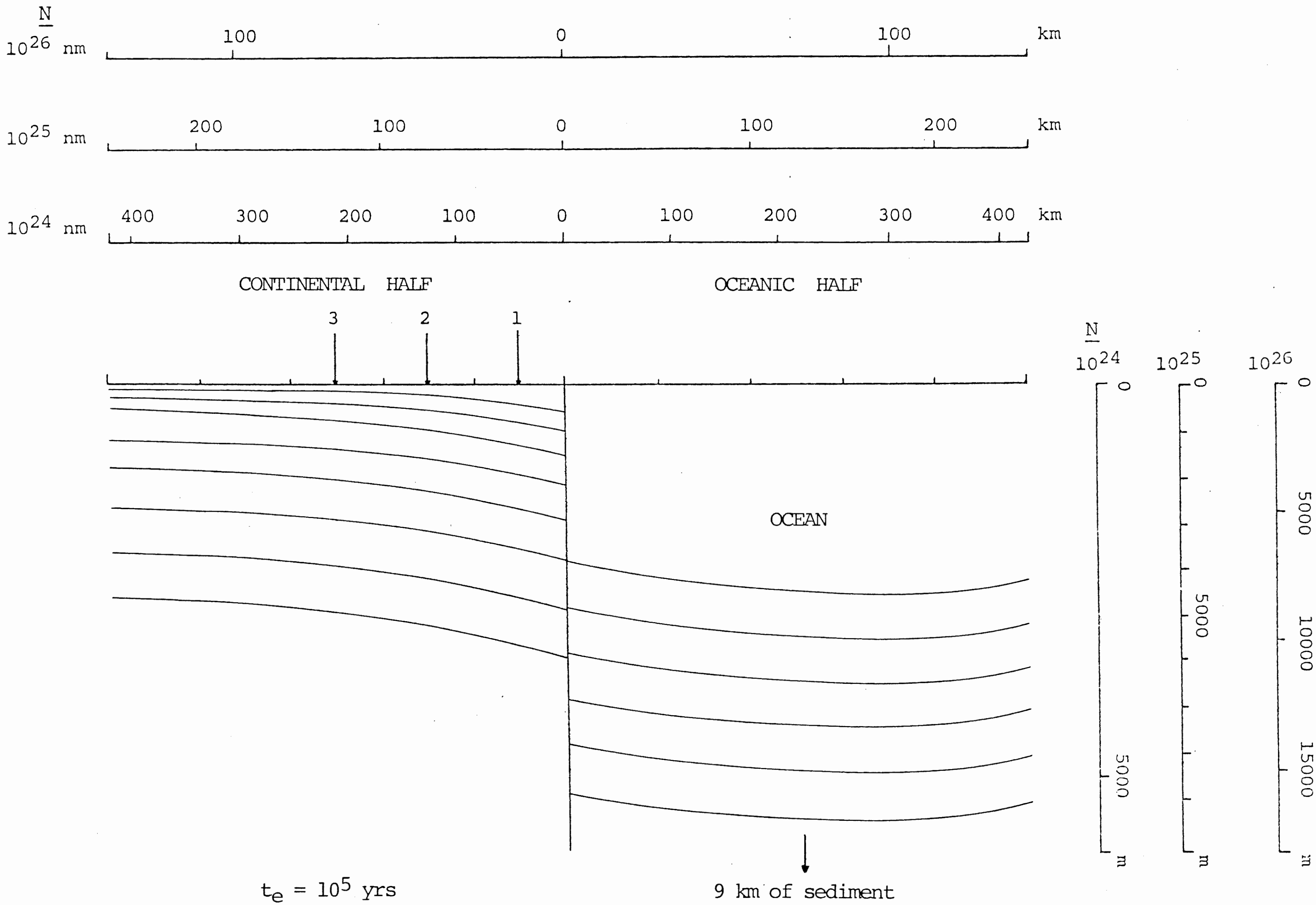
Table 3: Well data from theoretical wells 16:1, 16:2, and 16:3.

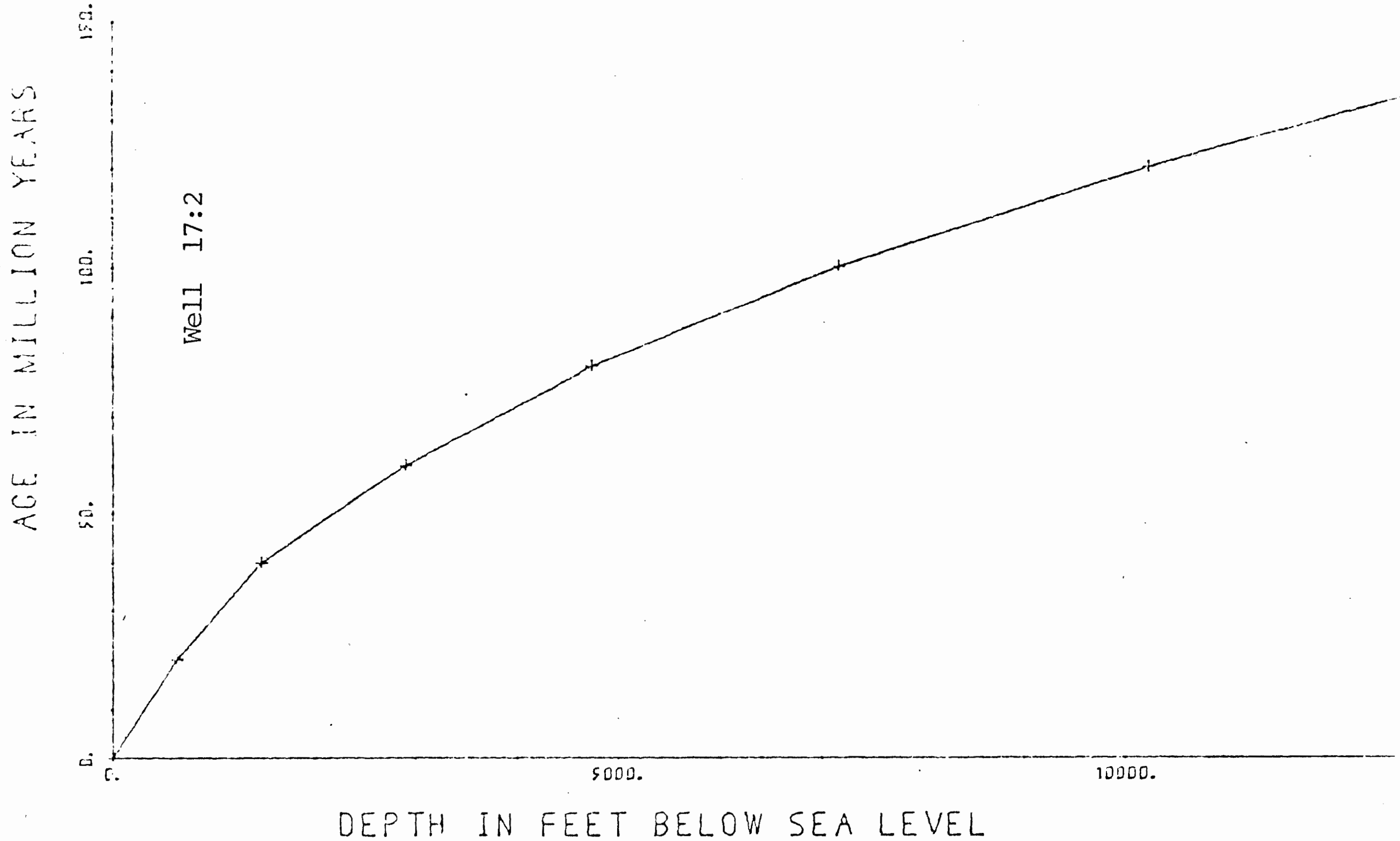
Theoretical Data for Subsidence Curves Using

$N = 10^{25}$, $t_e = 10^4$

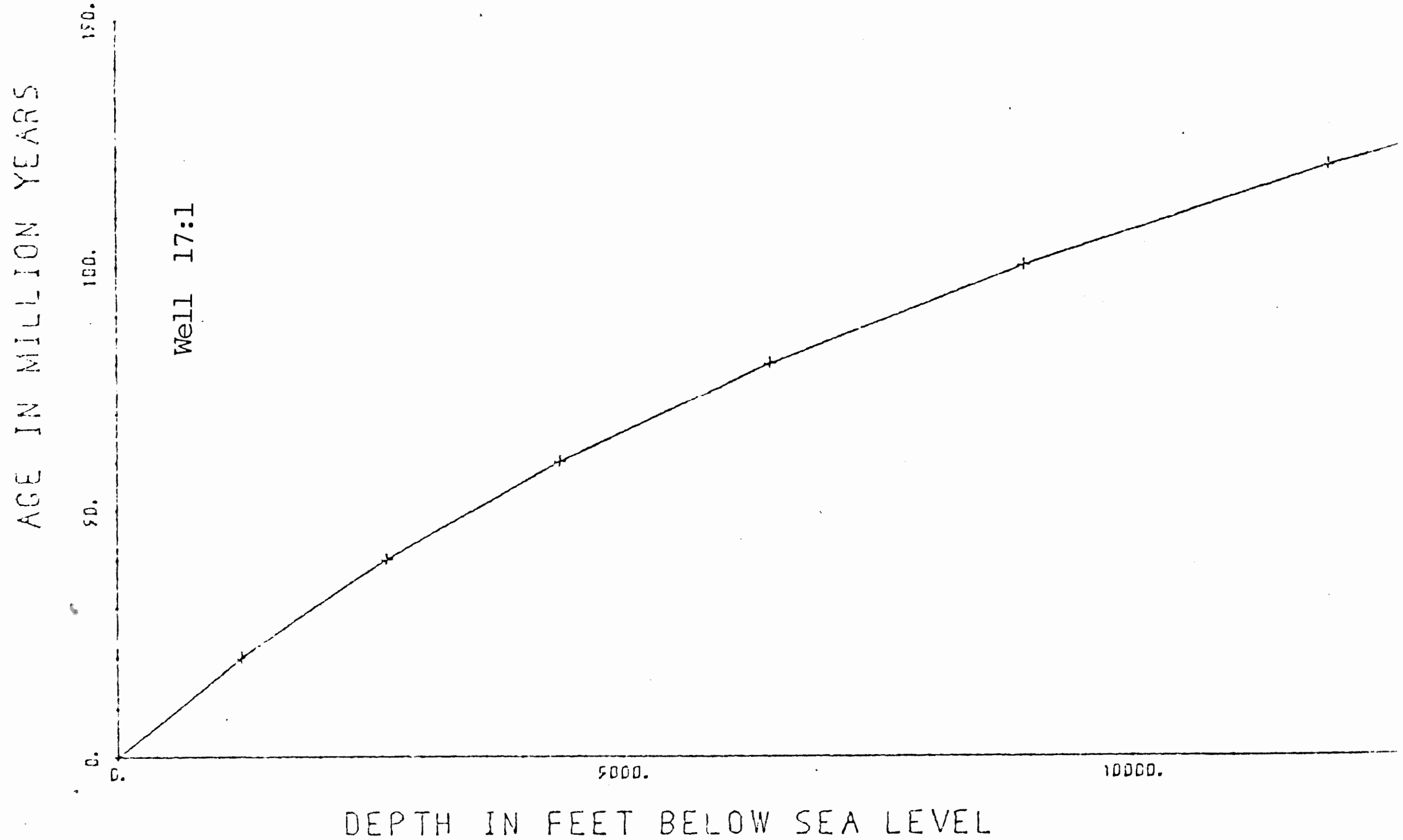
Age from initial t=0 (m.y.)	25 km from continental oceanic boundary		75 km from continental oceanic boundary		125 km from continental oceanic boundary	
	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)
0	0	5612.8	0	5338.8	0	5195.6
20	1050.7	4562.1	1023.8	4315.0	977.4	4218.2
40	1091.6	3470.5	1081.4	3233.6	1039.7	3178.5
60	953.6	2516.9	947.8	2285.8	914.0	2264.5
80	779.1	1737.8	758.3	1527.5	738.0	1526.5
100	615.7	1122.1	576.8	950.7	568.2	958.2
120	477.8	644.3	425.2	525.5	424.5	533.8
140	366.2	278.1	306.9	218.6	310.3	223.5
160	278.1	0	218.6	0	223.5	0

Figure 17: Cross section of theoretical basin using $N = 10^{25}$ n.m., $t_e = 10^5$ yrs. The following subsidence curves, Figures 17(i), 17(ii), 17(iii), and 17(iv) are taken from plotting age against depth at theoretical wells 17:1, 17:2, 17:3, and 17:4. This cross section may be used for any N, only the scale has to be changed.

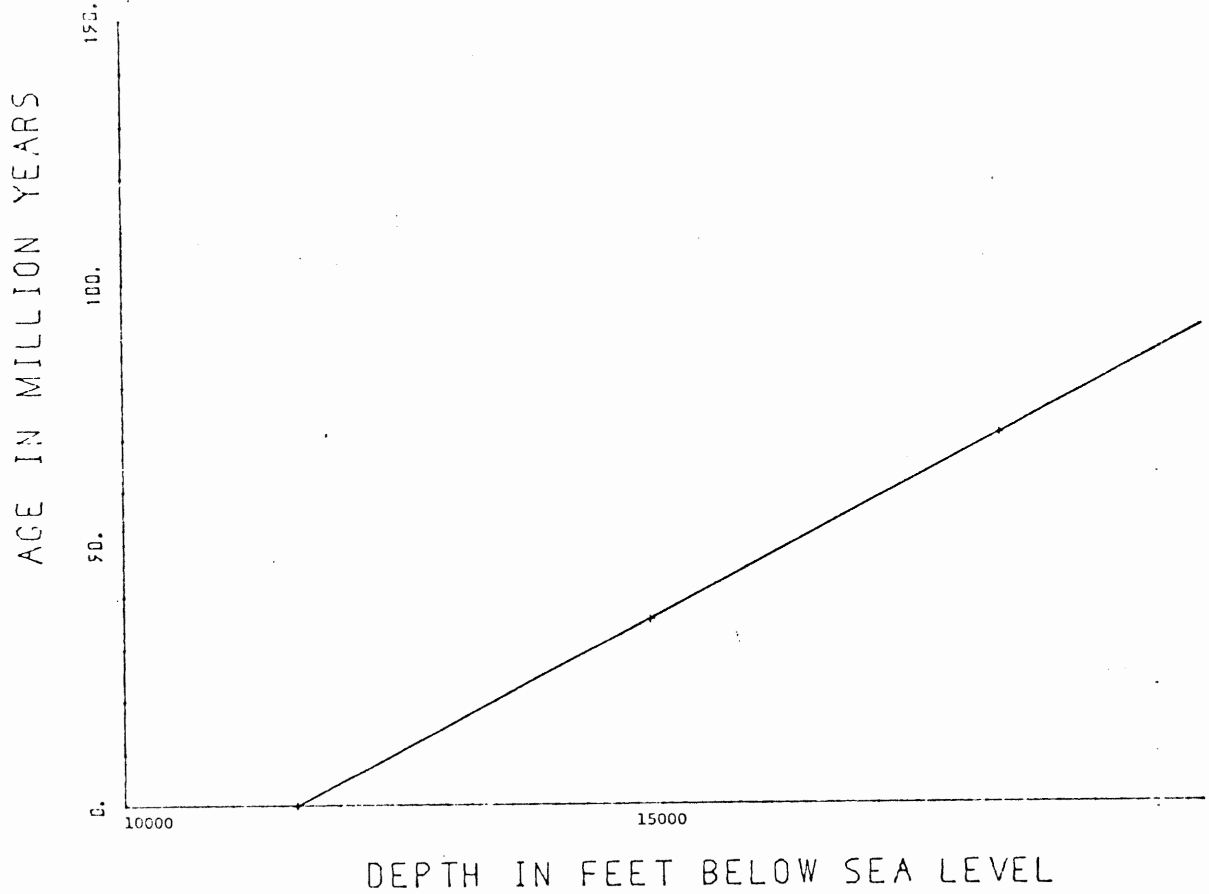

N
10^{26} nm
100
0
100
km
10^{25} nm
200
100
0
100
200
km
10^{24} nm
400
300
200
100
0
100
200
300
400
km
CONTINENTAL HALF
OCEANIC HALF
3
2
1
OCEAN
N
10^{24}
10^{25}
10^{26}
0
5000
m
0
5000
m
0
5000
10000
15000
m
$t_e = 10^5$ yrs
9 km of sediment



AGE IN MILLION YEARS
150.
100.
50.
0.
Well 17:2
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL



AGE IN MILLION YEARS
150.
100.
50.
0.
Well 17:1
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL


AGE IN MILLION YEARS
150.
100.
50.
0.
10000
15000
DEPTH IN FEET BELOW SEA LEVEL

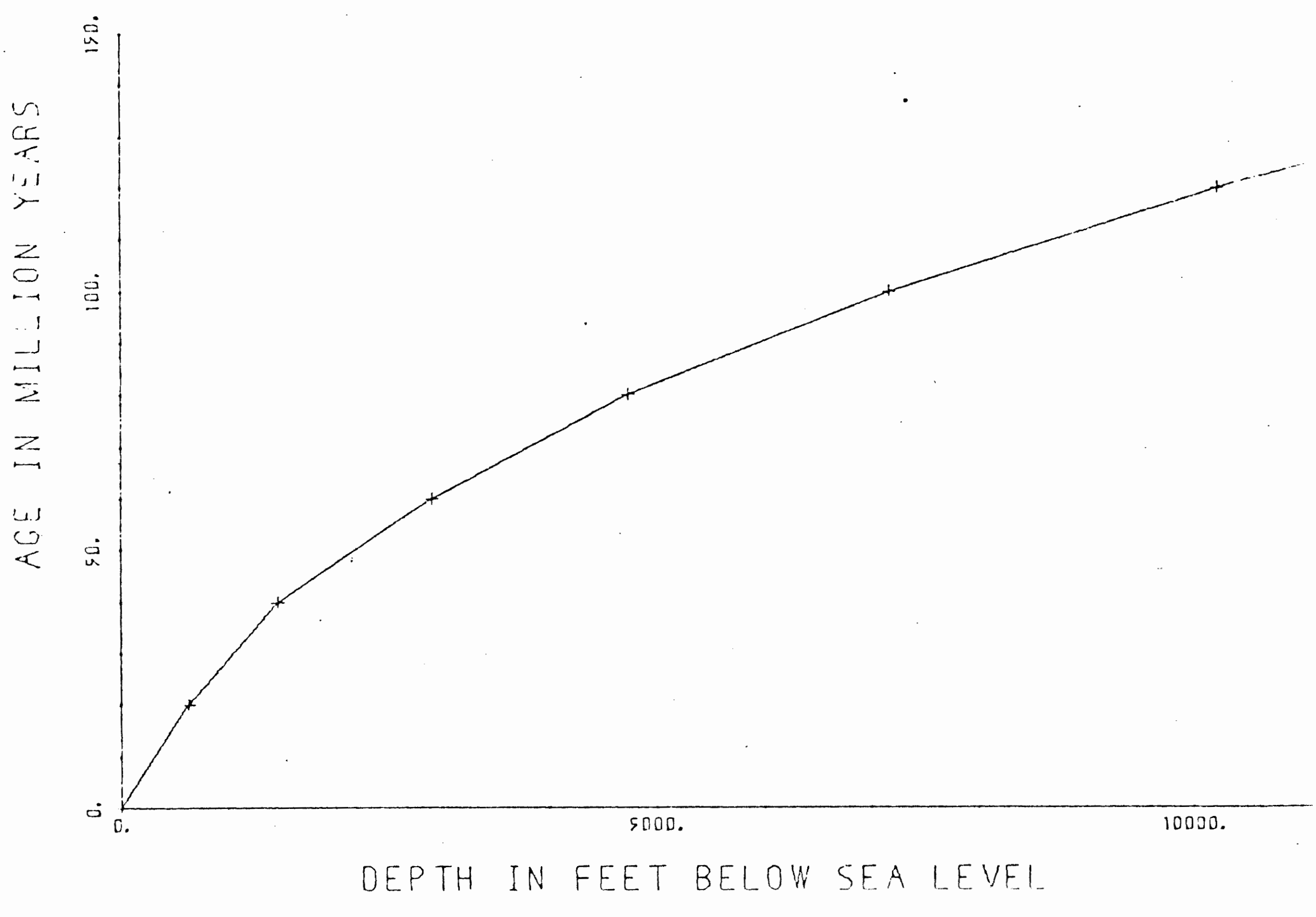

AGE IN MILLION YEARS
150.
100.
50.
0.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL

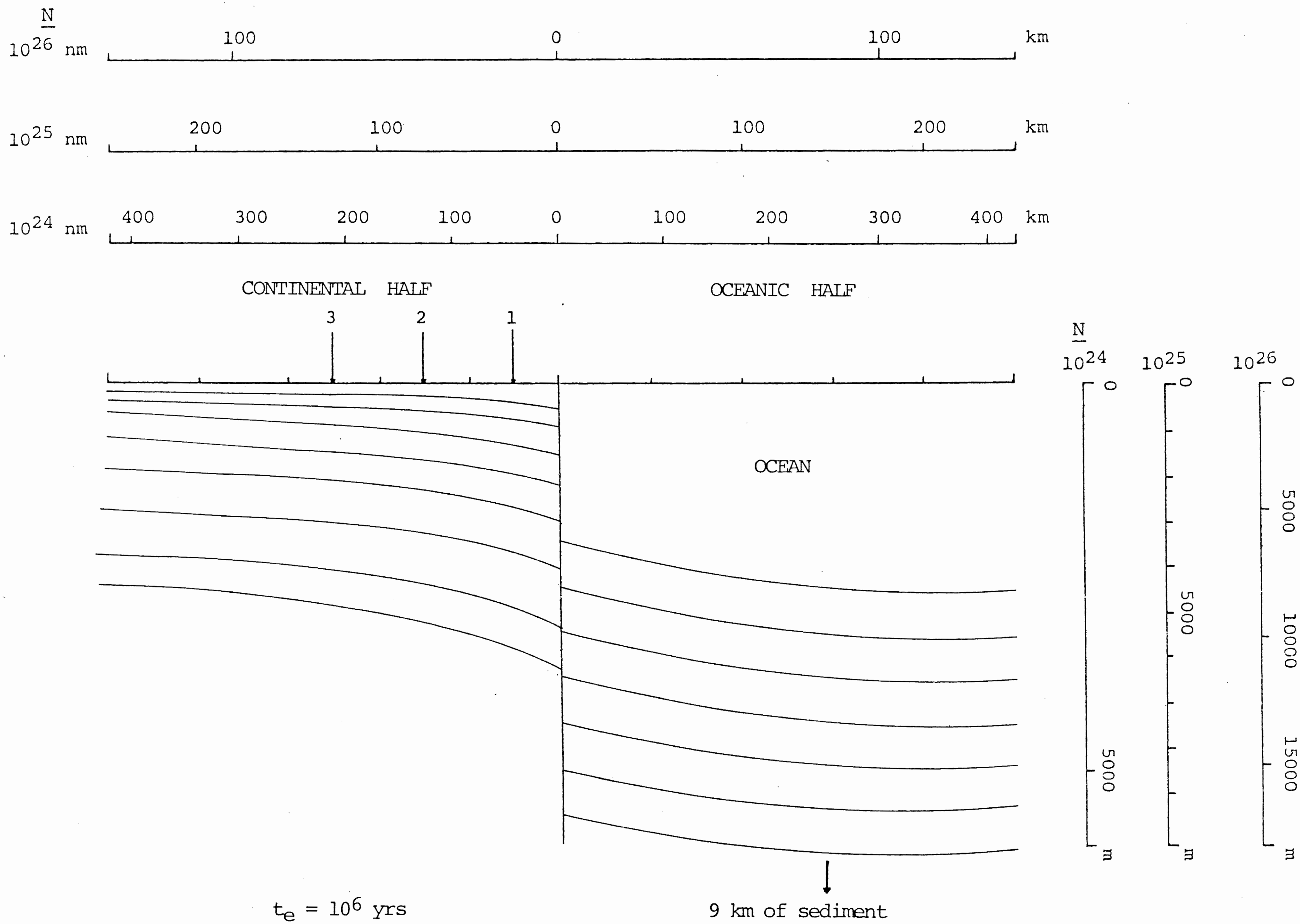
Table 4: Well data from theoretical wells 17:1, 17:2, and 17:3.

Theoretical Data for Subsidence Curves Using

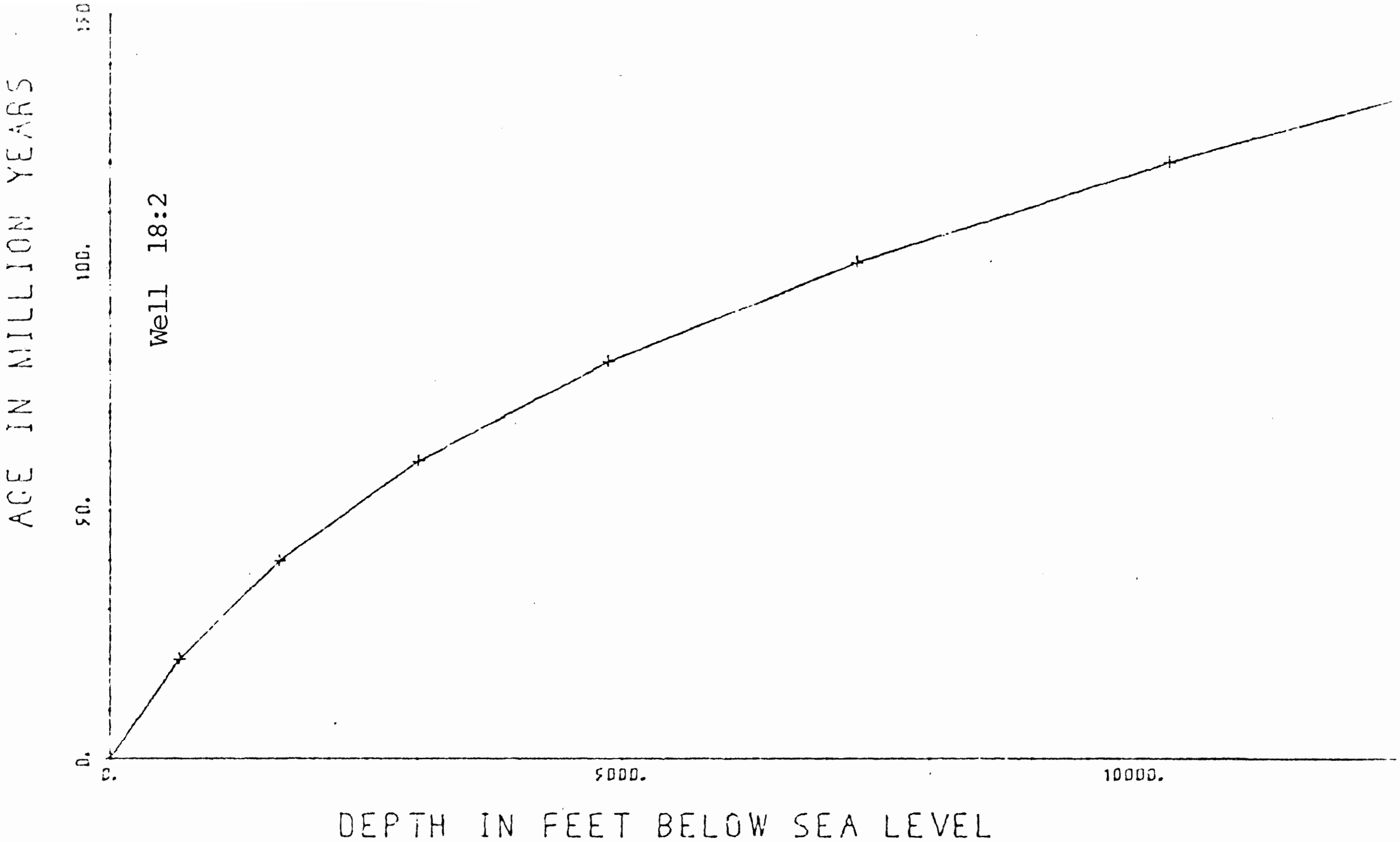
$N = 10^{25}$, $te = 10^{5}$

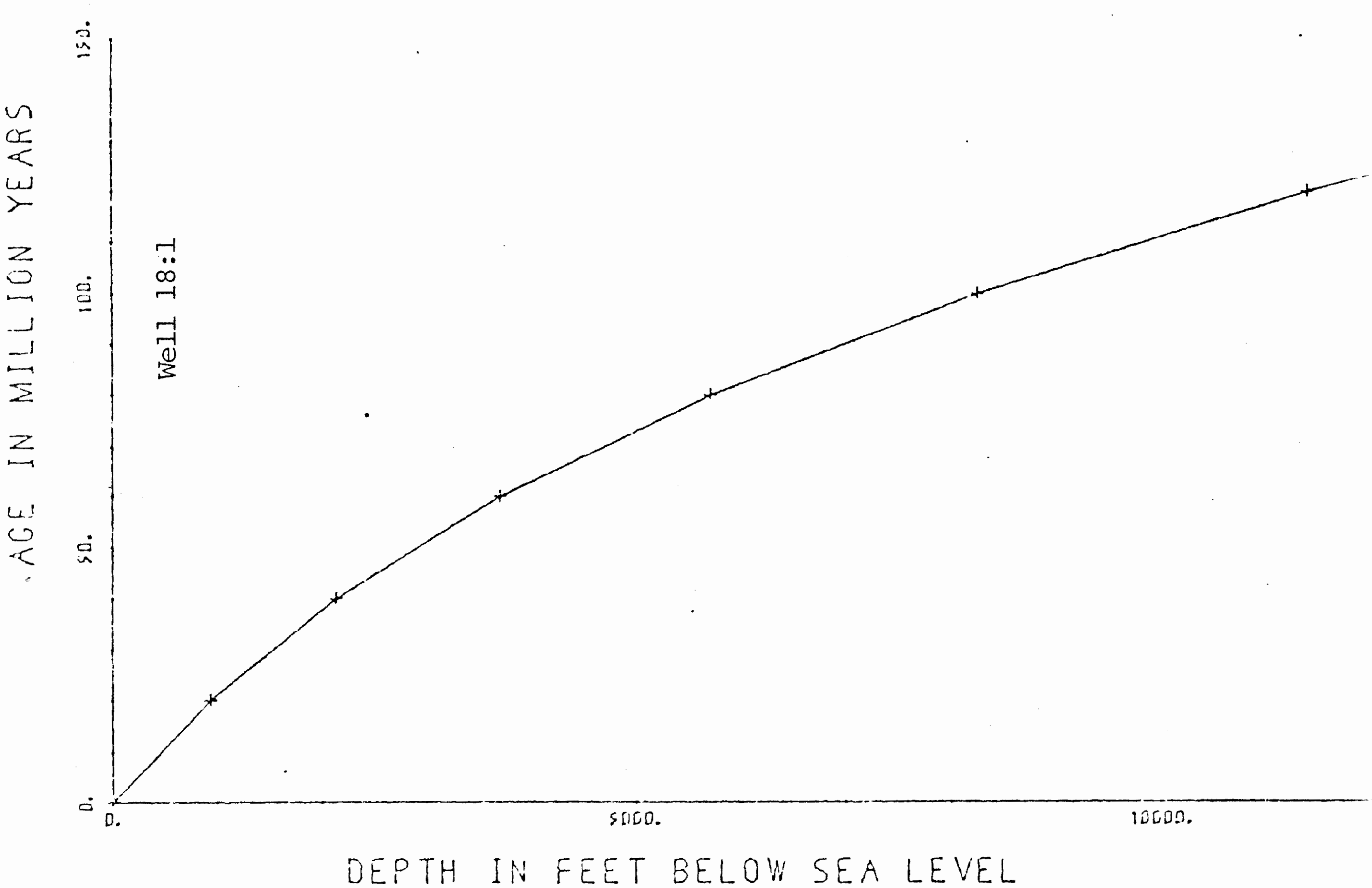
Age from initial t=0 (m.y.)	25 km from continental oceanic boundary		75 km from continental oceanic boundary		125 km from continental oceanic boundary	
	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)
0	0	5744.8	0	5236.0	0	5150.7
20	1050.9	4693.9	1024.0	4212.0	977.6	4173.1
40	1049.2	3644.7	1060.5	3151.5	1057.2	3115.9
60	916.2	2728.5	927.0	2224.5	930.8	2185.1
80	765.7	1962.8	742.0	1482.5	743.0	1442.1
100	631.5	1331.3	564.1	918.4	559.6	882.5
120	522.4	808.9	414.5	503.9	405.0	447.5
140	437.1	371.8	296.6	207.3	284.0	193.5
160	371.8	0	207.3	0	193.5	0

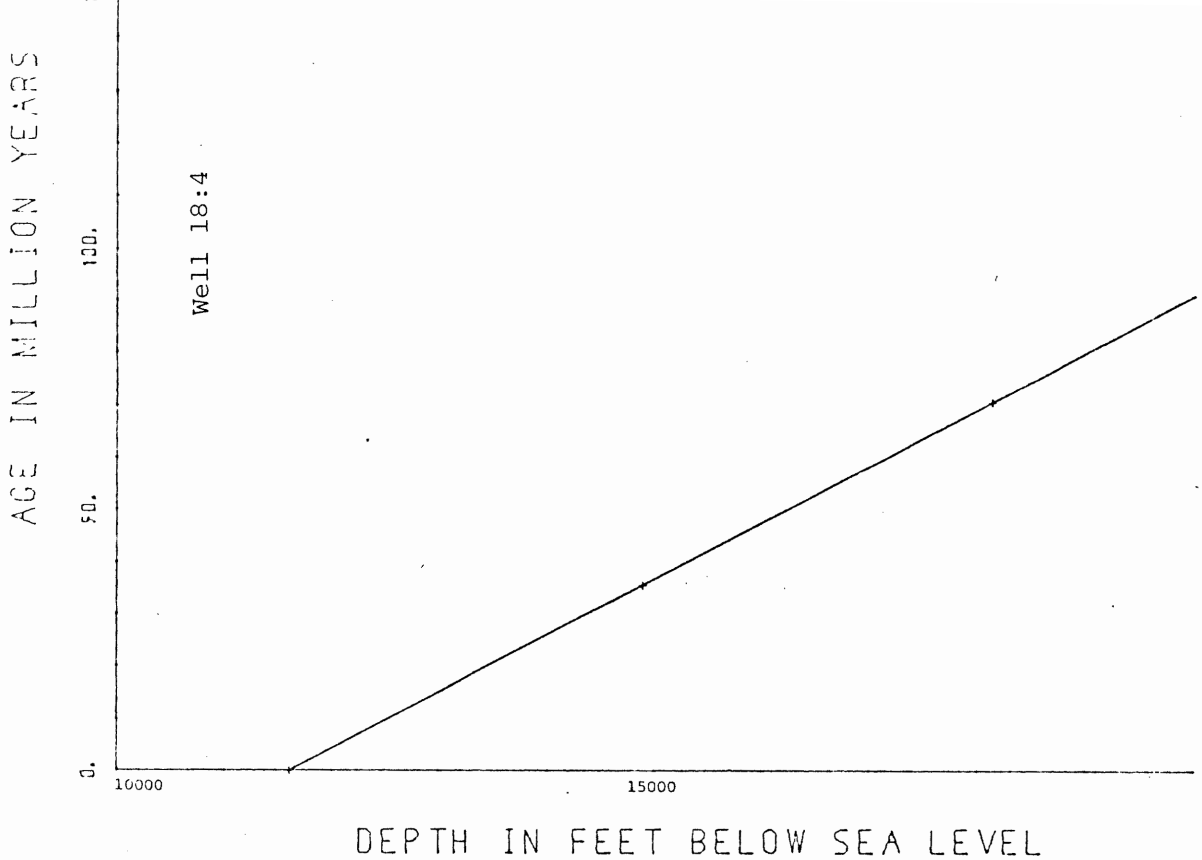
Figure 18: Cross section of theoretical basin using $N = 10^{25}$ n.m., $t_e = 10^6$ yrs. The following subsidence curves, Figures 18(i), 18(ii), 18(iii), and 18(iv) are taken from plotting age against depth at theoretical wells 18:1, 18:2, 18:3, and 18:4. This cross section may be used for any N, only the scale has to be changed.



N / 10^{26} nm
100
0
100
km
10^{25} nm
200
100
0
100
200
km
10^{24} nm
400
300
200
100
0
100
200
300
400
km
CONTINENTAL HALF
OCEANIC HALF
3
2
1
OCEAN
N / 10^{24}
10^{25}
10^{26}
0
5000
m
0
5000
m
0
5000
10000
15000
m
$t_e = 10^6$ yrs
9 km of sediment


AGE IN MILLION YEARS
Well 18:2
0.
50.
100.
150
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL


AGE IN MILLION YEARS
Well 18:1
0.
50.
100.
150.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL


AGE IN MILLION YEARS
100.
50.
0.
Well 18:4
10000
15000
DEPTH IN FEET BELOW SEA LEVEL

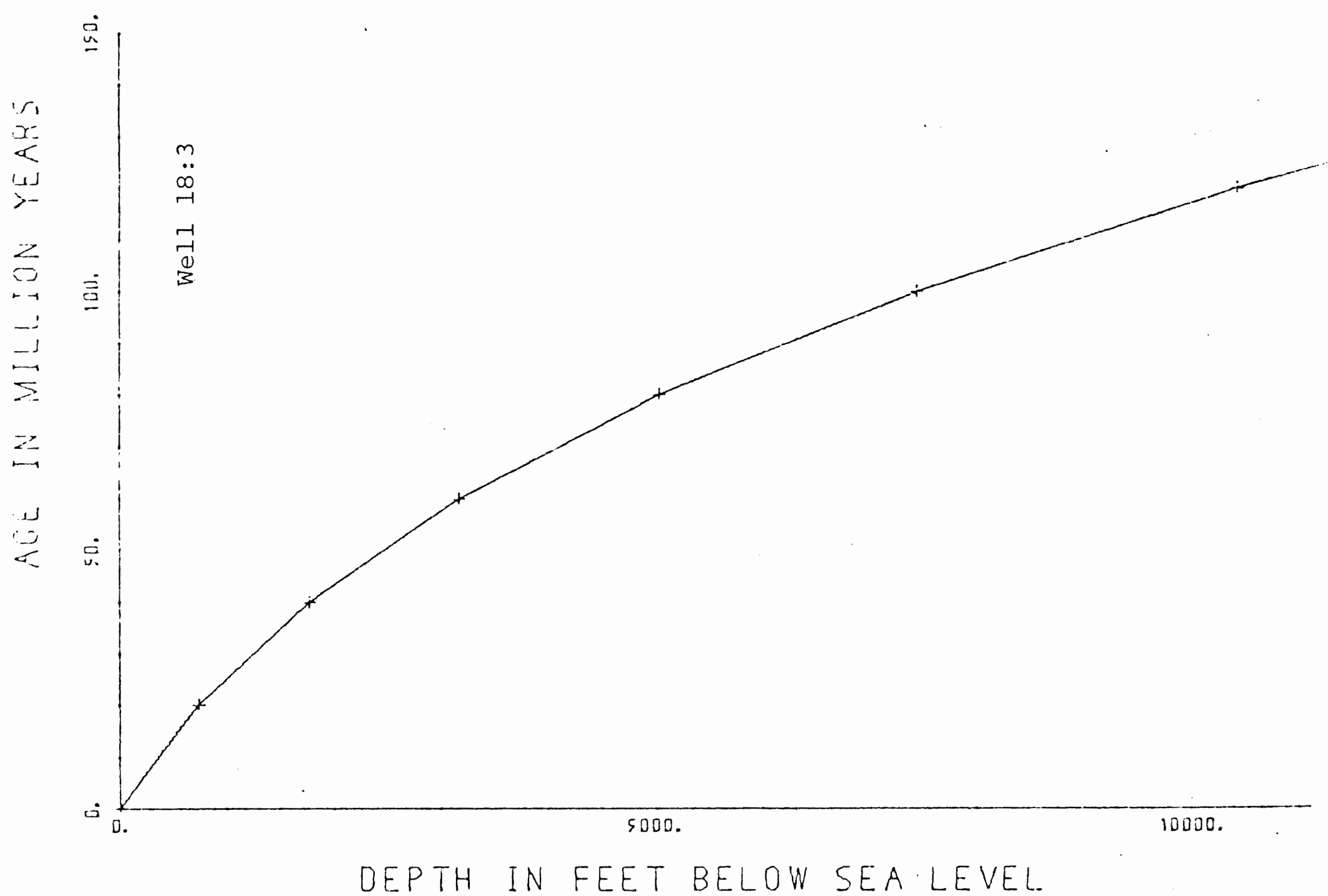

AGE IN MILLION YEARS
150.
100.
50.
0.
Well 18:3
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL

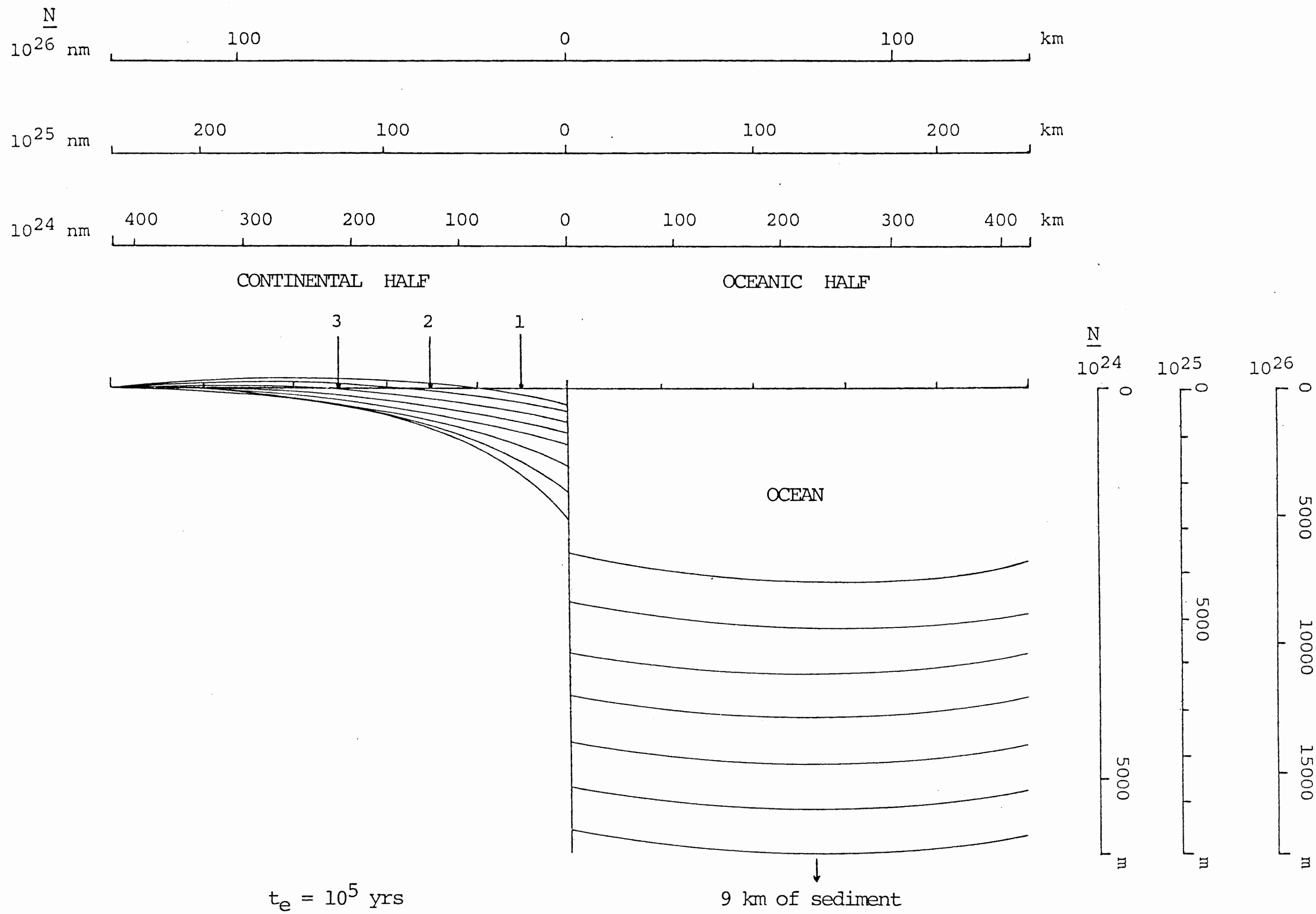
Table 5: Well data from theoretical
wells 18:1, 18:2, and 18:3.

Theoretical Data for Subsidence Curves Using

$N = 10^{25}$, $te = 10^{6}$

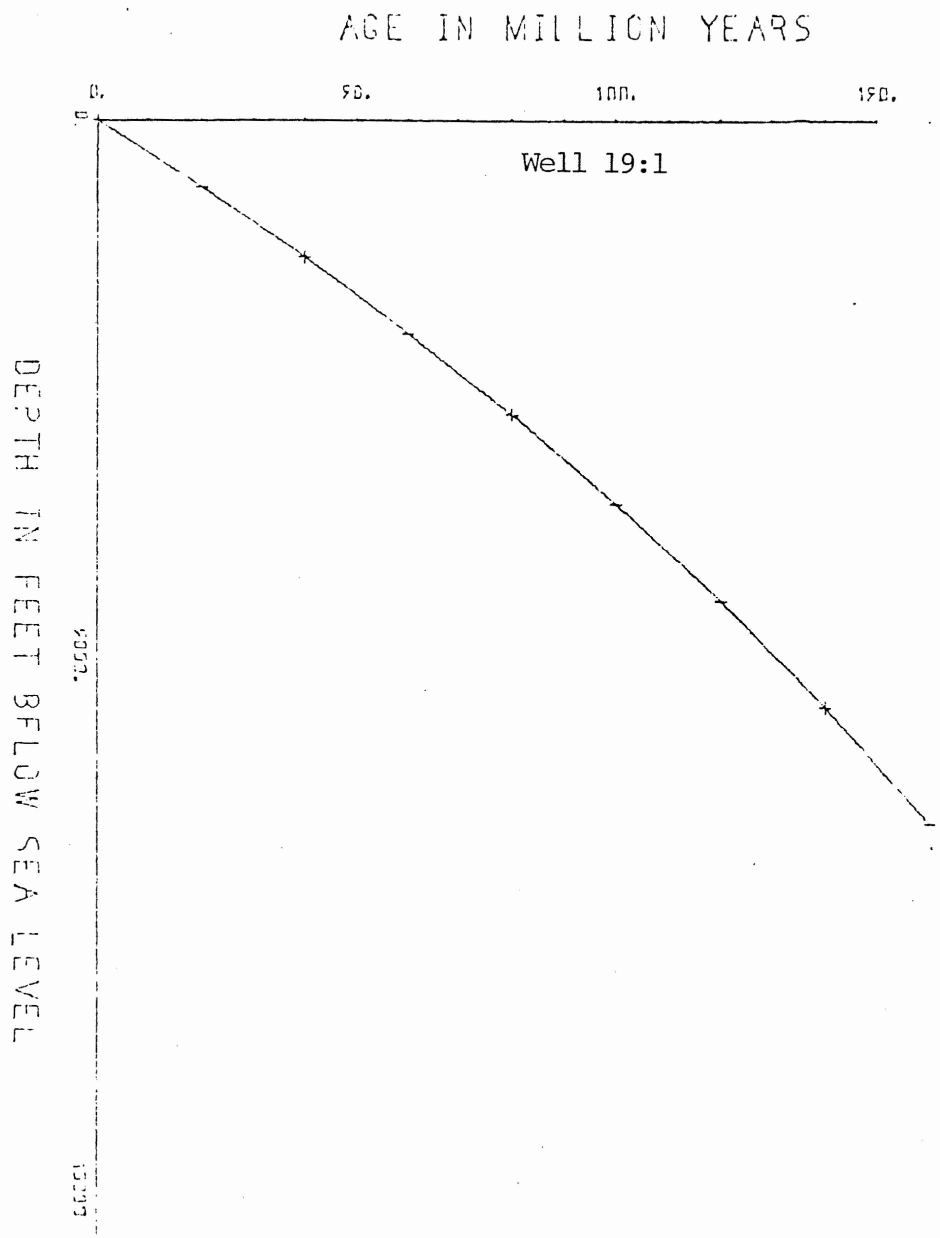
Age from initial t=0 (m.y.)	25 km from continental oceanic boundary		75 km from continental oceanic boundary		125 km from continental oceanic boundary	
	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)
0	0	6010.8	0	5607.0	0	5198.4
20	1050.7	4960.1	1023.8	4583.2	977.4	4221.0
40	1135.9	3824.2	1107.1	3476.1	1042.7	3178.3
60	967.0	2857.2	958.4	2517.7	909.6	2268.7
80	793.9	2063.3	777.3	1740.4	734.3	1534.4
100	652.0	1411.3	612.7	1127.7	568.4	966.0
120	543.3	868.0	476.0	651.7	427.4	538.6
140	463.1	404.9	367.8	283.9	313.8	224.8
160	404.9	0	283.9	0	224.8	0

Figure 19: Cross section of theoretical basin using only sedimentary loading. Subsidence curves are from wells # 19:1 and 19:2.



N
10^26 nm
10^25 nm
10^24 nm
100 0 100 km
200 100 0 100 200 km
400 300 200 100 0 100 200 300 400 km
CONTINENTAL HALF
OCEANIC HALF
3
2
1
OCEAN
N
10^24
10^25
10^26
0
5000
m
0
5000
m
0
5000
10000
15000
m
t_e = 10^5 yrs
9 km of sediment

$N = 10^{25}$ nm $t_e = 10^5$ yrs



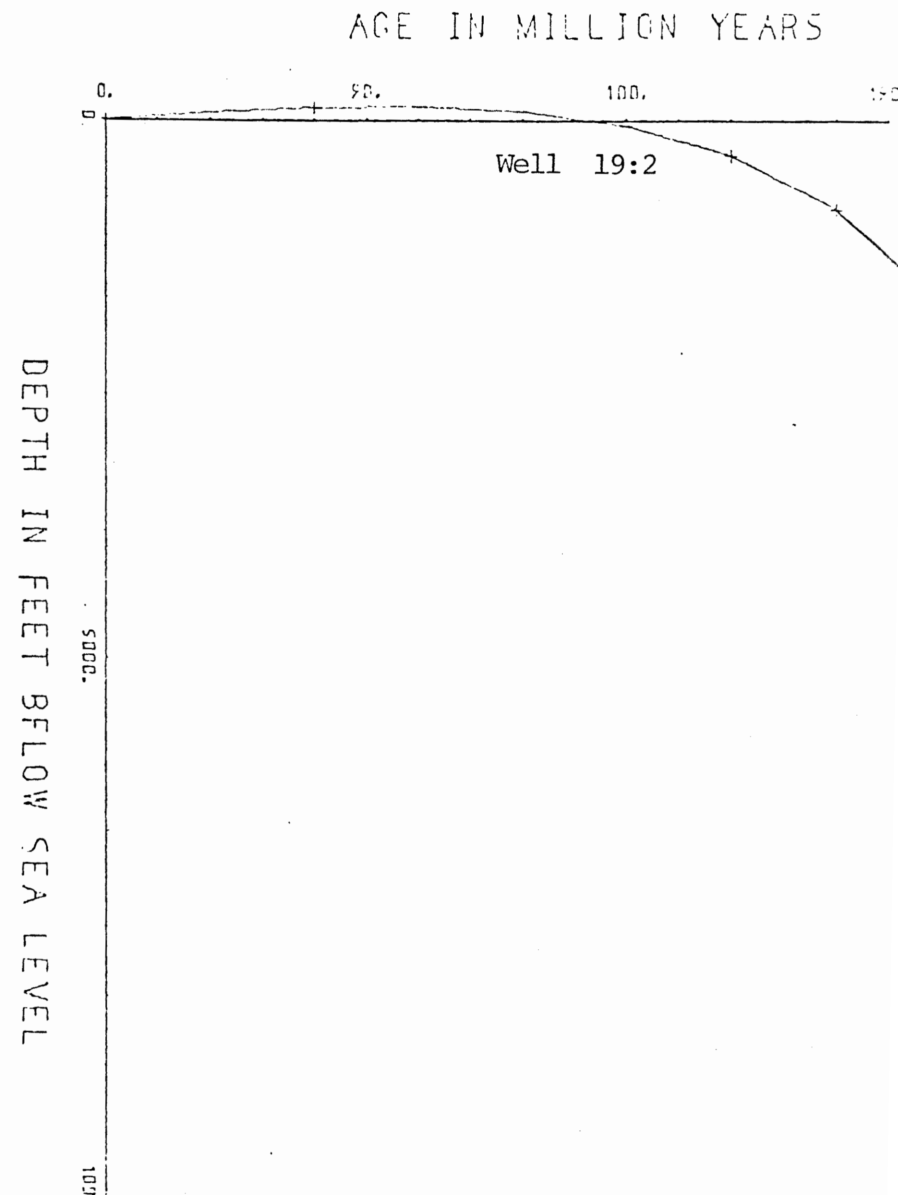


Table 6: Well data from theoretical wells 19:1, 19:2, and 19:3.

Theoretical Data for Subsidence Curves Using

$N = 10^{25}$, $t_e = 10^5$ and no exponential

Age from initial t=0 (m.y.)	25 km from continental oceanic boundary		75 km from continental oceanic boundary		125 km from continental oceanic boundary	
	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)	Thickness (m)	Depth (m)
0	0	1990.6	0	523.2	0	333.8
20	330.5	1660.1	274.0	249.2	219.0	114.8
40	300.5	1359.3	150.0	99.2	108.0	6.8
60	274.3	1085.0	83.8	15.4	47.5	+40.7
80	251.4	833.6	42.0	+26.6	13.8	+54.5
100	231.5	602.1	14.0	+40.6	4.4	+50.1
120	214.6	387.5	3.1	+37.5	13.6	+36.5
140	200.2	187.3	14.9	+22.6	17.6	+18.9
160	187.3	0	22.6	0	18.9	0

three models. These results were in reasonable agreement with the obtained observations. Using a viscous time constant of 10^6 yrs. resulted in the largest amount of accumulated sediments. Over 6 km of sediment accumulated at the margin which is close to that observed for the Scotian Basin. For data using t_e equal to 10^5 yrs. a little under 6 km of sediment accumulated at the edge of the margin, with the difference between a t_e of 10^6 yrs. or 10^5 yrs. being only 300 m. of sediment. For t_e as 10^4 yrs. the sediment accumulation was smaller again, but this was still within error limits of the observations for the Scotian Basin.

On the continental side of the basin the layers toward the continent with the greatest subsidence at the margin are in agreement with the observations. This can be compared with a cross-section of the Scotian Basin (Figure 21). The theoretical model basin simulates the observations well, showing the greatest amount of subsidence at the edge of the shelf and the gently dipping of the beds seaward.

The subsidence curves for the theoretical basin also confirm the validity of this type of model. The curves show an even exponential decay of subsidence rate with time as Sleep's (1971) model predicts. The reason minor variations in the subsidence rate are not observed is that the rate of sediment influx into the theoretical basin is always sufficient to keep the continental side of the basin filled which is not the case in the Scotian Basin. Transgressions and regressions are also ignored but could be included.

The theoretical curves show remarkable similarities to curves in the same spatial position on the Scotian Shelf. An example of this is the well Triumph P-50 which is located at about the same location as the first well in the series of theoretical wells shown with N equal to 10^{25} and varying t_e. The amount of sediment accumulated is approximately the same,and the shape of the curves are very similar. The only difference in the curves is the curvature of the theoretical curves is less than that of the Triumph well. Other comparisons were also made between Missisauga H-54 and theoretical well number 2 in the set of N equal to 10^{25} and different t_e's. This also showed that the model was successful as the wells showed almost identical characteristics with only the curvature in the theoretical wells being smaller. Finally, the results from theoretical hole number 3 were compared with a well in the same spatial location in the Scotian Basin, Wyandot E-53. Again the model simulated the subsidence history of this area with results that very well approximated the Scotian Basin. Here depths of 2150 m. (7000 ft.) were recorded in the theoretical case and approximately 2400 m. (8000 ft.) are observed.

On the oceanic side of the continental margin subsidence is more simple. With the distributed sedimentary load 1000 meters deep deposited every 20 m.y. the area (as can be seen in Figure 18) forms a U shaped depression. The oceanic sediment is buoyed up at the oceanic-continental boundary due to the differences in initial load and isostatic compensating forces as described earlier. For a more reslistic model on the oceanic half of the basin sediment should be decreasing seaward. However, for reasonable flexural rigidities of approximately 10^{25}, sediment that is a long way from the continent has little effect on the continental margin. Therefore no significant changes in the result would occur if we thinned the sediment seaward. The upward turning of the sediments at the seaward edge of the model is unrealistic, resulting from an edge effect. This effect would be removed if we had used a larger grid for the calculations.

Modifications to the Model

Even though the simple model used in this study did simulate a simplified version of the development of the Scotian Basin, minor modifications could be made to improve the model.

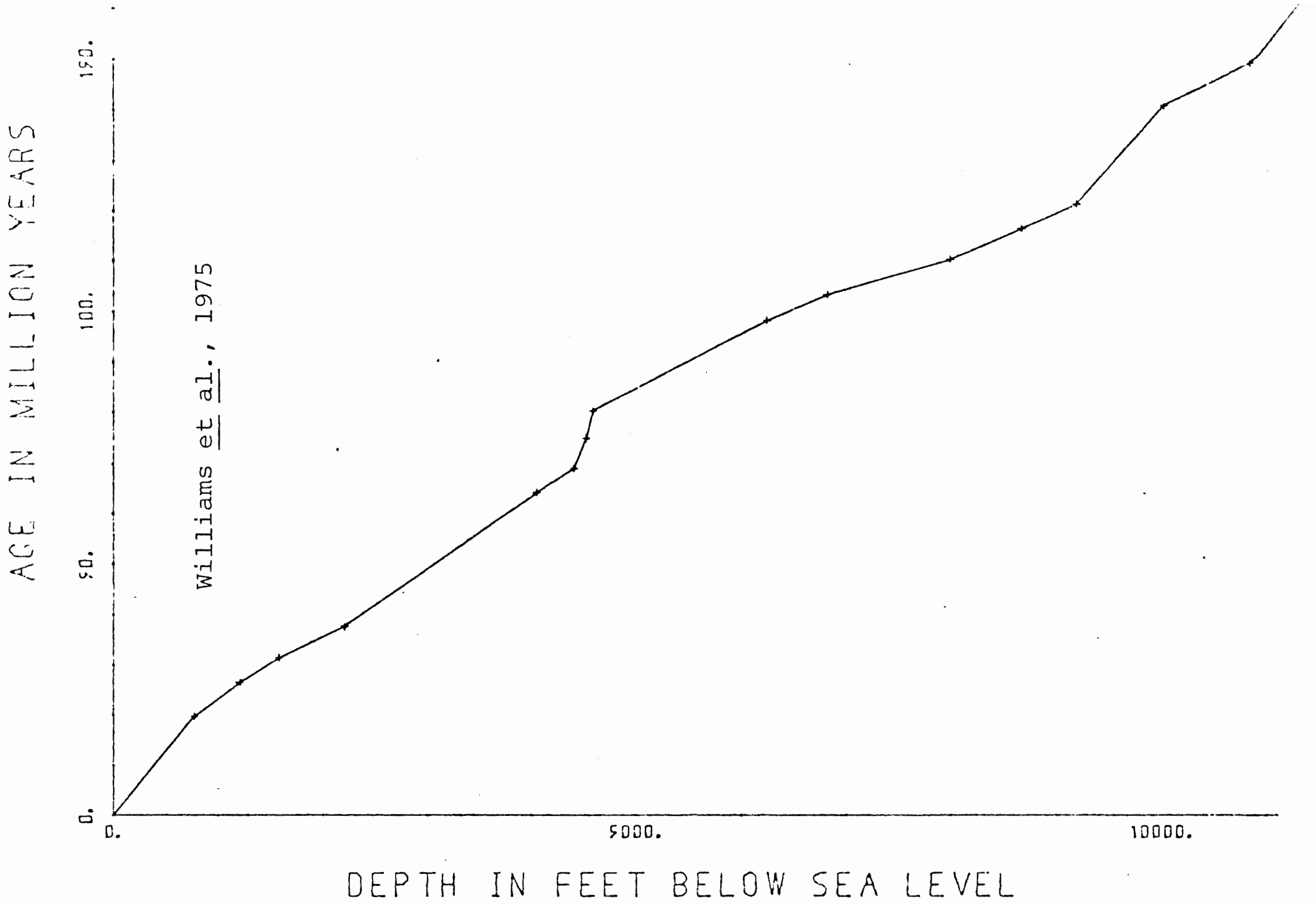
To be realistic the subsidence history of the basin must include the effects of changing sediment influx. Sediment influx into the oceanic area in our model was taken to be a uniform 1000 m every 20 m. yrs. If more accurate estimates become available from an improved knowledge of sedimentation patterns off the continental slope, these could very easily be incorporated into the model. This would have the effect of modifying subsidence rates depending on sediment load. The subsidence curves for such a model may coincide closely with those observed.

Another modification that could be included in the model is the removal of the vertical boundary between oceanic and continental sides of the area and the formation of a continental slope. This could be done by loading each individual grid square seaward from the margin with decreasing amounts of sediment thereby simulating the slope. As mentioned earlier this differential loading will produce results with similar characteristics to the present horizontal model. However, to make realistic estimates, we require a knowledge of the sediment budget. The shelf progrades seawards only when there is sediment in excess of that required to fill the shelf basin.

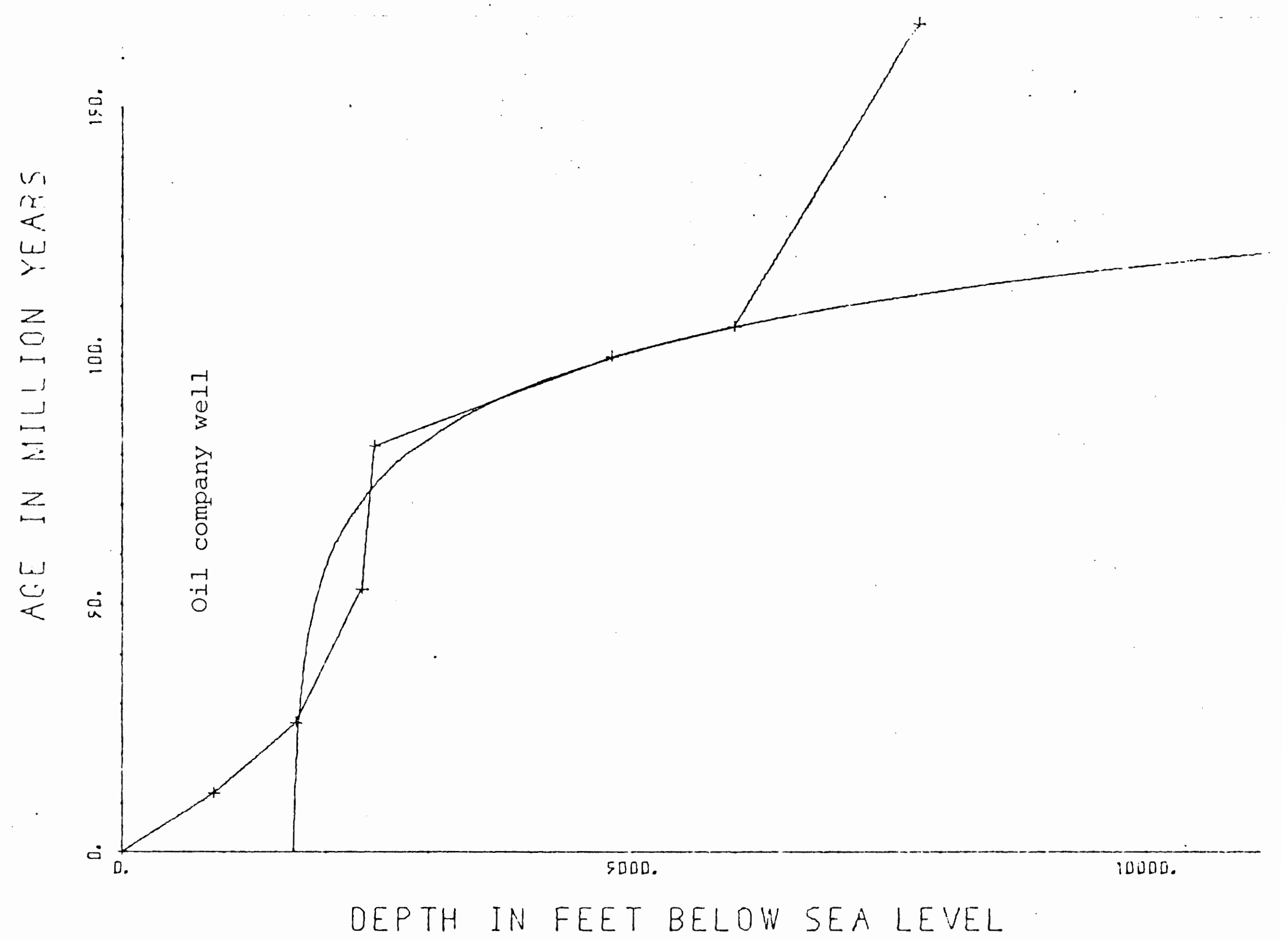
Regional transgressions and regressions could also be taken into account to simulate a more realistic basin. This could easily be done by lowering or raising the sea level at various times in the history of the basin corresponding to known world wide transgressions and regressions. This modification would also have to take into account the fact that some areas would become positive topographic features and would be subject to erosion during regressional periods.

Finally, more accurate observations of the subsidence history of the Scotian Basin itself are required. The wells used in this study were mostly taken from oil company reports and are uncorrected. Some of the wells have been reworked by Jansa et al., 1975, Gradstein et al., 1975, Smith, 1975, Williams, 1975 and others. These reworded wells (only a small number) give a much more accurate subsidence history. For example, comparison of well Oneida 0-25 taken from the preliminary oil company reports and in reworked form taken from Williams (1975) shows the increased data available (Figure 20). Only a few of these reworked wells are published, therefore the majority of wells used in this study are the oil company reports which produced a satisfactory basis for comparison.

Figure 20: Comparison of well Oneida O-25 from oil company report and reworked data done by Williams *et al*, 1975.

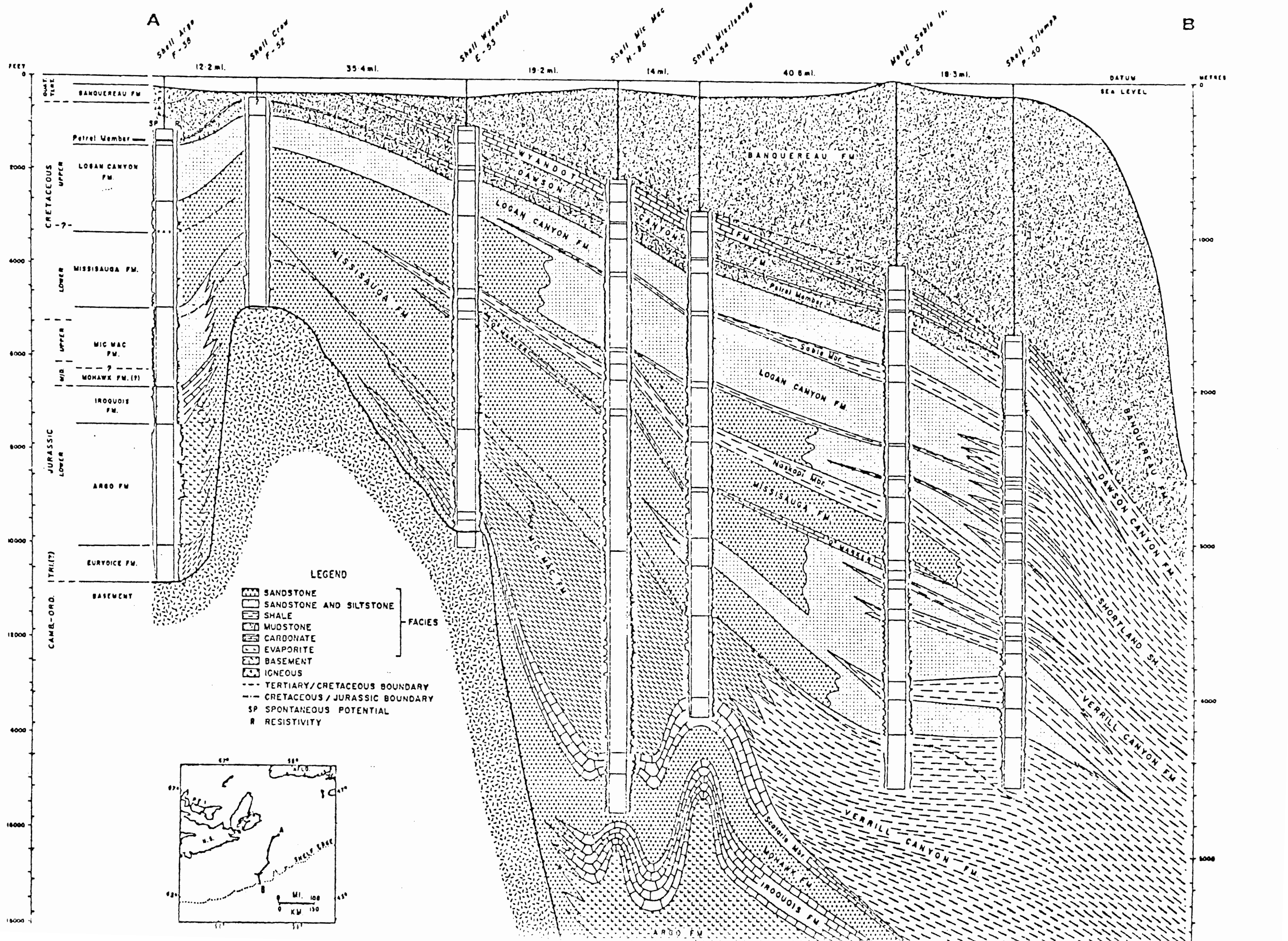


AGE IN MILLION YEARS
0.
50.
100.
150.
Williams et al., 1975
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL



AGE IN MILLION YEARS
0.
50.
100.
150.
Oil company well
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL

Figure 21: Cross section of the Scotian Basin. Wells used for comparison with theoretical basin are Triumph P-50, Missisauga H-84 and Wyandot E-53. (After Jansa *et al.*, 1975.)



A
B
Shell Argo F-38
Shell Crow F-52
Shell Wyandot E-53
Shell Mic Mac H-86
Shell Missisauga H-54
Mobil Sable Is. C-67
Shell Triumph P-50
12·2 mi.
35·4 mi.
19·2 mi.
14 mi.
40·8 mi.
18·3 mi.
DATUM
SEA LEVEL
FEET
METRES
BANQUEREAU FM
Petrel Member
LOGAN CANYON FM.
CRETACEOUS
UPPER
LOWER
MISSISAUGA FM.
MIC MAC FM.
MOHAWK FM. (?)
IROQUOIS FM.
JURASSIC
ARGO FM
EURYDICE FM.
BASEMENT
CAMB.-ORD.
WYANDOT
DAWSON
LOGAN CANYON FM
CANYON
MISSISAUGA FM
MIC MAC FM
Sable Mbr.
Naskapi Mbr.
BANQUEREAU FM
DAWSON CANYON FM
SHORTLAND SH
VERRILL CANYON FM
Scatarie Mbr.
MOHAWK FM.
IROQUOIS FM
ARGO FM
LEGEND
SANDSTONE
SANDSTONE AND SILTSTONE
SHALE
MUDSTONE
CARBONATE
EVAPORITE
BASEMENT
IGNEOUS
FACIES
TERTIARY/CRETACEOUS BOUNDARY
CRETACEOUS/JURASSIC BOUNDARY
SP SPONTANEOUS POTENTIAL
R RESISTIVITY
SHELF EDGE
MI.
KM

Conclusions

From the well data used in this study it is evident that as a first approximation subsidence in the Scotian Basin decreased exponentially with time, and that the sedimentation and minor tectonic features within the basin are compatible with modern Plate Tectonic theory. The minor tectonic elements of the Scotian Basin along with the rise of the Triassic-Jurassic Argo salt in the form of diapirs made the acquisition of a true subsidence history of the Scotian Basin very difficult and complicated. The available data agrees well with a model describing subsidence in terms of thermal contraction theory and the effects of sedimentary loading.

Since the known subsidence history of the Scotian Basin is complicated it is not surprising that the model fails to simulate the minor tectonic processes and other minor physical processes that occurred. The model developed was for a simplified version of the Scotian Basin. We have however suggested some improvements to the model that could easily be made. Nevertheless, significant improvements in the model results must await a better estimate of the sediment budget as a function of time.

The three models developed used a flexural rigidity of the visco-elastic plate of 10^{25} n.m. and had viscous time constants of 10^4, 10^5 and 10^6 yrs. Of these three models a viscous time constant, t_e equal to 10^6 yrs. gave the result closest to those observed in the Scotian

Basin. The results showed little dependence on the value of t_e, this is due to the fact that the time constant for thermal contraction of the lithosphere (50 m.yrs.) is much longer than that for the relaxation of the viscoelastic plate.

The amount of sediment accumulated over 160 m.y. was approximately the same in the model as in the Scotian Basin, the cross-sections of both basins are similar and the subsidence curves from the same locations in the model basin and Scotian Basin are remarkably alike. Therefore it can be concluded the model does explain the major features of the formation of the Scotian Basin.

The amount of subsidence in an area is governed by many factors, initial uplift followed by erosion and thermal contraction, sedimentary loading and to a minor extent changes in sedimentation rates and changes in paleobathymetry. However, given all of these factors, the amount a basin subsides depends on the physical properties of the lithosphere underlying the developing continental margin basin.

References

Bullard, E. 1975. Plate Tectonics and oil accumulation. Key note Address; Canada's Continental Margins, C.S.P.G., Memoir 4, 1-7.

Bullard, E., Everett, J. E. and Smith, A. C. 1965. The fit of the continents around the Atlantic. Roy. Soc. London, Phil. Trans., Ser. A, 258, 41-51.

Falvey, D. 1974. The development of continental margins in Plate Tectonic theory. APEA Journal, 1974, p. 95-105.

Foucher, J. P. and LePichon, X. 1972. Comments on "thermal effects of the formation of Atlantic continental margins by continental break up", by N. H. Sleep, Geophys. J. Roy. Astron. Soc., 23: 43-46.

Gradstein, F. M., Williams, G. L., Jenkins, W. A. M., Ascoli, P. 1975. Mesozoic and Cenozoic stratigraphy of the Atlantic Continental Margin, eastern Canada. Canada's Continental Margins, C.S.P.G., Memoir 4, 103-132.

Jansa, L. F. 1974. Stratigraphy and sedimentology of the Mesozoic and Tertiary rocks of the Atlantic Shelf. Geol. Surv. Can., Paper 74-1, Part B, p. 141-143.

Johnson, D. W. 1919. Shore processes and shoreline development. N. Y.: Wiley.

Keen, M. J., and Keen, C. E. 1971. Subsidence and fracturing of the continental margin of eastern Canada. Geol. Surv. Can. Paper 71-43, p. 23-42.

Keen, M. J. and Keen, C. E. 1973. Subsidence and fracturing on the continental margin of eastern Canada. Geol. Surv. Can., Paper 71-23, p. 23-42.

King, L. H. 1974. Geosynclinal development on the continental margin south of Nova Scotia and Newfoundland. Geol. Surv. Can., Paper 74-1, Part B, p. 199-206.

King, L. H., Hyndman, R. D. and Keen, C. E. 1975. Geologic development of the continental margin of Atlantic Canada. Geoscience Canada.

Le Pichon, X. and Fox, P. J. 1971. Marginal offsets, fracture zones and the opening of the North Atlantic. Jour. Geophys. Res., v. 76, p. 6294-6308.

Le Pichon, X., Francheteau, J. and Bonin, J. 1973. Plate Tectonics. Elsevier, New York, p. 201-207.

Renwick, G. K. 1973. Sea-floor spreading and the evolution of the continental margins of Atlantic Canada. M.Sc. Thesis, Dalhousie University, 89 p.

Schenk, P. E. 1971. Southeastern Atlantic Canada, northwestern Africa and continental drift. Can. Jour. Earth Sci., v. 8, p. 218.

Sleep, N. H. 1969. Sensitivity of heat flow and gravity to the mechanism of sea-floor spreading. Jour. Geophys. Res., v. 74, p. 542.

Sleep, N. H. 1971. Thermal effects of the formation of Atlantic continental margins by continental break-up. Geophys. J., v. 24, 325.

Sleep, N. H. 1976. Platform subsidence mechanisms and "eustatic" sea-level changes. In press.

Sweeney, J. F. 1977. Subsidence of the Sverdrup Basin, Canadian Arctic Islands. Geol. Soc. America Bull., v. 88, p. 41-48.

Wade, J. A. 1974. Regional geology of the Mesozoic-Cenozoic sediments of Nova Scotia and Newfoundland. Geol. Surv. Can., Paper 74-1, Part B, p. 147-149.

Williams, G. L. 1974. Dinoflagellate and spore stratigraphy of the Mesozoic-Cenozoic offshore eastern Canada. Geol. Surv. Can., Paper 74-1, Part B, p. 116, 135.

Subsidence of the Scotian Basin:

A Theoretical Model

Appendices

by

Robin C. Mann

Appendix I

A1: Location of wells drilled on the Scotian Shelf used in this study.

A2: Well data obtained from the oil company reports for the Scotian Shelf.

A3: Subsidence curves using well data, plotting absolute age against absolute depth for Scotian Shelf wells.

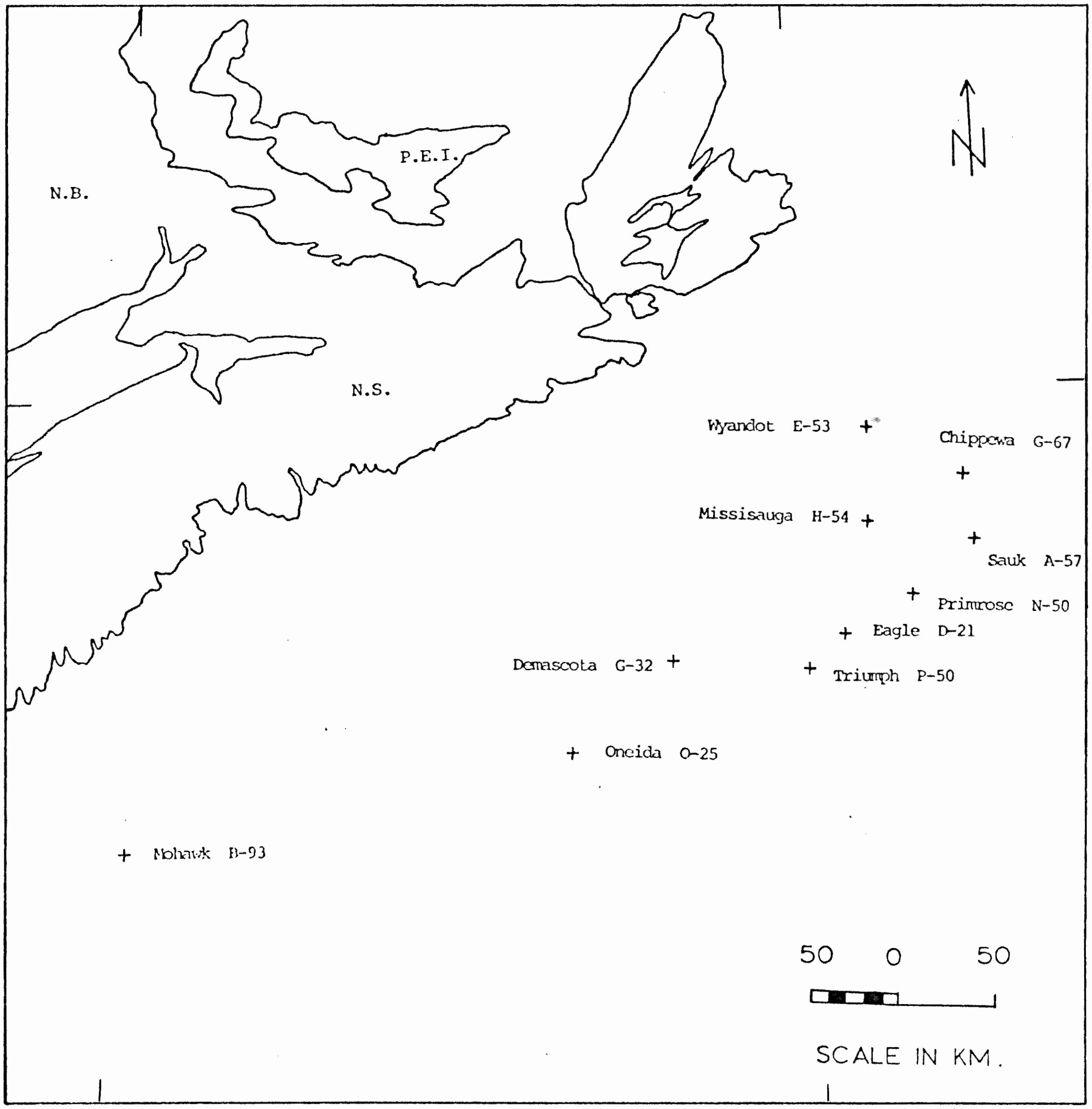
B1: Location of wells drilled on the Grand Banks used in this study.

B2: Well data obtained from the oil company reports for the Grand Banks.

B3: Subsidence curves using well data, plotting absolute age against absolute depth for Grand Banks wells.

A1

Location map for Scotian Shelf wells.


N.B.
P.E.I.
N.S.
N
Wyandot E-53
Chippewa G-67
Missisauga H-54
Sauk A-57
Primrose N-50
Eagle D-21
Demascota G-32
Triumph P-50
Oneida O-25
Mohawk B-93
50 0 50
SCALE IN KM.

A2

Well data for Scotian Shelf.

Shell Mohawk B-93

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Recent	1190	0	-	1.2	20.2	
Oligocene	180	1190	B	0.4	3.1	
Eocene	230	1370	C_1	0.5	3.9	
Palaeocene	407	1600	A/C_1	0.7	6.9	
L. Campanian	1583	2007	A	2.0	26.8	
Cenomanian	795	3590	A/C_2	4.0	13.5	
L. Cretaceous	12	4385	C_1	0.0	0.2	
U. Jurassic	1353	4397	D_1	1.6	22.9	
M. Jurassic	150	5750	B	-	2.5	
Basement	1030	5900	B	-	-	

Shell Triumph P-50

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Pliocene	1114	990	B	6.8	8.5	
Miocene	786	2104	C_1	1.3	6.0	
Oligocene	1600	2890	C_2	3.5	12.2	
Eocene	820	4490	A	1.9	6.2	
Paleocene	240	5310	A	0.6	1.8	
Maestrichtian	60	5550	A	0.3	0.5	
L. Campanian	700	5610	D_2	1.5	5.3	
Cenomanian	1760	6310	A	8.9	13.4	
Albian	2010	8070	A	10.2	15.3	
Aptian	2170	10,080	A/B	5.5	16.5	
Hauterivian	1000	12,250	A/B	5.1	7.6	
Valanginian	990	13,250	B	3.1	6.8	
Jurassic	927	14,150	A	-	-	

Shell Wyandot E-53

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Recent	1050	0	-	0.5	10.9	
Maestrichtian	80	1050	C_2	0.4	0.8	
Campanion-Santorian	693	1130	C_2	0.9	7.2	
Cenomanian	1192	1823	B	10.1	20.7	
Albian-Barremian	680	3815	A/B	1.7	7.1	
Barremian	805	4495	A/B	1.1	8.3	
U. Jurassic	4345	5300	A/B	-	45.0	
Basement	-	9645	B	-	-	

Shell Demascota G-32

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Recent	240	1010	B	0.3	1.7	
Mio-Oligocene	590	1250	C_2	1.0	4.2	
Eocene	240	1840	C_2	0.3	1.7	
Maestrichtian	1200	2080	A	6.1	8.6	
Campanion	1140	3280	A	1.5	8.2	
Cenomanian	1030	4420	A	5.2	7.4	
Albian	1200	5450	A	6.1	8.6	
Aptian	1100	6650	A	5.6	7.9	
L. Cretaceous	7180	7750	A/B	-	51.6	
M. Jurassic	-	14,930	A/B	-	-	

Shell Missisauga H-54

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Recent	1100	0	C_2	1.3	10.9	
L. Mio-Oligocene	620	1100	C_2	0.7	6.1	
L. Eocene	52	1720	C_2	0.3	0.5	
Paleocene	1282	1772	C_2	1.7	12.7	
Coniacian	781	3054	D_2	1.3	7.7	
Cenomanian	508	3935	B	2.6	5.0	
Cretaceous	4807	4443	B	8.1	47.6	
L. Cretaceous	400	9250	B	0.7	4.0	
U. Jurassic	450	9650	B	0.5	4.5	
U-M Jurassic	3687	10,100	A/B	-	-	

Shell-Mobil-Tetco Eagle D-21

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
U. Miocene	300	1592	B	1.8	2.2	
Miocene	116	1892	C_2	0.3	0.9	
L. Miocene	1744	2008	C_2	2.8	13.1	
Eocene	448	3752	C_2	1.1	3.4	
Palaeocene	930	4200	A	2.4	7.0	
U. Cretaceous	870	5130	D_1	0.9	6.5	
Cenomanian	1448	6000	B	7.4	10.8	
Albian	1757	7448	A	8.9	13.2	
Aptian	3395	9205	A	17.3	25.4	
Barremian	2350	12,600	A	4.0	17.6	
Berriasian	>340	14,950	B	-	-	

Shell Primrose N-50

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Tertiary	1410	1250	A	8.6	42.1	
Miocene	535	2660	A	0.5	15.1	
Eocene	341	3195	A	0.8	9.6	
Paleocene	862	3536	A	2.2	24.3	
Maestrichtian	37	4398	A	0.1	1.0	
Santonian	356	4435	A/D_2	0.6	10.0	
Cenomanian	433	4791	A/B	-	-	

Shell Sauk A-57

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Miocene	1022	1149	B	1.6	10.2	
Oligocene	387	2171	B	0.8	3.9	
Eocene	536	2558	B	1.2	5.3	
Paleocene	1506	3094	A	4.2	15.0	
Maestrichtian	120	4600	A	0.6	1.2	
Campanian-Santonian	890	4720	A/D_2	1.1	8.9	
Cenomanian	2304	5610	A	11.7	22.9	
L. Cretaceous	3286	7914	A/B	2.9	32.7	
Jurassic	3810	11,200	B	-	-	

Shell Chippwea G-67

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Recent	1000	0	-	4.4	9.1	
Mio-Pliocene	450	1000	C_2	0.6	4.1	
Oligocene	360	1450	C_2	0.8	3.3	
Eocene	180	1810	B/C_2	0.4	1.6	
Paleocene	1380	1990	B/C_2	3.7	12.6	
Maestrichtian	180	3370	C_2	0.5	1.6	
L. Santonian	782	3550	A	1.3	7.1	
Cenomanian	928	4332	A/B	4.7	8.4	
L. Albian	1220	5260	A/B	6.2	11.1	
Aptian	1770	6480	A/B	9.0	16.1	
L. Cretaceous	2000	8250	B	2.7	18.2	
L. Jurassic	739	10,250	A/B	0.9	6.7	
M. Jurassic	260	10,990	B	0	-	

Shell Oneida 0-25

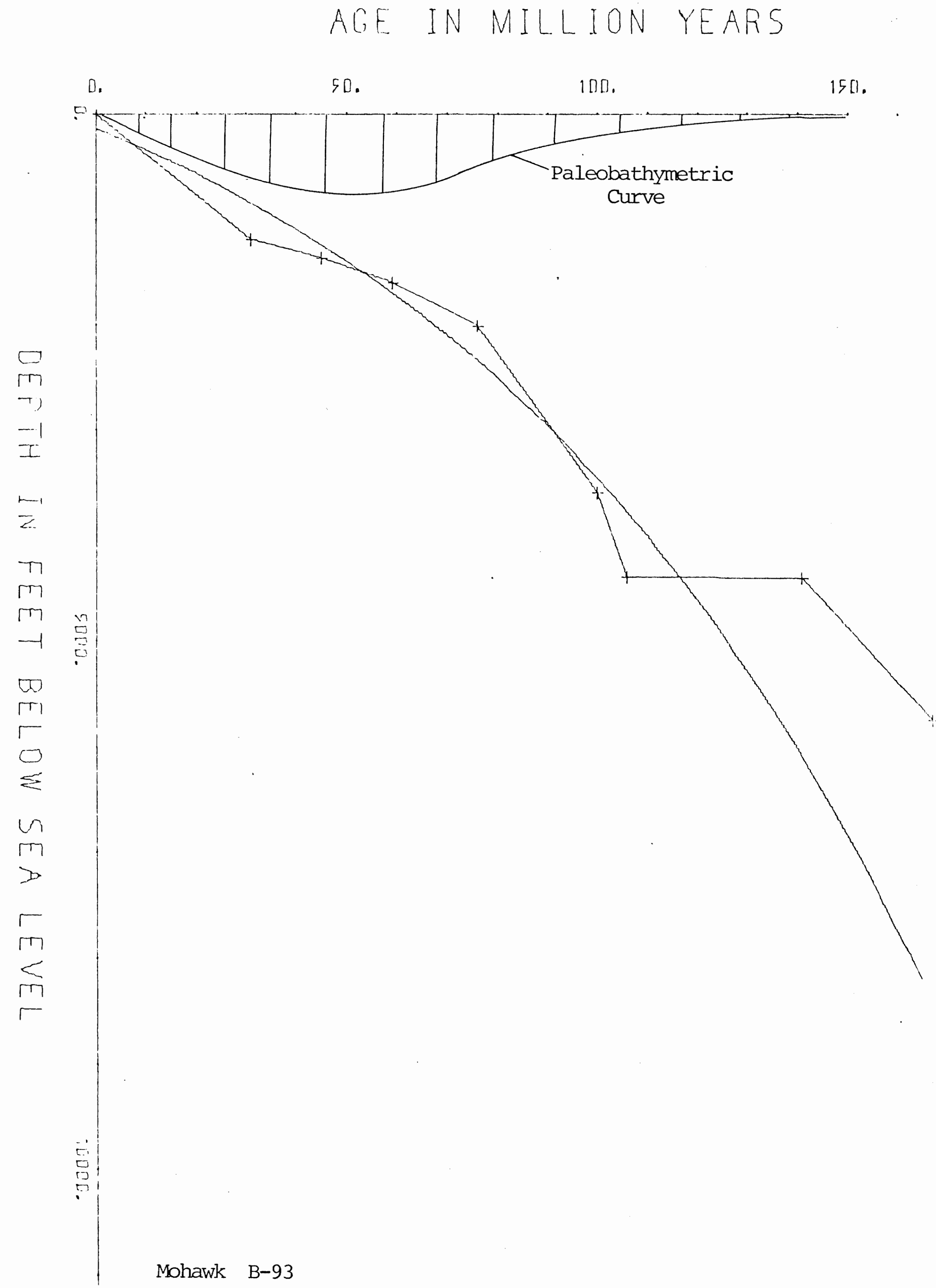
Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
M - Miocene	300	950	A/B	1.3	2.9	
E - Miocene	350	1240	B	2.1	3.4	
M - Oligocene	675	1600	A/B	2.9	6.5	
Eocene	200	2275	A	0.2	1.9	
Maestrichtian	505	2475	A	3.1	4.9	
Campanian	1020	2980	A/D_1	5.2	9.9	
Santonian	400	4000	D_1/A	2.0	3.8	
Coniacian	125	4400	A/B	0.5	1.2	
Turonian	75	4525	A/B	0.4	0.7	
Cenomanian	1800	4600	A	9.1	17.4	
Albian	625	6400	A	3.2	6.0	
Aptian	1275	7025	A/B	6.5	12.3	
Barremian	600	8300	A	3.1	5.8	

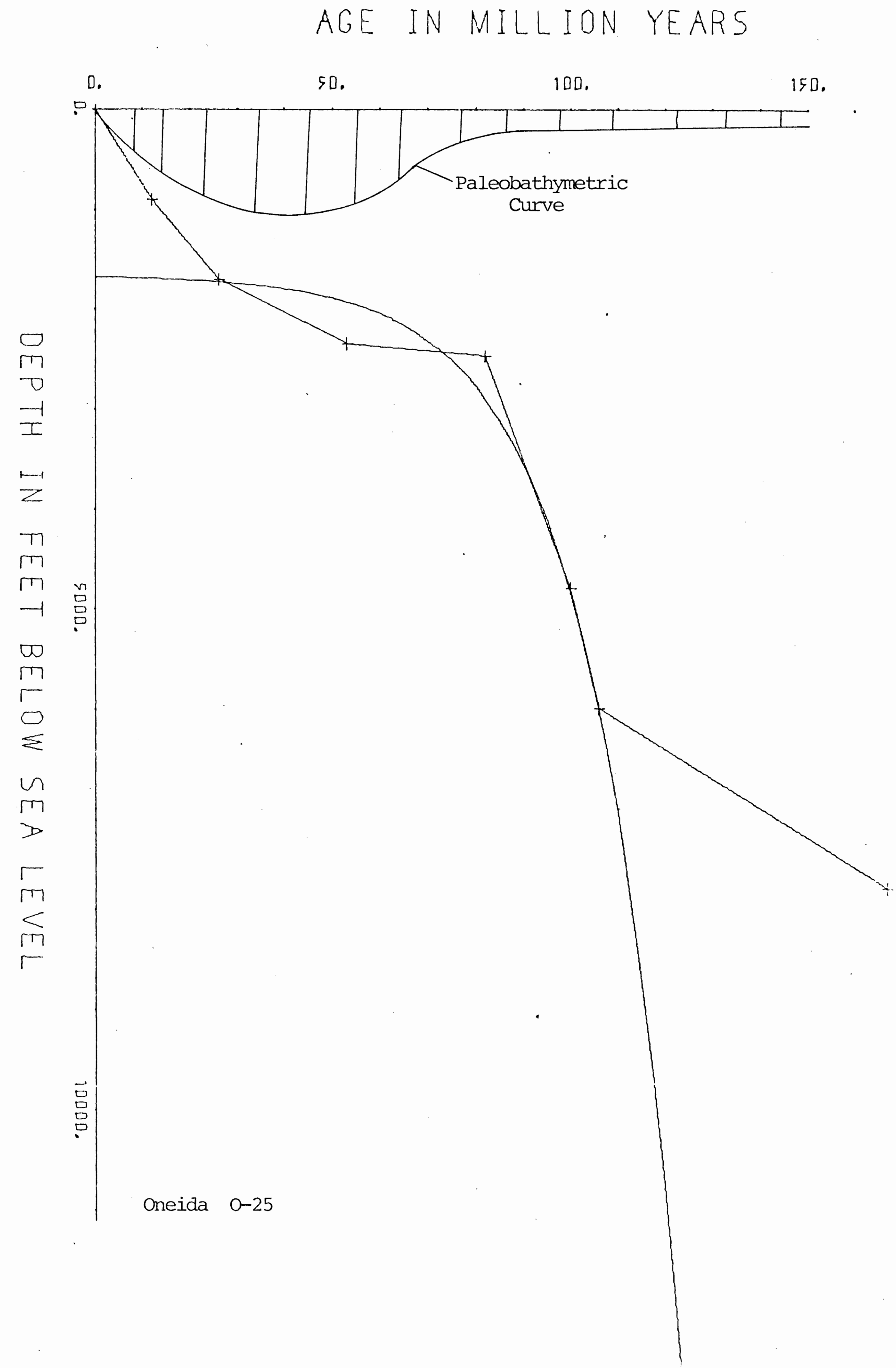
Shell Oneida 0-25 (Cont'd)

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Hauterivian	350	8900	A	1.8	3.4	
Valanginian	750	9250	D_1	1.3	7.3	
Kimmeridgian	940	10,000	D_1	2.9	9.0	
Oxfordian	350	10,940	D_1	1.8	3.4	
M - Jurassic	-	11.290	D_1/B	-	-	

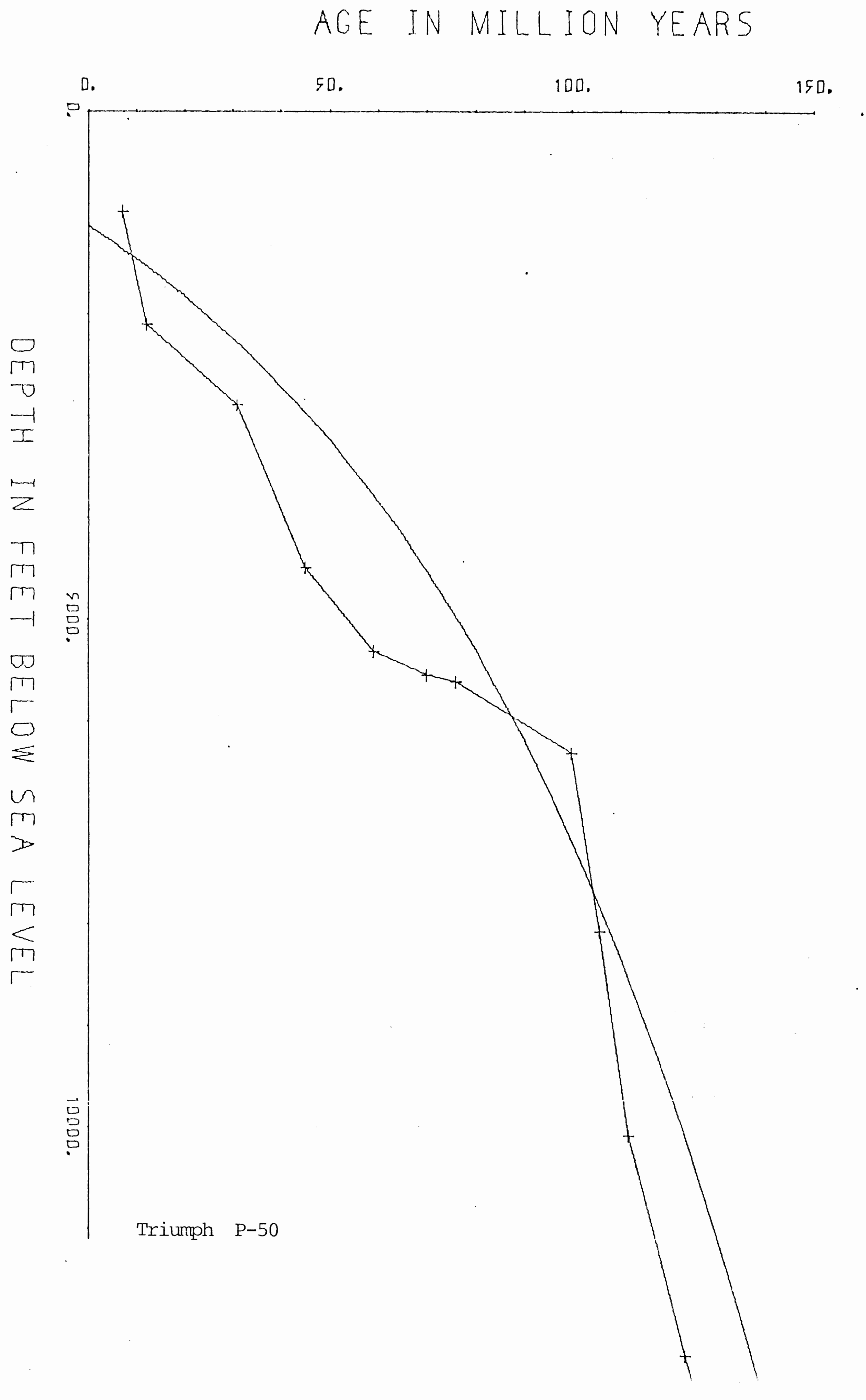
<u>A3</u>

Subsidence Curves for Scotian Shelf.

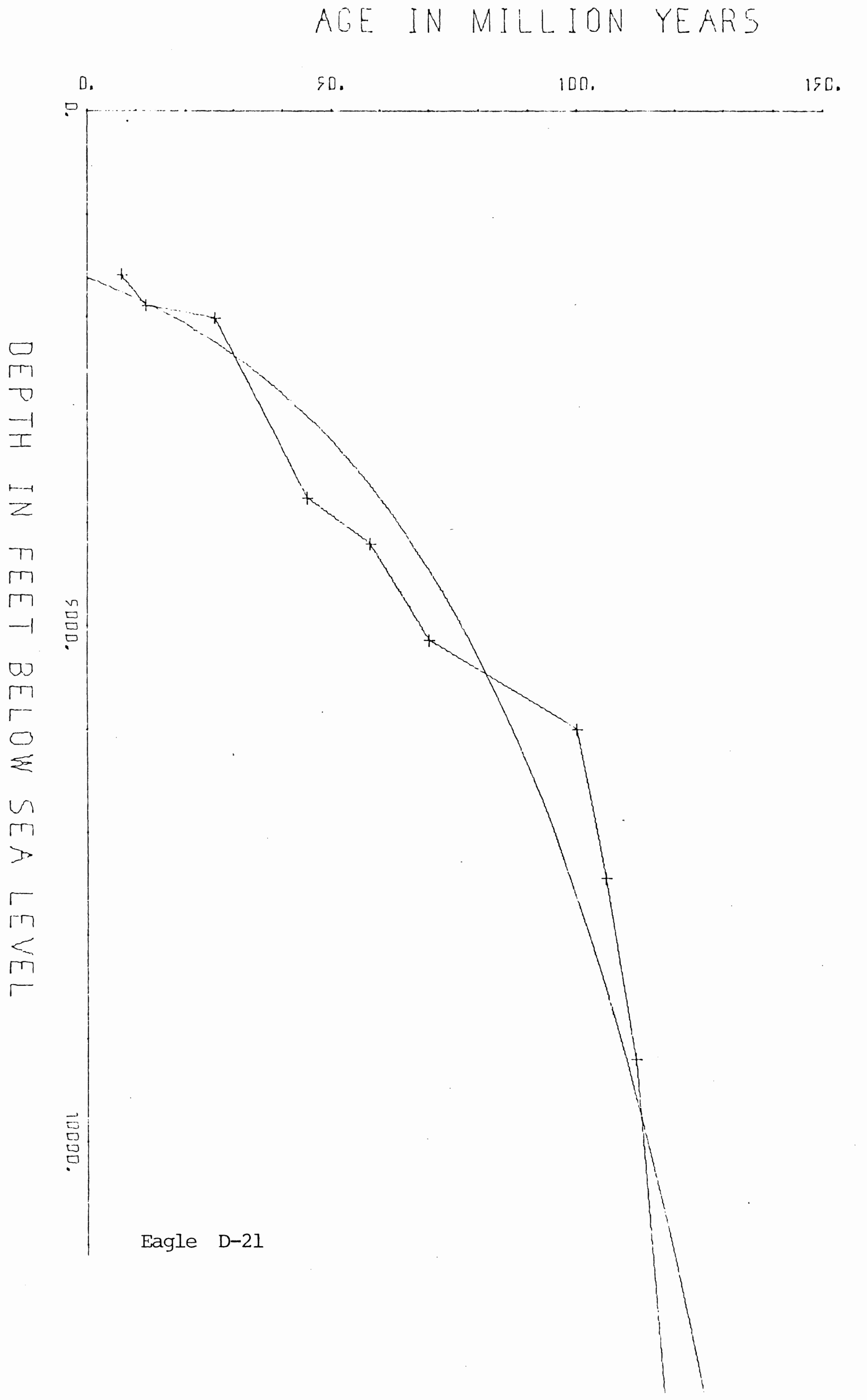

AGE IN MILLION YEARS
0.
50.
100.
150.
Paleobathymetric
Curve
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Mohawk B-93

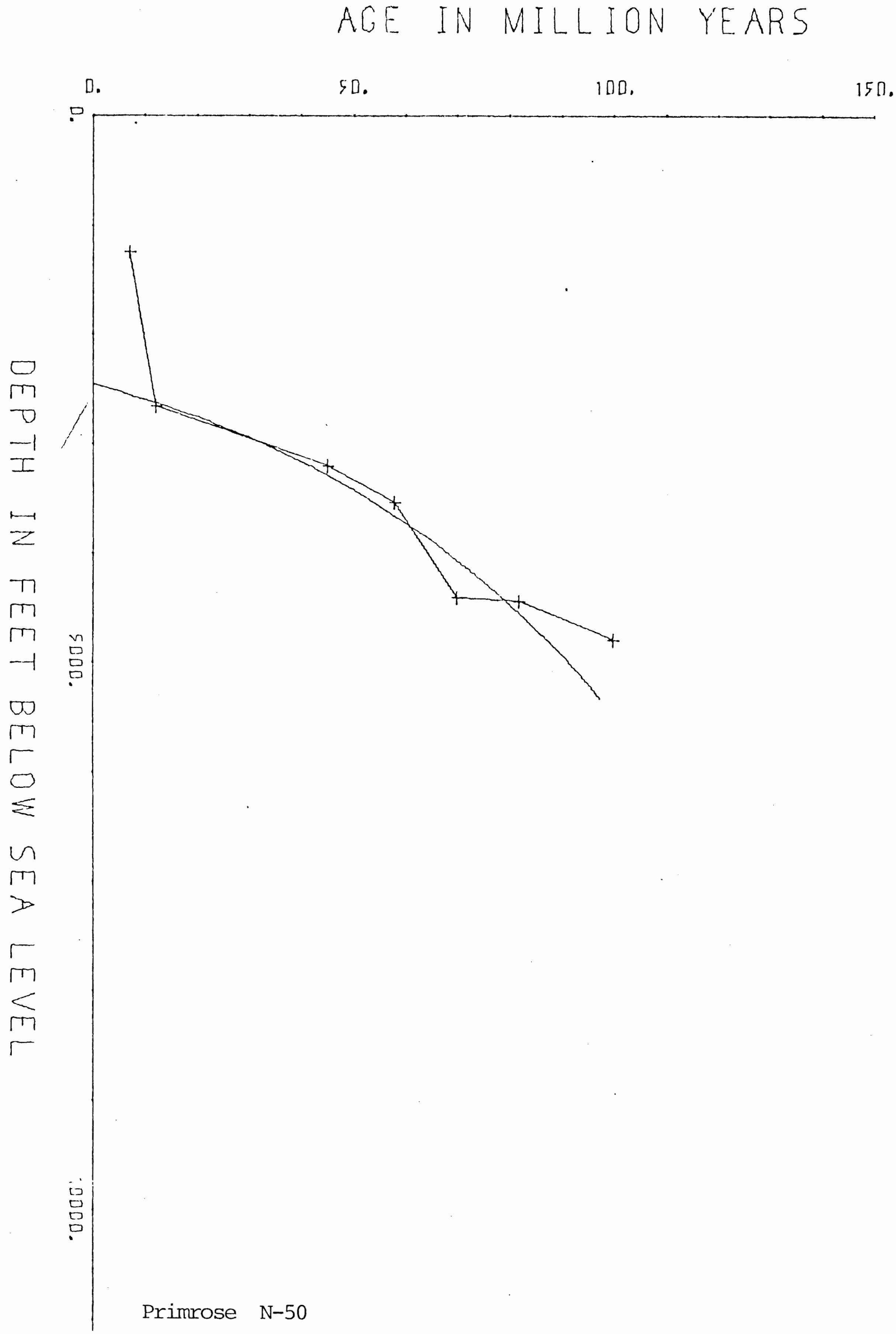


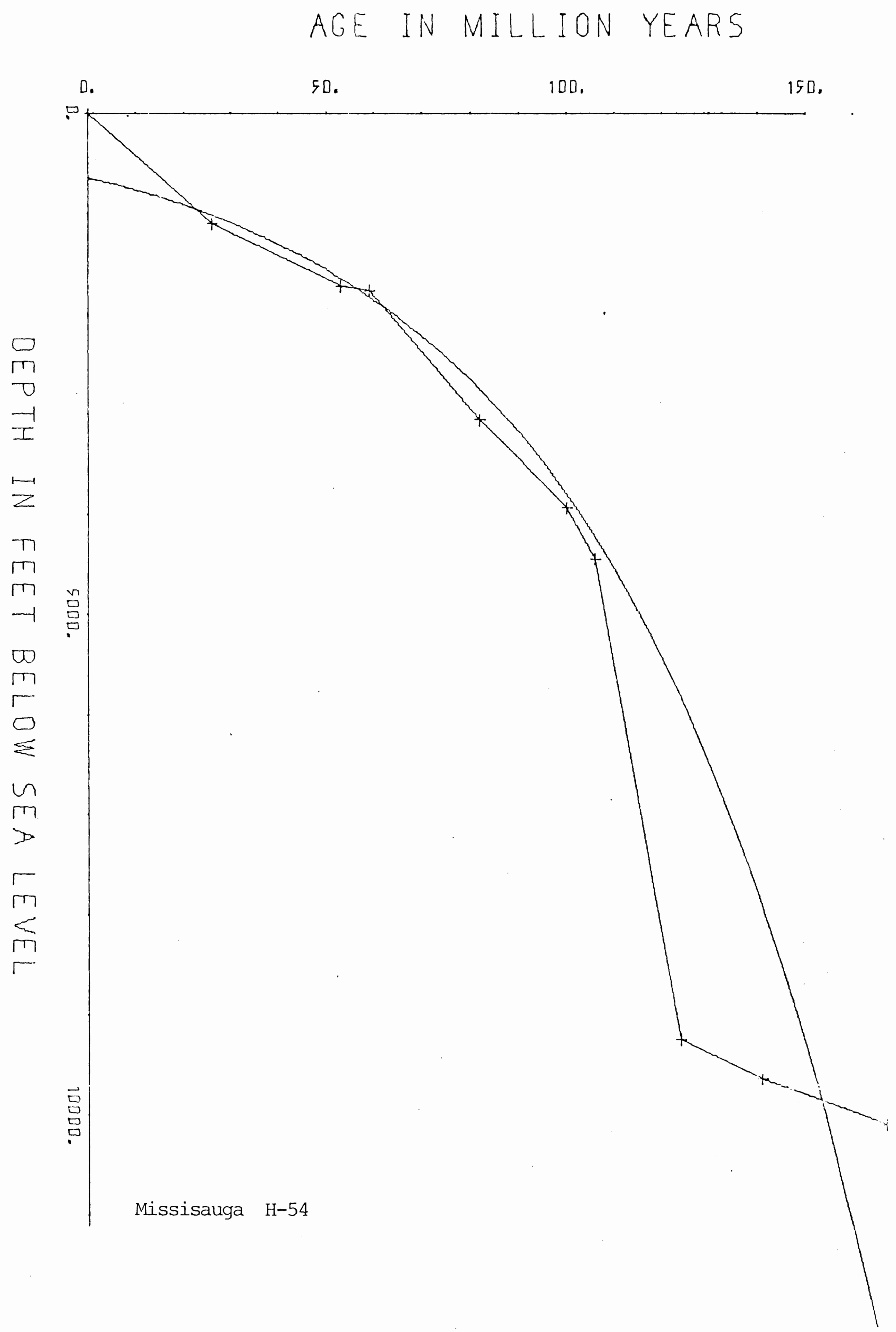
AGE IN MILLION YEARS
0.
50.
100.
150.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL
Paleobathymetric
Curve
Oneida O-25



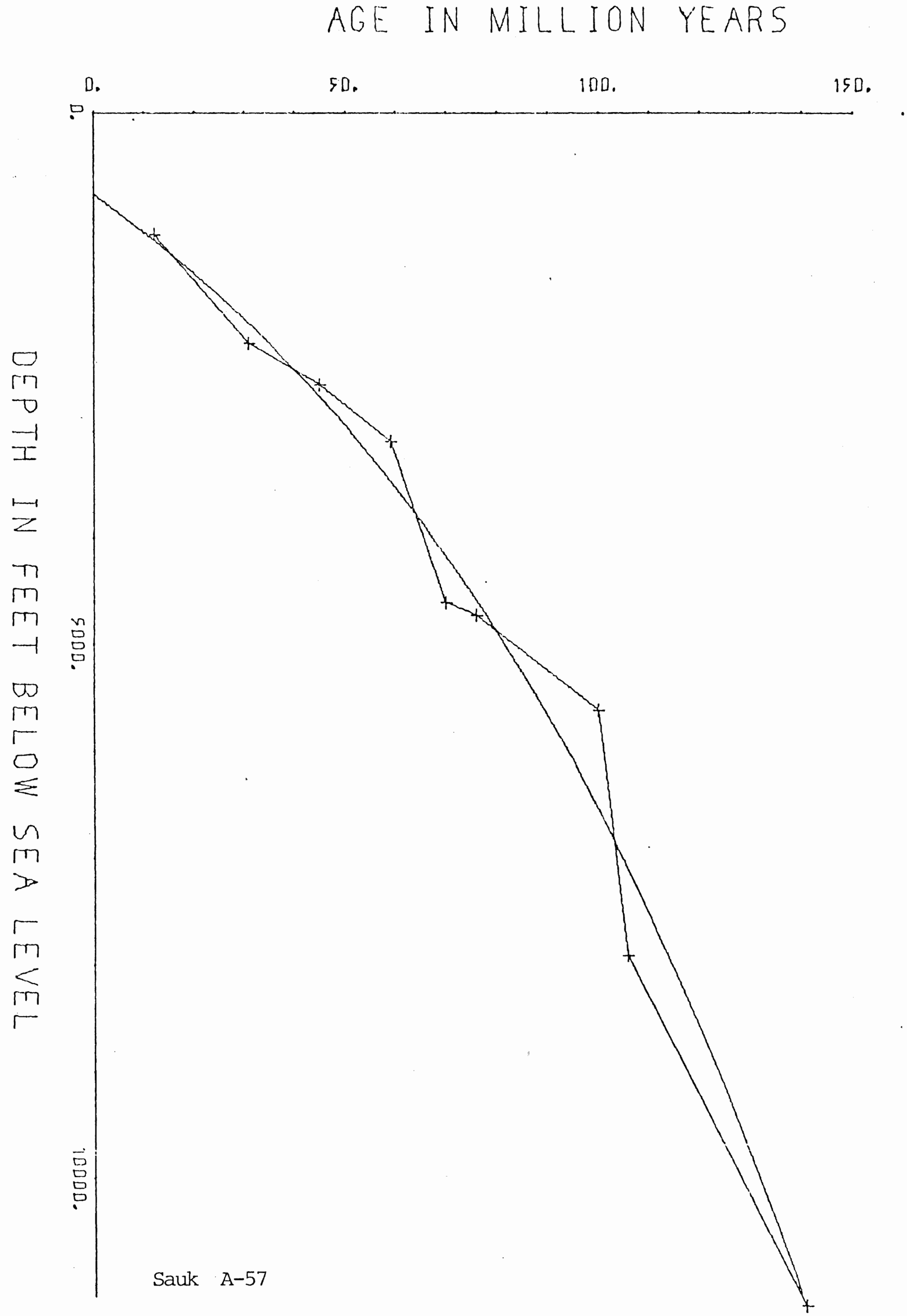
AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Triumph P-50


AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Eagle D-21

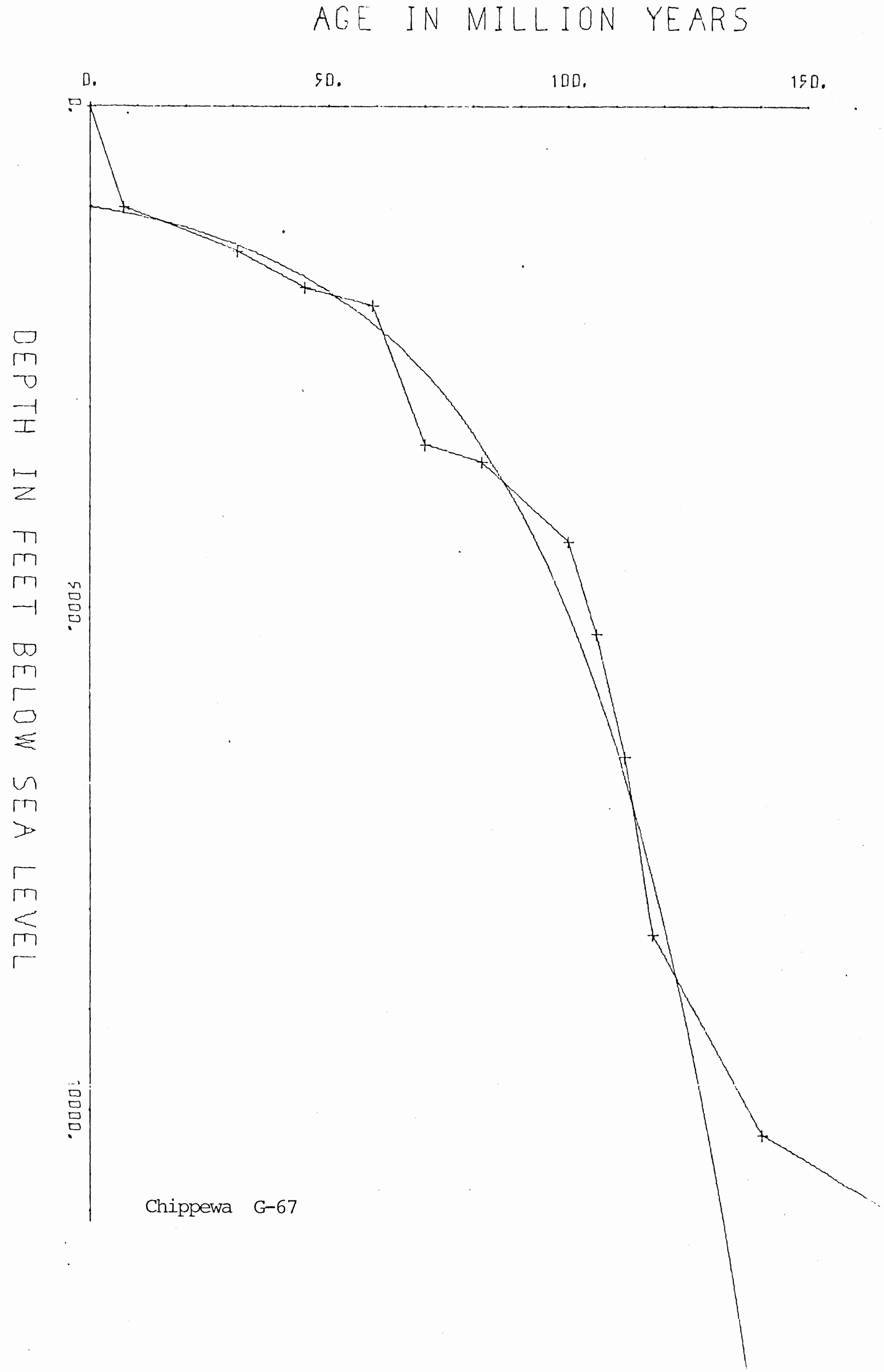

AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Primrose N-50



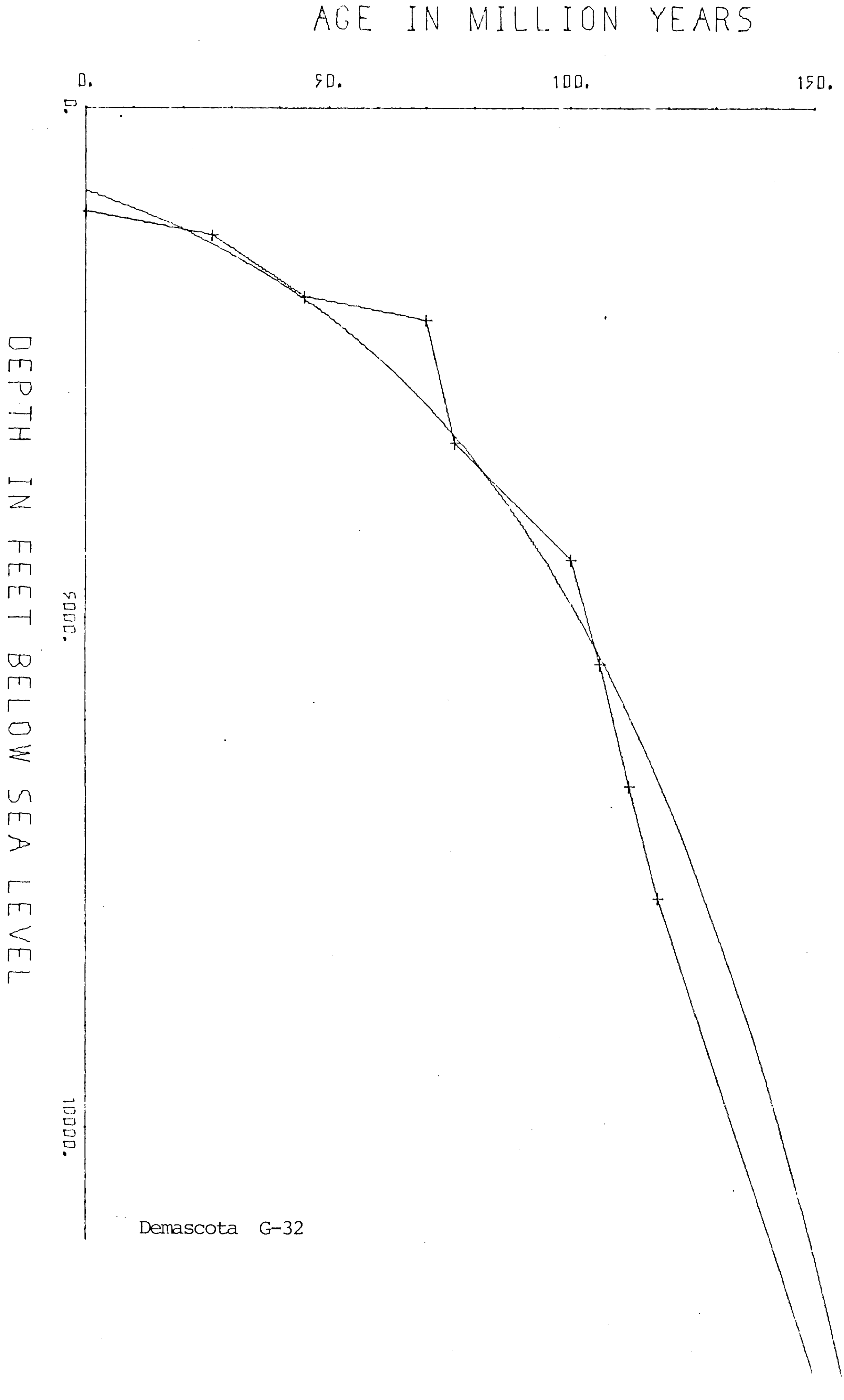
Missisauga H-54

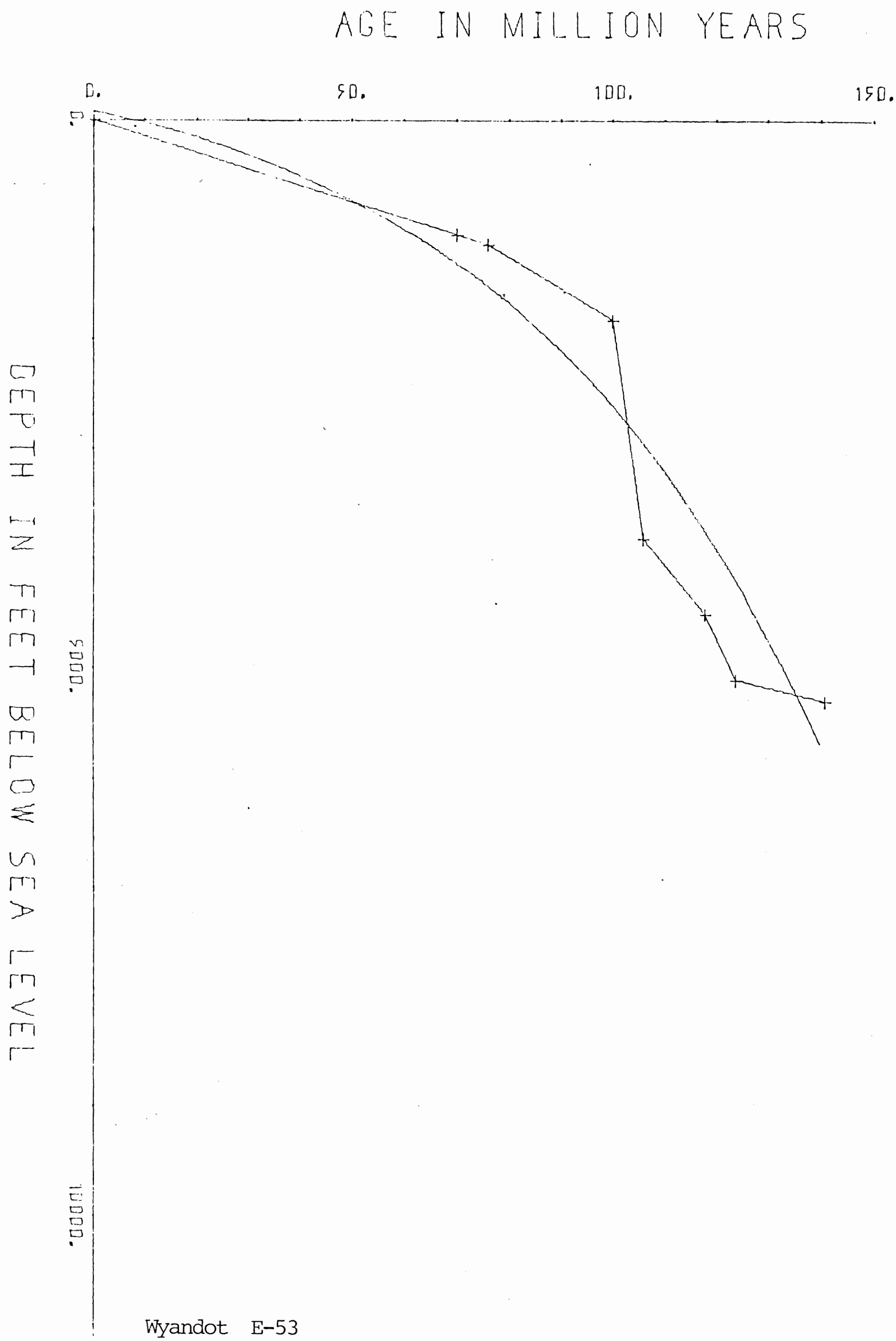


AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Sauk A-57



Chippewa G-67


AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Demascota G-32

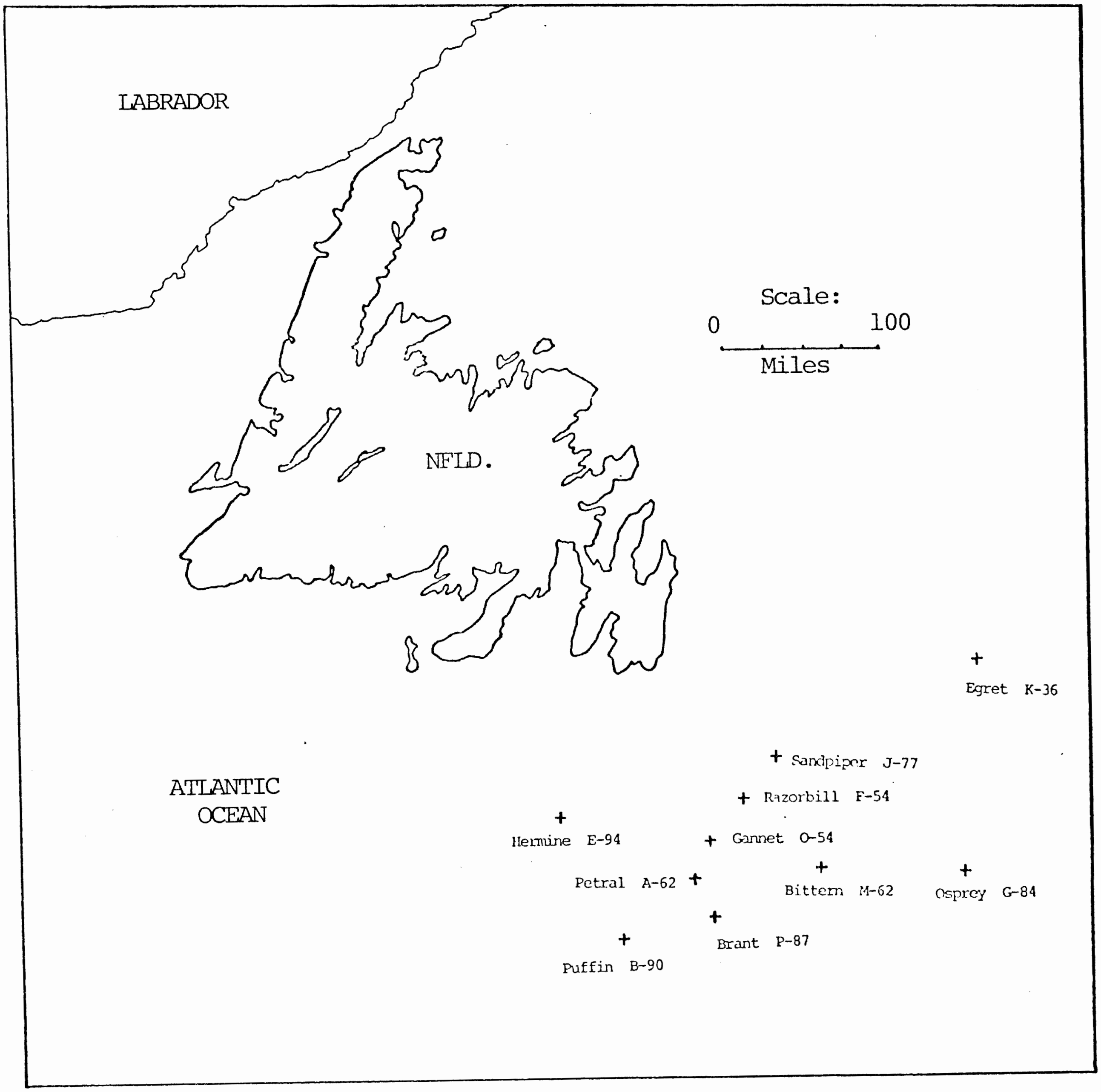


AGE IN MILLION YEARS
0.
50.
100.
150.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL

Wyandot E-53

B1

Location map for Grand Banks wells


LABRADOR
Scale:
0
100
Miles
NFLD.
Egret K-36
Sandpiper J-77
Razorbill F-54
ATLANTIC
OCEAN
Hermine E-94
Gannet O-54
Petral A-62
Bittern M-62
Osprey G-84
Brant P-87
Puffin B-90

B2

Well data for the Grand Banks.

Amoco-Imp Skelly A-1 Razorbill F-54

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Oligocene	150	1170	A/S	0.3	2.7	
U. Eocene	420	1320	A/C_1	1.6	7.5	
L. Eocene	210	1740	A	1.1	3.7	
U. Paleocene	480	1950	A	2.4	8.5	
L. Paleocene	210	2430	A	1.3	3.7	
L. Maestrichtian	270	2640	A	1.4	4.8	
Campanian	120	2910	A	0.6	2.1	
Santonian	210	3030	A	1.1	3.7	
Coniacian	360	3240	A	0.9	6.4	
Coniacian-Albian	510	3600	A	2.6	9.1	
Albian	475	4110	D_1	0.4	8.5	
U. Jurassic	230	4585	A	0.2	4.1	
L. Jurassic	1975	4815	D_1	12.0	35.1	
Pliensbachian	-	6790	A	-	-	

Amoco-Imp Skelly Sandpiper J-77

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Eocene	210	950	A	0.2	2.7	
Campanian	300	1160	A	1.5	3.7	
Santonian	480	1460	A	2.4	6.2	
Coniacian	570	1940	A	1.0	7.3	
Albian	300	2510	A	4.6	3.7	
Albian-Aptian	5	2810	D_1	0.0	0.1	
Aptian	60	2815	D_1	0.2	0.8	
Neocomian	115	2875	D_1	0.2	1.5	
Jurassic	5810	3030	A/D_1	-	74.7	
Basement	110	8730	A	-	-	

Amoco-Imp-Skelly Osprey G-84

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Oligocene	600	1010	B	1.3	5.9	
U. Eocene	900	1610	B	6.7	8.9	
M. Eocene	90	2510	A	0.7	0.9	
L. Eocene	120	2600	B	0.6	1.2	
Paleocene	60	2720	B	0.1	0.6	
Santonian	60	2780	A	0.3	0.6	
Coniacian	180	2840	A	1.8	1.8	
Turonian	200	3020	A	2.0	2.0	
Turonian-Cenomanian	150	3220	A	0.8	1.5	
Cenomanian	294	3370	B	0.2	2.9	
Jurassic	6166	3664	D_1	5.1	5.1	
L. Jurassic	1317	9830	A/E	-	13.0	
Basement	-	11,147	A/B	-	-	

Amoco-Imp-Skelly B-1 Egret K-36

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Oligocene	480	890	B/C_2	1.1	5.0	
U. Eocene	1110	1370	C_2	8.5	11.6	
Eocene	1080	2480	B	1.0	11.3	
Santonian-Coniacian	510	3560	E	0.7	5.3	
Albian	540	4070	E	2.7	5.7	
Aptian	330	4610	B/C_2	0.8	3.5	
Neocomian	2170	4940	B/C_2	2.5	22.7	
Kimmeridgian	450	7110	C_2	2.3	4.7	
Oxfordian	420	7560	D_1	2.6	4.4	
Callovian	2470	7980	D_1	15.1	25.8	
Buthonian	-	10,450	B/D_1	-	-	

Amoco-Imp - A-1 Bittern M-62

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Mio-Oligocene	1020	900	C_2	2.8	10.5	
Olig-Eocene	240	1920	C_2	0.9	2.5	
Eocene	180	2160	C_2	0.2	1.9	
Senonian	1090	2340	A/C_2	2.8	11.2	
Santonian	420	3430	A/D_1	0.2	4.3	
U. Jurassic	480	3850	A	0.6	4.9	
M. Jurassic	4695	4330	A	13.0	48.3	
L. Jurassic	1595	9025	A	-	16.4	
Basement	-	10,620	A/D_1	-	-	

Amoco-Imp-Petrel A-62

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Recent	1170	0	A/B	3.0	21.0	
Miocene	960	1170	A	3.3	17.2	
Oligocene	140	2130	C_1	0.3	2.5	
Eocene	660	2250	A	1.8	11.8	
Campanian	450	2910	A	2.3	8.1	
Santonian	150	3360	A	0.8	2.7	
Coniacian	618	3510	A	1.6	11.1	
Cenomanian	370	4128	A	1.9	6.6	
Albian	792	4498	A/B	4.0	4.0	
Aptian	280	5290	A	-	5.0	
Basement	814	5570	E	-	-	

Amoco-IOE A-1 Gannet 0-54

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Miocene	450	1170	C_2	0.7	7.9	
Oligocene	420	1620	C_2	0.9	7.4	
Eocene	1110	2040	B	1.1	19.5	
Campanian	870	3150	A/B	4.4	15.3	
Santonian	330	4020	A	0.8	5.8	
Santonian-Turonian	1020	4350	A	5.2	17.9	
Cenomanian-Albian	70	5370	D_1	0.4	1.2	
Albian	710	5440	A	3.6	12.5	
Aptian	720	6150	A	-	12.6	
L. Mississippian	1580	6870	C_1	-	-	

Amoco-IDE Puffin B-90

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Pleistocene	98	1066	B	0.6	0.9	
Pliocene	73	1165	A/B	0.5	6.7	
L. Miocene	1739	1870	B	8.8	15.8	
M. Miocene	1509	3609	A	5.6	13.7	
E. Miocene	525	5118	A	3.2	4.8	
M. Oligocene	98	5643	A	0.5	0.9	
E. Oligocene	689	5742	A	2.6	6.2	
L. Eocene	656	6431	A	5.0	5.9	
M. Eocene	131	7087	A	1.0	1.2	
E. Eocene	98	7218	A	0.5	0.9	
Paleocene	33	7349	A	0.1	0.3	
Maestrichtian	131	7382	D_2	0.7	1.2	
Campanian	443	7513	A	2.3	4.0	

Amoco-IDE Puffin B-90 (cont'd)

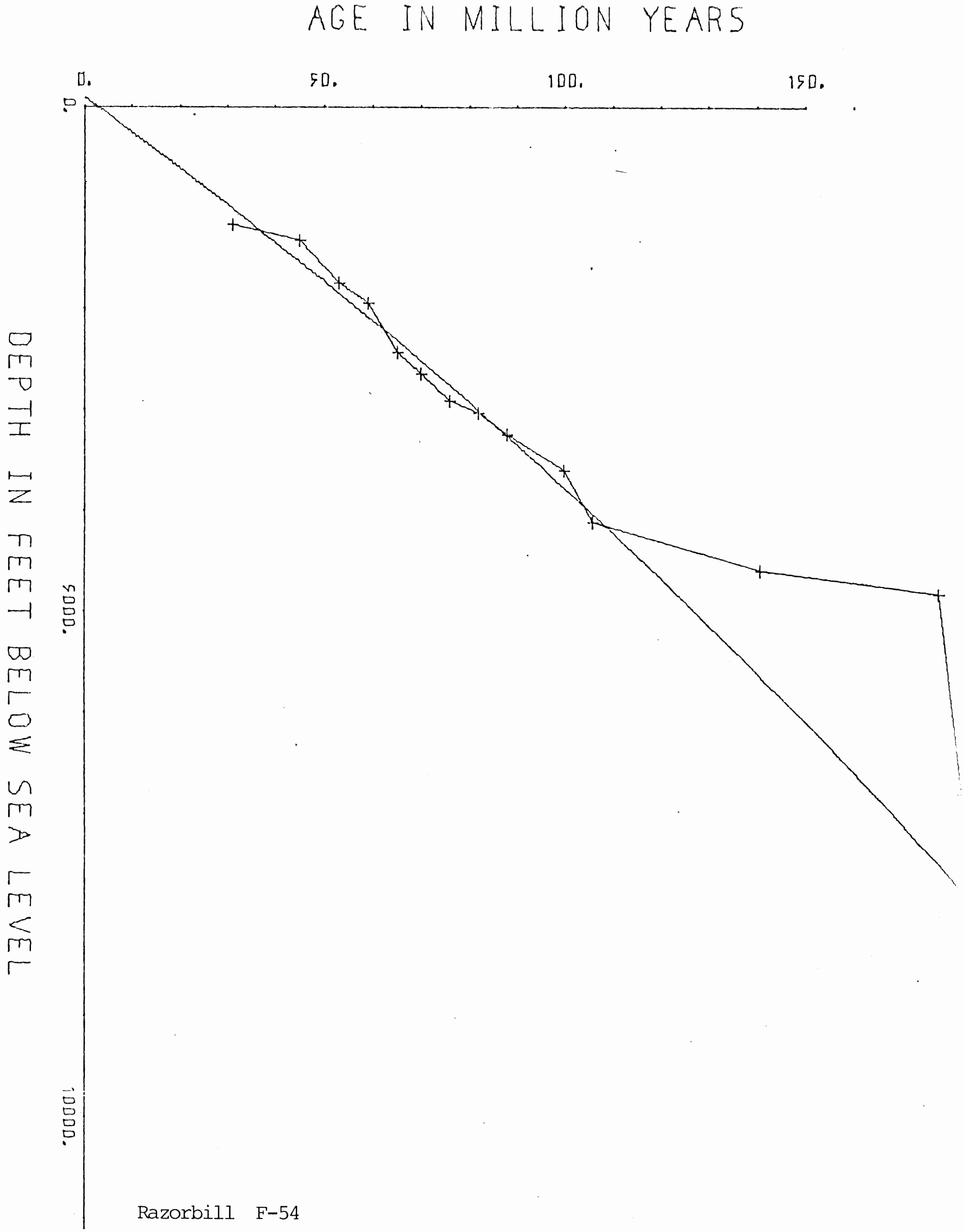
Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Santonian	722	7956	A	3.7	5.9	
Coniacian	344	8612	D_1	0.6	3.1	
Albian	459	8957	A/B	2.3	4.2	
Aptian	427	9416	D_1/A	2.2	3.9	
Barremian	1244	9843	B	6.3	11.3	
Hauterivian	1017	11,089	B	5.2	9.2	
Valanginian	-	12,107	A	-	-	

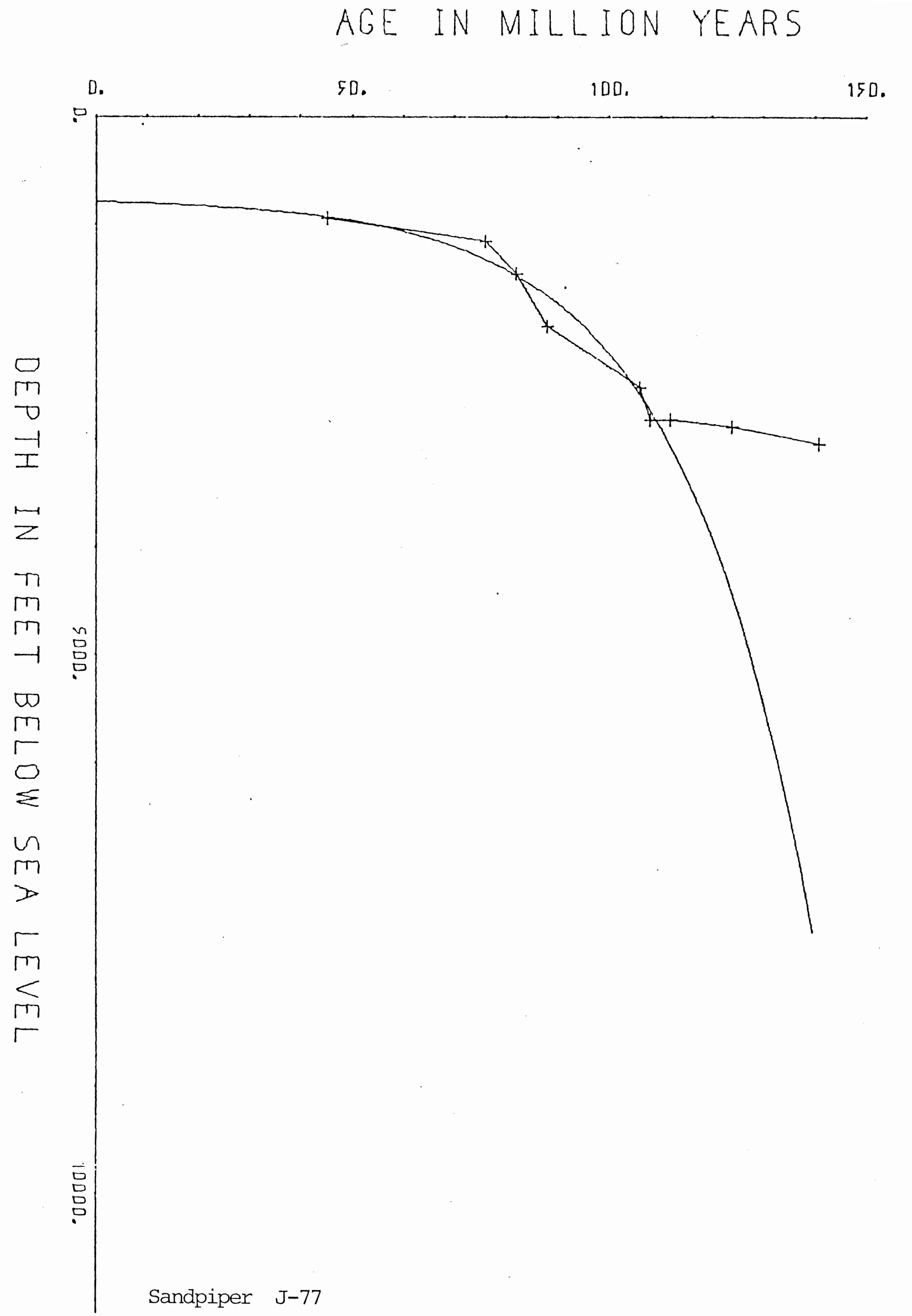
Elf Hermine E-94

Age	Thickness (feet)	Depth Below Sea Level (feet)	Lithology	Sedimentation Rate cm/1000 yrs.	Percent of Stratigraphic Column	
Pliocene	120	1250	C_2	0.7	2.8	
Miocene	450	1370	C_2	0.7	10.3	
Oligocene	270	1820	C_2	0.6	6.2	
Eocene	300	2090	B	0.7	4.9	
Paleocene	380	2390	C_1	1.1	8.7	
Maestrichtian	190	2770	C_2	1.0	4.4	
Campanian	100	2960	E	0.5	2.3	
Santonian	300	3060	E	0.5	6.9	
Cenomanian	850	3360	C_2	4.3	19.5	
Albian	590	4210	C_2	1.0	13.5	
Neocomian	820	4800	B	-	18.8	
Paleozoic	-	5620	C_1	-	-	

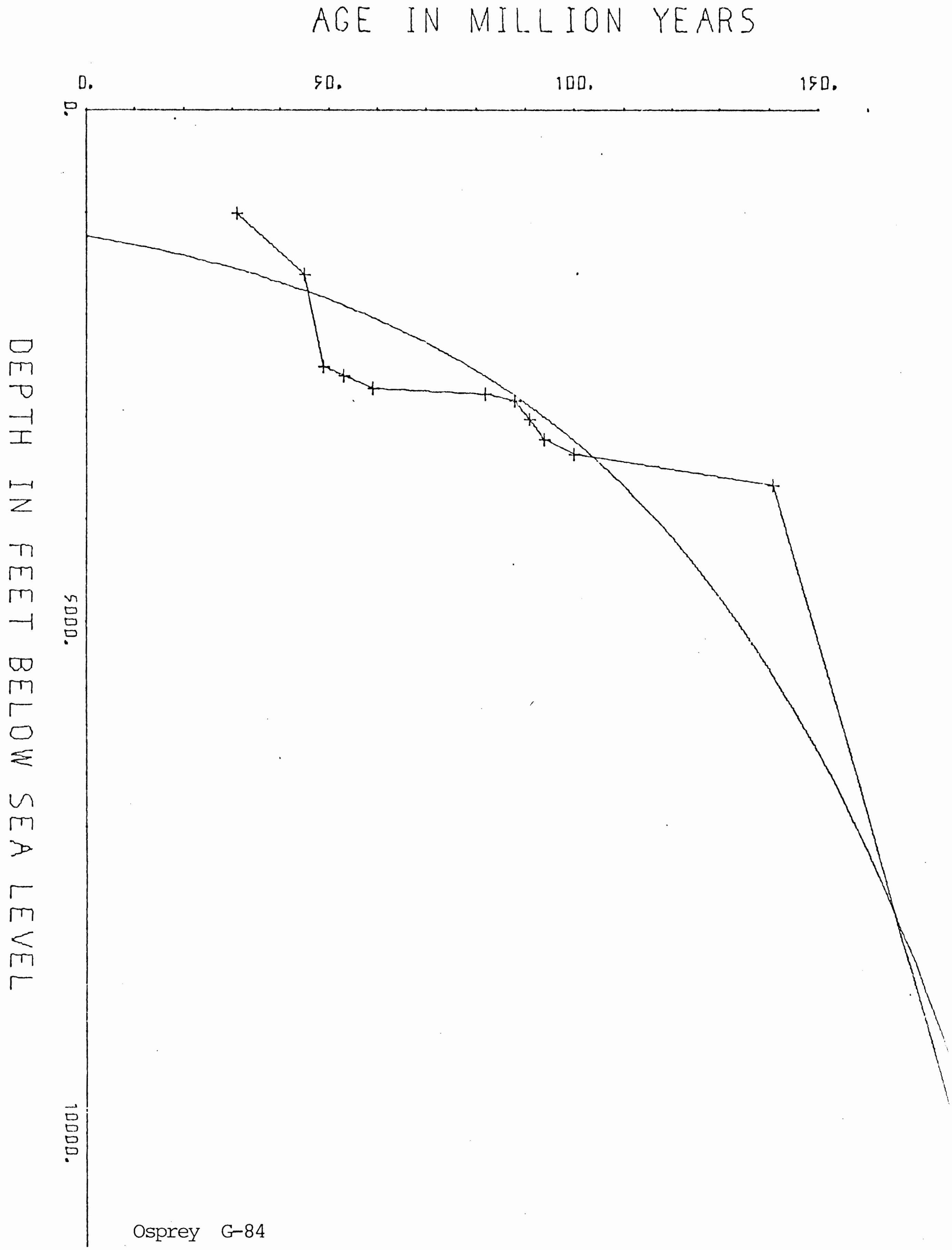
B3

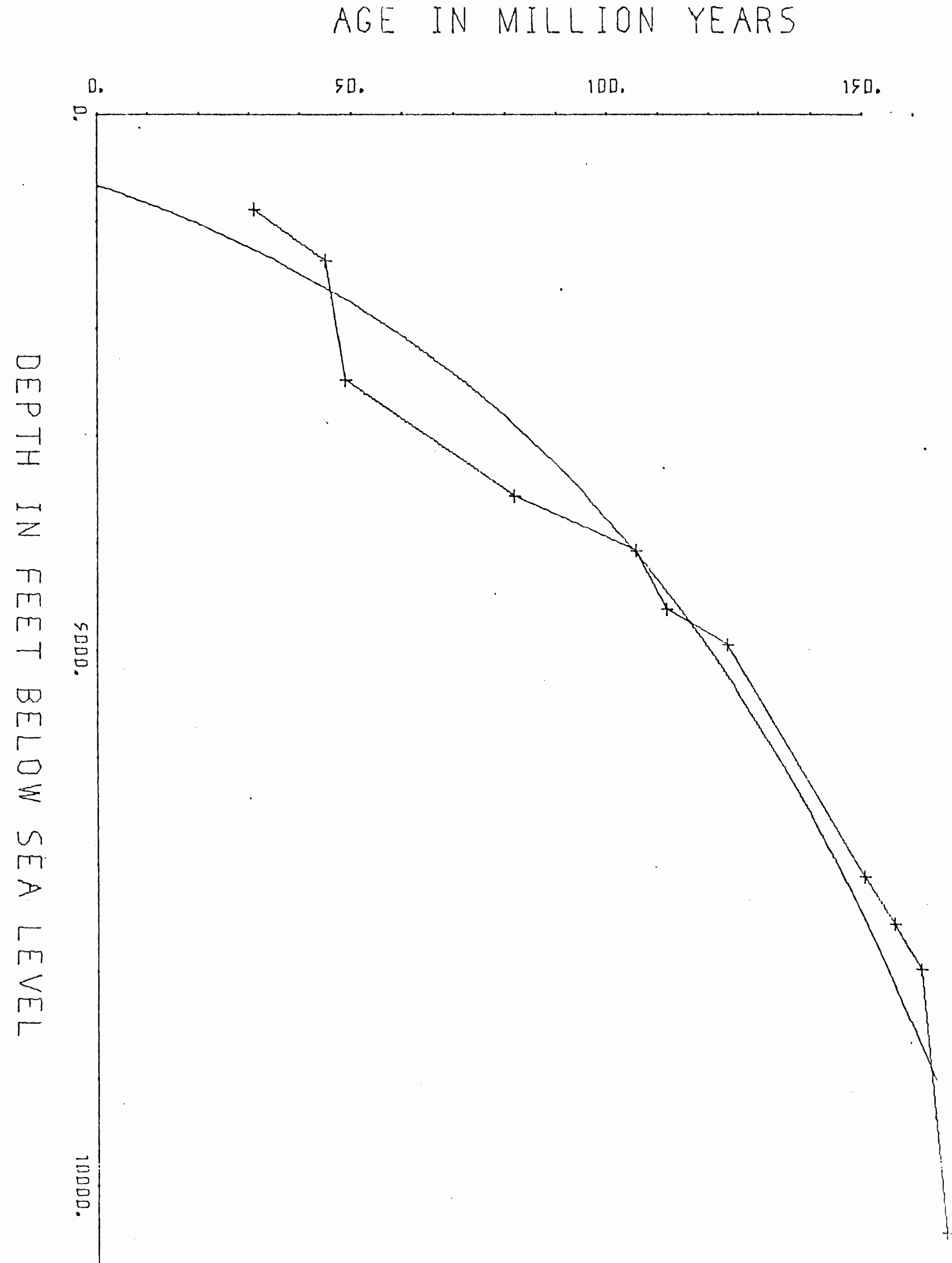
Subsidence curves for the Grand Banks.


AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Razorbill F-54

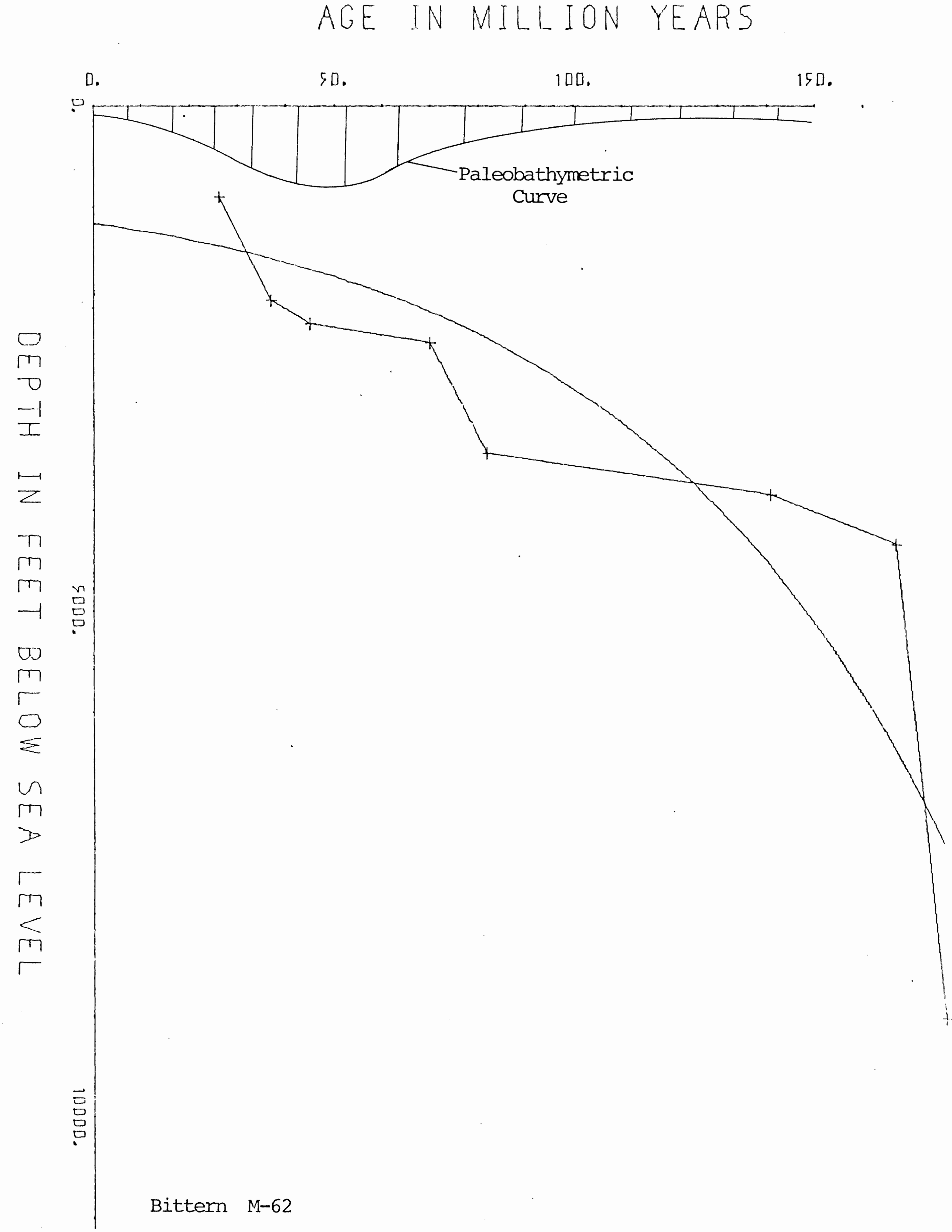


Sandpiper J-77

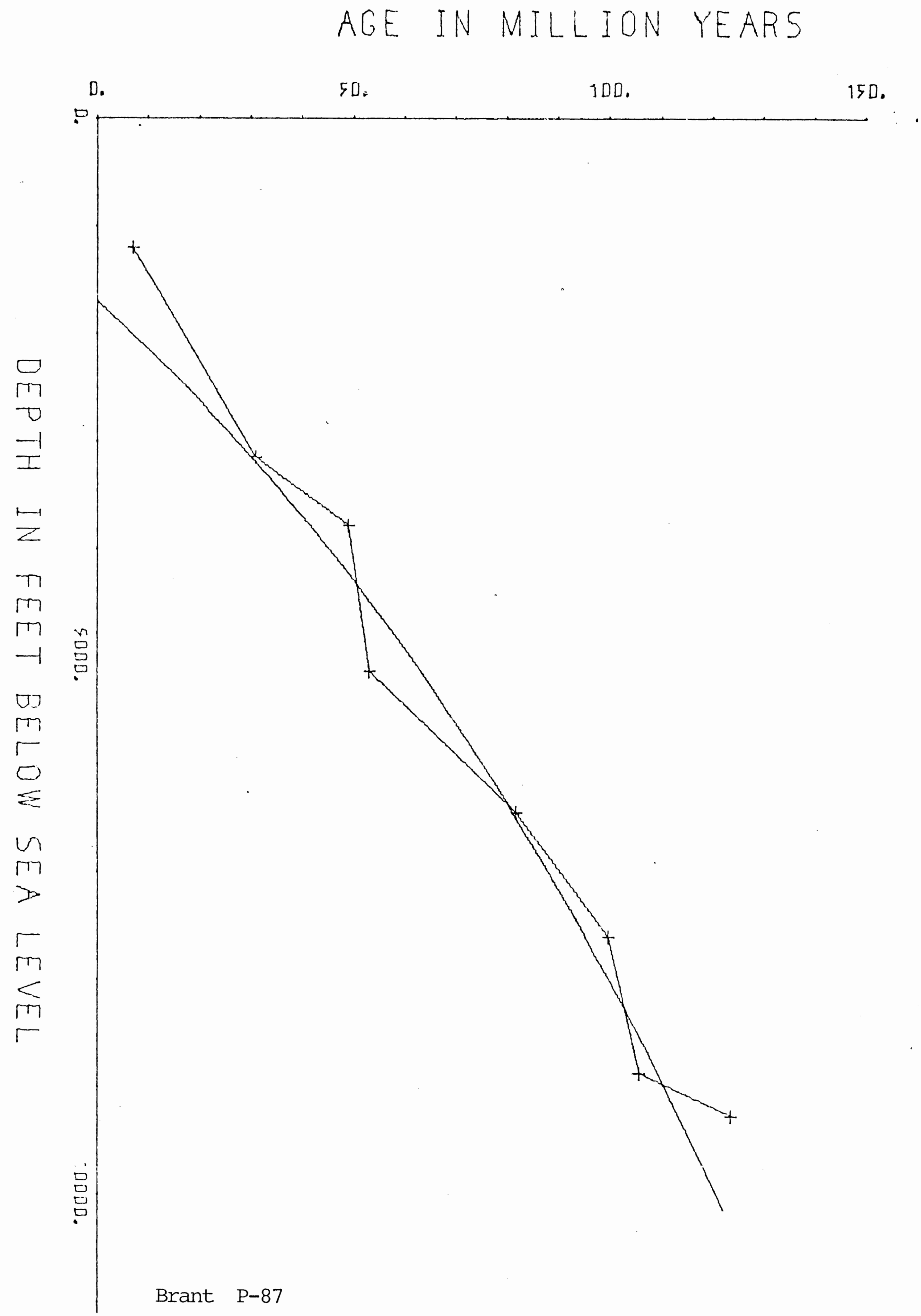

AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Osprey G-84

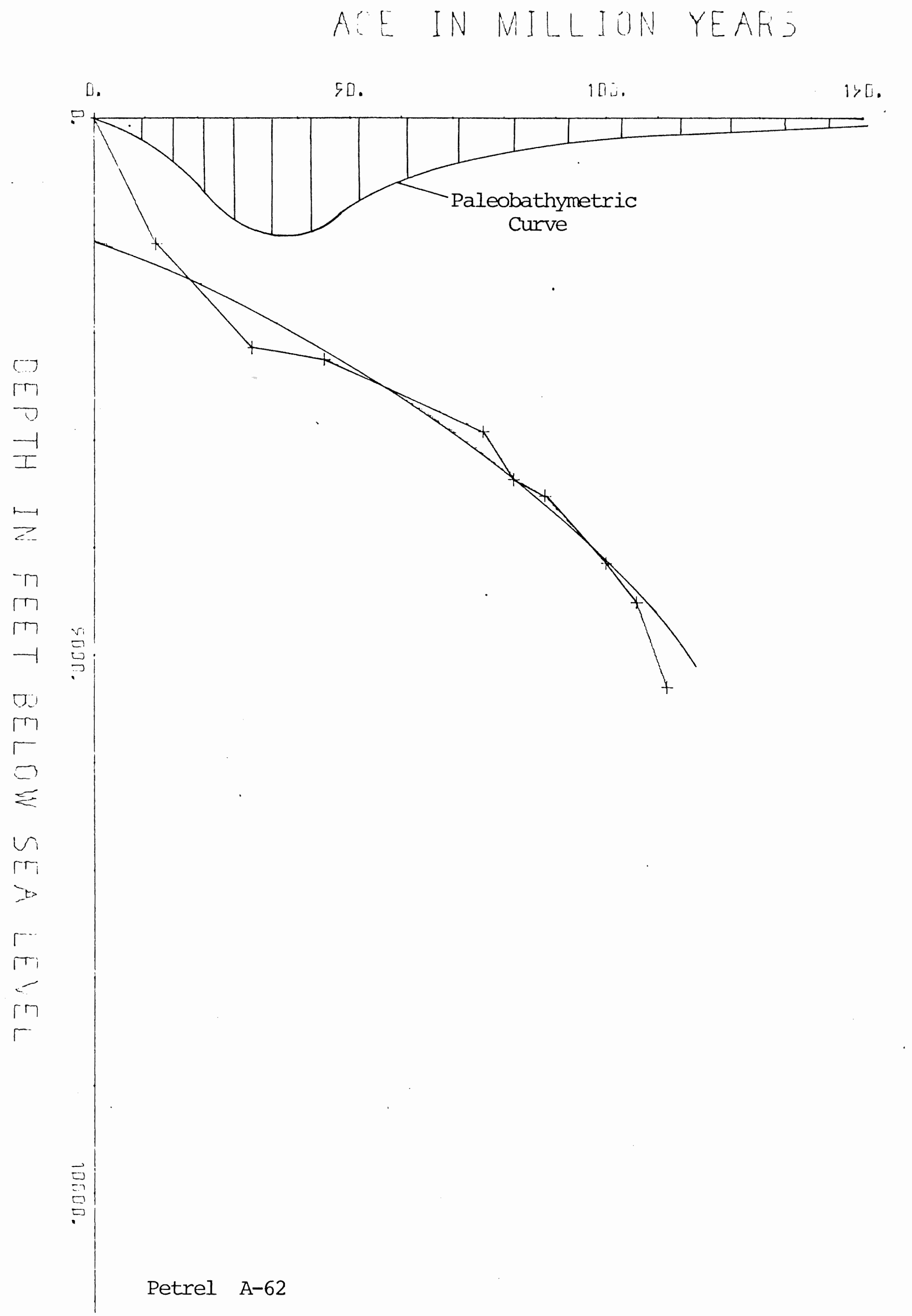

AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.

Egret K-36

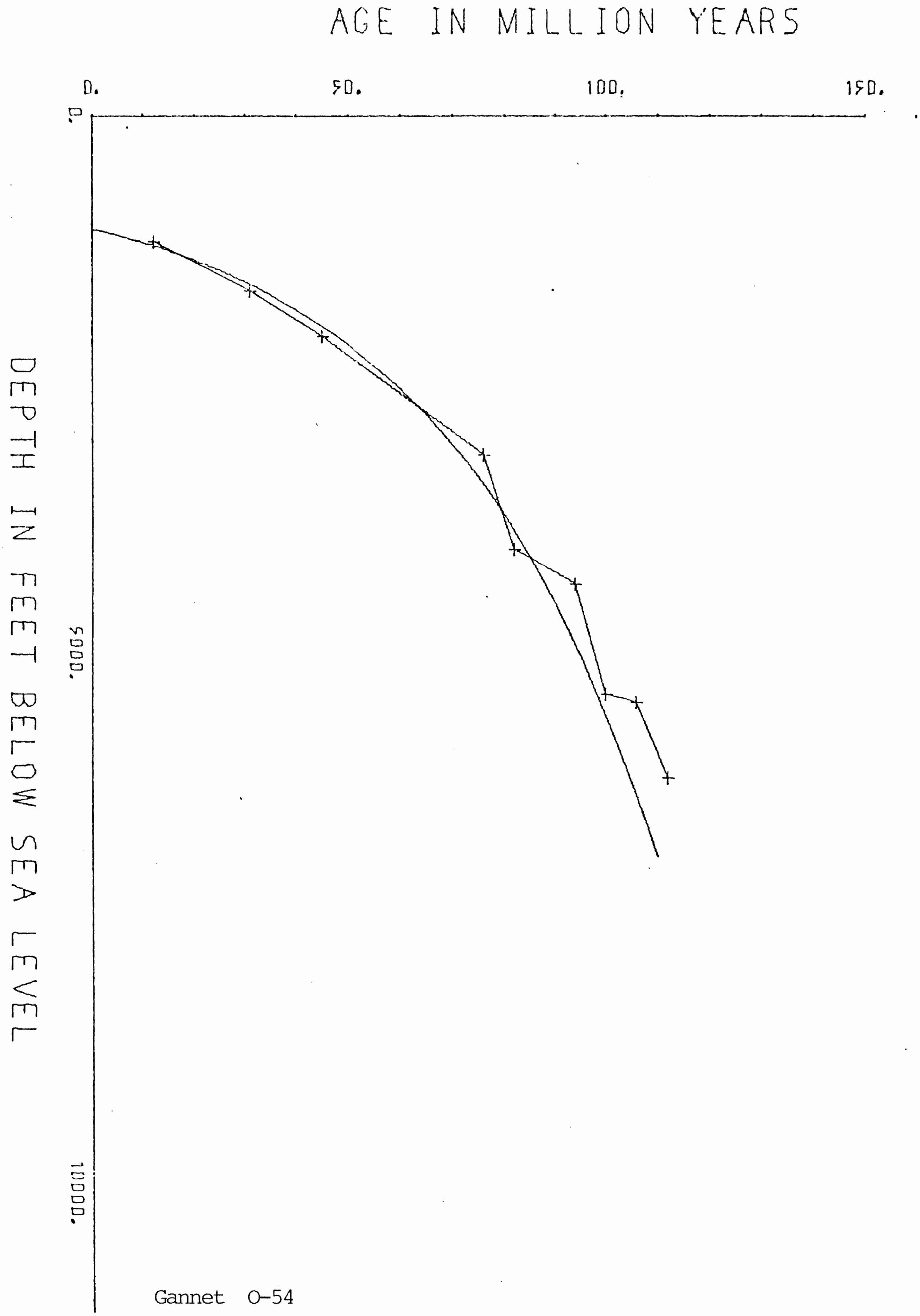


AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Paleobathymetric
Curve
Bittern M-62


AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.
Brant P-87

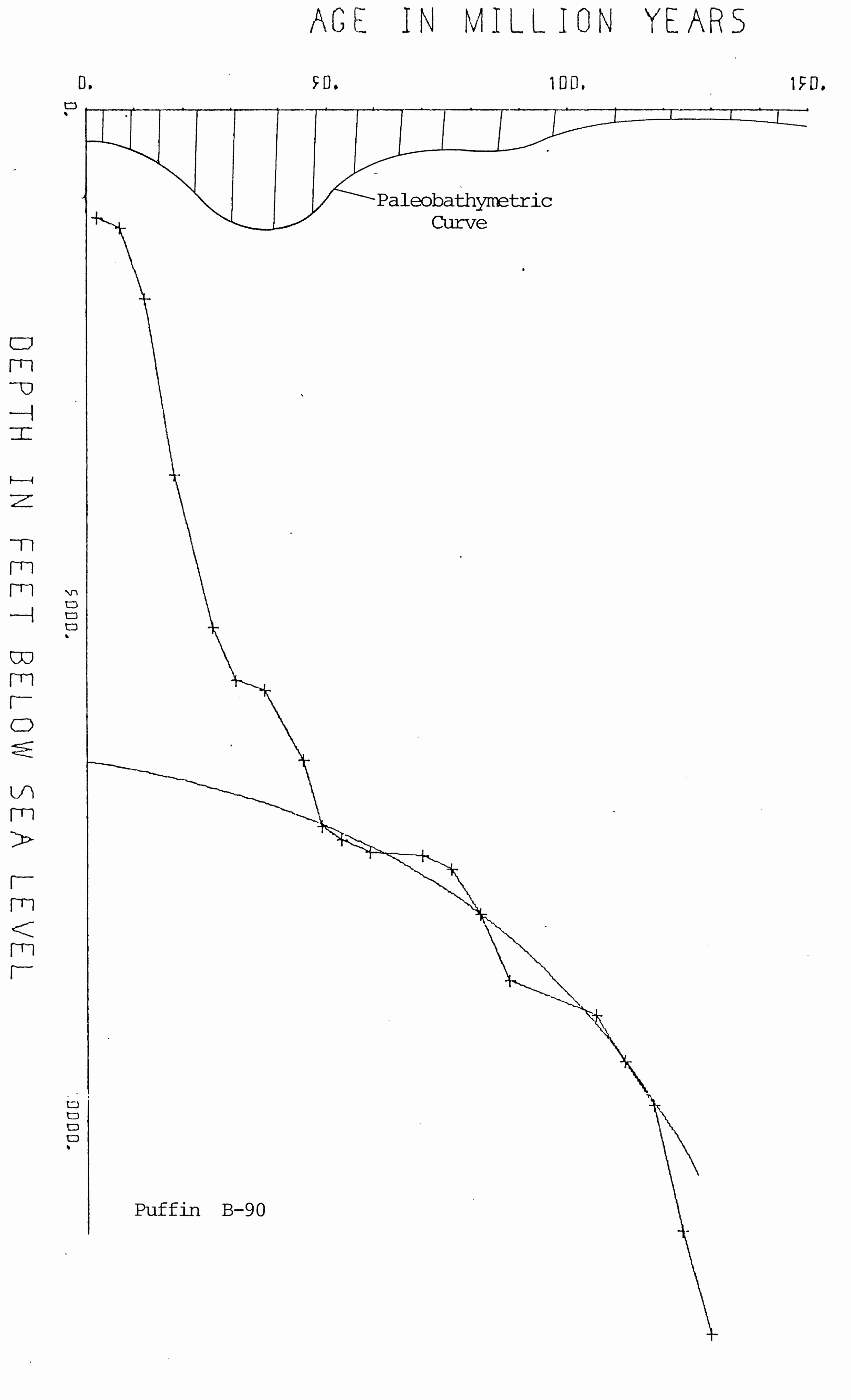

AGE IN MILLION YEARS
0.
50.
100.
150.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL
Paleobathymetric Curve

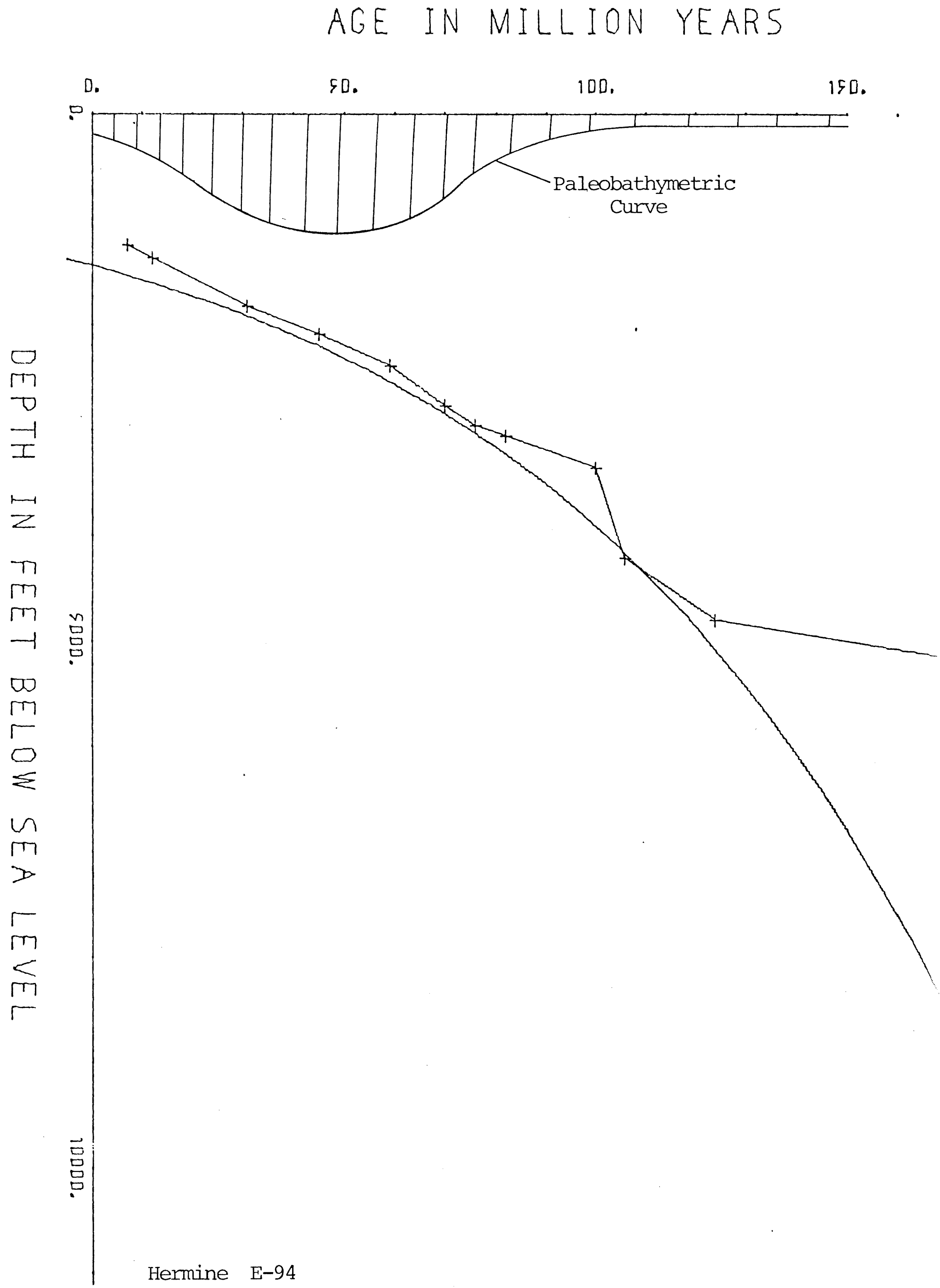
Petrel A-62



AGE IN MILLION YEARS
0.
50.
100.
150.
DEPTH IN FEET BELOW SEA LEVEL
0.
5000.
10000.

Gannet O-54


AGE IN MILLION YEARS
0.
50.
100.
150.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL
Paleobathymetric
Curve
Puffin B-90

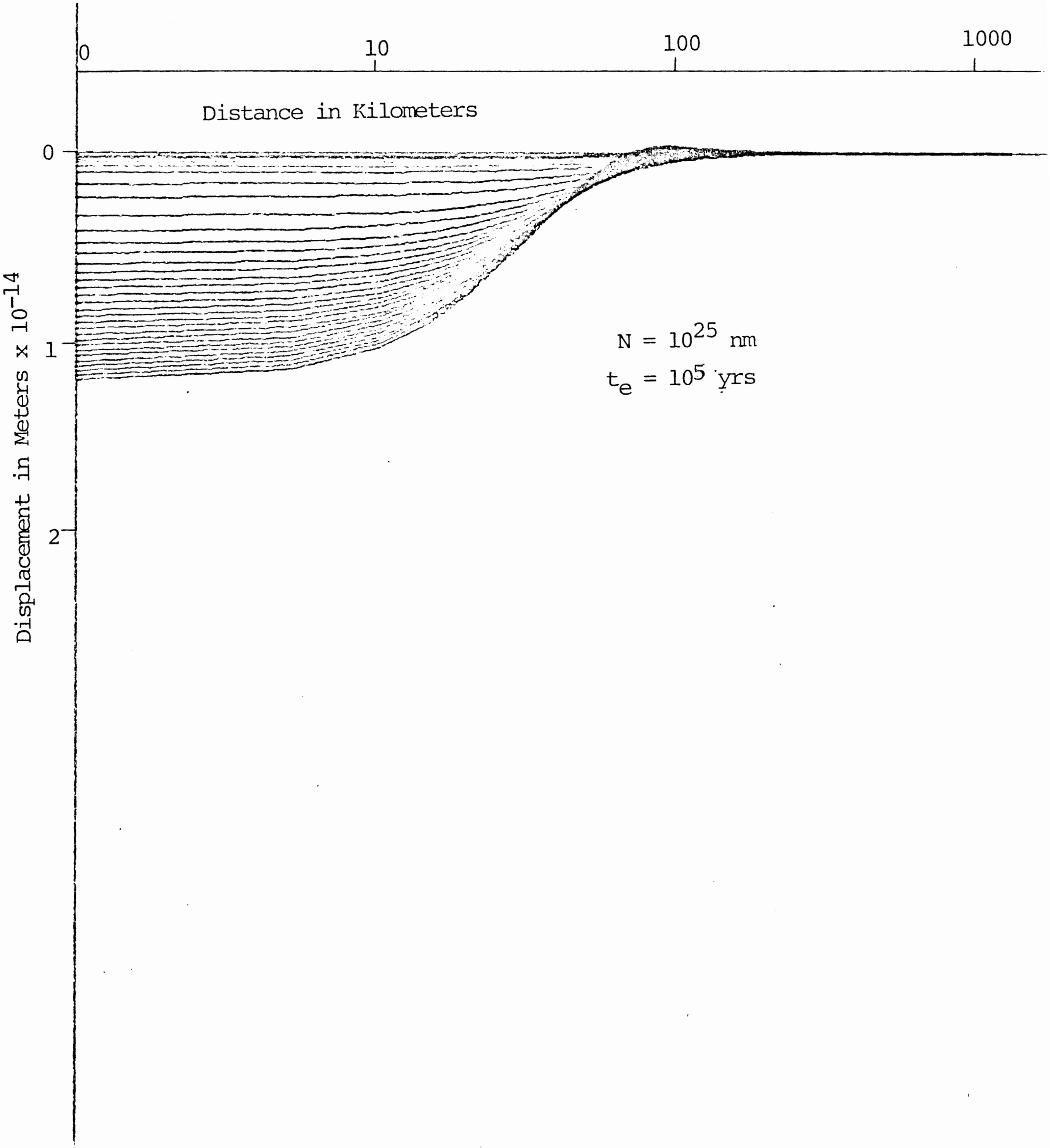

AGE IN MILLION YEARS
0.
50.
100.
150.
0.
5000.
10000.
DEPTH IN FEET BELOW SEA LEVEL
Paleobathymetric Curve

Hermine E-94

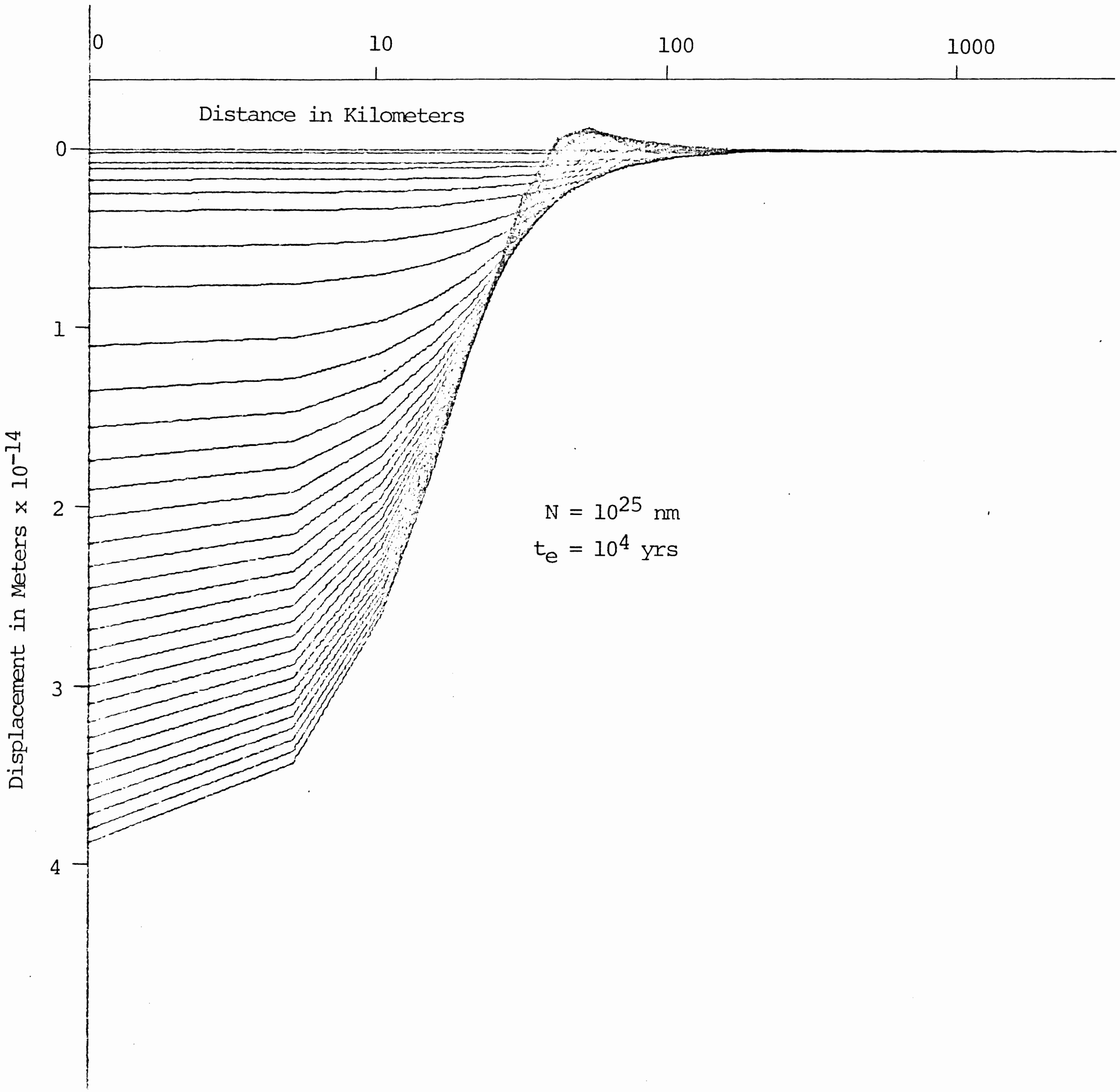
<u>Appendix II</u>

Green Functions: showing how the basin subsides through time, and migration inward of the peripheral bulge.

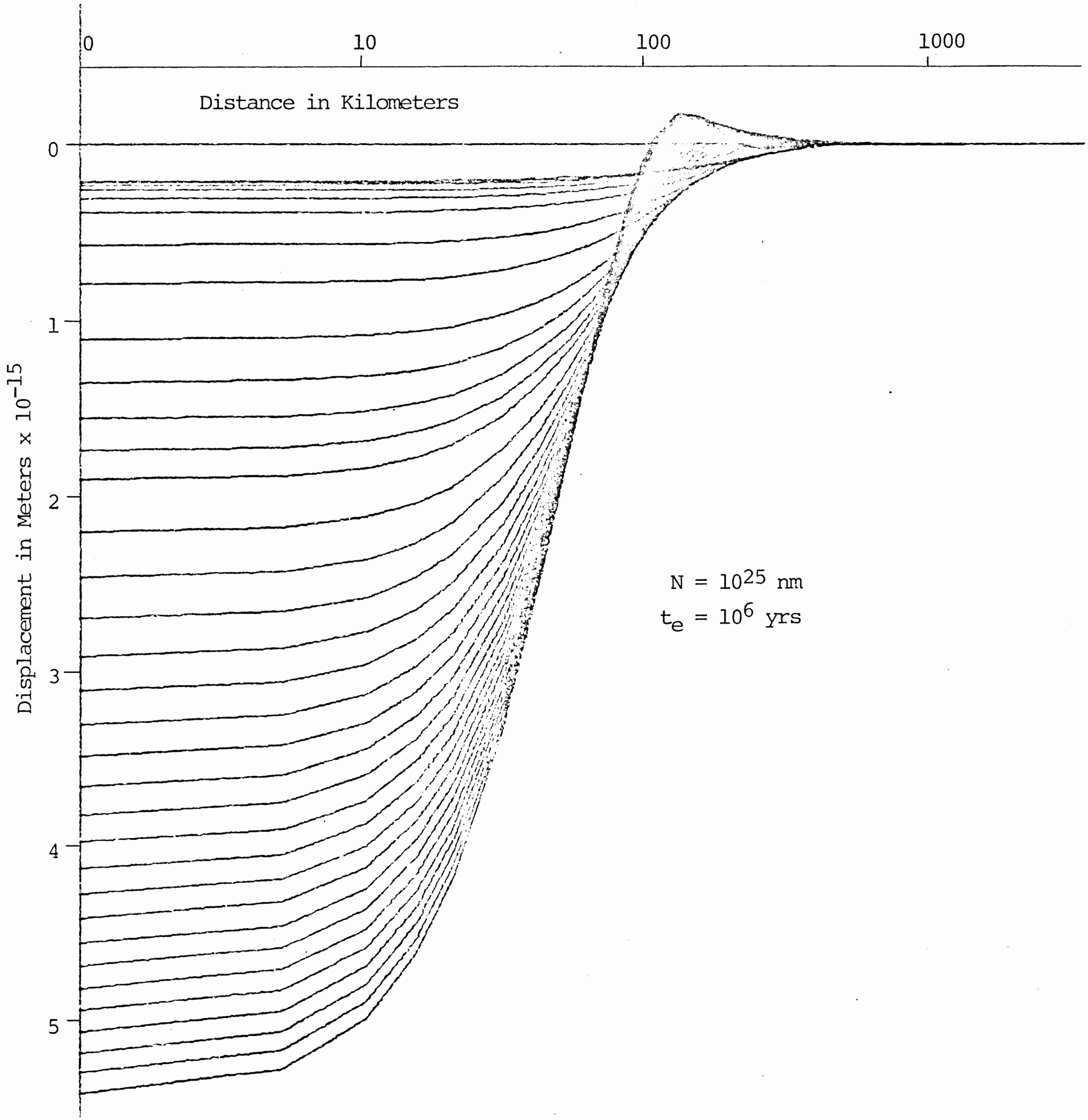
Green Functions for $t_e = 10^4$ yrs., $t_e = 10^5$ yrs., and $t_e = 10^6$ yrs. are shown.



0
10
100
1000
Distance in Kilometers
0
1
2
Displacement in Meters x 10^{-14}
$N = 10^{25}$ nm
$t_e = 10^5$ yrs



0
10
100
1000
Distance in Kilometers
0
1
2
3
4
Displacement in Meters x 10^-14
N = 10^25 nm
t_e = 10^4 yrs



0
10
100
1000
Distance in Kilometers
0
1
2
3
4
5
Displacement in Meters x 10^{-15}
$N = 10^{25}$ nm
$t_e = 10^6$ yrs

Appendix III

Computer programs:

A: ROMVPLA

B: INSTQ

C: CONVOL

D: EXPFIT

A

ROMVPLA

```
      PROGRAM ROMVPLA (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON/ROMBRG/ MMAX,MAX,TROW(19),TEST(18)
      COMMON/TGRARG/ ALF4,TE,P,T,GAMS,DISCA
      COMMON/BESARG/ N,D,IER
      COMMON/TAIL/ ACC,WORK(20),SUMSAV(20)
      COMMON VALR(200),TT(200),WPT(200),AINT(100)
      DIMENSION ZEROS(20)
C
C*********************************************************************
C*
C*      ROMVPLA ( ROMBERG INTEGRATION OF VISCOUS PLATE PROBLEM )
C*      USES ROMBERG INTEGRATION TO CALCULATE THE INVERSE HANKEL
C*      TRANSFORM OF W(S,T), W(R,T)
C*      WHERE W(R,T) IS THE GREEN FUNCTION FOR THE RESPONSE OF A
C*      VISCOELASTIC PLATE TO A POINT LOAD THAT IS APPLIED AT T=0
C*      AND REMAINS  A CONSTANT AMPLITUDE FOR T.GT.0.
C*      PROVISION IS MADE FOR DISTRIBUTING THE LOAD OVER A DISC OF
C*      RADIUS DISCA
C*
C*      THE INTEGRAND W(S,T)*JO(SR)*S IS EVALUATED BY THE  FUNCTION
C*      TGRAND(S)
C*      INTEGRAND IS W(S,T)*JO(S*R)*J(S*DISCA) FOR THE DISC LOAD
C*
C*      THE INTEGRATION FROM 0 TO INFINITY IS CARRIED OUT BY FUNCTIONS
C*      TAIL AND ROMBRG
C*      ROMBRG PERFORMS THE INTEGRATION FOR INTERVALS BETWEEN THE
C*      ZEROS OF THE INTEGRAND
C*      TAIL SUMS THE RESULTING ALTERNATING SERIES USING THE EULER
C*      CONTRACTION METHOD
C*
C*      THE  BESSEL FUNCTIONS JO(S) AND J1(S) ARE EVALUATED USING
C*      POLYNOMIAL EXPANSIONS
C*
C*      THE INTEGRAL IS EVALUATED FOR VALUES OF R SPECIFIED BY VALR(I)
C*      THE INTEGRAL IS ALSO EVALUATED OVER A RANGE OF VALUES OF T TO
C*      GIVE A SERIES OF SPACE TIME GREEN FUNCTIONS . THE VALUES OF
C*      T ARE SPECIFIED BY TT(I)
C*
C*      FOR A GIVEN VISCOELASTIC PLATE THE PARAMETERS ANFLEX,GAMS,TE
C*      P, ARE CONSTANTS
C*
C*
C*      INPUTS
C*      1 ANFLEX,GAMS,TE,P,DISCA   (E8.2,E8.3,3E8.2)
C*        ANFLEX = FLEXURAL RIGIDITY APPROX 1.E25 N-MS ( SI UNITS )
C*        GAMS = (RHOM-RHOS )*G   (SI UNITS )
C*        TE = VISCOUS TIME CONST G.T 1.E4  L.T. 1.E6  IN YEARS
C*        P = POINT LOAD ( SI UNITS )
C*        DISCA IS THE RADIUS OF THE DISC OVERWHICH THE LOAD IS APPLIED
C*        IN METERS . IF (DISCA.EQ.0.) A POINT LOAD IS ASSUMED
C*      2 NR,NT,NNN  ( 3I5 )
C*        NR = NO OF SPATIAL POINTS AT WHICH THE INTEGRAL IS EVALUATED
C*          IE NO OF VALUES IN VALR
C*        NT = NO OF TIME VALUES AT WHICH INTEGRAL IS EVALUATED ,IE
C*          NO OF POINTS IN TT
C*        NNN = NO OF ZEROS SPECIFIED FOR FUNCTION TAIL  LT.20
C*          ACCURACY OF EULER CONTRACTION IS  BASED ON NNN THEREFORE
```



```
C*          TRADEOF BETWEEN ACCURACY AND SPEED IS ADJUSTED USING NNN
C*      3 (VALR(I),I=1,NR)   (12E6.2)
C*        VALR ARE THE VALUES OF R AT WHICH THE INTEGRAL IS REQUIRED
C*        ( METERS )
C*      4 (TT(I),I=1,NT)   (10E7.2)
C*        TT ARE THE VALUES OF T AT WHICH THE INTEGRAL IS REQUIRED
C*        UNITS ARE THE SAME AS TE )
C*
C*********************************************************************
C
      READ(5,10) ANFLEX,GAMS,TE,P,DISCA
   10 FORMAT (E8.2,E8.3,3E8.2)
      READ(5,20) NR,NT,NNN
   20 FORMAT (3I5)
      WRITE(6,22)ANFLEX,GAMS,TE,P,DISCA
   22 FORMAT (1H1,5X*NFLEX,GAMS,TE,P,DISCA   *,5E12.5/)
      WRITE(6,25) NR,NT,NNN
   25 FORMAT (1H0,5X*NR,NI,NNN   *, 3I7/)
C
C      READ IN VALUES OF R AT WHICH THE INTEGRAL IS REQUIRED
C
      READ(5,30)   (VALR(I),I=1,NR)
   30 FORMAT (12E6.2)
      WRITE(6,35) (VALR(I),I=1,NR)
   35 FORMAT (1H0,5X*  VALR(I) *,12E8.2)
C
C      READ IN VALUES OF T FOR WHICH INTEGRAL IS REQUIRED
C
      READ(5,40) (TT(I),I=1,NT)
   40 FORMAT (10E7.2)
      WRITE(6,45) (TT(I),I=1,NT)
   45 FORMAT (1H0,5X*TT(I)   *,12F9.2)
C
C      PRELIMINARIES
C
      PI=3.14159265359
      PI2=2.*PI
      ALF4=4.*ANFLEX/GAMS
      PPI2=P/PI2
      N=0
      ALF=SQRT(SQRT(ALF4))
      WRITE(6,50) ALF4,ALF
   50 FORMAT (1H0,5X* ALPHA**4 =   *,E12.5,*  ALPHA =   *,E12.5/)
C
C      LOOP OVER T
C
      DO 100 J=1,NT
      T=TT(J)
C
C      EVALUATE NON BESSEL PART OF INTEGRAND
C
C
      START=1.0E-9
      STEP=SQRT(10.)
      DO 300 II=1,25
      A=GRAND(START)
      WRITE(6,300) START,A
```

```
      390 FORMAT (1H ,5X*X   , INTEGRAND/BESJ(XR)  *,2E12.5)
      380 START=START+STEP
C
C         LOOP OVER R
C
          DO 200 I=1,NR
          R=VALR(I)
C
C
C          CHOICE OF ZEROS OF THE INTEGRAND TO BE SUPPLIED TO TAIL
C          IF(DISCA. MUCH LT. R) THE FIRST ZEROS OF JO(X*R) WILL BE MUCH
C          CLOSER TO THE ORIGIN THAN THE ZEROS OF J1(X*DISCA). THEREFORE
C          TAIL IS SUPPLIED WITH THE ZEROS OF JO(X*R)
C          IF(DISCA. MUCH GT. R) THE FIRST ZEROS OF J1(X*DISCA) WILL BE
C          MUCH CLOSER TO THE ORIGIN THAN THE ZEROS OF JO(X*R). THEREFORE,
C          TAIL IS SUPPLIED WITH THE ZEROS OFJ1(X*DISCA)
C          IF(DISCA.APPROX.EQ.R) THE FIRST ZEROS OF JO(X*R) AND J1(X*DISCA)
C          ARE INTERLEAVED, THEREFORE BOTH SETS OF ZEROS ARE SUPPLIED TO TAIL
C          IN THIS CASE EULER CONTRACTION PROBABLY DOES NOT WORK
C
C          CALCULATE  ZEROS OF J(XR)
C          THE ASYMPTOTIC ZEROS OF JO(XR) ARE XR= 0, (M-0.25)*PI, ...
C
          ADD=-0.25
          F=R
          IF(DISCA.GT.R) ADD=0.25
          IF(DISCA.GT.R) F=DISCA
          ZZEROS(1)=0.
          DO 300 II=2,NNN
          ZZEROS(II)=(FLOAT(II-1)+ADD )*PI/F
      300 CONTINUE
          IF(F.EQ.R) WRITE(6,240)
          IF(F.EQ.DISCA) WRITE(6,241)
      240 FORMAT(1H0,5X* TAIL IS SUPPLIED WITH THE ZEROS OFJO(XR) */)
      241 FORMAT(1H0,5X* TAIL IS SUPPLIED WITH THE ZEROS OF J1(X DISCA) */)
          WRITE(6,250) (ZZEROS(K),K=1,NNN)
      250 FORMAT (1H0,5X* ZEROS = *,10E12.5)
C
C
C          EVALUATE INTEGRAND
C          USED IN DEBUGGING AND FOR DIFFICULT KERNALS
C
          STEP=ZZEROS(3)-ZZEROS(2)
          STEP=STEP/5.
          START=0.
          DO 350 II=1,100
          AINT(II)=GRAND(START)
          START=START+STEP
      350 CONTINUE
C         WRITE(6,375) (AINT(II),II=1,100)
      375 FORMAT (1H0,2X*INTEGRAND*,10E12.5)
C
C          CALCULATE INTEGRAL
C
          WRT(I)=TAIL(ZZEROS,NNN,EERREST)
          WRITE(6,700) EERREST,WRT(I)
      700 FORMAT (1H0,5X* ERROR ESTIMATE *,E12.5,* INTEGRAL  *,E12.5)
```

PROGRAM ROMVPLA 73/73 OPT=0 TRACE FTN 4.6+428 77/02/21. 15.08.20

```
          WRITE(6,710) (SUMSAV(II),II=1,NNN)
      710 FORMAT (1H ,5X* SUMSAV *,8E13.7)
          WRT(I)=WRT(I)*PPI2
      200 CONTINUE
          WRITE(6,500) T
      500 FORMAT(1H0,5X* VERTICAL DISPLACEMENT OF VISCOELASTIC PLATE FOR T=
         1   *,1E8.3/)
          WRITE(6,600) ((VALR(II),WRT(II)),II=1,NR)
      600 FORMAT (1H ,5X,2E12.4)
      100 CONTINUE
          CALL EXIT
          END
```

FUNCTION GRANF 73/73 OPT=0 TRACE FTN 4.6+428 77/02/21. 15.08.20

```
          FUNCTION GRANF(X)
          COMMON/TGRARG/ ALF4,TE,R,T,GAMS,DISCA
          X4=X**4
          AX=X*DISCA
          F=X
          IF(DISCA.NE.0.)  F=BBESJ1(AX)
          TX=(1.+(ALF4*X4)/4.)*TE
          TTEST=T/TX
          IF(TTEST.GT.675.8) GO TO 20
          GRANF=(1./GAMS)*((TE/TX-1.)*EXP(-T/TX)+1.)*F
C         GRANF=(1./GAMS)*F
          RETURN
       20 GRANF=(1./GAMS)*X
          RETURN
          END
```

FUNCTION GRAND 73/73 OPT=0 TRACE FTN 4.6+428 77/02/21. 15.08.20

```
          FUNCTION  GRAND(X)
          COMMON/TGRARG/ ALF4,TE,R,T,GAMS,DISCA
          X4=X**4
          RX=R*X
          AX=DISCA*X
          F=X
          IF(DISCA.NE.0.)  F=BBESJ1(AX)
          TX=(1.+(ALF4*X4)/4.)*TE
          TTEST=T/TX
          IF(TTEST.GT.675.8) GO TO 20
C         GRAND=(1./GAMS)*BBESJ(RX)*F
          GRAND=(1./GAMS)*((TE/TX-1.)*EXP(-T/TX)+1.)*BBESJ(RX)*F
          RETURN
```

FUNCTION BBESJ1 73/73 OPT=0 TRACE FTN 4.6+428 77/02/21. 15.08.20

```
      FUNCTION BBESJ1 (X)
C
C*******************************************************************
C*
C*     BBESJ1(X) COMPUTES THE 1ST ORDER BESSEL FUNCTION USING
C*     THE POLYNOMIAL APPROXIMATION ,ABRAMOWITZ AND STEGUN & 370
C*     ACCURACY APPROX 1.E-7
C*
C*******************************************************************
      IF(X.EQ.0.) GO TO 30
      IF(X.GT.3.) GO TO 20
C
C      USE APPROX FOR X.LE.3.
C
      X3=X/3.  $  X32=X3*X3  $  X34=X32*X32  $  X36=X34*X32
      X38=X36*X32  $  X310=X38*X32  $  X312=X310*X32
      C1=0.5  $  C2=0.56249985  $  C3=0.21093573  $  C4=0.03954289
      C5=0.00443319  $  C6=0.00031761  $  C7=0.00001109
      BBESJ1=(C1-C2*X32+C3*X34-C4*X36+C5*X38-C6*X310+C7*X312)*X
      RETURN
   20 CONTINUE
C
C      USE APPROX FOR X.GT.3.
C
      XS=SQRT(1./X)
      X3=3./X  $  X32=X3*X3  $  X33=X32*X3  $  X34=X33*X3
      X35=X34*X3  $  X36=X35*X3
      C1=0.79788456  $  C2=0.00000156  $  C3=0.01659667
      C4=0.00017105  $  C5=0.00249511  $  C6=0.00113653
      C7=0.00020033
      F1=C1+C2*X3+C3*X32+C4*X33-C5*X34+C6*X35-C7*X36
      T1=2.35619449  $  T2=0.12499612  $  T3=0.00005650
      T4=0.00637879  $  T5=0.00074348  $  T6=0.00079824
      T7=0.00029166
      THET1=X-T1+T2*X3+T3*X32-T4*X33+T5*X34+T6*X35-T7*X36
      BBESJ1=XS*F1*COS(THET1)
      RETURN
   30 BBESJ1=0.
      RETURN
      END
```

FUNCTION BBESJ 73/73 OPT=0 TRACE FTN 4.6+428 77/02/21. 15.08.20

```
      FUNCTION BBESJ(X)
      COMMON/BESARG/N,D,IER
C
C*******************************************************************
C*
C*     BBESJ COMPUTES THE ZERO ORDER BESSEL FUNCTION USING THE POLYNOMIAL
C*     APPROXIMATION ,ABRAMOWITZ AND STEGUN PAGE 369
C*     ACCURACY APPROX 1.E-8
C*
C*******************************************************************
C
C
C      USES APPROX FOR X.LE.3.
      IF(X.EQ.0.) GO TO 30
      IF(X.GT.3.) GO TO 20
      X3=X/3.
      X32=X3*X3  $X34=X32*X32  $  X36=X34*X32  $  X38=X36*X32
      X310=X38*X32  $  X312=X310*X32
      C1=2.2499997  $  C2=1.2656208  $  C3=0.3163866  $  C4=0.0444479
      C5=0.0039444  $  C6=0.0002100
      BBESJ=1.-C1*X32+C2*X34-C3*X36+C4*X38-C5*X310+C6*X312
      RETURN
   20 CONTINUE
C      USES APPROX FOR X.GT.3.
      XS=SQRT(1./X)
      X3=3./X  $  X32=X3*X3  $  X33=X32*X3  $  X34=X33*X3  $  X35=X34*X3
      X36=X35*X3
      C1=0.79788456  $  C2=0.00000077  $  C3=0.00552740
      C4=0.00009512  $  C5=0.00137237  $  C6=0.00072805
      C7=0.00014476
      F0=C1-C2*X3-C3*X32-C4*X33+C5*X34-C6*X35+C7*X36
      T1=0.78539816  $  T2=0.04166397  $  T3=0.00003954
      T4=0.00262573  $  T5=0.00054125  $  T6=0.00029333
      T7=0.00013558
      THET0=X-T1-T2*X3-T3*X32+T4*X33-T5*X34-T6*X35+T7*X36
      BBESJ=XS*F0*COS(THET0)
      RETURN
   30 BBESJ=1.
      RETURN
      END
```

```
      FUNCTION TAIL (ZEROS,NN,ERREST)
C$$$$ CALLS ROMBRG
C   FUNCTION FOR FINDING INTEGRAL TO INFINITY OF AN OSCILLATORY FUNCTION.
C                                 ARGUMENT LIST
C   ZEROS - AN ARRAY CONTAINING NN CONSECUTIVE ZEROS OF THE FUNCTION IN INCREASIN
C  -ING ORDER.
C   GRAND - THE INTEGRAND, WHICH WILL BE INTEGRATED FROM ZEROS1< TO INFINITY.
C    THE FUNCTION TO BE INTEGRATED MUST BE SUPPLIED IN THE FORM GRAND(X)
C     IT NEED NOT BE DECLARED EXTERNAL AS IT IS NOT AS AN ARGUMENT IN ANY
C    CALL TO ANOTHER FUNCTION
C   ERREST - AN ERROR ESTIMATE SET BY THE ROUTINE.
C                                 METHOD
C   A ROMBERG INTEGRATION IS PERFORMED ON INTERVALS OF SUCCESSIVE PAIRS OF
C   ZEROS 5SEE COMMENTS IN SUBROUTINE ROMBRG FOR DETAILS OF THE METHOD<.
C   THE CONTRIBUTION TO THE INTEGRAL OF EACH SUCH PARTIAL INTEGRAL ALTERNATES
C   IN SIGN, AND THEREFORE THESE CONTRIBUTIONS CAN BE VIEWD AS A SERIES OF ALTER
C  -NATING SIGN.  THIS SERIES IS SUMMED USING THE EULER CONTRACTION METHOD.  THUS
C   EVEN VERY SLOWLY CONVERGENT SERIES ARE QUICKLY SUMMED.  IT WILL BE SEEN THAT
C   THE SEQUENCE OF ZEROS NEED ONLY BE ASYMPTOTICALLY ACCURATE. THE FORM OF THE
C   EULER TRANSFORMATION USED HERE IS A MODIFICATION OF THE STANDARD METS04T 95
C   THAT BACKWARD DIFFERENCES ARE USED. THIS ELIMINATES THE NEED TO DECIDE HOW
C   FAR TO SUM WITHOUT CONTRACTION.
C                                 RESTRICTION
C   UP TO TWENTY ZEROS CAN BE INCLUDED IN THE EULER CONTRACTION.  IF MORE ZEROS
C   THAN THIS ARE PROVIDED, THE PARTIAL INTEGRALS WILL BE FOUND FOR ALL OF THEM
C   BUT THE CONTRACTION WILL BE PERFORMED ON THE LAST 20.  THE EULER CONTRACTION
C   IS AN ASYMPTOTIC APPROXIMATION, SO THAT WHEN THE TERMS IN THE CONTRACTED
C   SERIES BEGIN TO INCREASE, THE PROCEDURE IS TERMINATED AND AN ERROR ESTIMATE
C   MADE ON THE BASIS OF THE LAST ACCEPTED TERM.  NOTE THE TRUNCATION ERROR IN
C   THE INTEGRATION MAY EXCEED THIS ESTIMATE, AND THIS IS TAKEN INTO ACCOUNT
C   USING THE ACCURACY DEMAND FIGURE IN  ROMBRG.
C
C      SUMSAV SAVES THE DIRECT SUM OF THE INTEGRATIONS BETWEEN ZEROS
C
      DIMENSION ZEROS(NN)
      COMMON/TAIL/ ACC,WORK(20),SUMSAV(20)
      DATA ACC/1.0E-6/
C   K  IS THE NUMBER OF TERMS NOT INCLUDED IN THE CONTRACTION.
      K=MAX0(NN-21,0)
      ERREST=0.0
      N1=NN-1
      SUM=0.0
      SIGN=+1.0
C   DO-LOOP ENDING ON 1100 FORMS TERMS IN SERIES AND STORES THEM IF REQUIRED.
      DO 1100 I=1,N1
C
C      WRITES OF ZEROS AND WORKJ USED IN CHECKING CONVERGENCE
C       OF INTEGRATION
C
C
C   FORM INTEGRAL OVER INTERVAL BETWEEN 2 ZEROS. THEN ADD IT TO TOTAL INTEGRAL.
C   RELATIVE ACCURACY DEMAND IN ROMBRG IS  ACC, WHICH MAY BE CHANGED VIA /TAIL/
C     WRITE(6,100) ZEROS(I),ZEROS(I+1)
C 100 FORMAT (1H ,5X* ZEROS I,I+1 *,2E12.5)
```



```
      WORKJ=ROMBRG(ZEROS(I),ZEROS(I+1),ACC)
C     WRITE(6,200) WORKJ
C 200 FORMAT (1H ,5X* WORKJ *,E12.5)
      ERREST=AMAX1(ERREST,ABS(ACC*WORKJ))
      SUM=SUM+WORKJ
      SUMSAV(I)=SUM
C   CHECK IF THIS TERM IS TO BE USED IN CONTRACTION, IF NOT SKIP ON.
      IF (I.LE.K) GO TO 1100
C   MAKE SIGN UNIFORM THEN STORE TERM IN ARRAY  WORK.
      WORK(I-K)=WORKJ*SIGN
 1100 SIGN=-SIGN

 2000 FACTOR=0.5*SIGN
      N1=N1-K
      N3=N1-1
C   DO-LOOP ENDING ON 2200 PERFORMS EULER CONTRACTION.
      DO 2200 I=1,N3
      N2=N1-I
      SUM=SUM+FACTOR*WORK(N2+1)
      FACTOR=0.5*FACTOR
C   DO-LOOP ENDING ON 2100 DIFFERENCES THE SEQUENCE, STORING THE RESULTS OVER
C   THE PREVIOUS VALUES. THE ELEMENTS WORK5N1<,WORK5N1-1<,.... EVENTUALLY CONTAIN
C   THE BACKWARD DIFFERENCES TO BE USED IN THE CONTRACTION.
      DO 2100 J=1,N2
 2100 WORK(J)=WORK(J+1)-WORK(J)
C   IF NEXT DIFFERENCE GREATER THAN PREVIOUS ONE, OR NEXT TERM IN EULER SERIES
C   BELOW ROUND-OFF NOISE, TERMINATE EULER SERIES.
      IF(ABS(WORK(N2)/WORK(N2+1)) .GT.1.0 .OR.
     1  ABS(FACTOR*WORK(N2)/SUM).LT. 1.0E-10) GO TO 2300
 2200 CONTINUE
C   IF LOOP IS COMPLETED LAST TERM MUST BE ADDED.
      SUM=SUM+FACTOR*WORK(1)
C   ERROR ESTIMATE IS HALF THE LAST ACCEPTED TERM. IF THIS FIGURE IS EXCEEDED
C   BY THE ERROR IN THE INTEGRATION, USE THE LARGER ESTIMATE.
 2300 ERREST=AMAX1(ABS(FACTOR*WORK(N2+1)),ERREST)
      TAIL=SUM
      RETURN
      END
```

```
      FUNCTION ROMBRG (A,B,ACC)
C$$$$ CALLS GRAND)  DEFINED BY FUNCTION GRAND(X)
C  PERFORMS ROMBERG INTEGRATION ON A GIVEN FUNCTION TO A STATED ACCURACY.
C                                  ARGUMENT LIST
C   THE INTEGRAND MUST BE SUPPLIED AS THE FUNCTION GRAND(X)
C  A,B  ARE THE LOWER AND UPPER LIMITS OF INTEGRATION.
C  ACC  IS THE RELATIVE ACCURACY DESIRED - THE ROUTINE CONTINUES SUBDIVIDING
C  THE INTERVAL UNTIL THE DIFFERENCE BETWEEN 2 APPROXIMATIONS OVER THE INTEGRAL
C  IS LESS IN ABSOLUTE VALUE THAN  ACC.
C                                  REMARKS
C  ROMBERG INTEGRATION IS BASED ON EXTRAPOLATION OF TRAPEZIUM RULE APPROXIMATION
C  WITH THE SAMPLING INTERVAL CONTINUALLY HALVING.  THE METHOD IS DESCRIBED
C  ADEQUATELY IN %A 1ST COURSE IN NUMERICAL ANALYSIS%, RALSTON 1965.  WE
C  FOLLOW THE NOTATION USED THERE ROUGHLY.
C  THE HIGH PRECISION AND RAPID CONVERGENCE OF THE ANSWER DEPENDS CRITICALLY
C  ON THE EXISTANCE OF ALL DERIVATIVES IN THE CLOSED INTERVAL %A,B<.  ANY SING
C -ULARITIES WILL CAUSE A POOR ANSWER AND WASTE MUCH COMPUTATION TIME.
C  THE ADVANTAGE OF ROMBERG INTEGRATION OVER GAUSS-LEGENDRE QUADRATURE IS THAT
C  THE PRECISION OF THE RESULT IS EASILY ESTIMATED.
C  IF  MMAX IS 12, THEN 2048 SAMPLES WILL BE TAKEN IN %A,B< BEFORE THE ROUTINE
C  SURRENDERS AND PRINTS A MESSAGE OF DEFEAT.
C
      COMMON/ROMBRG/ MMAX,MAX,TROW(18),TEST(18)
      DATA MMAX/12/
C
      DO 5 I=1,18
    5 TEST(I)=0.
C
C  ARRAY  TROW CONTAINS THE LAST ROW OF THE ROMBERG MATRIX %RALSTON P. 123<.
C  FIND T 0,0 %SEE RALSTON<, AND INTIALIZE STEP LENGTHS ETC.
      SUM=0.5*(GRAND(A)+GRAND(B))
      H=B-A
      TROW(1)=SUM*H
C
C  INITIAL  TLAST  IS DUMMY TO ENSURE CONVERGENCE TEST IS NOT ACCIDENTALLY OK
      TLAST=-TROW(1)
C
C  THIS DO LOOP COUNTS NUMBER OF EXTRAPOLATION STEPS EMPLOYED.
      DO 3000 MAX=2,MMAX
      STEP=H
      H=H/2.0
      X=A+H
C
C  THIS LOOP ACCUMULATES THE TRAPEZIUM SUMS IN  SUM,  THE STEP AND STARTING
C  VALUE CHOSEN TO INTERLACE ALL PREVIOUS X-VALUES AND BISECT THE INTERVALS.
 1000 SUM=SUM+GRAND(X)
      X=X+STEP
      IF(X.LT.B) GO TO 1000
C
C  FINDS LASTEST TRAPEZIUM APPROXIMATION.
      TROW(MAX)=SUM*H
C
C  FINDS BOTTOM ROW OF ROMBERG EXTRAPOLATION MATRIX, SETTING IT IN TROW AND OVER
C -WRITING PREVIOUS VALUES.  TROW%1< IS THE HIGHEST ORDER ROMBERG APPROXIMANT.
      C1=1.0
      DO 2000 I=2,MAX
      K=MAX-I+1
```



```
      C1=C1*4.0
      TROW(K)=(C1*TROW(K+1)-TROW(K))/(C1-1.0)
 2000 CONTINUE
C
C  CHECKS IF SUCCESSIVE VALUES AGREE WITHIN REQUESTED ACCURACY, IF NOT CONTINUE.
      IF(ABS(TROW(1)-TLAST ).LT.ABS(TROW(1)*ACC)) GO TO 3100
      TLAST=TROW(1)
      TEST(MAX)=TLAST
 3000 CONTINUE
C
C  PRINTS WARNING MESSAGE IF CONVERGENCE NOT ATTAINED AFTER  MMAX ITERATIONS.
      PRINT 300,ACC,MMAX
  300 FORMAT (1H),5X* ROMBR, UNABLE TO ACHIEVE REQUIRED REL ACC OF
     1 *,E12.2, * AFTER EXTRAPOLATING *,I4, * TIMES */)
      WRITE(6,400)   (TEST(I),I=1,MMAX)
  400 FORMAT (1H .5X*INTEGRAL *,8E13.7)
C
C  COPIES ANSWER INTO FUNCTION  NAME AND EXITS.
 3100 ROMBRG=TROW(1)
      RETURN
      END
```

<u>B</u>

INSTQ

```
      PROGRAM INTSQ(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION XG(100),G(100),B(100),C(100),D(100),XINT(800),FINT(800)
      DIMENSION FPX(100),FPY(100),SUM(200),RR(200)
      DIMENSION ACE(80)
C
C*********************************************************************
C*
C*     INTSQ INTEGRATES THE GREEN FUNCTION G(I) OVER A SQUARE
C*     OF SIDE NSQ * UNIT BY DIVIDING THE SQUARE INTO SUBSQUARES OF SIDE
C*     UNIT ( SPECIFIED IN KM )
C*
C*     INPUTS
C*
C*     0  NJOB (I5) NUMBER OF GREEN FUNCTIONS TO BE INTEGRATED
C*
C*     THERE ARE NJOB SEQUENCES OF THE REMAINING CARDS
C*
C*
C*     1  ACE(I),I=1,80)  (80A1)  HEADER CARD WITH DESCRIPTION OF JOB
C*     1  NSQ,NG,NFP  (3I5)
C*       NSQ = NUMBER OF SUBDIVISIONS IN A SIDE
C*       NG = NUMBER OF VALUES OF GREEN FUNCTION
C*       NFP = NUMBER OF FIELD POINTS AT WHICH INTEG IS REQD
C*       THE SIZE OF THE SQUARE (NORMALLY 25 KM OR 40 KM ) FOR THE N=10**25
C*       CASE IS DETERMINED BY SPECIFYING NSQ (THE NUMBER OF SUBSQUARES
C*       IN A SIDE) AND (UNIT(THE LENGTH OF THE SUBSQUARE IN METERS )
C*       EG FOR 25KM NSQ=50 AND UNIT =500M GIVES A SUFFICIENTLY EFFICIENT
C*       YET ACCURATE INTEGRATION ( IF NSQ.GT.50 THE TIME FOR EACH CONVO
C*       LUTION INCREASES RAPIDLY )
C*
C*     2  ALPHA,UNIT,CODE,ANFLEX (2E8.3,F5.0,E8.3)
C*       ALPHA IS THE FLEXURAL PARAMETER IN METERS
C*       UNIT = SIDE OF SUBSQUARES IN METERS
C*       IF(CODE.EQ.0.) G(I) IS THE ACTUAL GREEN FUNCTION FOR THE RESPONSE
C*       OF A VISCOELASTIC OR ELASTIC PLATE TO A SURFACE LOAD
C*        IF(CODE.EQ.1.) G(I) IS THE DIMENSIONLESS GREEN FUNCTION FOR
C*       THE RESPONSEOF AN ELASTIC PLATE AND IS GIVEN IN UNITS OF S
C*       WHERE S=R/ALPHA , ALPHA IS THE FLEXURAL PARAMETER IN METERS
C*       THIS GREEN FUNCTION IS THE TABULATED VALUES OF KEI(0)
C*       IF(CODE.EQ.0.) ALPHA MUST BE SET TO 1.
C*       IF (CODE.EQ.1.) XG(I) MUST BE GIVEN IN UNITS OF S I.E.
C*       THE GREEN FUNCTIONS FROM ROMVPLA CAN BE SCALED FOR VARIATIONS
C*     IN FLEXURAL RIGIDITY (NFLEX)). ROMVPLA IS ALWAYS SOLVED FOR N=1.E25
C*       FOR N=1.E24 ,FOR EXAMPLE, THE DISTANCES XG(I) ARE SCALED BY
C*       SQRT(SQRT10.)) THUS SHORTENING THE VALUE OF ALPHA. THIS SCALING
C*       IS AUTOMATICALLY TAKEN CARE OF BY SPECIFYING THE VALUE OF NFLEX
C*       THAT IS REQUIRED FOR THE OUTPUT OF AINT AND SUPPLYING THE
C*       VALUES OFXG(I) FROM  THE SOLUTION FOR NFLEX=1.E25
C*
C*     3  G(I),I=1,NG)  (8E10.4)
C*       GREEN FUNCTION
C*     4  XG(I),I=1,NG  10E7.4
C*       XG(I) ARE THE DISTANCES AT WHICH THE GREEN FUNCTION IS SPECIFIED
C*       IN METERS
C*     5  FPX(I),I=1,NFP)  (10E7.3)
C*       FPX  =X DIST TO FIELD POINTS IN METERS
C*       FIELD POINTS ARE THE POINTS AT WHICH THE INTEGRATION IS EVALUATED
```



```
C*
C*********************************************************************
C
C
C      PRELIMINARIES
      PI=3.14159265359  $  RHO=3400.  $ GG=9.81
      ANCONV=SQRT(SQRT(10.))
      GAMS=RHO*GG
      READ(5,5) NJOB
    5 FORMAT (I5)
      DO 5000 IJK=1,NJOB
      READ(5,1) (ACE(I),I=1,80)
    1 FORMAT (80A1)
      WRITE(6,2) (ACE(I),I=1,80)
    2 FORMAT (1H1,5X,80A1)
C
C      CENTRE OF SQUARE
C
      CX=0.  $  CY=0.
C
C      CLEAR FPX AND FPY
C
      DO 10 I=1,100
      FPX(I)=0.
   10 FPY(I)=0.
      READ(5,20) NSQ,NG,NFP
   20 FORMAT (3I5)
      READ(5,30) ALPHA,UNIT,CODE,ANFLEX
   30 FORMAT (2E8.3,F5.0,E8.3)
      WRITE(6,40) NSQ,NG,NFP,ALPHA,UNIT,ANFLEX
   40 FORMAT (1H0//5X*NSQ,NG,NFP,ALPHA,UNIT,NFLEX  *,3I7,3E9.3//)
      WRITE(6,45) CODE
   45 FORMAT (1H0,5X* CODE IS  *,F5.0/)
C
      IF(ANFLEX.EQ.1.E26) DIV=1./ANCONV
      IF(ANFLEX.EQ.1.E25) DIV=1.
      IF(ANFLEX.EQ.1.E24) DIV=ANCONV
      IF(ANFLEX.EQ.1.E23) DIV=ANCONV**2
      IF(ANFLEX.EQ.1.E22) DIV=ANCONV**3
      IF(ANFLEX.EQ.1.E21) DIV=ANCONV**4
C
      READ(5,50) (G(I),I=1,NG)
   50 FORMAT(8E10.4)
      DO 55 I=1,NG
   55 G(I)=-G(I)
      WRITE(6,60) (G(I),I=1,NG)
   60 FORMAT (1H0,5X*G(I)  *,10E10.4)
      READ(5,65) (XG(I),I=1,NG)
   65 FORMAT (10E7.4)
C
C       IF(CODE.EQ.1.) CONVERT DIMENSIONLESS GREEN FUNCTION TO REAL
C       GREEN FUNCTION
      IF(CODE.EQ.0.) GO TO 66
      DO 68 I=1,NG
   68 XG(I)=XG(I)*ALPHA
C
C       SCALE KEI(0) BY P0/PI*ALPHA**2*GAMS
C
```

```
      SCALEF=1./(PI*ALPHA**2*GAMS)
      DO 67 I=1,NG
   67 G(I)=G(I)*SCALEF
      WRITE(6,64) (G(I),I=1,NG)
   64 FORMAT (1H0,5X*G(I) SCALED *,10E10.4)
   66 CONTINUE
      WRITE(6,69) (XG(I),I=1,NG)
   69 FORMAT (1H0,3X*XG   *,10E10.4)
C
C         NOW SCALE XG(I) FOR CORRECT VALUE OF ANFLEX SUPPLIED ON
C         INPUT CARD 2
C
      DO 75 I=1,NG
   75 XG(I)=XG(I)/DIV
      WRITE(6,69) (XG(I),I=1,NG)
C
      READ(5,70) (FPX(I),I=1,NFP)
   70 FORMAT (10F7.3)
      WRITE(6,80) (FPX(I),I=1,NFP)
   80 FORMAT (1H0,3X*FPX IN M *,12E9.3)
C     READ(5,70) (FPY(I),I=1,NFP)
      XSTART=CX-(NSQ*UNIT)/2.+UNIT/2.
      YSTART=CY+(NSQ*UNIT)/2.-UNIT/2.
      KGMAX=799
C
C        INTERPOLATE GREEN FUNCTION AND PLACE ON REGULAR GRID USING
C        CUBIC SPLINE INTERPOLATIONC
C        GENERATE POINTS AT WHICH INTERPOLATION IS REQUIRED
C
      DO 500 NSTEP=1,800
  500 XINT(NSTEP)=2.*FLOAT(NSTEP-1)*1.E3
C
C        SPLINE INTERPOLATION GIVES VALUES OF THE GREEN FUNCTION AT
C        AT 2 KM INTERVALS
C
      CALL SPLINE(NG,XG,G,B,C,D,XINT,FINT,800,C,IER)
C
C        CORRECT FINT FOR INCORRECT FIRST VALUE DUE TO ERROR IN SPLINE
C
      FINT(1)=G(1)
C
C        ENSURE THAT FINT(I)=0. FOR VALUES OF XINT(I) THAT ARE GREATER
C        THAN XG(NG)
C
      DO 85 JJ=1,800
      IF(XINT(JJ).LE.XG(NG)) GO TO  85
      FINT(JJ)=0.
   85 CONTINUE
C     WRITE(6,90) ((XINT(I),FINT(I)),I=1,800)
   90 FORMAT (1H ,5X,2E13.5)
      NCOUNT=0  $  KMIN=1
      DO 300 K=1,NFP
      IF(K.GT.9)  KMIN=K
      DO 350 M=KMIN,K
      FPY(M)=FPX(K)-(M-1)*50000.
      NCOUNT=NCOUNT+1
      SUM(NCOUNT)=0.
```

PROGRAM INTSQ 73/73 OPT=0 TRACE FTN 4.6+428 77/02/21. 15.07.57

```
      IF(FPX(K).GT.XG(NG))  GO TO 340
      DO 100 J=1,NSQ
      DO 200 I=1,NSQ
      Y=YSTART-(J-1)*UNIT-FPY(M)
C     Y=YSTART-(J-1)*UNIT-FPY(K)
      X=FPX(K)-(XSTART+(I-1)*UNIT)
      R=SQRT(Y**2+X**2)
C
C        R IS THE DISTANCE FROM THE SQUARE TO THE FIELD POINT IN METERS
C        CONVERT R FOR INTERPOLATION OF GREEN FUNCTION WHICH IS SPECIFIED
C        IN FINT AT INTERVALS OF 2 KM
C
      RKM=R/1000.
      KKM=RKM
      RKKM2=FLOAT(KKM)/2.
      KKM2=RKKM2
      FRAC=(RKM-FLOAT(KKM2*2))/2.
      IF(KKM2.GT.KGMAX) GO TO 200
      SQVAL=FINT(KKM2+1)+FRAC*(FINT(KKM2+2)-FINT(KKM2+1))
      SUM(NCOUNT)=SUM(NCOUNT)+SQVAL
  200 CONTINUE
  100 CONTINUE
  340 CONTINUE
      RR(NCOUNT)=SQRT(FPX(K)**2+FPY(M)**2)
C
C        MULTIPLY SUM BY AREAS OF INDIVIDUAL SUBSQUARES
C
      SUM(NCOUNT)=SUM(NCOUNT)*UNIT**2
  350 CONTINUE
  300 CONTINUE
C
C        SORT VALUES OF SUM BY INCREASING RR
C
      MCOUNT=NCOUNT-1
      DO 1200 J=1,1000
      SWITCH=0.
      DO 1000 I=1,MCOUNT
      IF(RR(I+1).GT.RR(I)) GO TO 1000
      SWITCH=SWITCH+1.
      RSAVE=RR(I+1)    $    SSAVE=SUM(I+1)
      RR(I+1)=RR(I)    $    SUM(I+1)=SUM(I)
      RR(I)=RSAVE    $   SUM(I)=SSAVE
 1000 CONTINUE
      IF(SWITCH.EQ.0.) GO TO 1500
 1200 CONTINUE
 1500 CONTINUE
      WRITE(6,2500) ((RR(I),SUM(I)),I=1,NCOUNT)
 2500 FORMAT (1H0,5X*RR(I) ,SUM(I)  *,F10.1,E13.5)
C
C       SORT OUT VALUES FOR WHICH RR IS THE SAME AND ELIMINATE
C
      DO 3000 I=1,MCOUNT
      II=I+1
      IF(RR(I).NE.RR(II)) GO TO 3000
      DO 3500 JJ=II,MCOUNT
      RR(JJ)=RR(JJ+1)
      SUM(JJ)=SUM(JJ+1)
```

```
 3500 CONTINUE
 3000 CONTINUE
      WRITE(6,2) (ACE(I),I=1,80)
      WRITE(6,2500)((RR(I),SUM(I)),I=1,NCOUNT)
      WRITE(6,2501) (SUM(I),I=1,NCOUNT)
 2501 FORMAT (1H ,5X,8E10.4)
 5000 CONTINUE
      CALL EXIT
      END
```


CARD NR.	SEVERITY	DETAILS	DIAGNOSIS OF PROBLEM
85	I	19 CD 85	FIELD WIDTH OF A CONVERSION DESCRIPTOR SHOULD BE AS LARGE AS THE MINIMUM SPECIFIED FOR
85	I	29 CD 85	FIELD WIDTH OF A CONVERSION DESCRIPTOR SHOULD BE AS LARGE AS THE MINIMUM SPECIFIED FOR
105	I	20CD 105	FIELD WIDTH OF A CONVERSION DESCRIPTOR SHOULD BE AS LARGE AS THE MINIMUM SPECIFIED FOR
132	I	20CD 132	FIELD WIDTH OF A CONVERSION DESCRIPTOR SHOULD BE AS LARGE AS THE MINIMUM SPECIFIED FOR


```
      SUBROUTINE SPLINE(N,X,A,B,C,D,XINT,FINT,NVAL,INIT,IER)
C
C.......................................................................
C
C        SUBROUTINE SPLINE
C
C        PURPOSE
C           TO COMPUTE COEFFICIENTS FOR, AND PERFORM, CUBIC SPLINE INTER-
C           POLATION
C
C        USAGE
C           CALL SPLINE(N,X,A,B,C,D,XINT,FINT,NVAL,INIT,IER)
C
C        DESCRIPTION OF PARAMETERS
C           N    - NUMBER OF KNOWN FUNCTION VALUES TO BE USED TO COMPUTE
C                  COEFFICIENTS
C           X    - A VECTOR OF LENGTH N OF X-COORDINATES, IN ASCENDING ORDER,
C                  FOR WHICH FUNCTION VALUES ARE KNOWN
C           A    - A VECTOR OF LENGTH N OF KNOWN FUNCTION VALUES, SUCH THAT
C                  A(J)=F(X(J)) FOR J=1 TO N.  THIS ARRAY CONTAINS  THE
C                  A-COEFFICIENTS FOR INTERPOLATION, SINCE A(J)=F(X(J))
C                  FOR J=1 TO N-1
C           B    - A VECTOR OF LENGTH N-1 IN WHICH THE COMPUTED B-COEFFICIENTS
C                  WILL BE PUT
C           C    - A VECTOR OF LENGTH N IN WHICH THE COMPUTED C-COEFFICIENTS
C                  WILL BE PUT
C           D    - A VECTOR OF LENGTH N-1 IN WHICH THE COMPUTED D-COEFFICIENTS
C                  WILL BE PUT
C           XINT - A VECTOR OF LENGTH NVAL CONTAINING, IN ASCENDING ORDER,
C                  VALUES OF X FOR WHICH INTERPOLATION IS TO BE DONE.  IF
C                  ONLY ONE VALUE IS DESIRED, XINT NEED NOT BE DIMENSIONED
C                  IN THE CALLING PROGRAM.
C           FINT - A VECTOR OF LENGTH NVAL IN WHICH THE RESULTING INTER-
C                  POLATED VALUES WILL BE PUT.  IT MAY BE THE SAME ARRAY
C                  OR ELEMENT AS XINT, IF DESIRED.  IF ONLY ONE VALUE IS
C                  DESIRED, FINT NEED NOT BE DIMENSIONED IN THE CALLING
C                  PROGRAM.  FINT(J) IS THE INTERPOLATED VALUE FOR
C                  F(XINT(J)) FOR J=1 TO NVAL.
C           NVAL - IF POSITIVE, NVAL IS THE NUMBER OF POINTS FOR WHICH
C                  INTERPOLATION MUST BE DONE.  IF NEGATIVE OR ZERO, NO
C                  INTERPOLATION IS ATTEMPTED.  INSTEAD, A 'RETURN' IS
C                  GIVEN DIRECTLY AFTER THE SECTION FOR COMPUTING COEFFI-
C                  CIENTS
C           INIT - INPUT CODE
C                        0 - COEFFICIENTS ARE TO BE COMPUTED
C                        1 - COEFFICIENTS HAVE ALREADY BEEN COMPUTED.  ONLY
C                            INTERPOLATION IS TO BE DONE
C           (N.B.  IF NVAL IS LESS THAN OR EQUAL TO 0, AND INIT=1, NOTHING
C                  IS DONE WITHIN THE SUBROUTINE.  A BRANCH IS MADE BACK TO
C                  THE CALLING PROGRAM DIRECTLY UPON ENTERING SPLINE)
C           IER  - ERROR CODE
C                                 0 - NORMAL RETURN AFTER DOING INTERPOLATION
C                                 1 - XINT(1) IS LESS THAN X(1)
C                                 2 - XINT(J) IS GREATER THAN X(N) FOR SOME
C                                     J FROM 1 TO NVAL
C                                 3 - COEFFICIENTS WERE COMPUTED, BUT NO
C                                     INTERPOLATION WAS DONE
```



```
C                                 4 - NO USEFUL WORK WAS DONE WITHIN THE
C                                     SUBPROGRAM; I. E., INIT=1 AND
C                                     NVAL IS LESS THAN OR EQUAL TO 0
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C           NONE
C
C        METHOD
C           USES METHOD DESCRIBED IN R. SAUER, I. SZABO, 'MATHEMATISCHE
C           HILFSMITTEL DES INGENIEURS,' PART III, SPRINGER-VERLAG, BERLIN,
C           1968, CHAPTER H, SECTION 4.  FOR A COMPREHENSIVE TREATMENT OF
C           SPLINES, SEE 'MATHEMATICS AND SCIENCE IN ENGINEERING,' VOLUME
C           38, J.H. AHLBERG, E.N. NILSON, J.L. WALSH, 'THE THEORY OF
C           SPLINES AND THEIR APPLICATIONS,' ACADEMIC PRESS, NEW YORK, 1967
C
C.......................................................................
C
C
      DIMENSION X(1),A(1),B(1),C(1),D(1),XINT(1),FINT(1)
      DIMENSION X(1),A(1),B(1),C(1),D(1),XINT(1),FINT(1),DINT(1)
C
C        IF COMPUTATION OF A,B,C, AND D HAS ALREADY BEEN DONE,
C        GO TO INTERPOLATING SECTION
C
      IER=4
      IF(INIT.NE.0)GO TO 3
C
C        BEGIN CALCULATION OF A, B, C, AND D'S.
C
```

```
      NM1=N-1
      TEMP1=0.0
C     THE H'S ARE STORED IN D.
C     THE RIGHT HAND SIDES ARE STORED IN C.
C
      DO 1 I=1,NM1
      D(I)=X(I+1)-X(I)
      TEMP2=(A(I+1)-A(I))/D(I)
      C(I)=3.0*(TEMP2-TEMP1)
      TEMP1=TEMP2
    1 CONTINUE
      C(1)=0.0
      C(N)=0.0
C
C     SOLVE THE EQUATIONS BY ELIMINATION AND BACK SUBSTITUTION
C
C     ELIMINATE
C
      TEMP1=0.0
      TEMP2=0.0
      DO 8 I=2,NM1
      C(I)=C(I)+TEMP1*C(I-1)
      B(I)=(X(I-1)-X(I+1))*2.0-TEMP1*TEMP2
      TEMP2=D(I)
      TEMP1=TEMP2/B(I)
    8 CONTINUE
C
```



```
C     BACK SUBSTITUTE
C
      I=NM1
    9 C(I)=(D(I)*C(I+1)-C(I))/B(I)
      I=I-1
      IF(I.GE.2)GO TO 9
C
C     NOW THE CORRECT VALUES FOR B AND D ARE COMPUTED
C
      DO 2 I=1,NM1
      B(I)=(A(I+1)-A(I))/D(I)-(2.0*C(I)+C(I+1))*D(I)/3.0
      D(I)=(C(I+1)-C(I))/(3.0*D(I))
    2 CONTINUE
      IER=3
C
C*********************************************************************
C     THE NEXT FOUR CARDS SHOULD BE COMMENT CARDS DURING NORMAL EXECU-
C     TION OF THE SUBPROGRAM.  THEY ARE PROVIDED FOR DEBUGGING PURPOSES.
C
C     WRITE(6,100)
C     DO 99 I=1,NM1
C  99 WRITE(6,101)I,A(I),B(I),C(I),D(I)
C     WRITE(6,102)N,A(N),C(N)
C
C*********************************************************************
C
    3 IF (NVAL.LE.0)GO TO 7
C
C     CHECK TO SEE THAT XINT(1) IS NOT LESS THAN X(1)
C
      IF(XINT(1).GE.X(1))GO TO 11
      IER=1
      GO TO 7
C
C     THE DO-LOOP 'DO 4' CAUSES US TO DO ALL THE POINTS FOR WHICH
C     VALUES MUST BE INTERPOLATED
C     K MARKS THE INDEX OF THE GREATEST X SMALLER THAN THE ONE FOR
C     WHICH WE ARE INTERPOLATING A VALUE
C
   11 K=1
      DO 4 I=1,NVAL
C
C     THE DO-LOOP 'DO 5' DETERMINES THE VALUE OF K
C
      DO 5 J=K,NM1
      IF(XINT(I).GT.X(J))GO TO 5
C
C     NOW THAT J IS SET TO THE FIRST X GREATER THAN THE POINT FOR WHICH
C     WE ARE INTERPOLATING A VALUE, SET K TO ONE LESS THAN J AND
C     GO INTERPOLATE A VALUE
C
      KKK=J-1
      GO TO 6
    5 CONTINUE
C
C     WHEN A VALUE MUST BE INTERPOLATED FOR AN X BIGGER THAN THE
C     LARGEST X PASSED FOR COMPUTING THE COEFFICIENTS, THE ERROR CODE IS
```



```
C     SET TO 2, AND PROGRAM BRANCHES TO RETURN STATEMENT
C
      IF(XINT(I).LE.X(N))GO TO 10
      IER=2
      GO TO 7
   10 K=NM1
C
C     INTERPOLATE THE VALUE USING HORNER'S SCHEME
C
    6 K=KKK
      TEMP1=XINT(I)-X(K)
      FINT(I)=((D(K)*TEMP1+C(K))*TEMP1+B(K))*TEMP1+A(K)
C
C     DINT IS THE SLOPE OF THE INTERPOLATED CURVE
C
      DINT(I)=(3.*D(K)*TEMP1+2.*C(K))*TEMP1+B(K)
    4 CONTINUE
      IER=0
    7 RETURN
C
C      FORMATS
C
C 100 FORMAT('1',20X,'TABLE OF COEFFICIENTS'/'0INDEX',6X,'A',14X,'B',
C    1 14X,'C',14X,'D'//)
C 101 FORMAT('0',I4,4(3X,G12.5))
C 102 FORMAT('0',I4,3X,G12.5,18X,G12.5)
C
      END
```

C

CONVOL

```
      PROGRAM CONVOL(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE2,TAPE3)
      COMMON/ARGEMAK/DD,TT,DC,TC,DLTA(50),DINO,DINC
      COMMON/EXPGARG/ W0,D,IG,INTAPT
      COMMON /GRENARG/GREEN(35,301)
      COMMON GI(601),DISP(20,20),DISPSAV(20,20,1))
      COMMON NCOL,NPECOL,CONS,GRIDSZE,SIMDISP,RESNEW(50),RESOLD(50)
      COMMON FORMAT(4),TIM(50),ACE(80)
      DIMENSION XINT(601),G(200),XG(200),BSP(200),CSP(200),DSP(200),
     1 GJ(601)
      DIMENSION ADATA(51)
      EQUIVALENCE (DISPSAV(1),XINT(1)),(DISPSAV(602),G(1)),(DISPSAV(802)
     1,XG(1)),(DISPSAV(1002),BSP(1)),(DISPSAV(1202),CSP(1)),(DISPSAV(
     1 1402),DSP(1)),(DISPSAV(1602),GJ(1))
C
C*******************************************************************
C*
C*       CONVOL CONVOLVES THE GREEN FUNCTION G(I,J) WITH LOADS DEFINED BY
C*        DISPSAV(II,JJ,NTIM) OVER A GRID OF N,M POINTS WITH SPACING
C*        DETERMINED BY GRIDSZE WHICH MUST BE THE SAME AS THE AREA
C*        OVERWHICH AINT INTEGRATED THE GREEN FUNCTIONS
C*
C*       N,M ARE DETERMINED BY THE DIMENSION OF DISPSAV(N,M,NN) ABOVE
C*
C*       G(I,J) ARE GREEN FUNCTIONS FOR A UNIFORM LOAD ON A  SQUARE OF
C*       SIDE GRIDSZE
C*       SQUARE. G(1,J) IS THE ELASTIC RESPONSE AND G(I.GT.1,J) ARE THE
C*       VISCOELASTIC DECAY SPECTRA GREEN FUNCTIONS
C*       THESE MUST BE PROVIDED AS INPUTS AND VARY DEPENDING ON THE
C*       CHOICE OF ALPHA, THE FLEXURAL PARAMETER,TE, THE VISCOUS DECAY
C*       CONSTANT,RHOM,THE DENSITY OF THE MANTLE,AND,N, THE FLEXURAL
C*       RIGIDITY,NOTE ALPHA**4=(4.*N)/(RHOM*G)
C*
C*       THE GRID IS DEFINED BY THE NUMBER OF COLUMNS IN THE X-DIRECTION
C*       (NCOL) AND THE NUMBER OF GRID POINTS PER COLUMN (NPECOL ) ,A
C*       UNIFORM SPACING OF GRIDSZE IS ASSUMED
C*
C*       THE VERTICAL DISPLACEMENT AT EACH GRID POINT (III,JJJ) DUE
C*       TO A GRIDSZE SQUARE LOAD AND DISPSAV(II,JJ,NTIM) CENTRED ON GRID
C*       POINT (II,JJ) IS GIVEN BY
C*         DISPSAV(II,JJ,NTIM)*G(I,J)*CONS
C*
C*
C*       G(I,J) HAS BEEN USED SYMBOLICALLY TO REPRESENT THE GREEN FUNCTIONS
C*       THE GREEN FUNCTIONS ARE IN FACT READ IN AT BEGINNING ON A
C*       SPARSE GRID DEFINED BY XG(I),SPLINE INTERPOLATED INTO A2KM GRID
C*       AND STORED ON TEMPORARY DISC FILES TAPES 11 TO 50 INC
C*
C*       BEFORE EACH CONVOLUTION THE REQUIRED GREEN FUNCTION IS LOADED
C*       INTO GI(I),NOTE ALL OPERATIONS GENERATING GREEN FUNCTIONS MUST BE
C*       COMPLETED BEFORE ENTERING VALUES INTO DISPSAV
C*
C*       CONVOLUTIONS FOR TIMES THAT ARE NOT SPECIFIED BY GREEN FUNCTIONS
C*       USE A GREEN FUNCTION SPECIFIED BY LINEAR INTERPOLATION
C*       BETWEEN THE TWO ADJACENT GREEN FUNCTIONS
C*
C*       PROVISION IS ALSO MADE FOR STOPPING AND RESTARTING A JOB
C*       AT END OF JOB WRITEPF IS CALLED WHICH WRITES ON TAPE3 NECESSARY
```



```
C*       CONSTANTS,ARRAYS GREEN FUNCTIONS AND THE ARRAY DISPSAV(II,JJ,
C*       K=1,NSAVE)
C*       LFN TAPE3 CAN BE SAVED OR CATALOGED FOR RESTARTING PROGRAM
C*       SEE BELOW
C*       READPF IS CALLED TO RESTART A JOB.THIS READS LFN TAPE3 WHICH
C*       HAS TO BE GETED OR ATTACHED
C*       NEW JOBS HAVE NEWJOB=1
C*       RESTARTS HAVE NEWJOB=0
C*
C*       DISPSAV(III,JJJ,1) IS THE AMPLITUDE OF EITHER A LOAD APPLIED
C*       TO THE SURFACE OR AN INITIAL DEPRESSION AND IS GIVEN IN METERS
C*       THE TYPE OF PROBLEM TO BE SOLVED IS GIVEN BY LODCOD,
C*          THE LOAD CODE
C*       IF(LODCOD.EQ.1) THE LOAD IS A SURFACE LOAD OF THE VOLCANIC
C*       ISLAND TYPE
C*       IF(LODCOD.EQ.1) THE LOAD IS THAT INFILLING A SURFACE DEPRESSION
C*       AND THE SOLUTION IS ACHIEVED BY THE ITERATIVE SOLUTION OF
C*       THE ASSOCIATED FREDHOLM INTEGRAL EQUATION OF THE SECOND KIND
C*
C*       INPUTS
C*       0   NEWJOB,NSTART,NEND (3I5)
C*          NEWJOB=1 IF THE JOB IS A COMPLETELY NEW JOB AND THE RESULTS OF
C*          PREVIOUS JOB ARE NOT TO BE READ FROM A PERMANENT FILE
C*                =0 IF JOB IS A CONTINUATION - READPF IS CALLED AND PREVIOUS
C*          RESULTS ARE READ IN TO START JOB NORMAL INPUT CARDS
C*          ARE REQUIRED AND A JCL CARD MUST ENSURE THAT LFN TAPE 3 IS GET
C*          OR ATTACHED
C*        NSTART AND NEND ARE THE NUMBERS SPECIFYING THE STARTING AND
C*          ENDING GREEN FUNCTIONS FOR THE CONVOLUTION.FOR A NEW JOB (NEWJOB=1)
C*          NSTART IS NORMALLY 1.THE CONVOLUTION WILL  CONTINUE TO GREEN
C*          FUNCTION NEND AND THEN TERMINATE BY SAVING DISPSAV AND THE
C*          DIFFERENTIAL GREEN FUNCTIONS ON LFN TAPE3
C*          NEND CANNOT BE LARGER THAN NG
C*          IF THIS IS A NEWJOB ALL THE GREEN FUNCTIONS THAT WILL BE NEEDED
C*          FOR THE TOTAL JOB MUST BE READ IN.THESE WILL BE SAVED ON TAPE3
C*       0A   (ACE(I),I=1,80)     (80A1)
C*          HEADER WITH INFORMATION ON JOB
C*       0B     INITP   (I5)
C*          NUMBER CHARACTERIZING INITIATION PROCESS
C*           INITP=0  CALLS HOLINST
C*      INITP=2 CALLS EXPBARG
C*       1 NCOL,NPECOL,NG,NGR,LODCOD     (5I5)
C*          NCOL  = NO OF COLUMNS IN GRID
C*          NPECOL = NO OF GRID SQUARES PER COLUMN
C*          NG=NO OF GREEN FUNCTIONS
C*          NGR= NO OF POINTS IN EACH GREEN FUNCTION
C*          LODCOD= LOAD CODE SEE ABOVE
C*       1A   (TIM(I),I=1,NG)    10E8.2)
C*          TIM(I) ARE THE TIMES AT WHICH THE CONVOLUTIONS ARE REQUIRED
C*          ( THEY ARE ALSO THE TIMES AT WHICH THE GREEN FUNCTIONS ARE
C*          SPECIFIED THOUGH THIS IS NOT NECESSARY )
C*          THE ELASTIC OF TIM(1) IS DEFINED AS 0
C*       2 ALPHA,GRIDSZE  (F8.3,F5.2)
C*          ALPHA = FLEXURAL PARAMETER IN METERS,NOTE CORRES GREEN FUNCT
C*            FUNCTIONS MUST BE USED
C*          GRIDSZE IS GRIDSIZE IN KM,NOTE IT MUST BE SAME AS THE SIZE
C*          OF SQUARE OVERWHICH GFS WERE INTEGRATED IN AINT
```

```
C*       2A FFORMAT (I),I=1,4)       (4A4)
C*         FORMAT FOR PRINTER PLOT  E.G.(80A1)
C*       3 GREEN FUNCTIONS ARE PRECEDED BY
C*         (XG(I),I=1,NGR)    (10F8.0)
C*         XG(I) = POINTS AT WHICH SPARSE GREEN FUNCTION IS DEFINED
C*         IN METERS
C*       4   G((NGR),1,NG)    (8E10.4)
C*         GREEN FUNCTIONS ELASTIC FIRST THEN VISCOELASTIC IF(NG.GT.1)
C*       5  DISPSAV(I,J,1) I FROM 1 TO NCOL,J FROM 1 TO NPECOL (10F7.3)
C*         DISPSAV(I,J,1) ARE THE SURFACE LOADS IN METERS
C*      6 DATA CARDS FOR INITIATING SUBROUTINES,
C*      EXPGRAB,EXPMARG ETC
C*
C*****************************************************************
C
C
C
C        INPUTS
C        NEWJOB,NSTART,NEND
C
      READ(5,5) NEWJOB,NSTART,NEND
    5 FORMAT (3I5)
      WRITE(6,7) NEWJOB,NSTART,NEND
    7 FORMAT(1H1//5X*NEWJOB = *,I7,* NSTART = *,I7,* NEND = *,I7)
      IF (NEWJOB.EQ.1)  WRITE(6,9)
    9 FORMAT(1H0,5X*NEWJOB = 1 DESIGNATES A NEWJOB*)
C
C        ACE
C
      READ(5,9) (ACE(I),I=1,80)
    9 FORMAT(80A1)
      WRITE(6,10) (ACE(I),I=1,80)
   10 FORMAT (1H0,5X,80A1)
C
C          INITIATION PROCESS
C
      READ(5,6) INITP
    6 FORMAT (I5)
C
C        NCOL,NPECOL,NG,NGR,LOCCOD
C
      READ(5,11) NCOL,NPECOL,NG,NGR,LOCCOD
   11 FORMAT (5I5)
      WRITE(6,20) NCOL,NPECOL,NG,NGR,LOCCOD
   20 FORMAT (1H0,5X*NCOL,NPECOL,NG,NGR,*,4I5/)
C
C        TIM(I)
C
      READ(5,25) (TIM(I),I=1,NG)
   25 FORMAT (10E8.2)
      WRITE(6,27) (TIM(I),I=1,NG)
   27 FORMAT (1H0,5X* TIM(I)  *,10E9.2)
C
C        ALPHA,GRIDSZE
C
      READ(5,30)  ALPHA,GRIDSZE
   30 FORMAT (E8.3,F5.0)
      WRITE(6,35) ALPHA,GRIDSZE
```



```
   35 FORMAT (1H0,5X* FLEXURAL PARAMETER = *,E10.3,* SIZE OF GRID = *,
     1F6.1)
C
C        FORMAT OF PRINTER PLOT
C
      READ(5,40) (FFORMAT(I),I=1,4)
   40 FORMAT (4A4)
C        GENERATE POINTS AT WHICH INTERPOLATED VALUES OF G ARE REQUIRED
C        THIS ENSURES THAT GI WILL BE DEFINED IN STEPS OF 4KM TO 1799KM
C
      DO 43 LVAL=1,300
   43 XINT(LVAL)=4.*FLOAT(LVAL-1)*1.E3
C
C        READ IN AND INTERPOLATE SPARSE GREEN FUNCTIONS
C
      READ(5,46) (XG(I),I=1,NGR)
   46 FORMAT (10F8.0)
      DO 49 J=1,601
   49 GI(I)=0.
C
C        LOOP OVER EACH GREEN FUNCTION
C
      DO 45 II=1,NG
      READ(5,48) (G(I),I=1,NGR)
   48 FORMAT (8E10.4)
C
C        SINCE THE LENGTH OF THE GREEN FUNCTION VARIES,REQUIRE NUMBER
C        OF 4KM STEPS FOR SPLINE INTERPOLATION OF THIS PARTICULAR
C        GREEN FUNCTION
C
      LMAX=((XG(NGR)/1000.)/4.)+1.
C
C        SPLINE INTERPOLATION
C
      DO 50 J=1,301
   50 GI(J)=0.
      CALL SPLINE (NGR,XG,G,BSP,CSP,DSP,XINT,LMAX,0,IER)
      GI(1)=G(1)
      DO 51 I=1,301
   51 GREENF(II,I)=GI(I)
   45 CONTINUE
      WRITE(6,54) II
   54 FORMAT (1H0,5X*READ AND PUT IN GREENF *,I5,* GREEN FUNCTIONS*)
C
C        AMPLITUDE OF LOADS ON EACH ZONE,I.E. DEPTH OF SURFACE DEPRESSION
C        IN METERS
C
      NSAVE=NEND+1
      DO 55 II=1,NCOL
      DO 55 JJ=1,NPECOL
      DO 55 KK=1,NSAVE
   55 DISPSAV(II,JJ,KK) =0.
C
C        IF(NEWJOB.EQ.0) DO NOT NEED TO SPECIFY SIZE OF DEPRESSION
C        THEREFORE SKIP TO 70 AND CALL READPR
C
      IF(NEWJOB.EQ.0)  GO TO 70
```

```
      GO TO 70
C
C      FOR TEST SET DISPSAV(I,J,1) INTERNALLY
      KC1=NCOL/2
      KC2=KC1+1
      DO 53 J=1,NCOL
      DO 53 I=KC1,KC2
   53 DISPSAV(I,J,1)=-1.E3
C     DISPSAV(5,5,1)=-1.E3
      GO TO 59
      DO 60 I=1,NCOL
   60 READ(5,65) (DISPSAV(I,J,1),J=1,NPECOL)
   65 FORMAT (10E7.3)
   59 CONTINUE
   70 CONTINUE
C
      CALL WRITDIS(1)
C
C      SET DISP(I,J) = 0.
C
      DO 80 I=1,NCOL
      DO 80 J=1,NPECOL
   80 DISP(I,J)=0.
   90 CONTINUE
      IF(NEWJOB.EQ.0)  CALL READPF(NG,LODCOD,NSTART,NEND,ALPHA,ACC)
C
C      PRELIMINARIES
C
      DO 95 KK=1,50
      RESOLD(KK)=0.
   95 RESNEW(KK)=0.
      ACC=1.E-2
      RHOM=3400.   $  RHOS=2400.   $  GG=9.81
      CONS=-RHOS*GG
C
C      THE MINUS SIGN IS USED SO THAT IN CONV AMP APPEARS AS A
C      POSITIVE QUANTITY. I.E. THE LOAD IS POSITIVE BUT THE DISPLACEMENT
C      IS NEGATIVE
C
C
C      CONS*DISPSAV(I,J,1) GIVES THE AMPLITUDE OF THE LOAD ON EACH GRID
C      SQUARE IN S.I. UNITS
C
C
C
C      SUMDISP IS USED IN ASSESSING OVERALL ACCURACY OF THE SOLUTION
C      AFTER EACH ITERATION THE DIFFERENCE BETWEEN SUMDISP OF EACH OF
C      THE LAST TWO ITERATIONS ,DELDISP, IS COMPARED WITH THE ABSOLUTE
C      MAGNITUDE OF SUMDISP.IF((DELDISP/SUMDISP).LE.ACC) ITERATION IS
C      TERMINATED.ACC IS THE SPECIFIED ACCURACY.THUS,THE ACCURACY OF THE
C      SOLUTION IS JUDGED ON AN OVERALL BASIS AND NOT ON AN INDIVIDUAL
C      SQUARE BY SQUARE BASIS
C
      SUMDISP=0.
      DO 85 I=1,NCOL
      DO 85 J=1,NPECOL
   85 SUMDISP=SUMDISP+DISPSAV(I,J,1)
```



```
C
C      LOOP OVER TIME STEPS FROM NSTART TO NEND
C      THE INTERVAL IN TIME IS DETERMINED BY THE INTERVAL BETWEEN GREEN
C      FUNCTIONS
C
      DO 3000 NTIM=NSTART,NEND
C
C      NTIM COUNTS THE FORWARD TIMESTEPS
C
      NUMLOD=NTIM
C
C      NUMLOD IS THE NUMBER OF LOADS THAT MUST BE CONSIDERED AT THIS
C      TIMESTEP. THE LAST OF WHICH IS THE ELASTIC LOAD FILLING THE
C      DEPRESSION
C
C      LOOP OVER LOADS FOR THIS STEP
C
      NUMLOD1=NUMLOD-1
C
C      NUMLOD1 IS THE NUMBER OF PRE-EXISTING LOADS THAT MUST BE CONVOLVED
C      WITH VISCOELASTIC GREEN FUNCTIONS TO DETERMINE THE SIZE OF
C      THE DEPRESSION CREATED DURING THE LAST TIME STEP
C
C
C      IF AT FIRST STEP DEPRESSION IS THAT READ IN THEREFORE GO TO
C      ELASTIC INFILLING PART
C
      IF(NTIM.EQ.1) GO TO 2600
C
C     TIME INCREMENT SINCE LAST CONVOLUTION
C
      TDELT=TIM(NTIM)-TIM(NTIM-1)
      WRITE(6,190) TDELT
  190 FORMAT (1H0,5X*TIME INCREMENT,TDELT = *,F9.2/)
C
C     CALCULATE OLD RESIDENCE TIMES OF LOADS,RESOLD(KK)
C
      DO 200 KK=1,NUMLOD1
  200 RESOLD(KK)=TIM(NTIM-1)-TIM(KK)
      WRITE(6,210) (RESOLD(KK),KK=1,50)
  210 FORMAT (1H ,5X,10F9.2)
C
C     CALCULATE NEW RESIDENCE TIMES RESNEW(KK) BY ADDING TIME INCREMENT
C     TDELT
C
      DO 250 KK=1,NUMLOD1
  250 RESNEW(KK)=RESOLD(KK)+TDELT
      WRITE(6,210) (RESNEW(KK),KK=1,50)
C
C     CLEAR DISPSAV(II,JJ,NTIM) OF LAST LOOPS VALUES OF DISP(II,JJ)
C
      DO 400 II=1,NCOL
      DO 400 JJ=1,NPECOL
  400 DISPSAV(II,JJ,NTIM)=0.
      DO 2500 LLOD=1,NUMLOD1
C
      CALL GRENS T(RESOLD(LLOD),RESNEW(LLOD))
```

```
          WRITE(6,450) (GI(IJK),IJK=1,10)
      450 FORMAT (1H),5X,10E9.2)
C
          CALL CONV(LLOD)
C
C
C          OUTPUT OF CONV IS THE DISPLACEMENT DISP CAUSED BY THIS LOAD
C
C          SAVE DISP IN DISPSAV(II,JJ,NTIM)
C          I.E. AT EACH TIMESTEP A NEW LOAD FUNCTION DISPSAV(II,JJ,NTIM)
C          IS CREATED
C          EACH DISPSAV HAS CONTRIBUTIONS FROM EACH OF THEDEFORMING LAYERS
C          HAVING CALCULATED DISPSAV(II,JJ,NTIM) THE DEPRESSION MUST THEN
C          BE FILLED ELASTICALLY WITH SEDIMENT UNLESS LODCOD=0
C
          SUMDISP=0.
          DO 500 II=1,NCOL
          DO 500 JJ=1,NPECOL
          SUMDISP=SUMDISP+DISP(II,JJ)
      500 DISPSAV(II,JJ,NTIM)=DISPSAV(II,JJ,NTIM)+DISP(II,JJ)
C
C          DISPSAV(II,JJ,NTIM) MUST NOW BE FILLED WITH SEDIMENT IN AN
C          ITERATIVE MANNER TO SOLVE THE FREDHOLM INTEGRAL EQUATION
     2500 CONTINUE
     2600 CONTINUE
          CALL WRITDIS(NTIM)
C-----------------------------------------------------------------------
C           ADD INITIATION PROCESS
C-----------------------------------------------------------------------
          IF(INITP.EQ.0) CALL HOLINST(NTIM)
          IF(INITP.EQ.1)  CALL EXPGRAB(NTIM)
           IF(INITP.EQ.2) CALL EXPMARG(NTIM)
          CALL WRITDIS(NTIM)
C
C          IF VOLCANIC ISLAND TYPE NO INFILLIG THEREFORE GO TO 2000
C
          IF(LODCOD.EQ.0) GO TO 2000
C
C          RE-ENTER HERE FOR EACH ITERATION
C
          LOOPNO=1  $  NTIN=NTIM
C
C          SPECIFYING RESNEW=0. ENSURES THAT GRENSET GETS THS ELASTIC G.F.
C
          CALL GRENSET(0.,0.)
      600 CONTINUE
          IF(LOOPNO.GT.1) NTIN=NTIM+1
           IF(INITP.NE.2) CALL CONV(NTIN)
           IF(INITP.EQ.2) CALL CONMARG(NTIN,LOOPNO)
C
C          ADD ELASTIC DISPLACEMENT TO VISCOELASTIC DISPLACEMENT
C          I.E. ADD DISPSAV(II,JJ,NTIM) AND DISP(II,JJ)
C          AND STORE THE NEW DEPRESSION ,DISP(II,JJ), IN DISPSAV(II,JJ,NTIM+1)
C          FOR NEXT ITERATION.NOTE DISPSAV(II,JJ,NTIM+1) HAS NOT BEEN USED
C
          SUNDISP=0.
          DO 700 II=1,NCOL
```



```
          DO 700 JJ=1,NPECOL
          SUNDISP=SUNDISP+DISP(II,JJ)
          DISPSAV(II,JJ,(NTIM+1))=DISP(II,JJ)
      700 DISPSAV(II,JJ,NTIM)=DISPSAV(II,JJ,NTIM)+DISP(II,JJ)
C
C          TEST TO SEE IF REQUIRED ACCURACY IS ACHIEVED
C
          IF(SUMDISP.EQ.0.) GO TO 2000
          DISPCHG=ABS(SUNDISP/SUMDISP)
          IF(DISPCHG.LE.ACC) GO TO 2000
C
C          IF(GO TO 2000 REQUIRED ACCURACY HAS BEEN ACHIEVED,GO TO NEXT
C          PHASE
C
          SUMDISP=SUMDISP+SUNDISP
C
C          REQUIRED ACCURACY NOT ACHIEVED,ITERATE AGAIN
C
          LOOPNO=LOOPNO+1
          GO TO 600
     2000 CONTINUE
C
C          IF(REQUIRED WRITE OUT NEW DISPLACEMENT OF SURFACE FOR THIS
C          TIMESTEP
C
          WRITE(6,550) NTIM,TIM(NTIM)
      550 FORMAT (1H),5X* TOTAL INCREMENT IN DEPTH FOR TIMESTEP = *,I5,*
         1TIME IS *,F9.2/)
          CALL WRITDIS(NTIM)
           IF(INITP.NE.2) GO TO 3000
C
C        FOR CONTINENTAL MARGINS MUST MODIFY
C        DISPSAV(II,JJ,NTIM) SO THAT LOAD IS
C        PRESERVED AND NOT THE HOLE SIZE.
C        THIS ARISES BECAUSE IN THE OCEAN THE HOLE
C        IS NOT FILLED
C
           DO 5000 II=1,5
           DO 5000 JJ=1,NPECOL
     5000  DISPSAV(II,JJ,NTIM)=DINF
           WRITE(6,5500) DINF
     5500  FORMAT(1H),5X*DINF = *,F9.2/)
           CALL WRITDIS(NTIM)
     3000 CONTINUE
C
C          SAVE NCOL,NPECOL,NSAVE AND DISPSAV ON TAPE 3
C
          CALL WRITEPF(NS,LODCOD,NSTART,NEND,ALPHA,ACC)
          CALL EXIT
          END
```

```
      SUBROUTINE SPLINE (N,X,A,B,C,D,XINT,NVAL,INIT,IER)
      COMMON /GRENARS/GREENF(35,301)
      COMMON FINT(601),DISP(20,20),DISPSAV(20,20,10)
      COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
      COMMON FFORMAT(4),TIM(50),ACE(80)
      DIMENSION XINT(1),A(1),X(1),B(1),C(1),D(1)
      IER=4
      IF(INIT.NE.0)GO TO 3
      NM1=N-1
      TEMP1=0.0
      DO 1 I=1,NM1
      D(I)=X(I+1)-X(I)
      TEMP2=(A(I+1)-A(I))/D(I)
      C(I)=3.0*(TEMP2-TEMP1)
      TEMP1=TEMP2
    1 CONTINUE
      C(1)=0.0
      C(N)=0.0
      TEMP1=0.0
      TEMP2=0.0
      DO 8 I=2,NM1
      C(I)=C(I)+TEMP1*C(I-1)
      B(I)=(X(I-1)-X(I+1))*2.0-TEMP1*TEMP2
      TEMP2=D(I)
      TEMP1=TEMP2/B(I)
    8 CONTINUE
      I=NM1
    9 C(I)=(D(I)*C(I+1)-C(I))/B(I)
      I=I-1
      IF(I.GE.2)GO TO 9
      DO 2 I=1,NM1
      B(I)=(A(I+1)-A(I))/D(I)-(2.0*C(I)+C(I+1))*D(I)/3.0
      D(I)=(C(I+1)-C(I))/(3.0*D(I))
    2 CONTINUE
      IER=3
    3 IF (NVAL.LE.0)GO TO 7
      IF(XINT(1).GE.X(1))GO TO 11
      IER=1
      GO TO 7
   11 K=1
      DO 4 I=1,NVAL
      DO 5 J=K,NM1
      IF(XINT(I).GT.X(J))GO TO 5
      KKK=J-1
      GO TO 6
    5 CONTINUE
      IF(XINT(I).LE.X(N))GO TO 10
      IER=2
      GO TO 7
   10 K=NM1
    6 K=KKK
      TEMP1=XINT(I)-X(K)
      FINT(I)=((D(K)*TEMP1+C(K))*TEMP1+B(K))*TEMP1+A(K)
    4 CONTINUE
      IER=0
    7 RETURN
      END
```



```
      SUBROUTINE GRENGET(RESO,RESN)
      COMMON /GRENARS/GREENF(35,301)
      COMMON GI(601),DISP(20,20),DISPSAV(20,20,10)
      COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
      COMMON FFORMAT(4),TIM(50),ACE(80)
C
C*********************************************************************
C*
C*     GRENGET RETRIEVES SPLINE INTERPOLATED GREEN FUNCTIONS FROM
C*     GREENF(35,301),INTERPOLATES THEM IN TIME AND CALCULATES THE INCRE
C*     GREEN FUNCTIONS THAT IS REQUIRED BY CONV.THE GREEN FUNCTION IS THEN
C*     LOADED INTO ARRAY GI(601)
C*
C*     LOGIC AND STEPS
C*
C*     CONVOLUTIONS ARE PERFORMED FOR NON-EQUAL FORWARD TIMESTEPS.
C*     THE TIMES ARE SPECIFIED BY THE ARRAY TIM(I) AND ARE GENERALLY
C*     EQUAL TO THE TIMES AT WHICH THE GREEN FUNCTIONS ARE SPECIFIED
C*
C*     EACH LOAD HAS AN ARRIVAL TIME AND A RESIDENCE TIME GIVEN BY
C*     ( CONVOLUTION TIME-ARRIVAL TIME ) .FOR EACH FORWARD TIMESTEP
C*     THE RESIDENCE TIME INCREASES BY THE LENGTH OF THE TIMESTEP AND
C*     A NEW LOAD IS ADDED
C*
C*     TO DETERMINE THE INCREMENT IN THE SIZE OF THE BASIN FOR EACH
C*     LOAD,CONV REQUIRES THE INCREMENT IN THE GREEN FUNCTION FROM
C*     THE RESIDENCE TIME OF THE LOAD AT THE PREVIOUS STEP TO THE RESIDENCE
C*     TIME OF THE LOAD AT THE PRESENT STEP
C*
C*     BECAUSE ALL LOADS HAVE DIFFERENT RESIDENCE TIMES EACH LOAD WILL
C*     REQUIRE A DIFFERENT GREEN FUNCTION
C*
C*     ALSO,IN GENERAL,THE GREEN FUNCTION WILL NOT BE SPECIFIED AT THE
C*     TIMES REQUIRED.THEREFORE, A LINEAR INTERPOLATION BETWEEN GREEN FUNCTIONS
C*     IS PERFORMED TO GET THE GREEN FUNCTIONS AT THE REQUIRED TIME
C*
C*     IF THE VALUE OF RESN=0 , THE CONVOLUTION IS IN AN ELASTIC FILLING LOOP
C*     ,THEREFORE THE REQUIRED GREEN FUNCTION IS G(1) STORED ON TAPE11
C*
C*********************************************************************
C
      IF(RESN.EQ.0.) GO TO 500
C
C     DETERMINE THE ADJACENT TIMES TO RESO AND RESN AT WHICH THE GREEN
C     FUNCTIONS ARE SPECIFIED
C
C     FIRST RESO
C
      DO 50 I=1,50
   50 IF(RESO.LT.TIM(I)) GO TO 60
C
C     TIM(I) IS THE CLOSEST LARGER TIME TO RESO
C
   60 DELTO=RESO-TIM(I-1)
      TSTEPO=TIM(I)-TIM(I-1)
      FRACO=DELTO/TSTEPO
C
```

```
C      SECOND RESN
C
       DO 70 J=1,50
    70 IF(RESN.LT.TIM(J)) GO TO 80
C
C      TIM(J) IS THE CLOSEST LARGER TIME TO RESN
C
    80 DELTN=RESN-TIM(J-1)
       TSTEPN=TIM(J)-TIM(J-1)
       FRACN=DELTN/TSTEPN
       WRITE(6,90) TIM(I-1),RESO,TIM(I),TIM(J-1),RESN,TIM(J)
    90 FORMAT (1H0,5X,6F9.2)
C
C      THERE ARE THREE POSSIBLE COMBINATIONS OF OVERLAPPING TIM(I)S AND
C      TIM(J)S THAT DETERMINE THE CORRECT METHOD OF READING THE DISC FILES
C
C    1 I=J,BOTH RESO AND RESN ARE LOCATED IN BETWEEN THE SAME GREEN FUNCTION
C      TIME SPECIFICATIONS
C
       IF(I.EQ.J) GO TO 100
C
C    2 I=J-1 ,RESO AND RESN ARE IN ADJACENT INTERVALS
C
       IF(I.EQ.(J-1)) GO TO 200
C
C    3 (J-1).GT.I, RESO AND RESN ARE IN WELL SEPARATED INTERVALS
C
       IF((J-1).GT.I) GO TO 300
C
   100 CONTINUE
       FF=FRACN-FRACO
       DO 150 K=1,301
   150 GI(K)=FF*(GREENF(J,K)-GREENF(I,K))
       RETURN
   200 CONTINUE
       I1=I-1
       FF=(1.-FRACN-FRACO)   $   FG=(-1.0+FRACO)
       DO 250 K=1,301
   250 GI(K)=FF*GREENF(I,K)+FRACN*GREENF(J,K)+FG*GREENF(I1,K)
       RETURN
   300 CONTINUE
       J1=J-1   $   I1=I-1
       FF=1.-FRACN   $   FG=1.-FRACO
       DO 350 K=1,301
   350 GI(K)=FF*GREENF(J1,K)+FRACN*GREENF(J,K)-FG*GREENF(I1,K)-FRACO*
      1GREENF(I,K)
       RETURN
   500 CONTINUE
C
C      IN ELASTIC FILLING LOOP
C
       DO 550 K=1,301
   550 GI(K)=GREENF(1,K)
       RETURN
       END
```



```
       SUBROUTINE CONV(LLOD)
       COMMON /GRENARG/GREENF(35,301)
       COMMON GI(501),DISP(20,20),DISPSAV(20,20,10)
       COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
       COMMON FFORMAT(4),TIM(50),ACE(50)
C
C**********************************************************************
C*
C*      CONV PERFORMS THE ACTUAL CONVOLUTION OF A LOAD WITH A GREEN
C*      FUNCTION.THE LOAD IS DEFINED ON A N*M GRID AND STORED IN
C*      DISPSAV(N,M,LLOD)
C*      LLOD DEFINES WHICH OF THE STORED LOAD FUNCTIONS IS USED IN THE
C*      CONVOLUTION
C*
C*      THE GREEN FUNCTION HAS BEEN LODED INTO GI BY GRENGET
C*
C*
C*      CONV ASSUMES GRID SIZE OF LOADED AREA IS EQUAL TO GRID
C*      SPACING OF THE GREEN FUNCTION
C*
C**********************************************************************
C
C
C       SCALE GRIDSZE BY DISTANCE BETWEEN INTERPOLATED POINTS
C       IN GI(I)
       GRID3=GRIDSZE/4.
C       MAKE SURE GI CONTAINS CORRECT GREEN FUNCTION
C
C       SET DISP TO 0.
C
       DO 50 I=1,NCOL
       DO 50 J=1,NPECOL
    50 DISP(I,J)=0.
       DO 100 II=1,NCOL
       DO 200 JJ=1,NPECOL
C
C       IF GRID IS NOT LOADED GO TO END
C
       IF(DISPSAV(II,JJ,LLOD).EQ.0.) GO TO 200
C
C      DETERMINE LOAD AMPLITUDES
C
       AMP=CONS*DISPSAV(II,JJ,LLOD)
C
C       NOW FIND VERTICAL DISP AT ALL GRID POINTS
C
       DO 300 III=1,NCOL
       DO 400 JJJ=1,NPECOL
C
C       LOCATE COORDS OF CENTRE OF EACH GRID SQUARE WITH RESPECT TO
C       LOADED SQUARE
C
       XDIST=III-II
       YDIST=JJJ-JJ
       R=SQRT(XDIST*XDIST+YDIST*YDIST)
C
C       CONVERT R TO FORM COMPATIBLE WITH THE POINT VALUES OF THE
```

```
C         GREEN FUNCTIONS AND INTEGRATION
C
      RG=SQRT[ ... ]
      DISPS2=(1.-[illegible])*GI(IRG+1)+[illegible]*GI(IRG+2)
      DISPIDT=DISPS2*AMP
      DISP(III,JJJ)=DISP(III,JJJ)+DISPIDT
  400 CONTINUE
  300 CONTINUE
  200 CONTINUE
  100 CONTINUE
      RETURN
      END
```

SUBROUTINE WRITDIS   73/73   OPT=0 TRACE   FTN 4.6+428   77/02/22. 15.54.49

```
      SUBROUTINE WRITDIS(NN)
      COMMON /GRENARG/GREENF(35,301)
      COMMON GI(501),DISP(20,20),DISPSAV(20,20,10)
      COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
      COMMON FFORMAT(4),TIM(50),ACE(50)
C
C*********************************************************************
C*
C*      WRITDIS IS USED TO WRITE OUT DISPSAV(N,M,NN) IN 4 PAGE FORMAT
C*      NOTE WRITDIS IS WRITTEN IN A FORM SUCH THAT IT CAN ACCOMMODATE
C*      A DISPSAV DIMENSIONED AS DISPSAV(40,40,NN).HOWEVER,ONLY
C*      VALUES UP TO AND INCLUDING DISPSAV(NCOL,NPECOL,NN) ARE WRITTEN
C*
C*      NOTE FOR DISPSAV DIMENSIONED LARGER THAN (20,20,10) COMMON STATEMENT
C*      MUST BE CHANGED
C*
C*      PAGE1=COLS 1 TO 10, PAGE2= COLS 11 TO 20 ,PAGE3 = COLS 21 TO 30
C*      PAGE 4= COLS 31 TO 40
C*
C*********************************************************************
C
      DO 100 K=1,4
      WRITE(6,700) K,NN
  700 FORMAT (1H ,5X*PAGE = *,I5,* ACCUMULATED LOAD FOR TIMESTEP = *,
     1I5//)
      KK=(K-1)*10+1
      LL=KK+9
      IF(LL.GT.NCOL) LL=NCOL
      DO 200 MM=1,NPECOL
  200 WRITE(6,900) (DISPSAV(N,MM,NN),N=KK,LL)
  900 FORMAT (1H0,5X,10F11.1)
      IF(LL.EQ.NCOL) GO TO 650
  100 CONTINUE
  650 CONTINUE
      RETURN
      END
```

SUBROUTINE WRITEPF   73/73   OPT=0 TRACE   FTN 4.6+428   77/02/22. 15.54.49

```
      SUBROUTINE WRITEPF(NG,LODCOD,NSTART,NEND,ALPHA,ACC)
      COMMON /GRENARG/GREENF(35,301)
      COMMON GI(501),DISP(20,20),DISPSAV(20,20,10)
      COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
      COMMON FFORMAT(4),TIM(50),ACE(50)
C
C*********************************************************************
C*
C*      WRITEPF SAVES TWO TYPES OF INFORMATION ON TAPE3 FOR SAVE OR
C*      CATALOG
C*
C*      1  CONSTANTS NCOL,NPECOL,NG,LODCOD,NSAVE,ALPHA,CONS,ACC,GRIDSZE,
C*      2  THICKNESS OF ACCUMULATED SEDIMENTS DISPSAV(I,J,K)
C*          FOR GRID SIZE NCOL,NPECOL AND K=1,NSAVE
C*      THIS ALLOWS RUNNING OF PROGRAM TO BE BROKEN INTO SEVERAL STEPS
C*
C*      NOTE JCL MUST BE SUPPLIED TO SAVE OR CATALOG TAPE3
C*
C*********************************************************************
C
      REWIND 3
      NSAVE=NEND+1
      WRITE (3) NCOL,NPECOL,NSAVE
      DO 50 I=1,NCOL
      DO 50 J=1,NPECOL
      DO 50 K=1,NSAVE
   50 WRITE (3) DISPSAV(I,J,K)
      WRITE(6,60) NSAVE
   60 FORMAT (1H0,5X*HAVE WRITTEN  *,I5,* SETS OF VALUES OF DISPSAV ON
     1TAPE 3*)
      RETURN
      END
```

SUBROUTINE READPF   73/73   OPT=0 TRACE   FTN 4.6+428   77/02/22. 15.54.49

```
      SUBROUTINE READPF(NG,LODCOD,ISTART,NEND,ALPHA,ACC)
      COMMON /GRENARG/GREENF(35,301)
      COMMON GI(501),DISP(20,20),DISPSAV(20,20,10)
      COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
      COMMON FFORMAT(4),TIM(50),ACE(50)
C
C*********************************************************************
C*
C*      READPF READS TWO TYPES OF INFORMATION STORED ON LFN TAPE3
C*      THIS MUST BE GET OR ATTACHED
C*
C*      1  CONSTANTS  NCOL,NPECOL,NSAVE
C*      2  THICKNESSES OF ACCUMULATED SEDIMENTS DISP(I,J,K) FOR GRID
C*         SIZE NCOL,NPECOL AND K=1,NSAVE
C*
C*      NOTE JCL MUST BE SUPPLIED TO GET OR ATTACH TAPE 3
C*
C*********************************************************************
C
      REWIND 3
      READ (3) NCOL,NPECOL,NSAVE
      DO 50 I=1,NCOL
      DO 50 J=1,NPECOL
      DO 50 K=1,NSAVE
   50 READ (3) DISPSAV(I,J,K)
      WRITE(6,60) NSAVE
   60 FORMAT (1H0,5X*HAVE READ  *,I5,*SETS OF VALUES OF DISPSAV FROM
```

```
      SUBROUTINE EXPGRAB(NTIM)
      COMMON/EXPGARG/ WG,NG,D,TG,TSTART
      COMMON /GRENARG/ GREENF(35,301)
      COMMON GI(501),DISP(20,20),DISPSAV(20,20,10)
      COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
      COMMON FFORMAT(4),TIM(50),ACF(40)
C
C*****************************************************************
C*
C*     EXPGRAB IS ONE OF A SERIES OF SUBROUTINES THAT ADDS
C*     THE INITIATING PROCESS DEPTHS TO DISPSAV(II,JJ,NTIM) AT EACH
C*     STEP
C*
C*     EXPGRAB FORMS AN EXPONENTIALLY SUBSIDING GRABEN,WIDTH W KM,
C*     FINAL DEPTH D KM (THE DEPTH IS THAT OF THE INITIATING PROCESS
C*     AND DOES NOT INCLUDE THE ISOSTATIC AMPLIFACATION)
C*     SUBSIDENCE OCCURS WITH A TIME CONSTANT TG IN MILLIONS OF YEARS
C*     TSTART IS THE TIME IN THE PAST WHEN EXPONENTIAL SUBSIDENCE
C*     FIRST STARTED , IN MILLIONS OF YEARS
C*
C*     NOTE W MUST BE A MULTIPLE OF THE GRIDSZE,I.E.NORMALLY A MULTIPLE
C*     OF 50KM
C*
C*****************************************************************
C
C      FIRST TIME SUBROUTINE IS CALLED ONLY THE ARGUMENTS ARE READ,
C      THIS HAS THE EFFECT OF GIVING ZERO DEPTH WHEN TIME IS ZERO
C
      IF(NTIM.GT.1) GO TO 100
      READ(5,10) W,D,TG,TSTART
   10 FORMAT (4F5.0)
      WG=W/GRIDSZE  $  D=D*1.E3  $  TG=TG*1.E6  $  TSTART=TSTART*1.E6
      NG=WG
      WRITE(6,20) W,D,TG,TSTART
   20 FORMAT (1H0,5X*W,D,TG,TSTART  *,F5.0,3E9.2)
C
C      IF GRABEN WIDTH IS AN ODD NUMBER OF GRID SQUARES NCOL SHOULD
C*     ALSO BE ODD.SIMILARLY,WHEN THE GRABEN WIDTH IS EVEN NCOL SHOULD BE
C      EVEN,OTHERWISE THE GRABEN WILL NOT BE AT THE CENTRE OF THE GRID
C
      DO 50 II=1,NCOL
      DO 50 JJ=1,NPECOL
   50 DISPSAV(II,JJ,NTIM)=0.
      RETURN
  100 CONTINUE
      N1=(NCOL-NG)/2+1
      N2=N1+NG-1
C
C      CALCULATE INCREMENT IN DEPTH SINCE LAST TIME STEP
C      AT LAST TIME STEP TIME=TIM(NTIM-1)
C      AT PRESENT TIMESTEP TIME=TIM(NTIM)
C
      DOLD=D*(1.-EXP(-TIM(NTIM-1)/TG))
      DNEW=D*(1.-EXP(-TIM(NTIM)/TG))
      DINC=DNEW-DOLD
      DINC=-DINC
C
```



```
C      INCREMENT BASIN DEPTH BY DINC
      DO 200 II=N1,N2
      DO 200 JJ=1,NPECOL
      SUMDISP=SUMDISP+DINC
  200 DISPSAV(II,JJ,NTIM)=DISPSAV(II,JJ,NTIM)+DINC
      WRITE(6,300) DINC
  300 FORMAT (1H0,5X*INCREASE IN EXPONENTIAL DEPTH AT THIS STEP = *,E9.2
     1,* METERS*)
      RETURN
      END
```



```
      SUBROUTINE HOLINST(NTIM)
      COMMON/GRENARG/ GREENF(35,301)
      COMMON GI(501),DISP(20,20),DISPSAV(20,20,10)
      COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
      COMMON FFORMAT(4),TIM(50),ACF(50)
C
C*****************************************************************
C*
C*     HOLINST IS A CATCHALL INITIATING SUBROUTINE
C*
C*****************************************************************
C
      IF(NTIM.GT.1) RETURN
      DISPSAV(5,5,1)=1.E3
      SUMDISP=SUMDISP+1.E3
      RETURN
      END
```

```
      SUBROUTINE EXPMARG(NTIM)
      COMMON/MARG/MARZ0?,TO,DC,TC,OLOAD(50),DINO,DINC
      COMMON/MARGZ/GRID(35,10)
      COMMON DI(?,1),DISP(?,?),DISPSAV(?,20,10)
      COMMON NCOL,NPECOL,?,?,SIMDISP,RESULT(50),RESID(50)
      COMMON FORMAT(4),TIM(50),AGE(50)
C
C*************************************************
C*
C*    EXPMARG IS ONE OF A SERIES OF SUBROUTINES THAT
C*    ADDS THE INITIATING PROCESS DEPTHS TO DISPSAV(
C*    II,JJ,NTIM) AT EACH STEP
C*
C*    EXPMARG USES A 10*10 GRID TO MODEL A SUBSIDING
C*    CONTINENTAL MARGIN
C*
C*    ONE HALF OF THE GRID I.E. 5X10 GRID SQUARES ARE
C*    OCEANIC.THE OTHER HALF ARE CONTINENTAL
C*    EACH GRID SQUARE IS 50X50 KM
C*
C*    AT EACH STEP A THICKNESS OF SEDIMENT EQUAL
C*    TO THAT GIVEN BY OLOAD(STEP)-OLOAD(STEP-1)
C*    IS ADDED TO THE OCEAN SIDE.THIS CAN BE ZERO
C*    IF REQD(UNITS ARE METERS)
C*
C*    AT EACH STEP THE OCEANIC SIDE ALSO SUBSIDES.
C*    THE FINAL TOTAL SUBSIDENCE IS DO AND SUBSIDENCE
C*    OCCURS WITH A TIME CONSTANT OF TO. THIS CAN BE
C*    MADE ZERO BY SETTING DO=0.
C*    (DO IS GIVEN IN KM,TO IN MILLIONS OF YEARS)
C*
C*    AT EACH STEP THE CONTINENTAL SIDE ALSO SUBSIDES
C*    THE FINAL TOTAL SUBSIDENCE IS DC AND SUBSIDENCE
C*    OCCURS WITH A TIME CONSTANT OF TC.THIS CAN
C*    BE MADE ZERO BY SETTING DC=0.
C*    (DC IS GIVEN IN KM,TC IN MILLIONS OF YEARS)
C*    ONLY THE CONTINENTAL SIDE OF THE BASIN IS FILLED
C*    TO THE SURFACE.SUBROUTINE CONV IS THEREFORE
C*    MODIFIED IN THE FILLING CALCULATIONS
C*
C*************************************************
C
C     FIRST TIME SUBROUTINE IS CALLED ONLY THE ARGUMENTS
C     ARE READ
C     THIS HAS THE EFFECT OF GIVING 0 SUBSIDENCE WHEN
C     TIME IS ZERO
C     THE OCEANIC SIDE IS HOWEVER CONSIDERED TO BE AT A
C     DEPTH OF OINITIAL TO START WITH,THAT IS APPROX 2 KM,
C     THE DEPTH OF A MID OCEANIC RIDGE
C
      IF(NTIM.GT.1) GO TO 100
      READ(5,10) DC,TC,DO,TO,NSTEP
   10 FORMAT(4F5.1,I5)
      DC=DC*1.E3 $ DO=DO*1.E3
      TC=TC*1.E6 $ TO=TO*1.E6
C
C     READ IN PRESCRIBED SUBSIDENCE SEQUENCE,NOTE IT IS GIVEN AS THE
```



```
C     TOTAL DEPTH AT THE END OF EACH STEP
      READ(5,20) (OLOAD(I),I=1,NSTEP)
   20 FORMAT(10F8.0)
      WRITE(6,15) DC,TC,DO,TO
   15 FORMAT(10X,4F10.2)
      WRITE(6,25) (OLOAD(I),I=1,NSTEP)
   25 FORMAT(1H ,10X,10F8.0)
      DO 50 II=1,NCOL
      DO 50 JJ=1,NPECOL
   50 DISPSAV(II,JJ,NTIM)=0.
      DINO=0. $ DINC=0.
      RETURN
  100 CONTINUE
C     INCREMENT IN DEPTH OF LOAD ON OCEANIC SIDE SINCE
C     LAST TIME IS GIVEN BY THE SUM OF THE EXPONENTIAL
C     SUBSIDENCE AND OLOAD(NTIM)-OLOAD(NTIM-1),EITHER
C     ONE OF WHICH COULD BE SET TO ZERO
C
C     AT LAST TIME STEP TIME=TIM(NTIM-1)
C     AT PRESENT TIME STEP TIME=TIM(NTIM)
C
      DOLD=DO*(1.-EXP(-TIM(NTIM-1)/TO))+OLOAD(NTIM-1)
      DNEW=DO*(1.-EXP(-TIM(NTIM)/TO))+OLOAD(NTIM)
      DINO=DNEW-DOLD
      DINO=-DINO
C
C     INCREMENT BASIN DEPTH BY DINO
C
      DO 200 II=1,5
      DO 200 JJ=1,NPECOL
      SUMDISP=SUMDISP+DINO
  200 DISPSAV(II,JJ,NTIM)=DISPSAV(II,JJ,NTIM)+DINO
      WRITE(6,300) DINO
  300 FORMAT(1H0,5X*INCREASE IN DEPTH OF OCEAN SIDE
     * OF BASIN AT THIS STEP=*,F9.2,*METERS*)
C
C     INCREMENT DEPTH OF BASIN ON CONTINENTAL SIDE
C
C     AT LAST TIME STEP TIME=TIM(NTIM-1)
C     AT PRESENT TIME STEP TIME=TIM(NTIM)
      DOLD=DC*(1.-EXP(-TIM(NTIM-1)/TC))
      DNEW=DC*(1.-EXP(-TIM(NTIM)/TC))
      DINC=DNEW-DOLD
      DINC=-DINC
C
C     INCREMENT CONTINENTAL BASIN DEPTH BY DINC
C
      DO 400 II=6,NCOL
      DO 400 JJ=1,NPECOL
      SUMDISP=SUMDISP+DINC
  400 DISPSAV(II,JJ,NTIM)=DISPSAV(II,JJ,NTIM)+DINC
      WRITE(6,500) DINC
  500 FORMAT(1H0,5X*INCREASE IN DEPTH OF CONTINENTAL
     * SIDE OF BASIN AT THIS STEP=*,F9.2,*METERS*)
      RETURN
      END
```

```
      SUBROUTINE CONMARG(LLOD,LOOPND)
      COMMON/ARGEMAR/OD,IO,OC,IC,ILOAD(50),DINO,DINC
     COMMON /GREMARG/GREENF(35,301)
     COMMON GI(501),DISP(20,20),DISPSAV(20,20,10)
     COMMON NCOL,NPECOL,CONS,GRIDSZE,SUMDISP,RESNEW(50),RESOLD(50)
     COMMON FFORMAT(4),TIM(50),ACC(40)
C
C*************************************************************************
C*
C*      CONV PERFORMS THE ACTUAL CONVOLUTION OF A LOAD WITH A GREEN
C*      FUNCTION.THE LOAD IS DEFINED IN A NXM GRID AND STORED IN
C*      DISPSAV(N,M,LLOD)
C*      LLOD DEFINES WHICH OF THE STORED LOAD FUNCTIONS IS USED IN THE
C*      CONVOLUTION
C*
C*      THE GREEN FUNCTION HAS BEEN LOADED INTO GI BY GRENGET
C*
C*
C*      CONV ASSUMES GRID SIZE OF LOADED AREA IS EQUAL TO GRID
C*      SPACING OF THE GREEN FUNCTION
C*
C*************************************************************************
C
C
C
C       SCALE GRIDSZE BY DISTANCE BETWEEN INTERPOLATED POINTS
C       IN GI(I)
     GRID3=GRIDSZE/4.
C       MAKE SURE GI CONTAINS CORRECT GREEN FUNCTION
C
C       SET DISP TO 0.
C
      DO 50 I=1,NCOL
      DO 50 J=1,NPECOL
   50 DISP(I,J)=0.
      DO 100 II=1,NCOL
      DO 200 JJ=1,NPECOL
C
C       IF GRID IS NOT LOADED GO TO END
C
       IF(LOOPND.GT.1.AND.II.LE.5) GO TO 200
C
C      DETERMINE LOAD AMPLITUDES
C
      AMP=CONS*DISPSAV(II,JJ,LLOD)
       IF(LOOPND.EQ.1.AND.II.LE.5) AMP=CONS*DINO
C
C       NOW FIND VERTICAL DISP AT ALL GRID POINTS
C
      DO 300 III=1,NCOL
      DO 400 JJJ=1,NPECOL
C
C       LOCATE COORDS OF CENTREOF EACH GRID SQUARE WITH RESPECT TO
C       LOADED SQUARE
C
      XDIST=III-II
      YDIST=JJJ-JJ
      R=SQRT(XDIST*XDIST+YDIST*YDIST)
```



```
C
C       CONVERT R TO FORM COMPATIBLE WITH THE POINT VALUES OF THE
C       GREEN FUNCTIONS AND INTERPOLATE
C
      RG=R*GRID3  $  NRG=RG  $  DELR=RG-NRG
      DISPSO=(1.-DELR)*GI(NRG+1)+DELR* GI(NRG+2)
      DISPTOT=DISPSO*AMP
      DISP(III,JJJ)=DISP(III,JJJ)+DISPTOT
  400 CONTINUE
  300 CONTINUE
  200 CONTINUE
  100 CONTINUE
      RETURN
      END
```

D

EXPFIT

```
      PROGRAM EXPFIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION TI(30),TH(30),A(200),B(200),C(200),FIT(200)
      READ(5,100) NCASE
C     NCASE = NUMBER OF CURVES TO BE READ IN
  100 FORMAT(I10)
      DO 50 L=1,NCASE
      READ(5,103) N,NZONE,KTYPE,N1,NN
  103 FORMAT(5I10)
C     NZONE = ZONE NUMBER, N = NUMBER OF OBSERVED DATA POINTS FOR NZONE,
C     KTYPE = TYPE OF CURVE TO BE FIT - 1 = LINEAR,OTHERWISE EXPONENTIAL
C     N1,NN = LOWER AND UPPER BOUNDS OF DATA TO BE FIT
      READ(5,110) (TI(I),I=1,N)
      READ(5,110) (TH(I),I=1,N)
  110 FORMAT(10F8.0)
C     TI = THICKNESS // TH = TIME
      IF(N1.EQ.0) GO TO 50
      WRITE(6,105) NZONE
  105 FORMAT(////5X,4HZONE,I5//)
      STH = TH(N1)
      STH2 = TH(N1)*TH(N1)
      NO = N1+1
      DO 10 I=NO,NN
      STH = STH+TH(I)
      STH2 = STH2+(TH(I)*TH(I))
   10 CONTINUE
      Q = STH/(NN-N1+1)
      IF(KTYPE.EQ.1) GO TO 35
      K = TI(N1)/10
      CC = -1.0
   15 M = 1
   20 C(M) = CC+K*(M-1)
   22 IF(C(M).GE.TI(N1)) GO TO 25
      GO TO 26
   25 K = K/10
      C(M) = C(M-1)+K
      GO TO 22
   26 SUMY = ALOG(TI(N1)-C(M))
      SUMZ = SUMY*TH(N1)
      DO 30 I=NO,NN
      G = ALOG(TI(I)-C(M))
      SUMY = SUMY+G
      SUMZ = SUMZ+(G*TH(I))
   30 CONTINUE
      GO TO 38
   35 M = 1
      SUMY = TI(N1)
      SUMZ = TI(N1)*TH(N1)
      DO 37 I=NO,NN
      SUMY = SUMY+TI(I)
      SUMZ = SUMZ+(TI(I)*TH(I))
   37 CONTINUE
   38 B(M) = (SUMZ-(Q*SUMY))/(STH2-(Q*STH))
      AA = (SUMY-(B(M)*STH))/(NN-N1+1)
      IF(KTYPE.EQ.1) GO TO 66
      A(M) = EXP(AA)
      FIT(M) = (TI(N1)-(A(M)*EXP(B(M)*TH(N1)))-C(M))**2
      DO 40 I=NO,NN
```



```
      FIT(M) = FIT(M)+(TI(I)-(A(M)*EXP(B(M)*TH(I)))-C(M))**2
   40 CONTINUE
      WRITE(6,200) A(M),B(M),C(M),FIT(M)
  200 FORMAT(6X,4G20.10)
      IF(M.EQ.1) GO TO 45
      IF(FIT(M).GE.FIT(M-1))GO TO 60
   45 M = M+1
      IF(M.GT.200) GO TO 50
      GO TO 20
   60 IF(M.GT.2) GO TO 62
      CC = C(M-1)
      GO TO 63
   62 CC = C(M-2)
   63 IF(IABS(K).LT.10) GO TO 65
      K = K/10
      GO TO 15
   65 IF(IABS(K).LE.1) GO TO 70
      K = 1
      GO TO 15
   67 K = -100000000
      GO TO 15
   66 FIT(M) = (TI(N1)-AA-B(M)*TH(N1))**2
      DO 68 I=NO,NN
      FIT(M) = FIT(M)+(TI(I)-AA-B(M)*TH(I))**2
      FIT(I) = B(M)*TH(I)+AA
   68 CONTINUE
      WRITE(6,220) AA,B(M),FIT(M)
  220 FORMAT(6X,10HINTERCEPT ,G20.10,10X,6HSLOPE ,2G20.10,13H    LINEAR F
     *IT,)
      FIT(N1) = B(M)*TH(N1)+AA
      GO TO 80
   70 M = M-1
      IF(C(M).EQ.-1.0) GO TO 67
      DO 75 I=N1,NN
      FIT(I) = (A(M)*EXP(B(M)*TH(I)))+C(M)
   75 CONTINUE
   80 TT = TI(NN)-TI(N1)
      WRITE(6,210) (TI(I),I=N1,NN),TT
      WRITE(6,210) (FIT(I),I=N1,NN)
  210 FORMAT(//10X,15F6.0)
   50 CONTINUE
      STOP
      END
```