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THE ORPHEUS GRABEN, OFFSHORE NOVA SCOTIA: PALYNOLOGY, ORGANIC GEOCHEMISTRY, MATURATION AND TIME - TEMPERATURE HISTORY

By

ERIK LYNGBERG

B.Sc., University of British Columbia, 1979

A Thesis Submitted in Partial Fulfillment of

The Requirements for the Degree of

MASTER OF SCIENCE

In

The Faculty of Graduate Studies

Department of Geological Sciences

We accept this thesis as conforming to

the required standard

The University of British Columbia

December 1984

Department of GEOLOGY

The University of British Columbia
1956 Main Mall
Vancouver, Canada
V6T 1Y3

Date January 2,1985

ABSTRACT

Palynological biostratigraphy and maturation data are combined to reconstruct the burial and thermal history of the Orpheus Graben, offshore Nova Scotia.

Palynological analysis indicated that, 1) the age of sediments in the Orpheus Graben range from Upper Triassic to Turonian (Upper Cretaceous) with unconformities occurring in two wells, 2) recycled palynomorphs are ubiquitous in the wells examined, but do not occur in large numbers, 3) the Jurassic section is dominated by *Classopollis*, indicating an arid environment. The Cretaceous section is dominated by *Cyathidites, Taxodiaceapollinites, Gleicheniidites* and bisaccate pollen indicating wet tropical or sub-tropical conditions.

Maturation zones were determined primarily by spore colour and correlation to vitrinite reflectance and pyrolysis data. Thermally mature rocks occur as shallow as 500 m in one well. The Dawson Canyon and Logan Canyon Formations contain the riches oil prone source rock. Enhanced levels of maturity were found to occur over salt structures.

Burial history diagrams are shown for all six wells drilled in the Orpheus Graben as well as burial diagrams for a basin cross section through time. Two models of Tertiary subsidence are considered, 1) with minimal Tertiary deposition, 2) with up to 2000 m of Tertiary deposition.

The temperature history of each well drilled in the Orpheus Graben can be inferred by combining the Time-Temperature Index and maturation data. Two temperature distributions are considered, 1) a simple temperature history with geothermal gradients twice the present and up to 2000 m of Tertiary deposition and, 2) a complex Temperature history with geothermal gradients up to six times the present with minimal Tertiary deposition. The complex temperature history yields Time-Temperature Index values that are closer to the observed maturity.

The future exploration potential is discussed, with enhanced exploration objectives suggested for the region further eastward along the axis of the Orpheus Graben.

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ACKNOWLEDGEMENTS

I wish to thank Dr. G.E. Rouse for his encouragement, direction, support and advice throughout this project, Dr. R.L. Chase and Dr. R.M. Bustin for useful discussions, and Dr. W.H. Mathews and Dr. J.W. Murray for critical reading of the manuscript.

This thesis was supported by Shell Canada Resources Ltd. who provided drafting services, palynology slides, analytical organic geochemistry data and well log data. My appreciation also extends to Shell Geologists, G.W. Graff (Manager, East Coast Exploration), M.M. Given (Organic geochemistry), A.P. Audretsch and F.R. Poeltl (Palynology), A.W. Rupp (Thesis Co-ordinator), and R.L. McKellar (Geologist) for useful comments and discussion.

CHAPTER 1 GEOLOGY OF THE ORPHEUS GRABEN

Regional Setting:

The Scotian Shelf is the southernmost of three major continental shelves located off the east coast of Canada. The other two are the Grand Banks, east of Newfoundland and, the Labrador Shelf east of Labrador (Jansa and Wade, 1975a). The Scotian Shelf extends 1000 km northeastward from the Northeast Channel, separating the Scotian Shelf from the Georges Bank, to the Laurentian Channel, separating the Scotian Shelf from the Grand Banks. The Scotian Shelf is up to 400 km in width. Figure 1 depicts the tectonic framework of the Scotian Shelf. The two major tectonic elements are the LaHave Platform, a region of relatively thin sedimentary cover and the Scotian Basin, the major depocentre (Jansa and Wade, 1975a). The Scotian Basin is further divisible, on the basis of basement faulting into grabens and half grabens (McIver, 1972). These sub-basins are the, Sable, Abenaki, and the Orpheus (Given, 1977).

The study area of this thesis is the Orpheus Sub-basin, located on the northeast corner of the Scotian Shelf between latitudes 45° 20'N, and 45° 40'N and longitudes 58° W and 61° W (Fig.2). The Orpheus Sub-basin plunges east from Chedabucto Bay on the Nova Scotian mainland to the Laurentian Channel (Jansa and Wade, 1975a). Structurally the basin is a graben, bounded by the

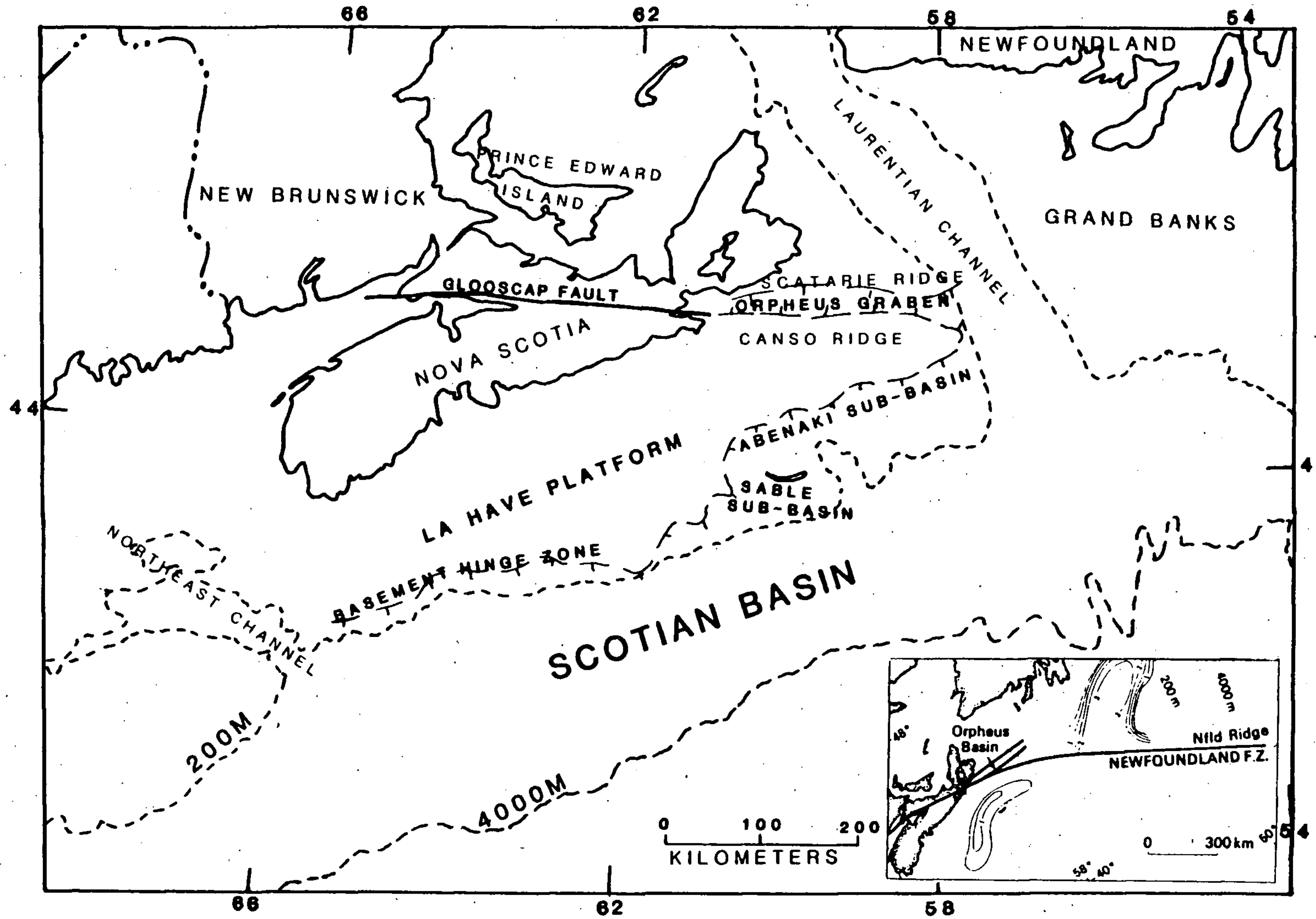

Fig. 1 Tectonic elements of the Scotian Shelf (after Jansa and Wade,1975).
Inset: Relationship between the Orpheus Graben and the Newfoundland Fracture zone (after Wilson and Williams,1979)

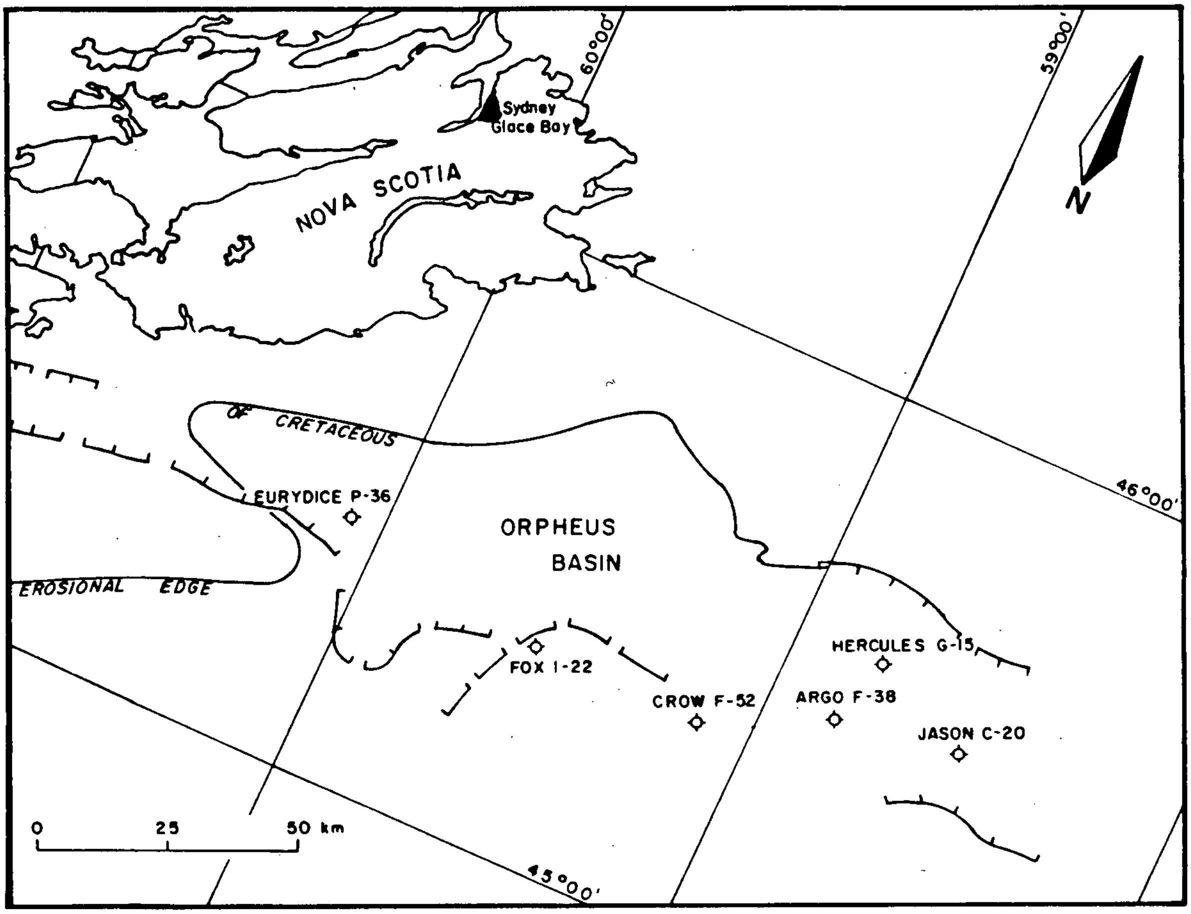

Fig.2 Orpheus Graben, showing well locations,basement fault patterns,and the erosional edge of the Cretaceous

Canso Ridge to the south and the Scatarie Ridge to the north. The graben is outlined by a discontinous series of subparallel faults, detected in the basement rocks by seismic methods. Some of these faults curve into the basin (obtained from seismic structure maps provided by Shell Canada Resources Ltd.). Seismically, the Orpheus Graben is divisible into an east and west region, separated by an area of weak seismic reflection and a lack of major sedimentary structures. Sedimentary thicknesses exceed 9000m (30000') along the axis of the graben.

Purpose

The ultimate objective of the thesis is to reconstruct the subsidence and thermal history of each well and the graben as a whole by combining the biostratigraphy with the maturation data. To achieve this, the following immediate objectives were established:

1.) The palynological biostratigraphy and zonation of four wells, Argo F-38, Hercules G-15, Jason C-20 and Eurydice P-38;

2.) significance of recycled palynomorphs;

3.) paleoecological reconstructions, based upon interpretation of palynomorph assemblages;

4.) maturation history of six wells from microscopic and geochemical analysis;

5.) the character and richness of the organic matter using microscopic and analytical methods.

Exploration History

Offshore drilling activity on the east coast of Canada began in 1967 when Amoco Canada and Imperial Oil drilled Tors Cove D52 to 1453 m (4767') on the Grand Banks. On the Scotian Shelf, drilling began a year later when Mobil Oil Canada completed Sable Island No.1 drilled to 4604 m (15105'). To September 1984 approximately 95 wells have been drilled offshore Nova Scotia.

The Orpheus Graben was first tested in January 1971 when Shell Canada Resources drilled Shell Argo F-38 (Fig. 2). Subsequently 5 more wells were drilled within the Orpheus Graben (Fig.2): Shell Crow F-52, April 1971 on the Canso Ridge; Shell Fox I-22, May 1971 on the Canso Ridge; Shell Eurydice P-36, October 1971; Union et al. Hercules G-15, August 1974; and Union et al. Jason, July 1974. Objective reservoirs were considered to be Jurassic limestones and dolomites and Jurassic-Cretaceous sandstones. The objectives were situated over salt diapirs in the graben whereas a basement high and stratigraphic pinchout provided possible traps on the Canso Ridge (Fig. 3). All six tests failed to encounter hydrocarbons, resulting in the abandonment of the Orpheus region as an active exploration area. The structural geology for each well is summarized in Appendix I.

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Fig. 3 See ~~back pocket~~

Geology

McIver (1972), Jansa and Wade (1975a, 1975b), and Given (1977), presented the most complete discussions of the stratigraphy of the Scotian Shelf. A more specific discussion of stratigraphy was given by Eliuk (1978). A summary of the stratigraphy is presented in Fig 4. McIver (1972) first proposed the stratigraphic nomenclature for the Mesozoic-Cenozoic section on the Scotian Shelf, consisting of 12 formations and 3 groups. Jansa and Wade (1975a) added the Eurydice Formation, while Given (1977) cleared up some of the stratigraphic problems and established the Mohican Formation. The stratigraphy of the Orpheus Graben is described in more detail in Appendix II.

The basement rocks of the Scotian Shelf are composed of the Cambrian-Ordovician Meguma Group, a sericitic schist that was originally a quartz metawacke turbidite sequence deposited as a deep sea fan complex (Schenk, 1978) on a subsiding ocean crust. The Meguma rocks have a source area to the southeast and are inferred to have been deposited on the eastern side of the proto-Atlantic Ocean, off the coast of Northwestern Africa (Schenk, 1971). During the Devonian Acadian Orogeny the Meguma rocks were juxtaposed against the rocks of the Avalon Zone by transcurrent faulting which followed folding, faulting, and metamorphism in the Upper Silurian. The Glooscap fault system separates the Meguma Group from the Avalon Zone (Schenk, 1978).

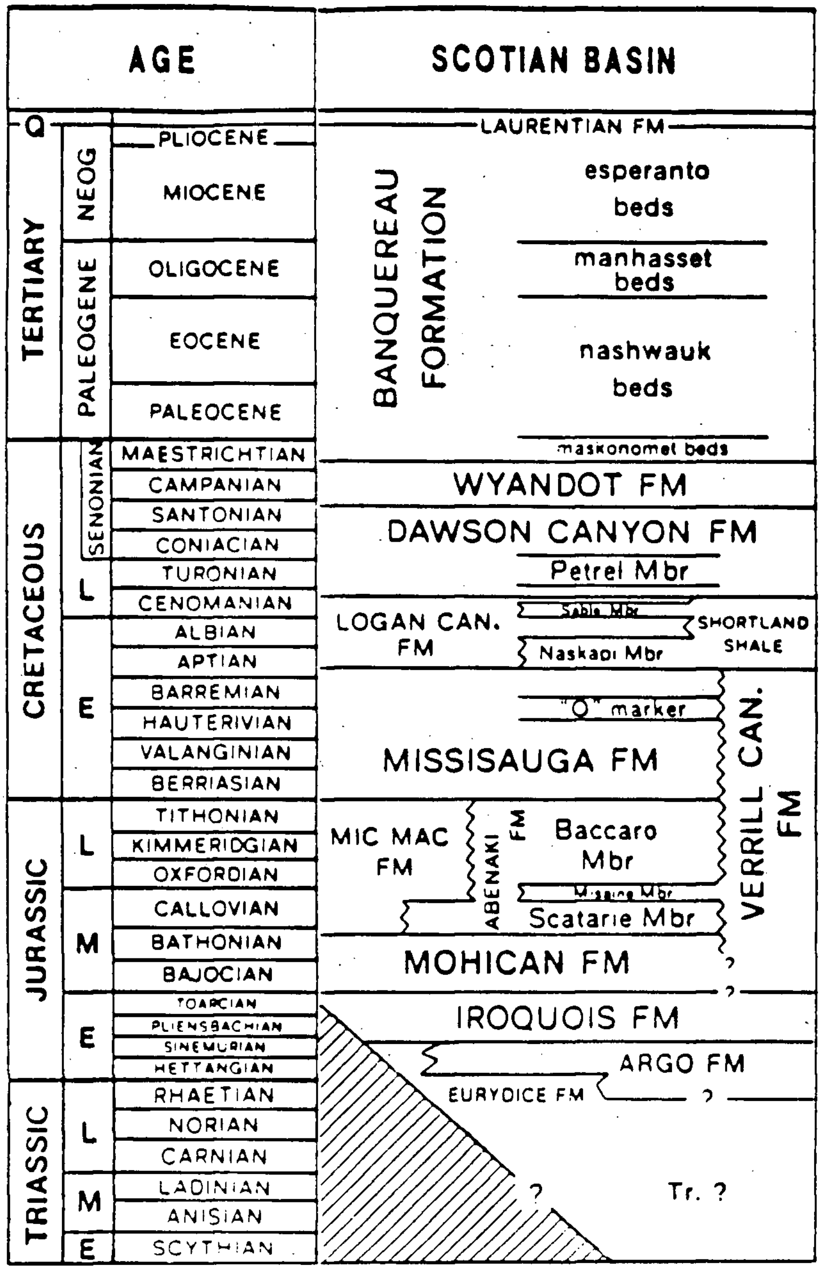

Fig.4 Stratigraphic column for the Scotian Basin (after Purcell et. al.,1979)

Intrusion of granites into the Meguma Group occurred in the Late? Devonian as a consequence of the Acadian Orogeny (Schenk, 1978; King et al., 1975). The collision between the North American plate and African plate resulted in a dominant northeast-southwest structural grain. The associated right lateral shear (Uchupi et al., 1976) was reactivated later during continental breakup.

Mississippian to Triassic strata have not been encountered in any of the wells drilled on the Scotian Shelf, although Carboniferous strata occur on the Grand Banks (Jansa and Wade, 1975a). This hiatus is probably related to the latest phase of the Hercynian Orogeny which continued intermittently from the Carboniferous to the Permian (Jansa and Wade, 1975a; Sherwin, 1972).

Rifting on the Atlantic margin is considered to have begun around 180 Ma. (McWhae, 1981; King et al., 1975; Pitman, 1978; Bally and Snelson, 1980) although earlier dates, 190 Ma. (Royden and Keen., 1980a) and later dates, 176 Ma. (Purcell et al., 1979), 175 Ma. (Van Houten, 1977; Sclater et al., 1977) have been cited. The breakup resulted in the development of the Triassic Newark System (Uchupi et al., 1976), a series of Triassic rift valleys that extended from Florida to Nova Scotia, (Ballard and Uchupi, 1972). A similar series of basins formed on the African margin (Lehrner and De Ruiter, 1977).

As the African Plate moved away from the North American plate during and after the Triassic, a northwest-southeast transform faulted margin developed on the Atlantic margin. The Orpheus Graben is a consequence of the rift induced reactivation of the pre-existing structurally weak fault zone between the Meguma and Avalon platform. The Orpheus Graben probably connects the northeast-southwest trending Triassic rift basins of the American continental margin via the Glooscap fault system to the Newfoundland fracture zone (Fig.1), (King, 1975, Wilson and Williams, 1979). The Newfoundland fracture zone defined the northern limit of the Atlantic Ocean during the early Jurassic.

Early redbed sedimentation (Eurydice Formation) was probably restricted to structurally low areas (McIver, 1972), following a period of bevelling which may have peneplained the basement (Given, 1977). As rifting progressed, a western extension of the Tethys invaded the Atlantic Basin. Restricted marine conditions ensued, resulting in evaporite deposition of the Argo Formation. Further widening of the basin destroyed the restricted marine conditions in the early Jurassic, allowing carbonates of the Iroquois Formation to be deposited (Evans, 1978).

The Middle Jurassic transgression, following continental clastic deposition of the Mohican Formation, produced a carbonate shelf complex facing a deep water basin, the Western Bank Group (Given, 1977). The Canso Ridge was probably emergent until the Middle Jurassic (Jansa and Wade, 1975a).

By the early Cretaceous, the deltaic complex of the Missisauga Formation had prograded over the carbonates as a regressive pulse resulting from the rejuvenation of continental source areas (Given, 1977). The Avalon uplift was a result of the separation of the Grand Banks from the European Plate dated as early Cretaceous (Haworth, 1975; Jansa and Wade, 1975b); and 90 Ma (Bally and Snelson, 1980).

A marine transgression began in the Albian, resulting in the deposition of shallow to marginal marine sand, silt and shale sequences, the Logan Canyon Formation (Jansa and Wade, 1975b). A restricted marine to non-marine shale, (Given, 1977), the Naskapi Formation, in some places separates the Missisauga Formation from the Logan Canyon (McIver, 1972). Deposition of the marginal marine to inner neritic shales and mudstones (Dawson Canyon Formation) followed by outer neritic to upper bathyal chalk deposition (Wyandot Formation) marked the transgressive culmination (Given, 1977). In the Orpheus Graben, deposition continued as an alluvial plain environment from the Upper Jurassic to the Cenomanian (Jansa and Wade, 1975b).

Tertiary deposits consist of mudstones with increased sand content in the upper half of the section, the Banquereau Formation of McIver, (1972) indicating a shallowing of water depth. The Wyandot and Banquereau Formations may be present in the Orpheus Graben although sample cuttings and mechanical logs were not collected from the upper part of the wells to prove or disprove this hypothesis (Hardy, 1975). Quaternary deposition consisted of glaciomarine sediments.

CHAPTER 2. PALYNOLOGY

Introduction:

Ditch-cutting and sidewall-core samples from four wells, Argo F-38, Jason C-20, Hercules G-15 and Eurydice P-36, drilled in the Orpheus Graben were analyzed palynologically. The oldest sediments are probable Upper Triassic-Jurassic sediments in Eurydice P-36; the youngest are Upper Cretaceous, Turonian, in Argo F-38. Major Middle-Jurassic unconformities were found in Eurydice P-36 and Hercules G-15.

The number of species of palynomorphs identified in each well are:

	#dinoflagellates	#spores/pollen
Jason C-20	69	105
Hercules G-15	8	65
Argo F-38	59	102
Eurydice P-36	0	24

Methods:

The palynological slides for each of the wells in the Orpheus Graben were provided by Shell Canada Resources Ltd. Most slides were 9 m to 30 m (30' to 100') composite samples from ditch cuttings, although in some wells, sidewall core and conventional core samples were available. Two hundred palynomorphs, if present, were counted per slide. Three hundred and eighty slides were examined.

Each well was zoned and dated using microplankton assemblages, first occurrences of species, or known palynological ranges. The palynological zonation is based on Williams (1975), Williams and Brideaux (1975), Bujak and Williams (1977), Bujak and Williams (1978), and Barss, Bujak and Williams (1979). A summary of the assemblage zones and equivalent stages established for the Scotian shelf are shown in Fig. 5. There are ten zones in the Jurassic, comprising one peak zone and nine assemblage zones. In the Cretaceous there are eleven zones; two peak zones and nine assemblage zones.

Identification of recycled palynomorphs was based upon the palynomorph identification and generally darker colour and/or evidence of erosion.

The occurrence of reworked spores, the number of palynomorphs counted per sample interval and the percentage of spores and dinoflagellates per sample interval were also plotted. For several species of spores and pollen, percent frequency diagrams are used to illustrate possible paleoecological relationships among the floras.

				EURYDICE P-36	ARGO F-38	HERCULES G-15	JASON C-20
CRETACEOUS	LATE	Maastrichtian	Dinogymnium euclaensis Zone				
		Campanian	Odontochina operculata Zone				
		Santonian	Cordosphaeridium truncigerum Zone				
		Coniacian	Oligosphaeridium pulcherrimum Zone				
		Turonian	Surculosphaeridium longifurcatum Zone		X		
		Cenomanian	Cleistosphaeridium polypes Zone		X		
	EARLY	Albian	Spinidinium cf. S. vestitum - Eucommiidites minor Zone; Rugubivesiculites rugosus Subzone		X	X	X
		Aptian	Subtilisphaera perlucida-Systematophora schindewolfii Zone		X		X
		Barremian	Doidyx anaphrissa Zone				
		Hauterivian	Ctenidodinium elegantulum Zone				
		Valanginian	Phoberocysta neocomica Zone				
		Berriasian					
JURASSIC	LATE	Portlandian	Ctenidodinium panneum Zone				
		Kimmeridgian	Gonyaulacysta cladophora Zone		X	X	X
		Oxfordian	Gonyaulacysta jurassica Zone				X
	MIDDLE	Callovian	Valensiella vermiculata Zone		X		X
		Bathonian	Gonyaulacysta filapicata Zone				
		Bajocian	Mancodinium semitabulatum Zone				
		Aalenian					
	EARLY	Toarcian	Nannoceratopsis gracilis Zone				
		Pliensbachian					
		Sinemurian	Echinitosporites cf. E. iliacoides Zone	X	X	X	X
		Hettangian	Cycadopites subgranulosus Zone	X			
LATE TRIASSIC			Classopollis meyeriana Zone	X	X?		

Fig. 5 Summary of palynological zonation for the east coast of Canada (after Barss et.al.,1979) Right column, an 'X' indicates those zones observed in the well examined.

Results and Discussion

The palynomorph range charts for the four wells are presented on Figures 6 to 12. Each well, except for Eurydice P-36 from which only spores were recovered, has two range charts, one for microplankton and one for spores and pollen. The zonation is indicated on the figures with the stages on both the horizontal and vertical scales. An 'X' denotes the presence of a particular palynomorph at a particular depth, rather than abundance. Some species were particularly abundant, and percentage frequency diagrams were compiled for these species.

In the Orpheus Graben, many of the species used to define zones by Barss et al. (1979) were present, though with some exceptions. Figure 5 compares zonation of Barss et al. (1979) to the four wells in this study. Key species representing Berriasian to Barremian and Toarcian to Bajocian stages were not observed. The Berriasian to Barremian interval in the Orpheus Graben was non-marine due to the regressive Missisauga delta, so dinoflagellates representing these stages would probably not occur. However the second <u>Classopollis classoides</u> peak observed in Argo F-38 and Jason C-20 indicates a Lower Cretaceous age. Chaloner (1962) noted a similiar double maxima for <u>Classopollis</u>. The first maximum occurred in the Early Jurassic (Liassic), the second in the early Cretaceous (Purbeckian-Berriasian) (Van Eysinga, 1978).

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Fig. 6 See ~~back pocket~~.

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Fig. 7 See ~~back pocket~~.

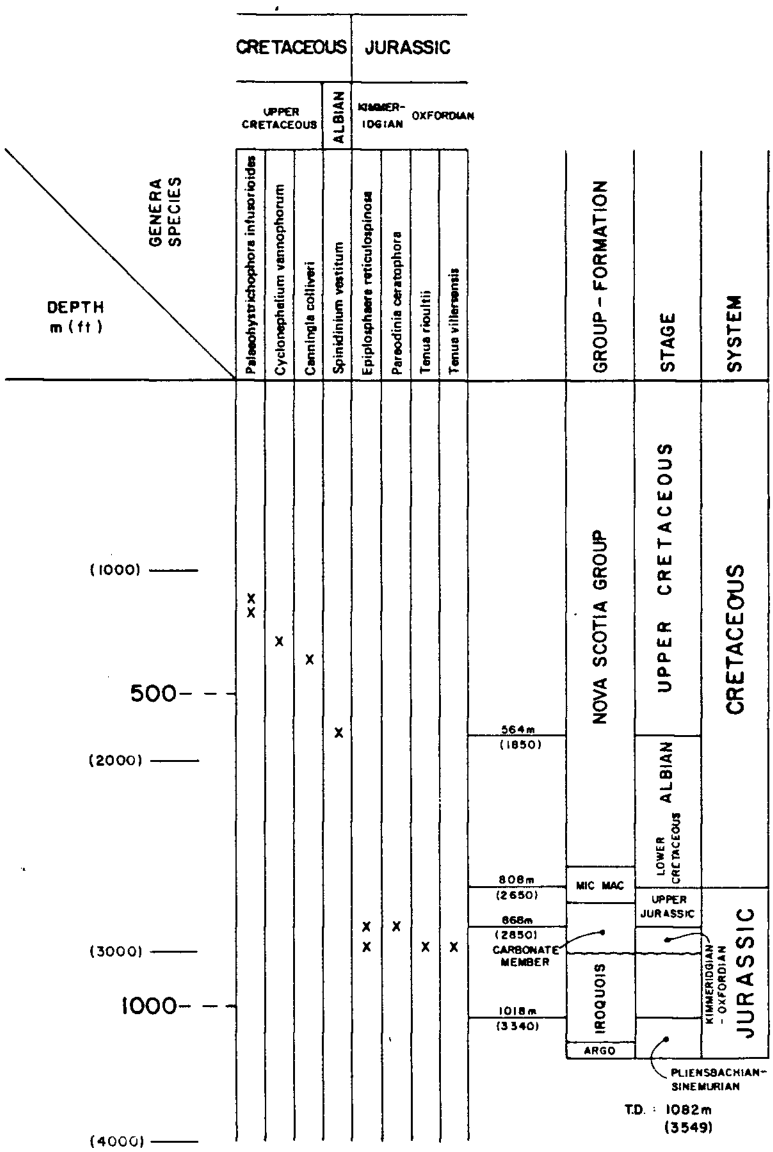

FIG. 8 MICROPLANKTON DISTRIBUTION FOR
UNION et al HERCULES G-15

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Fig. 9 See ~~back pocket~~ Special Collections

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Fig. 10 See ~~back pocket~~.

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Fig. 11 See ~~back pocket~~.

Fig. 12 See Special Collections ~~back pocket~~

Deposition during the Toarcian to Bajocian ages in the Orpheus Graben occurred under continental to fluvial deltaic conditions. Again, the key dinoflagellates would not be expected under those environmental conditions. Other characteristic palynomorphs that could be used for dating this interval were not observed.

Palynomorph Recovery: The number of palynomorphs (spores, pollen, and microplankton) counted for each sample interval for the four wells is plotted on Figures 13 to 16. The recovery of palynomorphs for each formation is summarized on Table I.

Recycled Palynomorphs: The identification of recycled palynomorphs could be potentially valuable for indicating the presence of host strata at depth or of presumably close stratigraphic outliers, either nearshore, onshore, or offshore that could have contributed the recyclants by erosion and redeposition. The recycled palynomorphs are plotted by Geologic Period of origin vs depth on the right hand side of Figures 7, 9, 11, and 12. The number of recycled palynomorphs is low, constituting at best only a few specimens per slide. A partial list of recycled spores is given in Appendix III. The most common reworked spore was *Lycospora* sp. (Carboniferous).

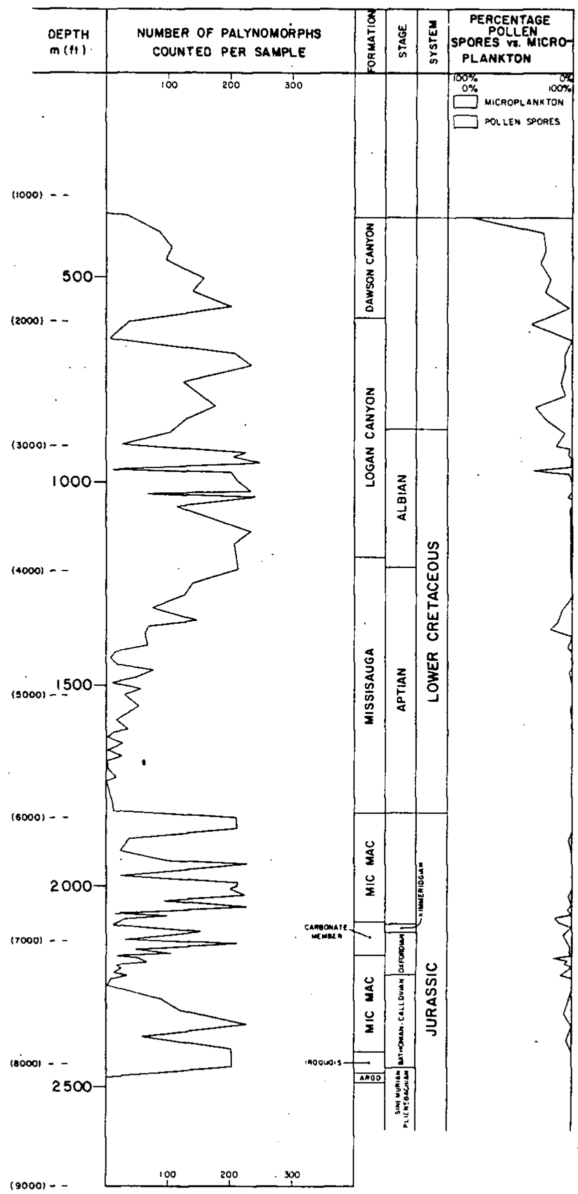

FIG. 13
UNION et al JASON C-20
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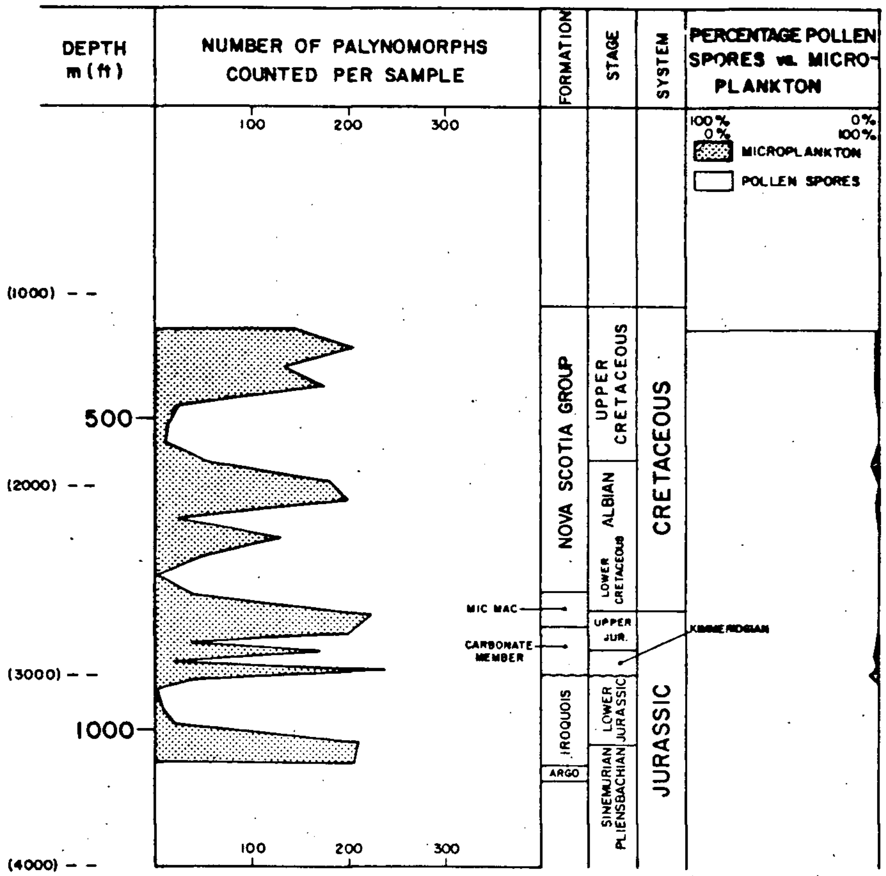

FIG. 14

UNION et al HERCULES G-15

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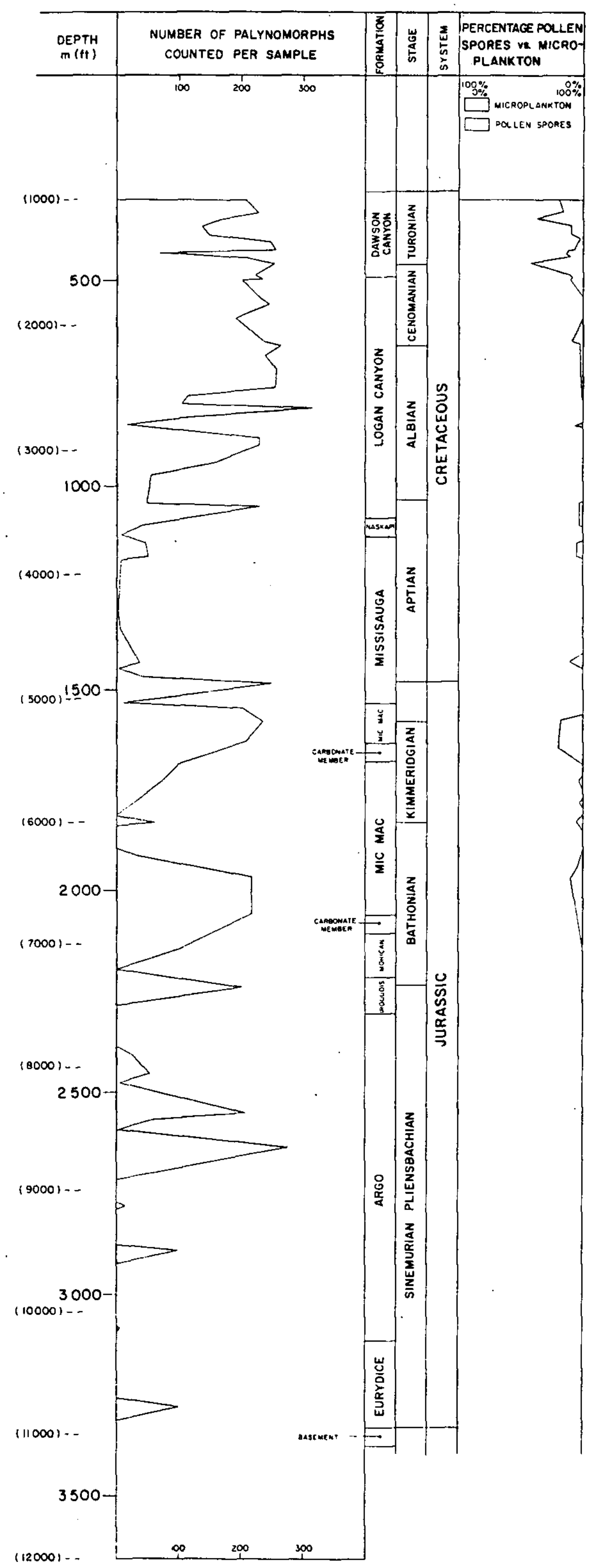

FIG. 15

SHELL ARGO F-38

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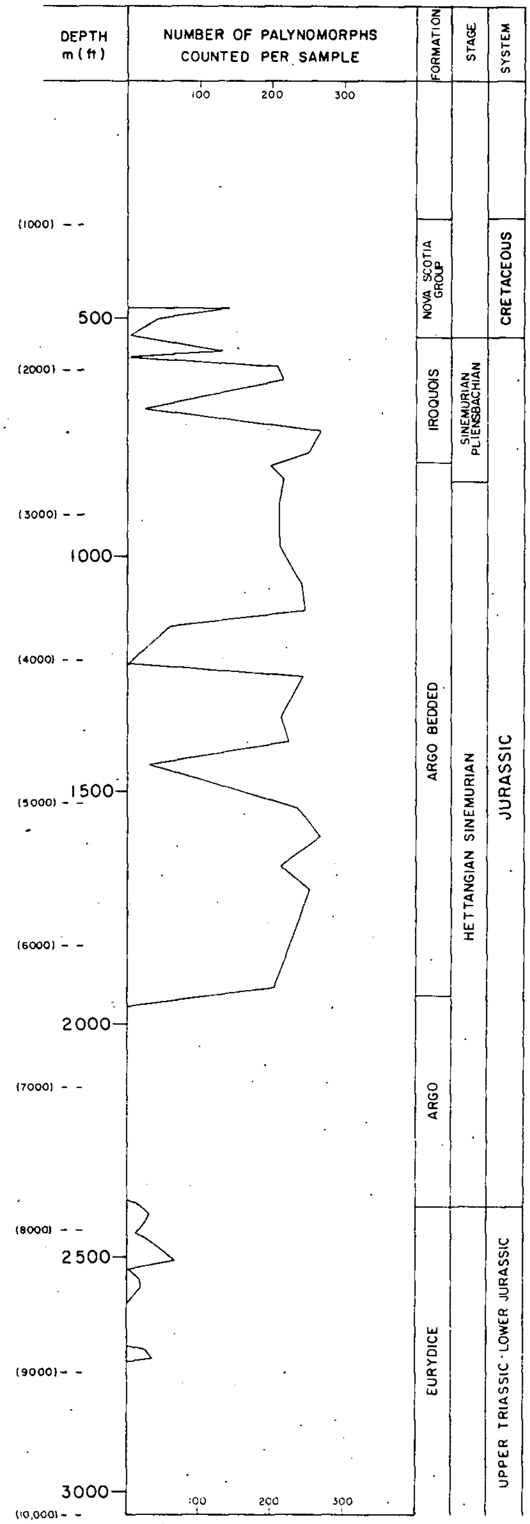

FIG 16

SHELL EURYDICE P-36

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I-241b

Table I Summary of Palynomorph Recovery (includes: pollen, spores, microplankton)

Spores Pollen, and Microplankton Recovered	Poor	Fair	Good	Excellent	Microplankton Present
	0-50	50-100	100-150	150+	
Formation					
Eurydice	x	x[1]			No
Argo	x			x[2]	No
Iroquois				x[3]	No
Mohican		x			Very Few
MicMac	x	*	x	x	Yes
Upper Carbonate Member of MicMac	x	*	x	x	Yes
Missisauga	x	x			Yes[4]
Naskapi	x				Very Few
Logan Canyon				x	Yes
Dawson Canyon				x	Yes

[1] Most intervals barren, occassional spore rich intervals.

[2] In shaley interbeds.

[3] Generally more spores at base of formation than at top.

[4] In upper part of section.

* Variable

Paleoecology

The occurrence of dinoflagellates probably indicates marine or at least brackish conditions (although a few modern fresh water dinoflagellates are known). The main marine intervals are the following.

Argo F-38	Bathonian - Kimmeridgian stages, Lower Cretaceous to Turonian.
Jason C-20	Bathonian stage to Jurassic-Cretaceous boundary Aptian stage to Upper Cretaceous
Hercules	Aptian to Albian stages.

The percentage frequency diagrams indicate the vegetative changes through time and can be used to reconstruct paleoecological as well as paleoclimatic parameters. Appendix III shows spore species and possible plant affinities.

The percentage frequency diagrams can be divided into two main zones: a Lower Jurassic - Lower Cretaceous palynoflora dominated by Classopollis species; and a Cretaceous palynoflora dominated by Cyathidites australis (Plate 3, Fig. 27.), Taxodiaceaepollenites hiatus, Gleicheniidites senonicus (Plate 3, Fig. 28), and bisaccates.

The Classopollis zone is dominated by the two species Classopollis meyeriana (Plate 2, Fig. 13; Triassic - Lower Jurassic) and Classopollis classoides (Lower Jurassic - Lower Cretaceous). The change from Classopollis meyeriana to Classopollis classoides is near the Eurydice Fm. - Argo Fm.

boundary. This change probably represents a successional change in response to changing terrestrial climatic conditions, from the arid desert environment at the time of the Eurydice Formation (Jansa and Wade, 1975b) to a more marine, though still dry environment, conducive to formation of evaporites during development of the Argo Formation. S.K. Srivastava (1976) concluded that Classopollis-producing plants were members of the conifer family Cheirolepidaceae that occupied uplands slopes and lowlands near the coast.

The occurrence of Cycadopites sp. (Plate 2, Fig.11,12) in the Eurydice well and its absence in the other wells suggests that the plants producing Cycadopites pollen may have preferred a more inland terrestrial environment. Other spores occurring in the Orpheus region during the Jurassic have affinites to the Pteridophyta and Coniferophyta (Appendix III). In Argo F-38 and Jason C-20 there is a second increase in Classopollis after the main Classopollis zone. Chaloner (1962) suggested that the double maximum of Classopollis may have been caused by favourable climatic conditions that occurred twice, or by maxima of two distinct parent plants with nearly identical pollen.

The Cretaceous is marked by a large increase in the number of spore and pollen species, most with affinities to the Pteridophyta (refer to Figures 7, 9, 11, 13 and Appendix III for spore affinities). Four pollen and spore types dominate the Cretaceous section Cyathidites australis, Taxodiaceaepollenites hiatus, Gleicheniidites senonicus and bisaccate pollen. Taxodiaceaepollenites - producing trees (eg. Taxodium) probably occupied the strand line in a swamp-like environment similar to that suggested by Kedves (1960) for the Paleocene of Europe. In the Orpheus Graben region there was probably an oscillation among Cyathidites, Gleicheniidites, Taxodiaceaepollenites, and bisaccate pollen. The tree ferns representing Cyathidites probably alternated with Taxodiaceaepollenites - producing trees in dominance, in response to changes in sea level. Ferns producing Gleicheniidites sp. probably occupied clear areas, based on the report by Andrews and Pearsell (1941) of nearly pure stands of Gleicheniidites coloradensis. Bisaccate pollen was probably blown and/or rafted into the basin from upland locations. The dominance of the schizacaeceous spores indicates that a well developed pteridpophyte ecosystem existed during the Cretaceous in the vicinity of the Orpheus Graben. Modern schizaeceous spores are generally restricted to wetter tropical and subtropical environments. The environment during the Cretaceous was probably similar, with the schizaeceous ferns forming the understory and also occupying clear areas with Gleicheniidites sp. The appearance of pollen such as Vitreisporites (caytonian seed ferns) and Eucommiidites (Coniferophyta) (Plate 4, Fig. 41) may indicate the appearance of a specific environment for a short duration, or be a response to changing regional climatic conditions.

CONCLUSIONS

1. Palynological analysis indicates that the age of sediments in the Orpheus basin range from Upper Triassic to Turonian, with unconformities occurring in Eurydice P-38 and Hercules G-15.
2. The number of palynomorphs recovered varies with the formation. For example, the Iroquois, MicMac, Logan Canyon and Dawson Canyon Formations, have consistently greater numbers of palynomorphs.
3. Recycled palynomorphs are ubiquitous in the wells examined, but do not occur in large numbers.
4. The Jurassic section is dominated by Classopollis species, whereas the Cretaceous section is dominated by Cyathidites, Taxodiaceapollinites, Gleicheniidites, and bisaccate pollen.
5. The Jurassic climate was probably arid, changing to wet tropical or subtropical in the early Cretaceous.
6. Cretaceous Taxodiaceaepollenites pollen oscillated with Cyathidites spores in a coastal environment with schizaeceous and Gleicheniidites ferns forming the dominant understory and open - area plants.

CHAPTER 3 GEOCHEMISTRY

Introduction

The organic matter deposited in sediments and the level of its thermal maturity are important factors which control the generation of hydrocarbons. If the maturation level and the type and quantity of organic matter are identified, then it is possible to determine those lithofacies in which hydrocarbon generation has taken place.

Thermal maturation of organic matter is a function of two factors: 1) the geothermal gradient and; 2) burial history, especially the maximum burial and the duration of this burial. Thermal diagenesis will result in changes in the properties of the organic matter that can be assessed by both visual and analytical methods. For example, spores and pollen will become darker, progressively changing in colour from yellow to brown to black. The Thermal Alteration Index (T.A.I.) assigns numerical values to the colour changes, permitting an assessment of the level of organic maturity for a given horizon. Vitrinite reflectance is a quantitative measure of the level of thermal maturity. The reflectance of the maceral vitrinite increases with increasing levels of coalification (thermal diagenesis). Hence the measurement of the reflectance of vitrinite provides an analytical measurement of thermal maturity that can be compared to T.A.I.

The pyrolysis techniques, gas chromatography and flame ionization, are analytical techniques that characterize the type of hydrocarbon, measure the level of maturity and provide an estimate of the richness of the organic matter, ie., percentage of organic carbon.

Organic matter is divisible into four basic groups of macerals: Type I or Alginite: for example the alga Botryococcus sp.

Type II or Exinite: for example, dinoflagellates, spores, pollen, cuticle;

Type III or Vitrinite, which includes wood and humic matter; and

Type IV or Inertinite, which includes fusinite and semifusinite

The term, "amorphous matter", is assigned to organic matter that lacks form.

The type of organic matter present will determine the type of hydrocarbon that can be generated from a source rock at an appropriate level of maturity. In a thermally mature zone a source rock containing a high component of alginite is highly oil prone; a source rock containing high exinite is also oil prone, with some gas possible; and a source rock with high amounts of vitrinite is mostly gas prone with some condensate possible (Tissot and Welte, 1978). Inertinite has minimal possibilities for dry gas generation. When amorphous matter is present, it is often difficult to determine the original source of the amorphous component. If the amorphous matter originates from algal matter or exinite it will be oil prone, but if the amorphous matter is a result of degradation of vitrinitic matter then it will be gas prone.

Increasing levels of maturity will cause changes in the generated hydrocarbons. If oil was generated initially, progressive increase in depth of burial and temperature will cause it to first break down into wet gas and condensate, and then into dry gas (Tissot and Welte, 1978). (Oil prone organic matter will generate hydrocarbons at lower levels of thermal diagenesis than gas prone organic matter, Tissot and Welte, 1978; Snowdon and Powell, 1982). The interval between the limits at which oil first begins to be generated and no longer can be generated (the oil deadline), is called the oil window (Pusey, 1973). The gas deadline is reached when gas can no longer be generated or preserved.

For the Scotian Basin, several authors have completed studies of the characteristics of the organic matter, though not specifically in the Orpheus Graben (Robbins and Rhodehamel, 1976; Hacquebard, 1974; Bujak et al., 1977a, 1977b; Casssou et al., 1977; Purcell et al., 1977; Powell and Snowdon, 1979; Royden and Keen, 1980; Powell, 1982).

A Shell Technical Report (1972) suggested that for the platform area of the Scotian Basin most of the section is immature, with a Level of Maturity (L.O.M.) of 10 (Vitrinite reflectance = 0.83%) being reached in only the deeper tests. (see Figure 17 for comparison of the various maturity scales the onset of maturity occurs at a vitrinite reflectance of 0.5%). No depths to maturity were given.

Geothermal gradients were used by Robbins and Rhodehamel (1976) to predict the petroleum potential of the Scotian Basin. Approximate geothermal gradients were given for 35 wells including 4 drilled in the Orpheus Graben. For Argo F-38 and Eurydice P-36 the gradient was 14.4°C/Km, (0.8°F/100) for Crow F-52 5.4° C/Km (0.3°F/100'), and for Fox I-22 25.2° C/Km (1.4° F/100'). The average geothermal gradient for the Scotian Basin was 21.6°C/Km (1.2°F/100') with the onset of maturity at 2400 m (7874'). The optimum depth for petroleum occurrence was 3650 m (11975').

Hacquebard (1974) produced a composite coalification curve for the Maritimes based upon vitrinite reflectance. The depth to the oil window, between vitrinite reflectance 0.5% to 1.0%. was 2450 m (8000') to 4000 m. (13100').

Bujak et al. (1977a; 1977b) discussed the organic type and thermal maturity using the thermal alteration index (T.A.I.) for the east coast of Canada. They concluded that the onset of oil generation was deeper than suggested by Robbins and Rhodehamel

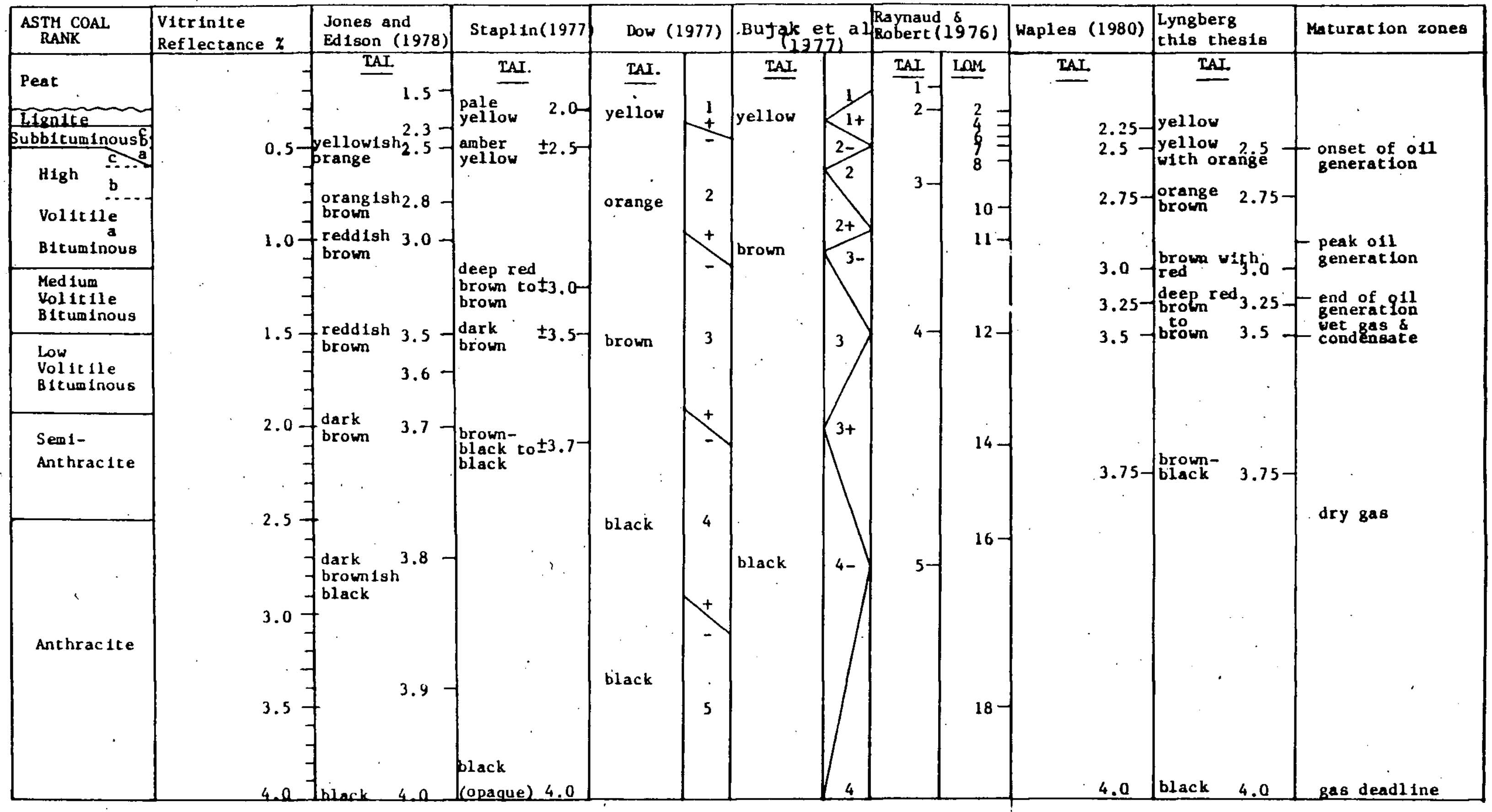

Fig. 17 Comparison of Vitrinite Reflectance to Thermal Alteration Indices (T.A.I.),spore colour,Level of Maturity(L.O.M.),and maturation zones

(1976), and that the organic type generally had poor hydrocarbon generative potential. One well, Primrose N-50 (Fig. 18), drilled on a salt diapir, had an anomalously higher T.A.I. indicating maturation at a shallower depth.

Cassou et al. (1977) studied the maturation and subsidence history for a number of wells on the east coast, including six on the Scotian Shelf. The top of the oil window for the six Scotian Shelf wells ranged from 1200 m (4000') to 2600 m (8500'), with an average depth of 1900 m (6200'). The age of the sediments at the top of the oil window was Lower Cretaceous. They correlated the montmorillite - illite transition with basement subsidence and to the top of the oil window.

Using four different maturation indicators: spore colour, light gas analysis, C-15 extract data and the 65° C isotherm, Purcell et al. (1979) calculated the depth to maturity for nine wells in the Sable and Abenaki Basins (Fig. 18). Light gas analysis (when C1 - C4 exceeds 50% of wet gases) indicated a maturity at 2200 m (7200') a depth similar to that of the 65° C isotherm. Spore colour indicated "marginally mature" at an average of 3500 m (11500') and "fully mature" at 4600 m (15100'). Gas chromatography produced slightly deeper maturation zones. The conclusion was that the onset of maturation began at a depth of 2200 m (7200'), with the "fully mature" zone about 2000 m deeper. The average geothermal gradient for the 9 wells was 2.35° C/100 m (1.3° F/100').

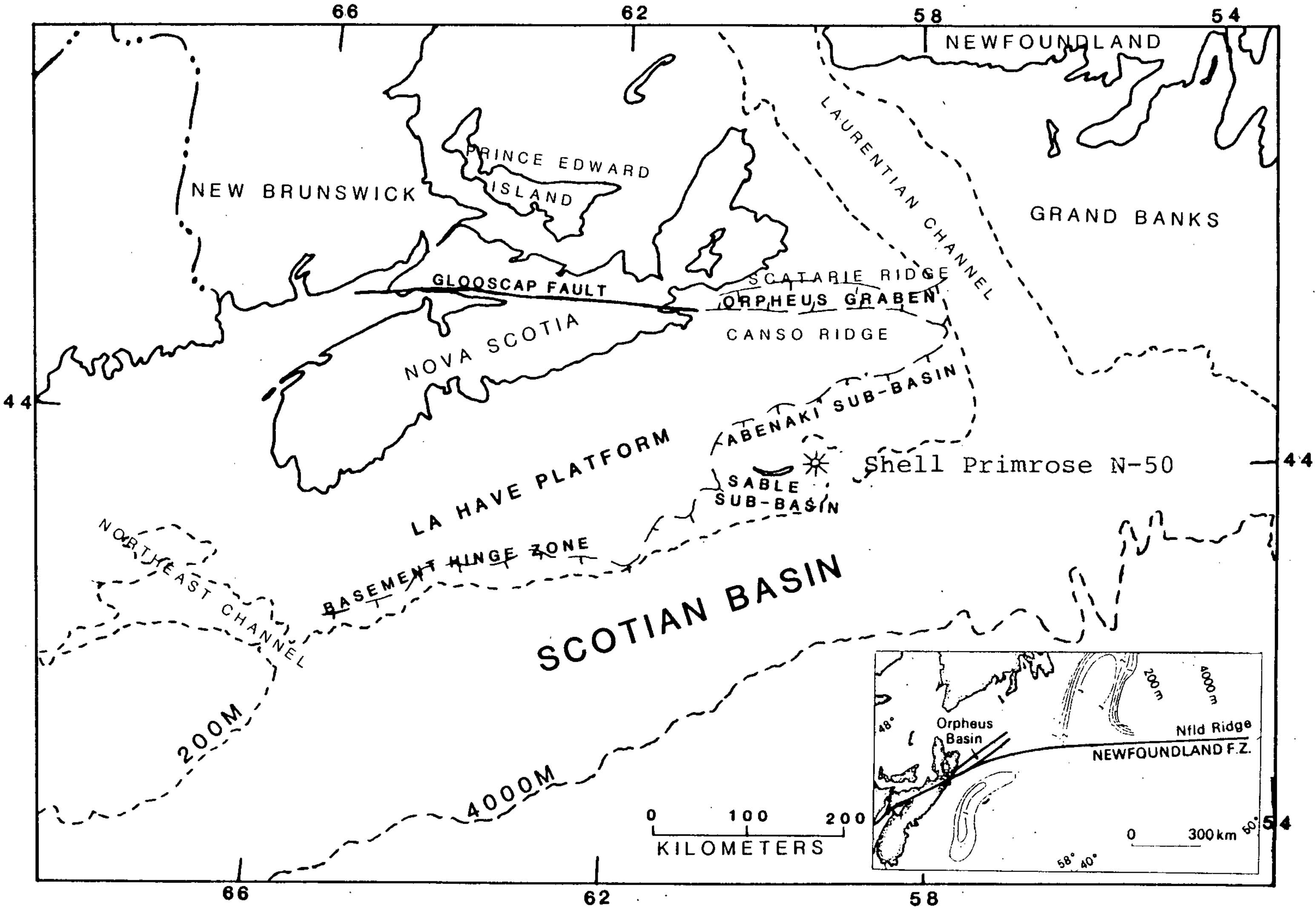

Fig. 18 Location of Shell Primrose N-50

The maturity zones of Purcell et al (1979) were given vitrinite reflectance values 0.5% R_o for 2200 m (7200') marginally mature, and fully mature 0.7% R_o at 4200 m (13800') by Powell and Snowdon (1979).

Royden and Keen (1980) calculated the stratigraphic paleotemperature distribution for the Scotian Basin for various times. Paleotemperature estimates obtained by their modelling predicted vitrinite reflectance values higher than those measured.

The maturity of the Verril Canyon Formation, the basinward equivalent of the Missisauga Formation and Abenaki Formation, was determined by Powell (1982). Along the shelf edge, the basal parts of the Cretaceous section were mature for oil generation.

Methods

Thermal Maturity based upon Spore Colour

The Thermal Alteration Index ranges from 1 to 5 but in reality is only useful between 2.0 to 4.0. Below 2.0 the colour changes are too subtle to discern, while above 4.0 the spores are black. Numerous T.A.I. scales are available (Fig. 17). For this study a modified version of the Jones and Edison (1978) T.A.I. scale was used (Table II), since their scale has been correlated to both maturity zones and vitrinite reflectance values (Waples, 1980).

Table II

Comparison of T.A.I. to Vitrinite Reflectance with Associated Spore Colours and Maturation Zones

Thermal Alteration Index	Vitrinite Reflectance (%)	Spore Colour	Maturation Zone
2.25	0.40	yellow	
2.5	0.50	yellow with orange	onset of oil generation
2.75	0.77	brown orange	
			2.9 = peak oil generation
3.0	1.15	red brown	
3.25	1.33	dark red brown	oil deadline, wet gas and condensate
3.5	1.50	dark brown	
3.75	2.25	brown black	dry gas
4.0	4.0	black	gas deadline

There is general agreement on the values for these zones, except for the onset of oil generation. Waples (1980), Dow (1977) and Gretner and Curtis (1982), place the top of the oil window at a vitrinite reflectance of 0.65%, while Vassovich et al. (1969), Bostick (1979) Middleton (1982) and others place it at 0.5%. Some consider that hydrocarbons can be generated at vitrinite reflectances as low as 0.3% (Cannon and Cassou, 1980) or 0.45% (Snowdon and Powell, 1982) from some types of kerogen.

Since colour determination is subjective, it is important for each operator to standardize the procedure to produce consistent and repeatable results. Following spore identification, in this investigation, the colour was noted and placed within increments 0.25, for example 2.5 to 2.75 or assigned a plus/minus value, for example, 3.0 ± 0.12. The limits of human colour perception prevent finer subdivisions. The colours assigned were checked against the verbal colour descriptions, given above, and against a Shell Canada Resources Ltd. colour chart. The lightest coloured part of the spore wall was used for colour determination, except for a T.A.I. of 2.5 where the presence of an orange tinge would determine the onset of hydrocarbon generation. Consistency was further ensured by using the same spore species for the same stratigraphic intervals in all six wells. <u>Classopollis</u> sp. was used for the Jurassic and Lower Cretaceous sections, whereas <u>Cyathidites australis</u> was used in the Cretaceous section. For sections where none of the above spores were present, T.A.I. values were assigned to other spores and pollen, provided they were not recycled and did not have overly thick or thin exines.

The macerals present for each interval were placed by visual identification into one of four groups. 1) amorphous, 2) exinite, 3) vitrinite, 4) inertinite. A percentage value, based upon the area occupied by each maceral, was assigned each maceral group by reference to percent estimation charts.

Vitrinite Reflectance

The number of vitrinite reflectance values obtained are proportional to the amount of vitrinite contained in the sample. For most samples, insufficient vitrinite was present to provide an accurate reading. For the Orpheus Graben, concentration of the vitrinite by physical separation of the organic matter was necessary. The samples were mounted and polished so no scratches were visible at 750X magnification. Standard procedures were followed throughout the rest of the determination.

Pyrolysis - Gas Chromatography, Flame Ionization

The gas chromatography and flame ionization techniques employed by Shell Canada Resources are proprietary and cannot be discussed.

RESULTS AND DISCUSSION

The geochemical and maturation data are presented for each well on Figures 19 to 24. Curves were drawn on a best fit basis provided there was enough data. Shell Canada provided the vitrinite and pyrolysis analysis data.

Maturation Data

Thermal Alteration Index

The T.A.I. profiles for each well show a gradual change in spore colour with depth indicating an increase in thermal maturity. The individual values are not as important as the profile for determining maturation zones. Table III is a compilation of the depth to different maturation levels based upon spore colour.

The depth to a given maturation zone is not consistent over the basin. The onset of oil generation, T.A.I.=2.5 can be as shallow as 500 m (1600') in Argo F-38 to 1150 m (3800') in Crow F-52. For peak oil generation, the depth varies from 900 m (2950') in Hercules to 2100 m (6900') in Argo. Figure 25 is a structural cross section of the Orpheus Graben with isopleths of T.A.I. values, showing variation in depth to given T.A.I. values. One noteworthy feature is that near salt diapirs the T.A.I. values are elevated. Enhanced levels of maturity over salt structures has also been documented on the Scotian Shelf by

Fig. 19 See ~~back pocket~~ Special Collections.

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Fig. 20 See ~~back pocket~~.

Fig. 21 See ~~back pocket~~ Special Collections.

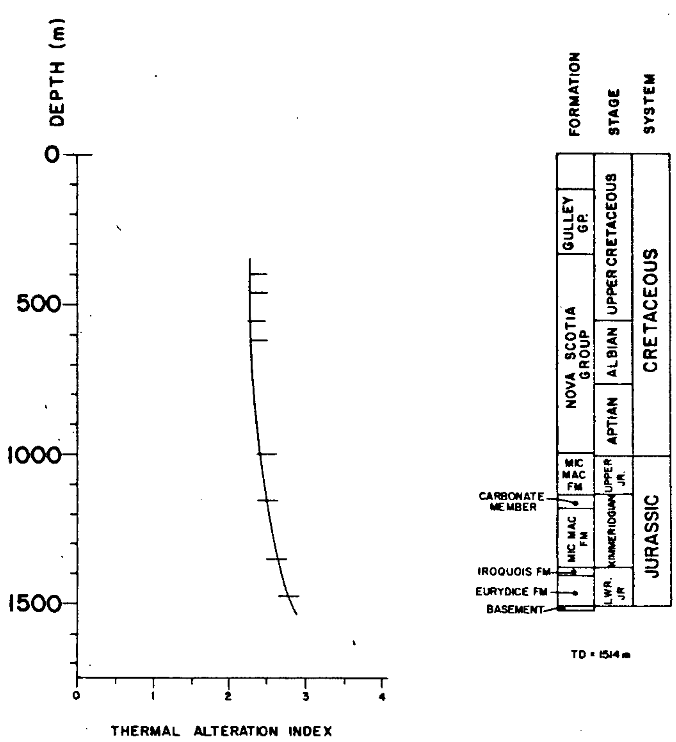

FIG. 22 THERMAL ALTERATION INDEX PROFILE

SHELL CROW F-52

I-241k

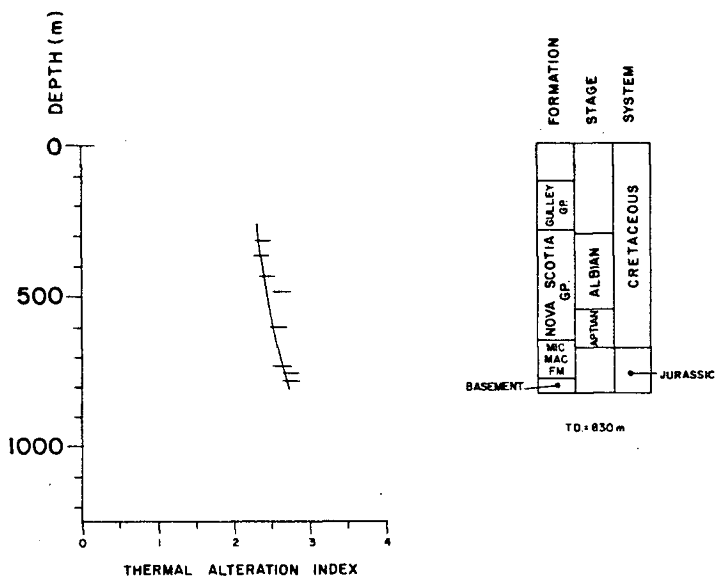

FIG. 23 THERMAL ALTERATION INDEX PROFILE

SHELL FOX I-22

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Fig. 24 See ~~back pocket~~.

TABLE III

COMPARISON OF DEPTHS TO DIFFERENT MATURITY ZONES

Well Name	T.A.I. (and Equivalent Vitrinite Reflectance Values %)		
	2.5 (0.5%)	2.9 (1.0%)	3.25 (1.3%)
Eurydice	800 m (2600')	1550 m (5100')	2100 m (6900')
Fox	550 m (1800')	-	-
Crow	1100 m (3600')	-	-
Argo	500 m (1650')	2100 m (6900')	2600 m (8550')
Hercules	-	900 m (2950')	
Jason	800 m (2600')	1750 m (5750')	2250 m (7400')

Where 2.5 = onset of oil generation

2.9 = peak oil generation

3.25 = oil deadline

Orpheus Graben - Present Day 10 X Vertical Exaggeration

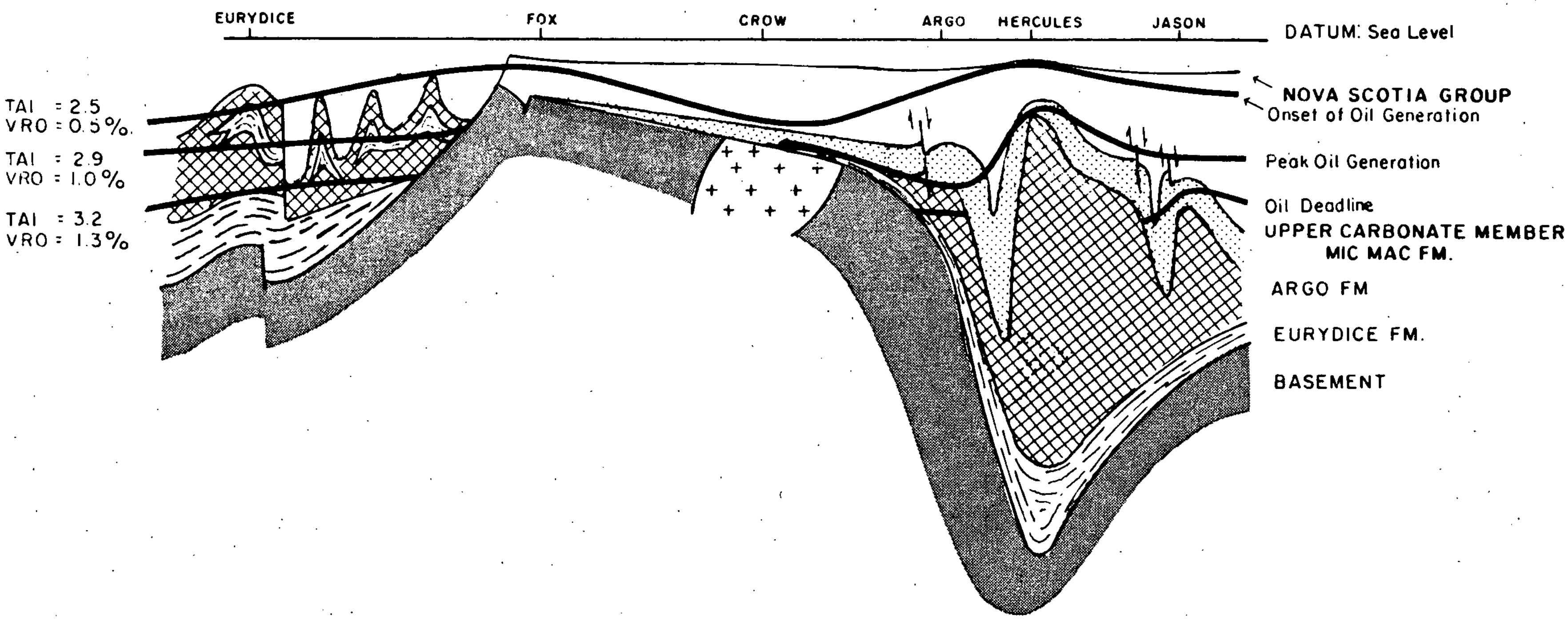

Fig. 25 Cross Sections of the Orpheus Graben showing Isopleths of T.A.I. and Vitrinite Reflectance

Rashid and McAlary (1977), who suggested that increase in maturity was a response to the thermal and pressure effects of the salt structure. Keen (1983) modeled the temperature history of two salt diapirs on the Scotian Shelf and concluded that the thermal effects within the salt itself were not enough to cause a significant increase in maturity. Rather, Keen postulated that the migration of hot fluids up the sides and across the top of the diapir would most likely cause a significant increase in thermal maturity. Another opinion was expressed by Powell and Snowdon (1979) and Gretner (1981) who suggested that the high thermal conductivity of salt would focus the geothermal heat towards the highs in the structure. In addition, the overlying sediments may insulate the top of the salt causing an increase in temperature. This last opinion may in fact account for slight increase in spore colour at or near the top of the salt in Eurydice P-36 (Fig. 24a).

A volcanic unit occurs in 3 wells, Argo (1366 m - 1376 m, 4481'-4514'), Hercules (757.5 m - 776 m, 2485'-2546') and Jason (1366 m - 1376 m, 4481' - 4514'). The maturation profile is not deflected above the volcanic unit, but immediately below it there is a notable darkening of spore colour. Below the volcanic unit in Hercules G-15 there is an increase in T.A.I. to 3.0 from 2.75 (Fig. 20a), in Argo an increase to 3.0 - 3.25 from 2.5 (Fig. 21a), and in Jason there is an increase in T.A.I. to 3.0 from 2.75 (Fig. 19a). The volcanic unit was probably a surface flow.

Only the underlying rock would then have been affected by the heat. Dow (1977) illustrated a similar effect, using vitrinite reflective values from a well in the Delaware Basin in Texas. Dow (1977) found that contact metamorphism affects maturity of the rock above and below the dyke to a maximum of 2X the thickness of the intrusive.

Enhanced thermal maturity resulting from proximity to crystalline basement rocks probably accounts for the more rapid increase in maturity near the basement-sediment contact for Fox I-22, Crow F-52 and Argo F-38. This is probably a result of the difference in thermal conductivity between the basement crystalline rocks and the overlying sediments.

Vitrinite Reflectance:

Only a few vitrinite reflective values were obtained (provided by Shell), so it was not possible to reconstruct a maturation profile based upon vitrinite reflectance. The main reason for this is a general paucity of vitrinite contained in the samples from the wells. The vitrinite values that were obtained came from the Missisauga or Logan Canyon formations, at the top of the section. The vitrinite reflectance results are similar to the equivalent T.A.I. values, although the vitrinite tends to indicate a less mature condition. The same vitrinite values were obtained from samples spaced up to 1000 m (3280') apart in some wells. In Argo F-38 (Fig. 21b) a sample at 1598 m

(5243') was 0.14% lower in reflectance than the other two values at 1478 m (4849') and 734 m (2408'). These results could result from caving, misidentification of macerals, oxidation of macerals, or variation in composition of macerals. The two decimal accuracy of vitrinite reflectance measurements is deceptive since the vitrinite value is an average of several measurements (Jones and Edison, 1978). During the course of palynological examination it was noted that in some samples the palynomorphs were obviously caved-in from above. It would be impossible to determine the amounts of macerals that also resulted from caving-in. A solution to this problem would be to use sidewall cores for vitrinite reflectance, but the problem of dearth of vitrinite would remain.

Pyrolysis

In Eurydice P-36, enough pyrolysis data were available to produce a curve by linear regression through those data points obviously not based on caved material (Fig. 24b). Comparison of the T.A.I. curve (Fig. 24a) to the pyrolysis curve for Eurydice P-36 (Fig. 24b) shows that the same maturation zones occur at similar depths. The onset of oil generation, T.A.I= 2.5 vitrinite reflectance = 0.5%, occurs at the same depth, 800 m (2600'); peak oil generation T.A.I.= 2.9, vitrinite reflectance =1.0% is at approximately 1600 m (5250'); whereas the oil deadline T.A.I. = 3.25, vitrinite reflectance =1.3 occurs at 2200 m (7200').

Organic Matter

The distribution of maceral types for the four wells indicates the types of organic material present in each formation, (Figures 19c, 20c, 21c, 24c). Overall there does not appear to be an overly rich interval. Vitrinite and inertinite dominate, with local abundances of exinite and amorphous matter. In some cases the area under a peak is a result of a relatively thick sample interval rather than from concentration in particular horizons. The type of organic matter is related to depositional environment, which is illustrated in the Orpheus Graben. For example, the organic matter in the red beds of the Eurydice Formation Fig. 21c, 24c, is primarily inertinite. Again, the pure salt intervals of the overlying Argo Formation contain largely vitrinite and inertinite, with exinite-rich intervals confined to the shaley interbeds. The Iroquois dolomite, formed during a transgressive phase, contains significant amounts of exinite with some vitrinite rich intervals. The Mohican Formation (Fig. 21c) consists of continental clastics accompanied by relatively high amounts of inertinite. From the Bathonian to the Kimmeridgian a slow regional trangression occurred, which is reflected in the increased numbers of dinoflagellate cysts deposited during this interval. The MicMac Formation, deposited in a coastal plain environment, contains higher amounts of exinite and amorphous matter which peak at the top of the MicMac Formation.

The early Cretaceous Missisauga and Logan Canyon Formations are largely alluvial plain deposits. The lower part of the Missisauga Formation is dominated by vitrinite and inertinite. The slow regional transgression which began in the Aptian resulted in increased amounts of exinite and amorphous matter being incorporated into the upper Missisauga, Logan Canyon and Dawson Canyon Formations.

The Geological Survey of Canada Open File 714 (Barss et al., 1980) contains similar though more general diagrams for the Eurydice, Hercules and Argo wells. The results are similar in that the same units tend to have comparable increases and decreases in types of organic matter.

Pyrolysis and Organic Carbon

Comparison of the percent lipid-humic (Fig. 19d, 19e, 20d, 20e, 21d, 21e, 24d, 24e) and pyrolysable hydrocarbons to the maceral analysis (Fig. 19c, 20c, 21c, 24c) yielded some comparable results, but lack of data for the analytical technique hindered direct comparison. For Jason C-20, a percent organic carbon profile (Fig. 19f) was plotted from Geological Survey of Canada Open File 694. The percent organic carbon is over 6% in the lower Logan Canyon Formation, then tapers off to less than 1% at the base of the Missisauga Formation. In the MicMac, carbonate member of the MicMac, and Mohican Formations, organic carbon is as high as 3%. The minimum amount of organic carbon neeeded for a a rock to be a source rock for hydrocarbons is 0.5% organic carbon (Tissot and Welte, 1978; Hunt, 1979).

Comparison of the organic matter, specifically exinite peaks, to the percent organic carbon peaks shows that the exinite peaks generally mirror the percent organic carbon profile, although some peaks do not correlate.

SUMMARY AND CONCLUSIONS

1. The formations can be classified by the organic matter they contain. For example the Eurydice, the Argo and lower part of the Missisauga Formations, are characterized by large inertinite and vitrinite components. The Iroquois and MicMac Formations contain higher amounts of exinite and amorphous matter.

The lower parts of the Dawson Canyon and Logan Canyon Formations contain the highest amounts of exinite and amorphous matter and could be a good oil-prone source rocks. However, for the wells in this survey, the Dawson Canyon is thermally immature and the Logan Canyon marginally mature; hence there is little probability of hydrocarbon generation. In the thermally mature zones of the MicMac Formation there are greater amounts of oil-prone organic matter rather than gas-prone organic matter, which could have acted as source for oil. In the mature zones vitrinite and inertinite are most common, so gas would be the hydrocarbon most likely to have been generated.

2. The Thermal Alteration Index is a useful tool to determine maturation zones in the absence of other maturation indicators. The advantages are that it is a quick technique, and can detect recycling and down-hole caving of organic matter. The disadvantages are that it is subjective, and requires standardization of procedures to ensure meaningful results.

3. Over salt features enhanced levels of maturity occur. The result is that in the Orpheus Graben more mature rocks occur at shallower depths than the rest of the Scotian Shelf.

4. Maturation based on pyrolysis provides a check for maturity determination based upon spore colour. In the Orpheus wells, the depths to equivalent maturity zones are similar. The mature zones begin as shallow as 500 m depth, with peak oil generation beginning at 900 m in one well.

5. Used together, spore colour, vitrinite reflectance, and pyrolysis can serve as checks on each other and can prevent erroneous interpretations.

CHAPTER 4

A. SUBSIDENCE AND THERMAL HISTORY OF THE ORPHEUS GRABEN

Introduction

The maturation profile of a well, obtained from spore colour, vitrinite reflectance or other methods, is partly a reflection of the thermal history that the well has undergone. The highest temperatures reached will affect the organic matter the most. The changes in the organic matter resulting from elevated temperatures are irreversible, so that a decrease in the geothermal gradient will not be recorded.

In this chapter, the subsidence history for the six wells in the Orpheus region is reconstructed, and probable geothermal history for each well determined by combining maturation profiles with the Lopatin method as refined by Waples (1980). The Lopatin method determines the maturity by combining the effects of temperature and time to produce a Time-Temperature Index (T.T.I.). Waples (1980) has correlated the temperature time index to other indicators of maturation. For the Scotian Shelf, possible temperature distributions through time have been determined using theoretical methods by Keen (1979) and Royden and Keen (1980). Issler (1984), recalibrated the Time-Temperature Index for the Scotian Shelf.

Methods

To calculate the Temperature-Time Index, the burial history and the temperature history or maturity must be known. The burial history was determined for the six wells by combining the palynologic zonation with the absolute time scale of Palmer (1983), and time-depth plots were constructed. For uniformity of construction, the Triassic-Jurassic boundary is assumed to be the onset of subsidence. For those wells that did not reach basement (Meguma Group), depth to basement is estimated from seismic profiles. Paleobathymetry was not plotted since sedimentation in the Orpheus region occurred under either continental or shallow marine conditions (Given, 1977; Jansa and Wade, 1975b).

Once the time-depth plots are complete, a subsurface temperature grid is specified. If the present day geothermal gradient for a well is assumed to have remained constant through time, the temperature grid then consists of a series of equally spaced lines of constant depth (Waples, 1980). Since the Lopatin method assumes that the rate of chemical reaction approximately doubles for every 10°C increase in temperature, the most convenient spacing of isotherms is 10°C.

The Time-Temperature Index is calculated using the expresssion:

$$T.T.I. = \sum_{n\ min}^{n\ max} 2^{n}\ Tn \quad \text{(Waples, 1980)}$$

$$\text{where } n = \frac{\text{initial temperature} - 100}{10}$$

n max,
n min, = highest and lowest temperature intervals encountered.

2 = represents a doubling of the reaction rate with every 10 C increase in temperature.

Tn = amount of time (Ma) spent in each 10 C interval.

Table IV shows the n values for different temperature intervals. The maturity is obtained by summing the product of 2^n and the amount of time (in millions of years) spent in each 10 C temperature interval. Table V (Waples, 1980) shows the correlations among T.T.I., T.A.I. and vitrinite reflectance.

Isslers (1984) recalibration of the Time-Temperature Index was not used in this study. The data are based upon 15 wells drilled in the Scotian Basin, and are specific to the Scotian Basin. These 15 wells are at or near their burial and thermal maximums (Issler, 1984). The Orpheus Graben has undergone different burial and thermal histories; hence Waples' (1980) more general T.T.I. values were used.

TABLE IV

VALUES OF n FOR DIFFERENT TEMPERATURE INTERVALS
(AFTER WAPLES 1980)

HYPOTHETICAL CALCULATION OF TIME TEMPERATURE INDEX
(SHELL FOX I-22 MICMAC FORMATION)

TEMPERATURE INTERVAL °C	n	2^n	T(m.y.)	T.T.I.
40-50	-6	0.0156	12	0.19
50-60	-5	0.0313	10 + 7	0.53
60-70	-4	0.0625	10	0.63
70-80	-3	0.1250		
80-90	-2	0.25		T.T.I.=1.35
90-100	-1	0.50		
100-110	0	1.00		
110-120	1	2.00		
120-130	2	4.00		
130-140	3	8.00		
140-150	4	16.00		

TABLE V

CORRELATION OF TIME TEMPERATURE INDEX TO T.A.I. AND VITRINITE REFLECTANCE (AFTER WAPLES, 1980)

Time-Temperature Index	Thermal Alteration Index	Vitrinite Reflectance (%)
<1	2.25	0.4
3	2.5	0.5
10	2.6	0.6
20	2.7	0.7
30	2.75	0.77
40	2.8	0.85
75	2.9	1.00
110	3.0	1.15
130	3.1	1.22
160	3.2	1.30
170	3.25	1.33
180	3.3	1.36
230	3.4	1.42
300	3.5	1.50
500	3.6	1.75
900	3.75	2.0
23000	4.0	4.0

If the temperature history is not known, but the organic maturity is, then the thermal history can be modeled to determine the temperature distribution through time that will best fit the observed maturity.

Modelling the temperature history of this subsiding basin requires that a model of passive continental margin formation be specified. Three models have been proposed to explain subsiding basins, (Middleton and Falvey, 1983):

1) cooling of the lithosphere before and after breakup (Sleep, 1971; Turcotte and Ahern, 1977);
2) extension of the lithosphere with cooling (Mackenzie, 1978);
3) deep crustal metamorphism and cooling (Falvey, 1974).

For the east coast of North America, extension with subsequent attenuation of the lithosphere (Royden and Keen, 1980; Hellinger and Sclater, 1983; Sawyer et al., 1982) is considered to be the most likely mechanism for rifting and continental breakup. The extension model predicts that thinning of the lithosphere creates a thermal anomaly by the passive upwelling of the hot asthenosphere close to the surface (Sawyer et al., 1982). The result is that the geothermal gradient becomes steeper, with a broad based thermal anomaly occurring under the shelf (Hellinger and Sclater, 1983). The thermal anomaly may cause changes in elevation before and during rifting. Following rifting thermal decay occurs (cooling), the lithosphere thickens and subsidence begins. Sediment loading will enhance subsidence.

It is essential to know the time of the onset of rifting, the duration of rifting and the rate of thermal decay to the present in order to model the temperature history of the basin. The onset of rifting along the Western Atlantic is considered to be at 190 Ma. by Royden and Keen (1980), whereas Sawyer et al. (1982) suggested 200 Ma. Rifting continued for 25 Ma. according to Sawyer et al. (1982), or 15-20 Ma. (Royden and Keen, 1980). The initiation of rifting can be taken as the peak thermal point (Middleton and Falvey, 1983). For the Baltimore Canyon, south of the Scotian Shelf, Sawyer et al. (1982) suggested thermal subsidence began about 175 Ma. with thermal equilibrium being established by the end of the Jurassic (ca 140 Ma). Royden and Keen (1980) suggested the most rapid changes in temperature occurred in the Jurassic and Cretaceous.

For the temperature modeling in this paper the onset of rifting is considered to be 200 Ma., (with an associated thermal peak) and thermal decay beginning after 20-30 Ma. By the early Tertiary, the thermal gradients would probably have been similar to those presently measured in the Orpheus Graben (20 C/km, 1.1 F/100'). Surface temperature is assumed to be 10 C.

The observed maturity is plotted on the depth of burial diagram along with the present day geothermal gradient. The temperature distribution through time is modeled by calculation of the T.T.I. for specific maturation horizons in the context of the thermal model. Once the thermal and burial history of each well has been determined, then the thermal and burial history for the basin can be plotted for different periods of time.

Several factors will affect the spacing and location of isotherms. Conductivity contrasts between the basement and overlying sediments and between the salt and overlying sediments should affect the spacing of isotherms. In the salt, isotherms are interpreted to be farther apart. In sediments overlying the salt, a thermal anomaly will occur so the isotherms will be spaced closer together. The high thermal diffusity of salt may postpone thermal decay.

RESULTS AND DISCUSSION

Burial History of Wells

The burial histories for the wells drilled in the Orpheus Graben are presented in Figures 26 a-f and 27 a-f. Except for Eurydice P-38 and Hercules G-15 where salt movement has created an unconformity, deposition was continuous. The Eurydice and Hercules wells are situated on the axis of the basin over the thickest part of the salt. Diapirism in the middle Jurassic exhumed the Iroquois Formation allowing a localized unconformity to occur in these two wells.

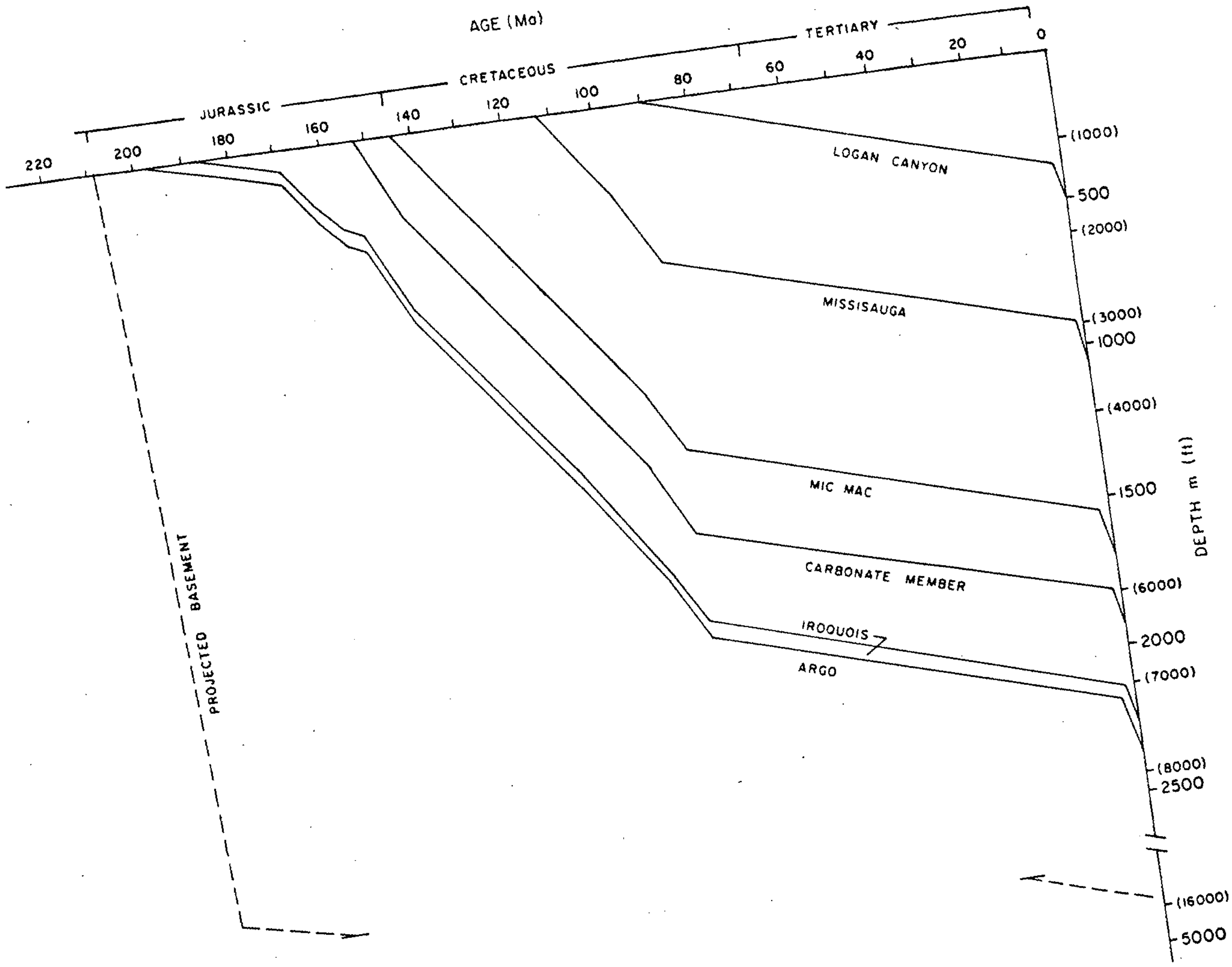

Fig. 26a UNION etal JASON C-20
Burial history assuming little
Tertiary deposition

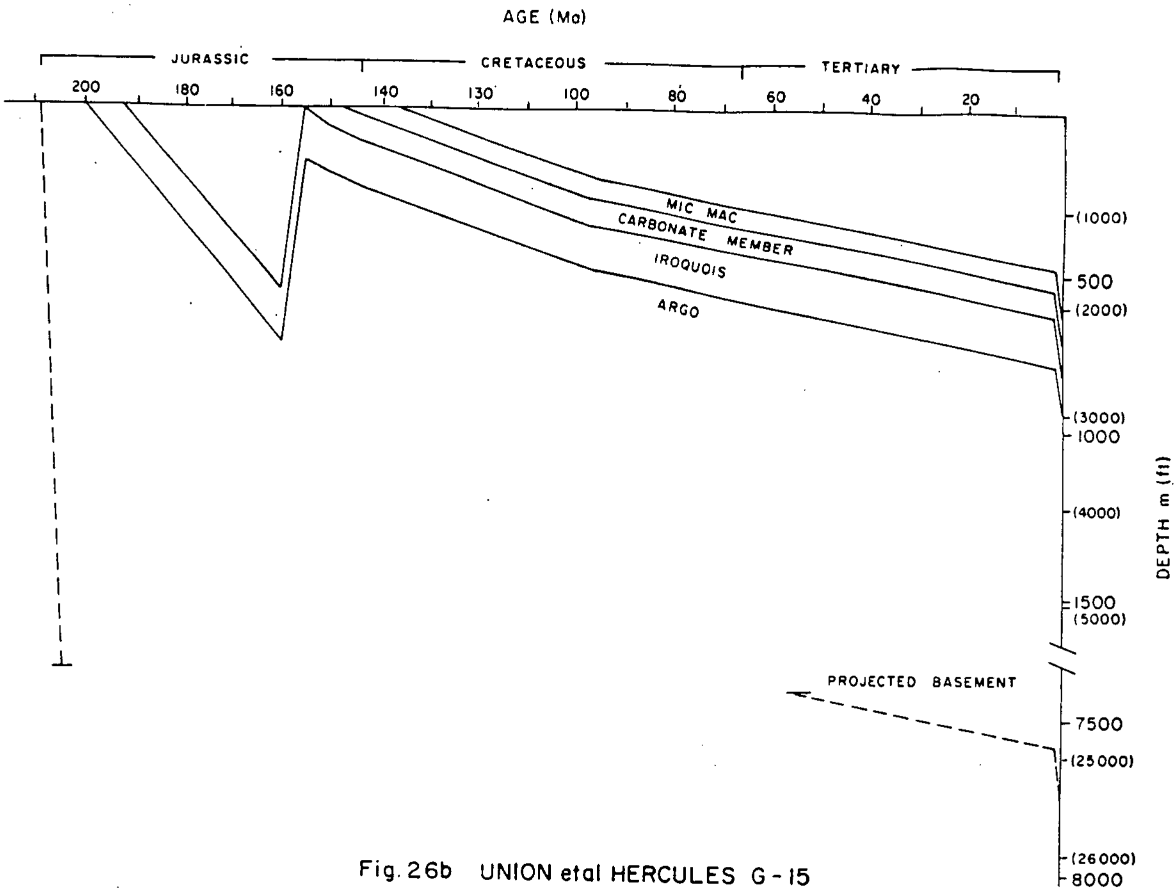

Fig. 26b UNION etal HERCULES G-15

Burial history assuming little Tertiary deposition

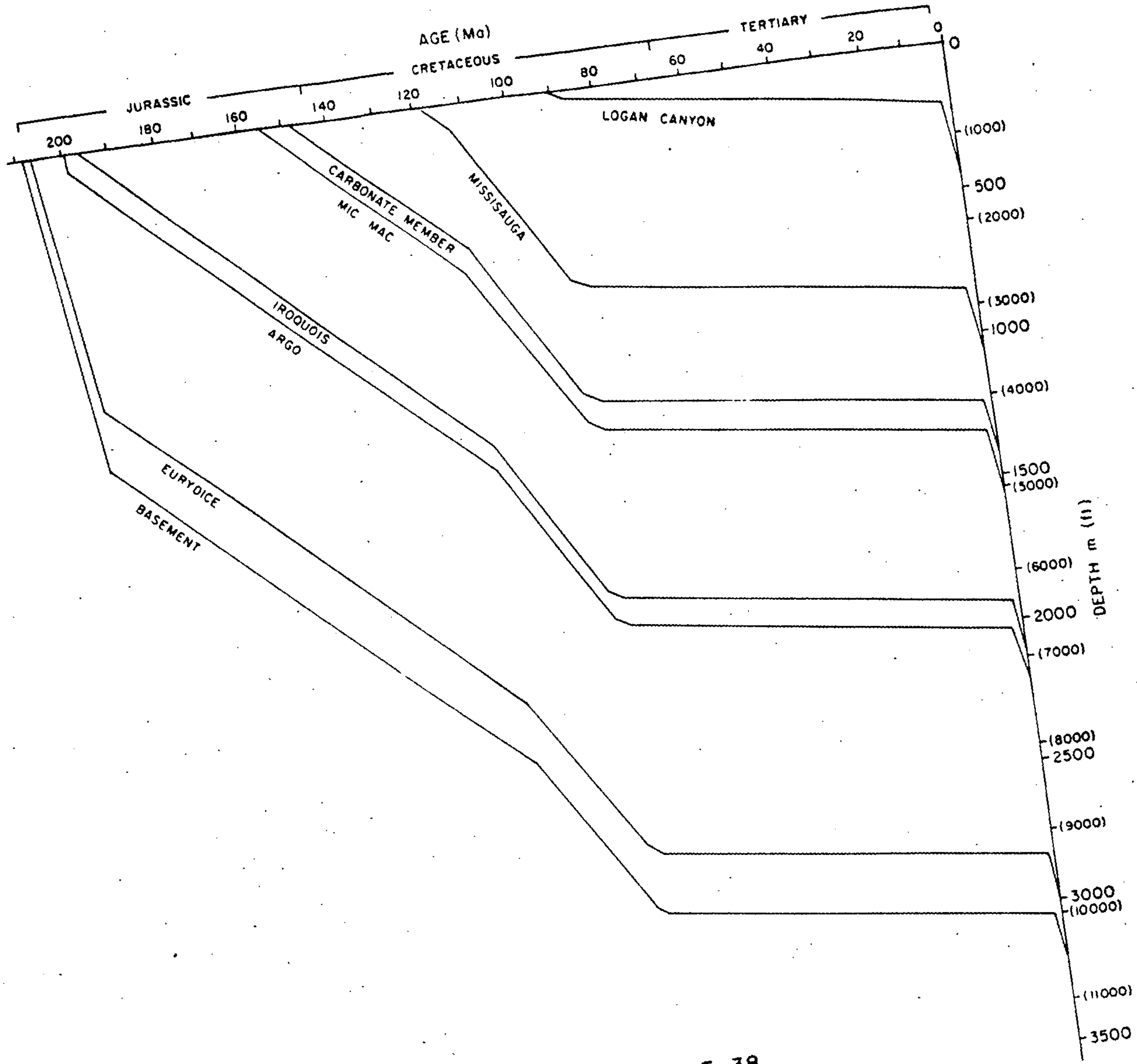

Fig. 26c SHELL ARGO F-38

Burial history assuming little Tertiary deposition

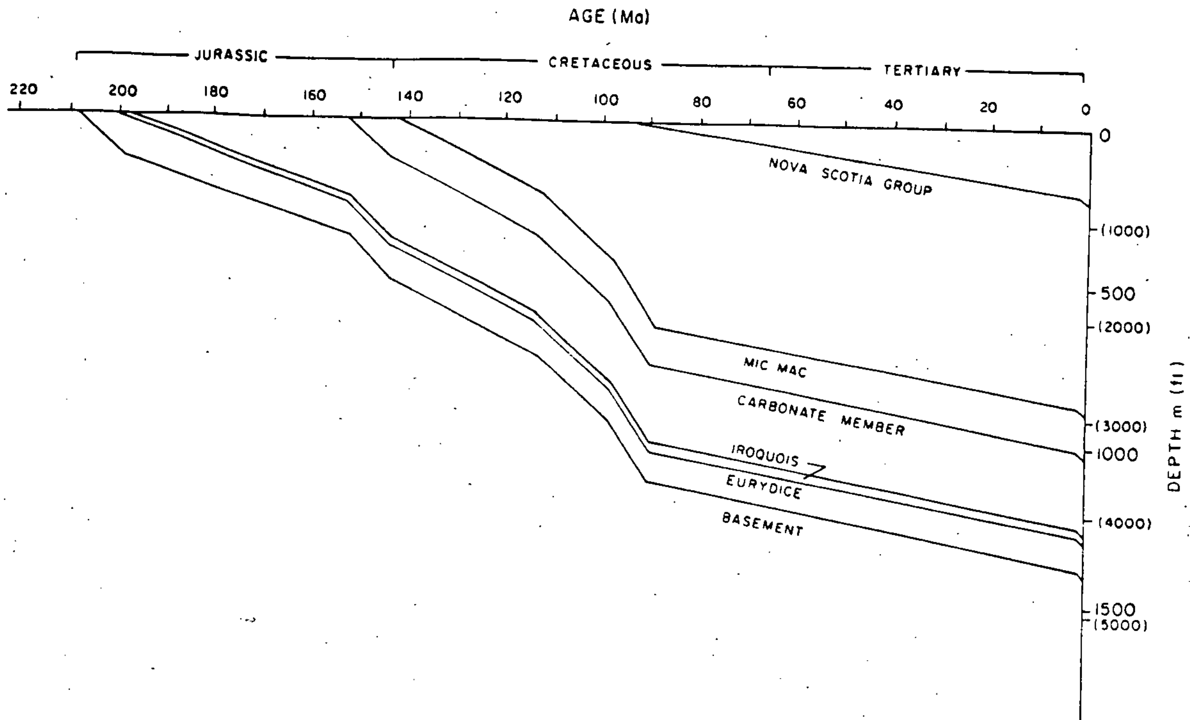

Fig.26d SHELL CROW F-52

Burial history assuming little Tertiary deposition

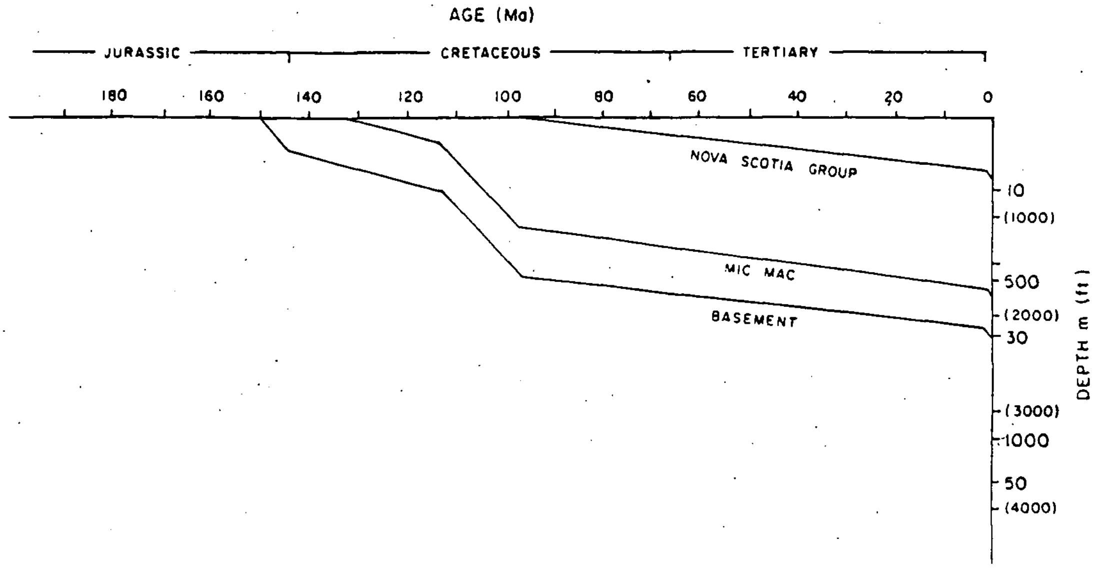

Fig. 26e SHELL FOX I-22
Burial history assuming little Tertiary deposition

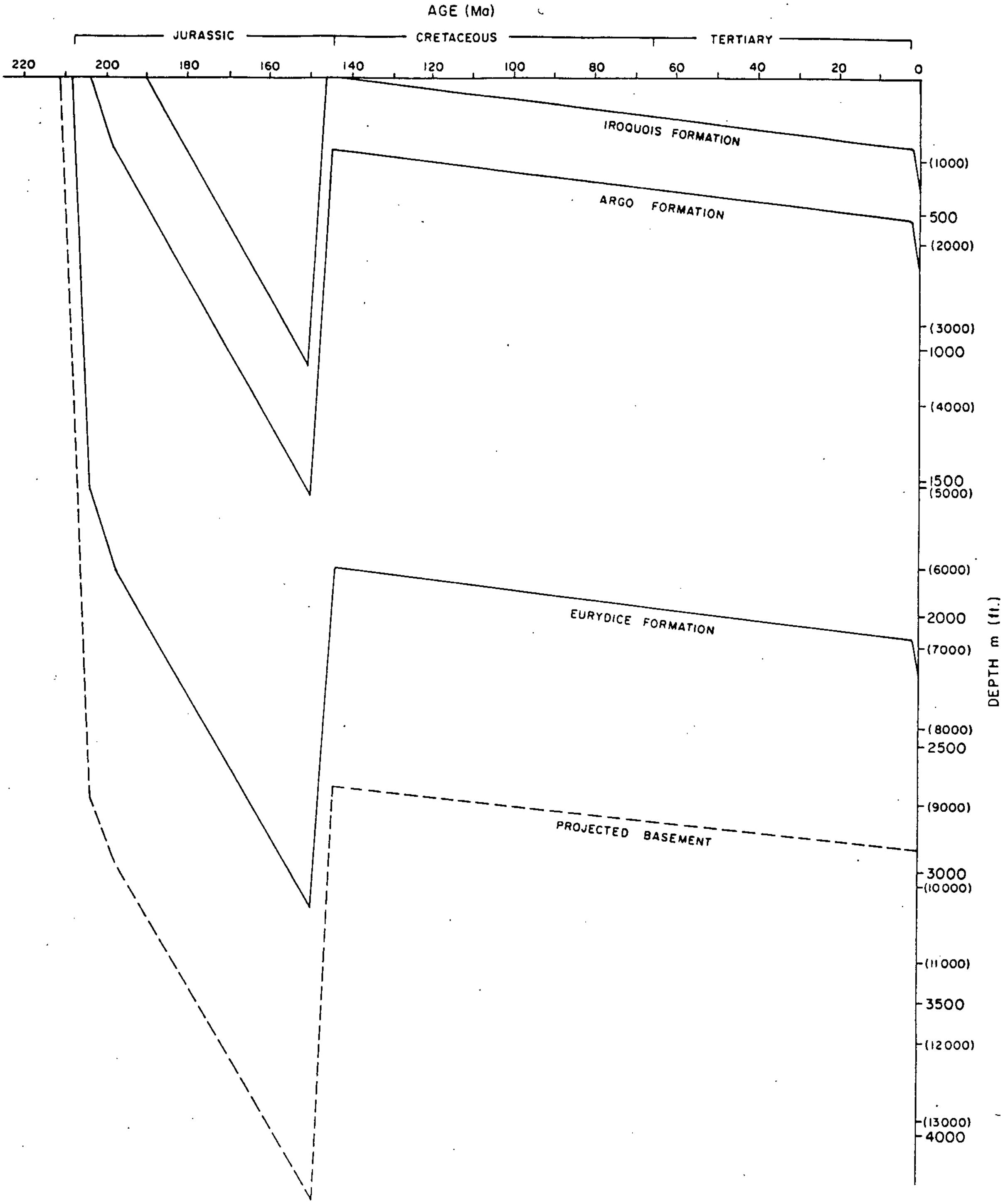

Fig. 26f SHELL EURYDICE P-36

Burial history assuming little Tertiary deposition

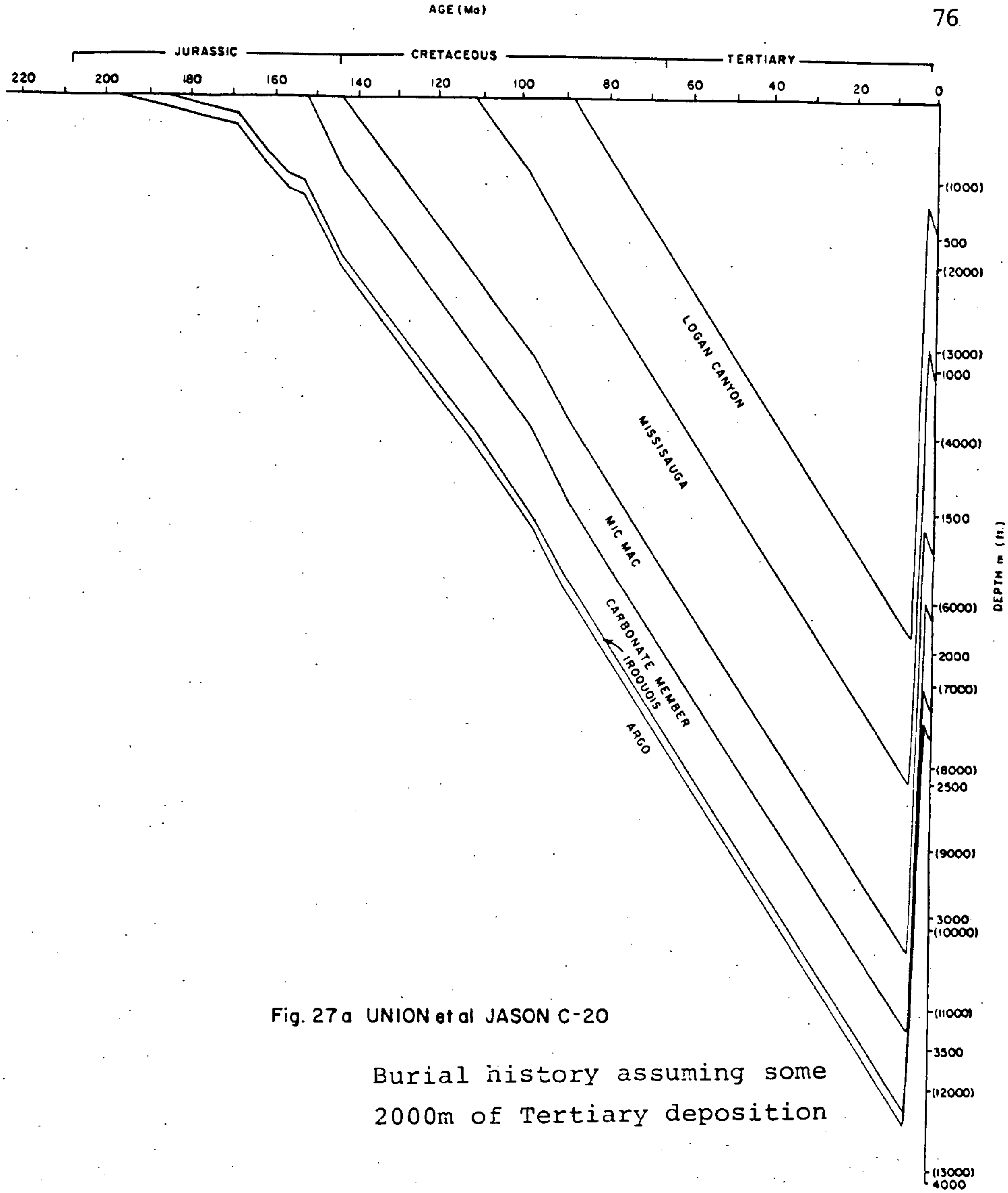

Fig. 27a UNION et al JASON C-20

Burial history assuming some 2000m of Tertiary deposition

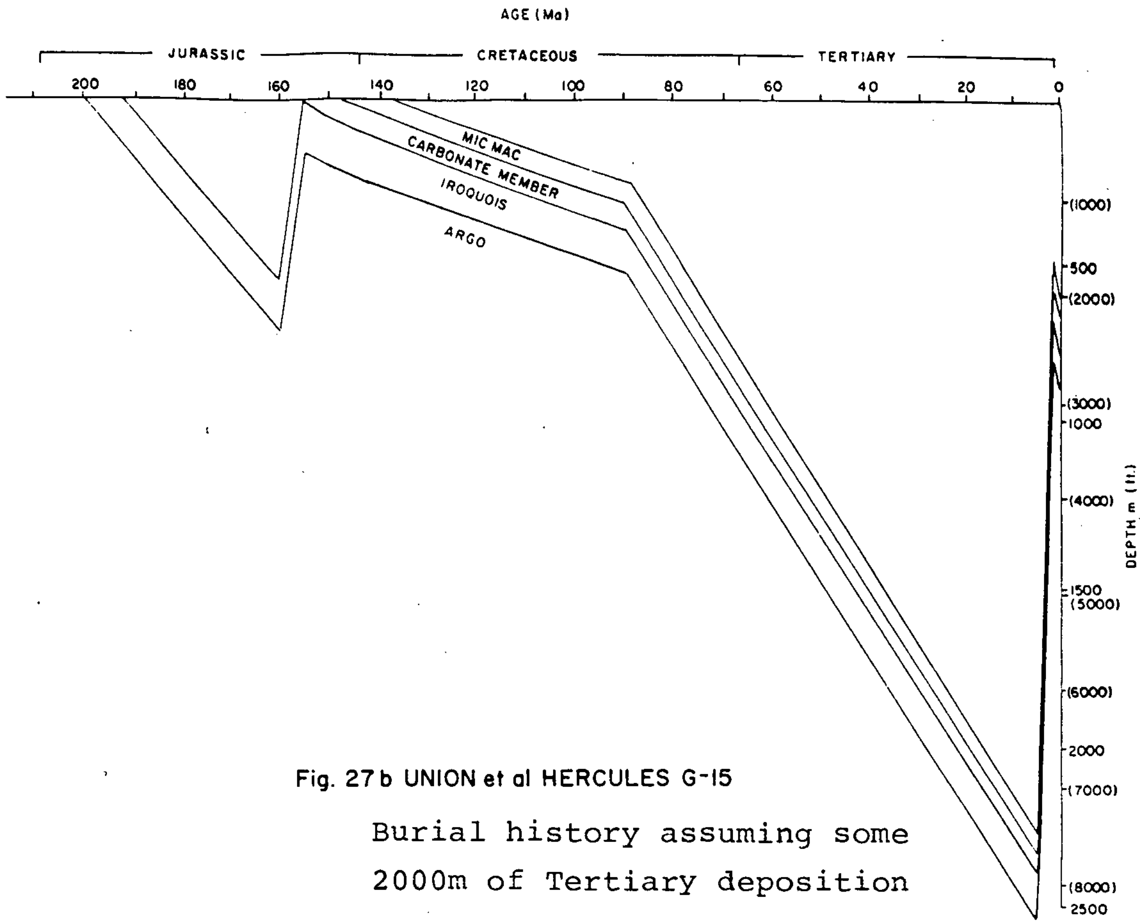

Fig. 27 b UNION et al HERCULES G-15

Burial history assuming some 2000m of Tertiary deposition

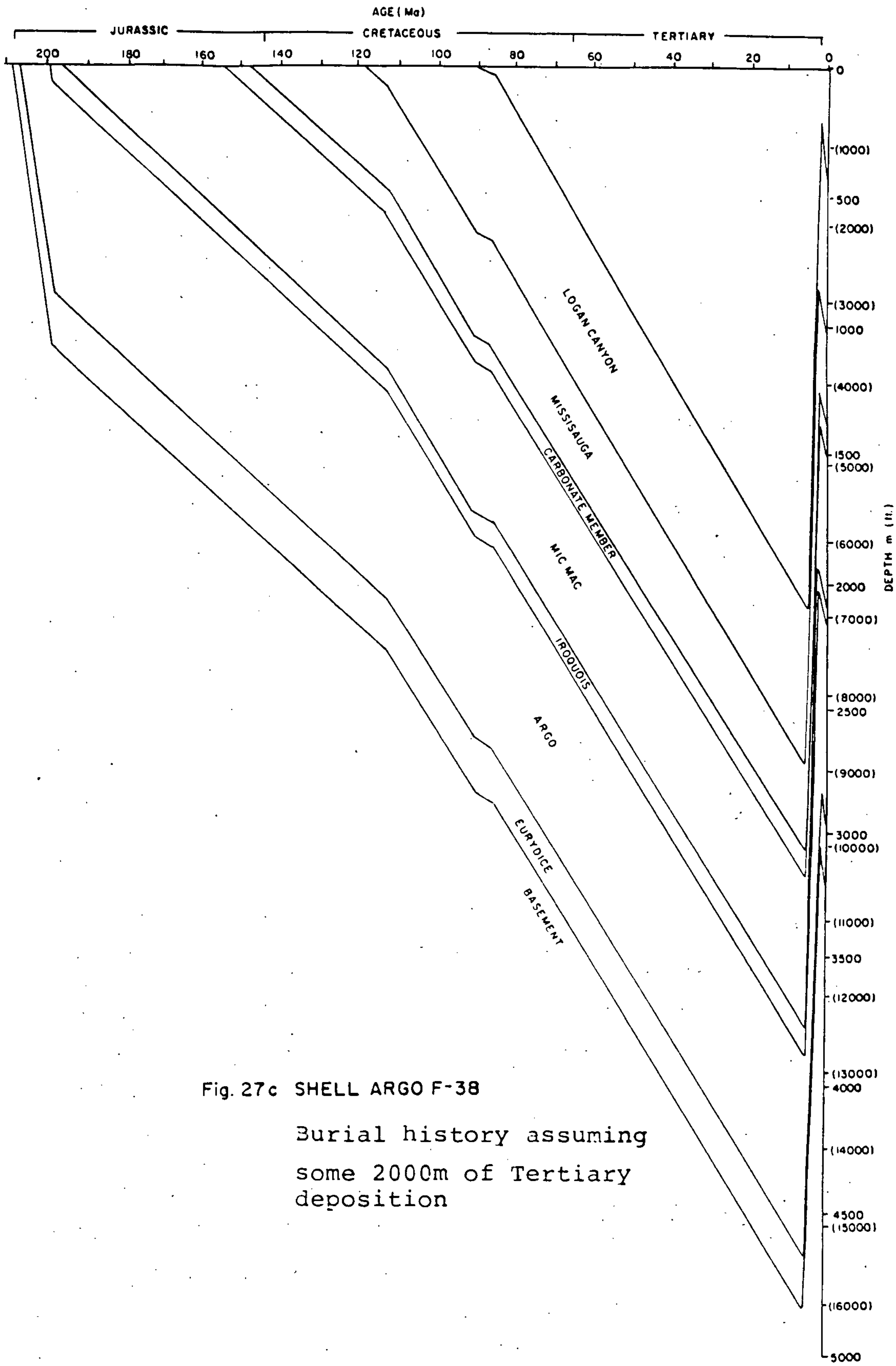

Fig. 27c SHELL ARGO F-38

Burial history assuming some 2000m of Tertiary deposition

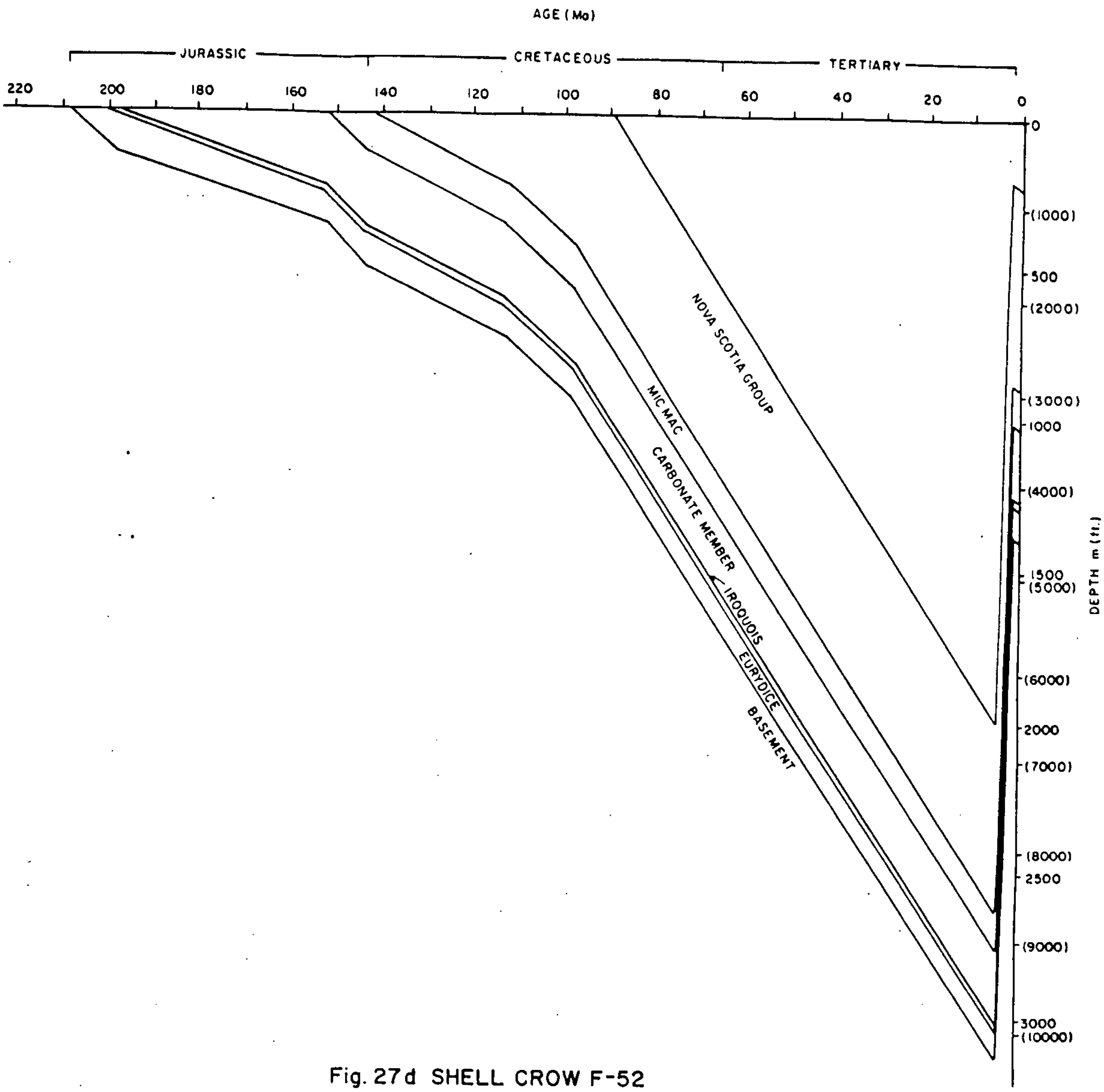

Fig. 27d SHELL CROW F-52

Burial history assuming some 2000m of Tertiary deposition

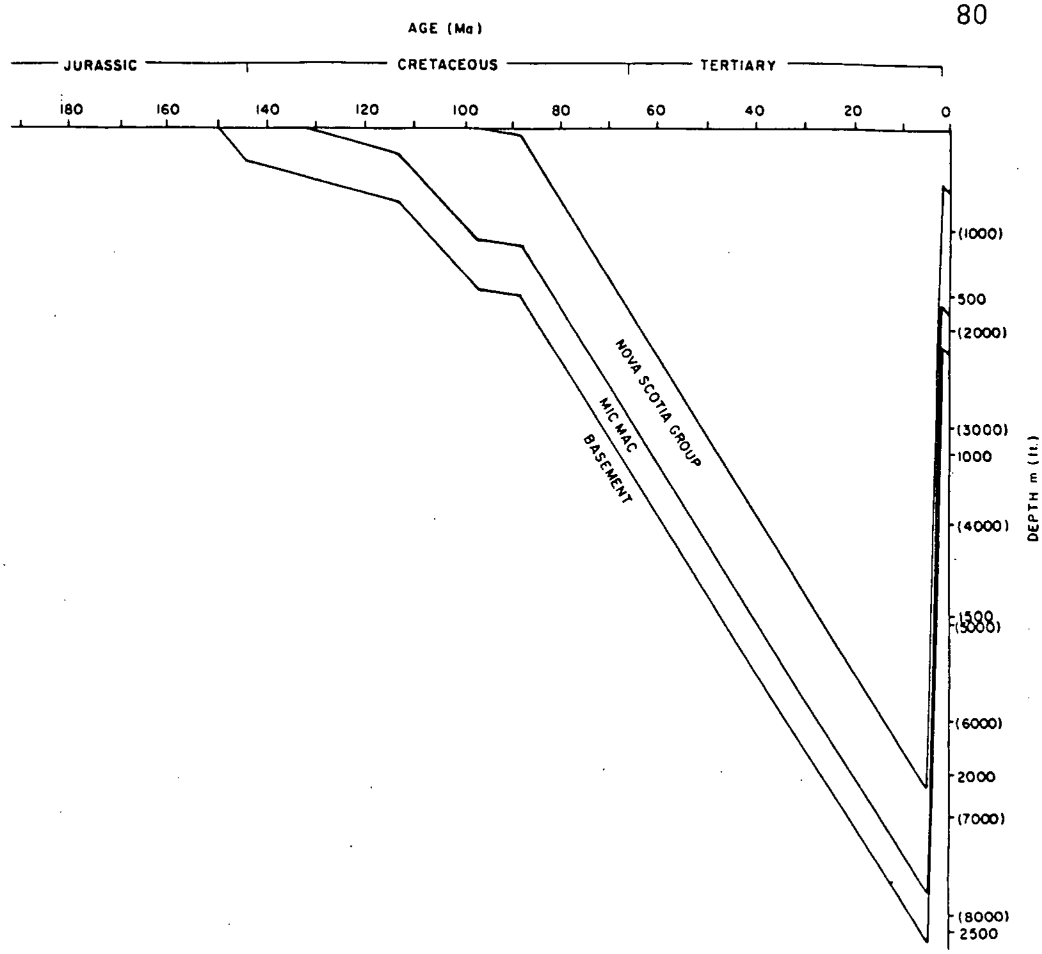

Fig. 27e SHELL FOX I-22
Burial history assuming some
2000m of Tertiary deposition

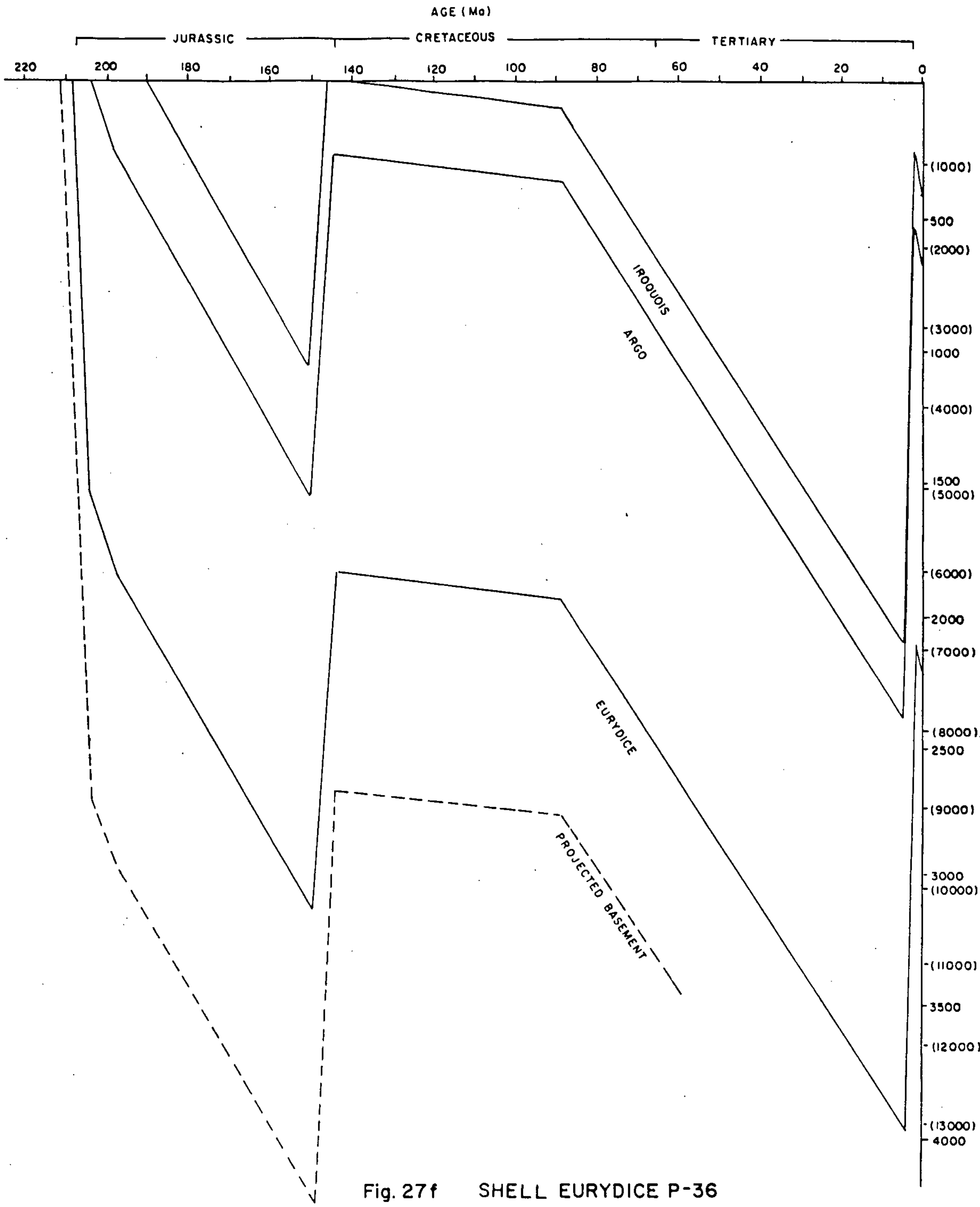

Fig. 27f SHELL EURYDICE P-36

Burial history assuming some 2000m of Tertiary deposition

Initial subsidence in the Orpheus Graben was rapid during the late Triassic and early Jurassic. From the early Jurassic to the Albian, the rate of subsidence decreased slightly. The more rapid subsidence characterizing the Albian to the Cenomanian was probably a response to the separation of the Grand Banks from the European Plate, which occurred at the same time. Since Tertiary rocks were not encountered in any of the wells drilled in the Orpheus Graben two depth of burial models are possible for the Tertiary. Figures 26 a-f depict a minimal amount of Tertiary deposition, resulting in slow subsidence. Figures 27 a-f show deposition of 2000 m of Tertiary strata that were then uplifted and eroded by the Pleistocene. (The 2000 m thickness of Tertiary is obtained by adding together the maximum thicknesses of the four Tertiary formations encountered in Scotian Shelf edge wells, farther seaward). Actual Tertiary deposition probably falls between these two models.

Basin Subsidence

Subsidence in the Orpheus Graben is shown at four different periods in Figures 28 a-d. By 200 Ma. a significant amount of subsidence had occurred in the axis of the basin. The Canso Ridge was exposed at this time, probably shedding sediments into the salt.

Orpheus Graben - 200 Ma. 10X Vertical Exaggeration

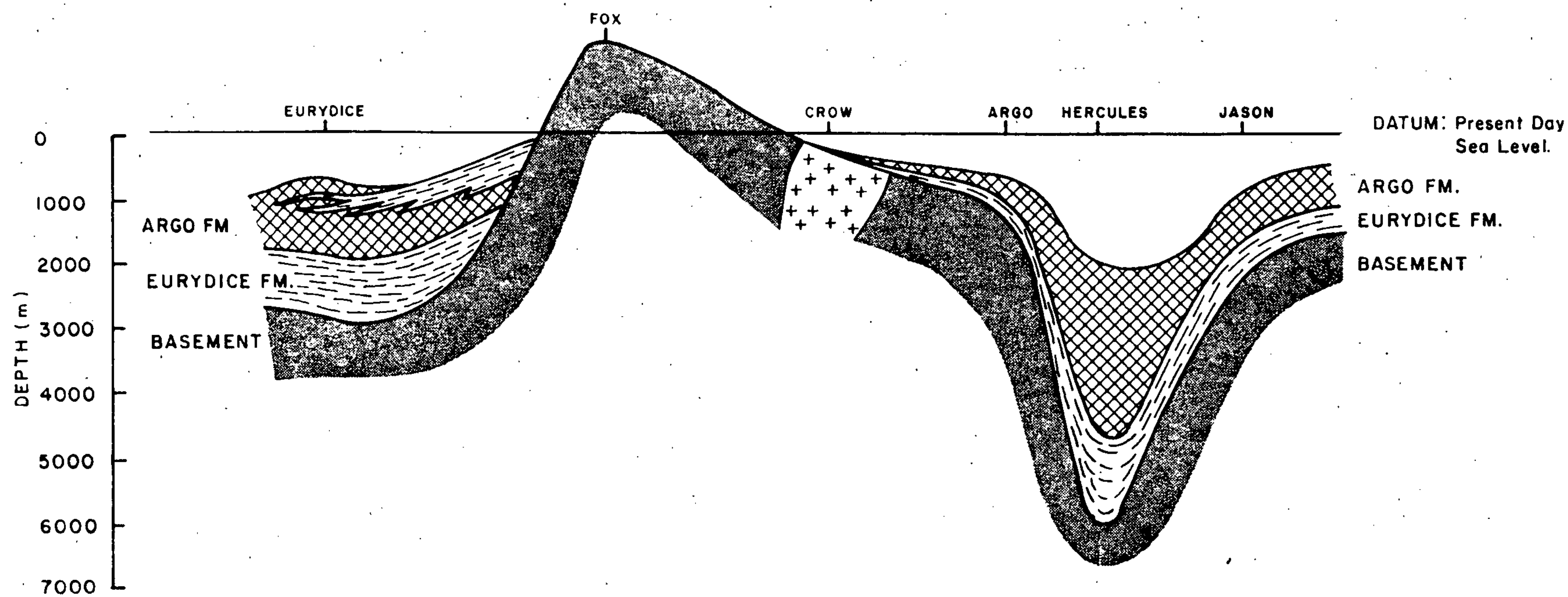

Fig. 28a Cross section of the Orpheus Graben during the early Jurassic

Orpheus Graben - 144 Ma. 10X Vertical Exaggeration

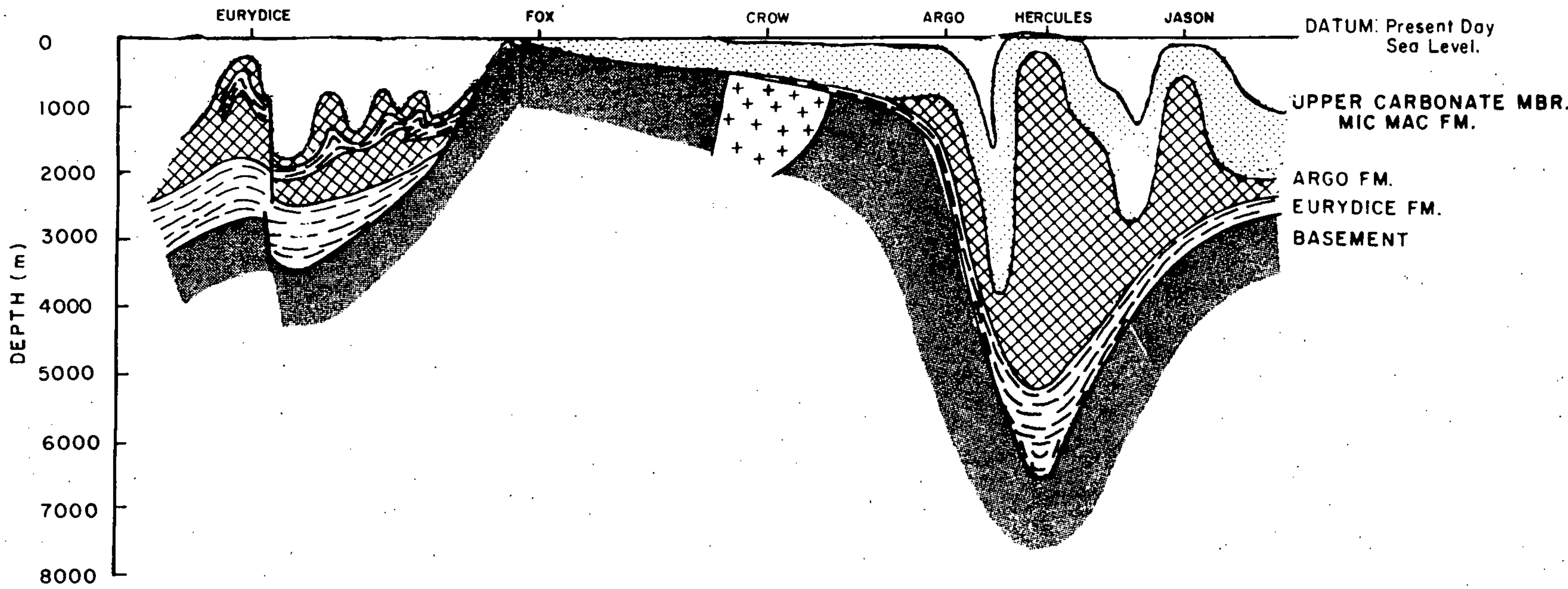

Fig. 28 b Cross section of the Orpheus Graben at the Jurassic-Cretaceous boundary.

Orpheus Graben - 66 Ma. 10X Vertical Exaggeration

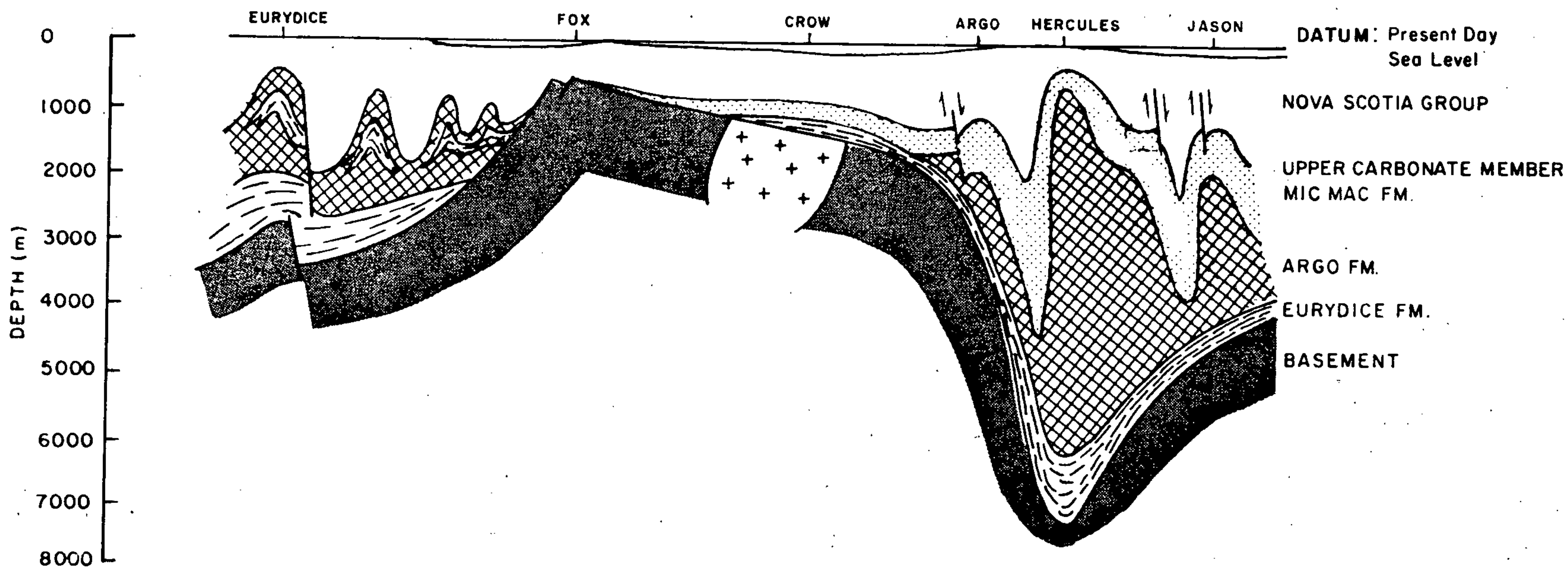

Fig. 28c Cross section of the Orpheus Graben at the Cretaceous-Tertiary boundary

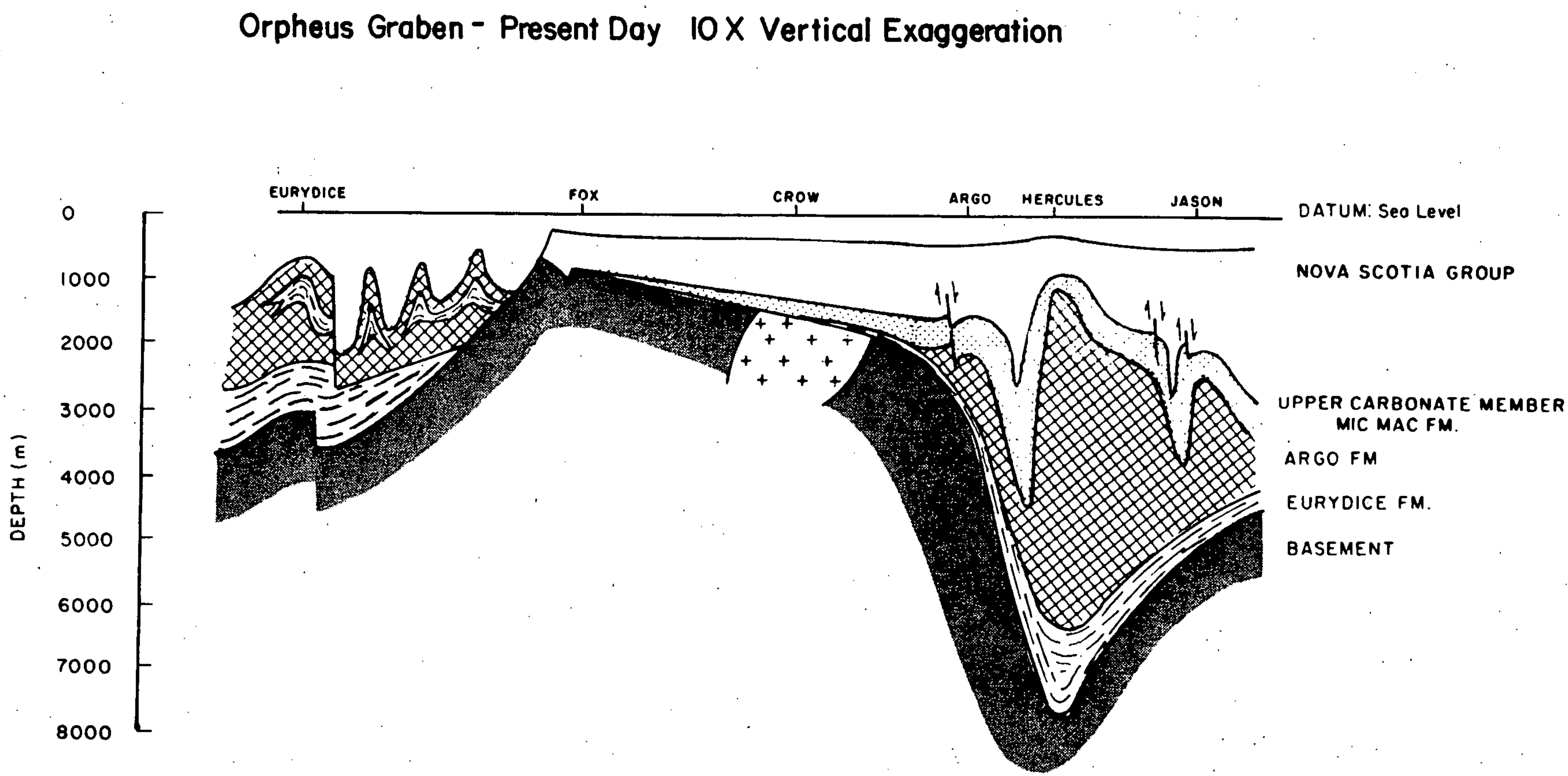

Fig. 28d Cross section of the Orpheus Graben

By 144 Ma., diapirs and salt ridges had become prominent at Eurydice and Hercules (Fig. 28b). Sedimentation patterns were probably affected by salt diapirs. Through a combination of erosion and subsidence, the Canso Ridge had become covered by sediments of the MicMac Formation.

From 144 Ma. to the present (Fig. 28 b-d) general subsidence occurred, accompanied by faulting over the diapiric structures. The amount of subsidence occurring during the Tertiary would depend upon which geological model is used.

Temperature History

Two possible temperature distributions were considered for the six wells drilled in the Orpheus region: 1.) A simple temperature history with double the initial geothermal gradient (Figures 29 a-f), with rapid Tertiary subsidence and uplift, and 2.) a complex temperature history (initial high geothermal gradients) with slow Tertiary subsidence (Figures 30 a-f).

For the complex temperature history an initial geothermal gradient was determined. Different geothermal gradients were tested for each well by calculating the T.T.I. for those gradients and comparing the result with the observed maturity. Table VI compares the initial geothermal gradients for the complex temperature history that best fit the observed maturity, and the simple temperature history to the present geothermal gradients. (Present geothermal gradients provided by Shell Canada Resources Ltd.)

TABLE VI

COMPARISON OF POSSIBLE INITIAL GEOTHERMAL GRADIENTS TO THE PRESENT GEOTHERMAL GRADIENTS

Well	Present geothermal gradient	Complex Temperature History calculated initial geothermal gradient	Simple Thermal History initial geothermal gradient
Jason C-20	30° C/km	120° C/km	60° C/km
Hercules G-15	45° C/km	120° C/km	90° C/km
Argo F-38	20° C/km	100° C/km	40° C/km
Crow F-52	22° C/km	120° C/km	44° C/km
Fox I-20	44° C/km	150° C/km	88° C/km
Eurydice P-38	20° C/km	70° C/km	40° C/km

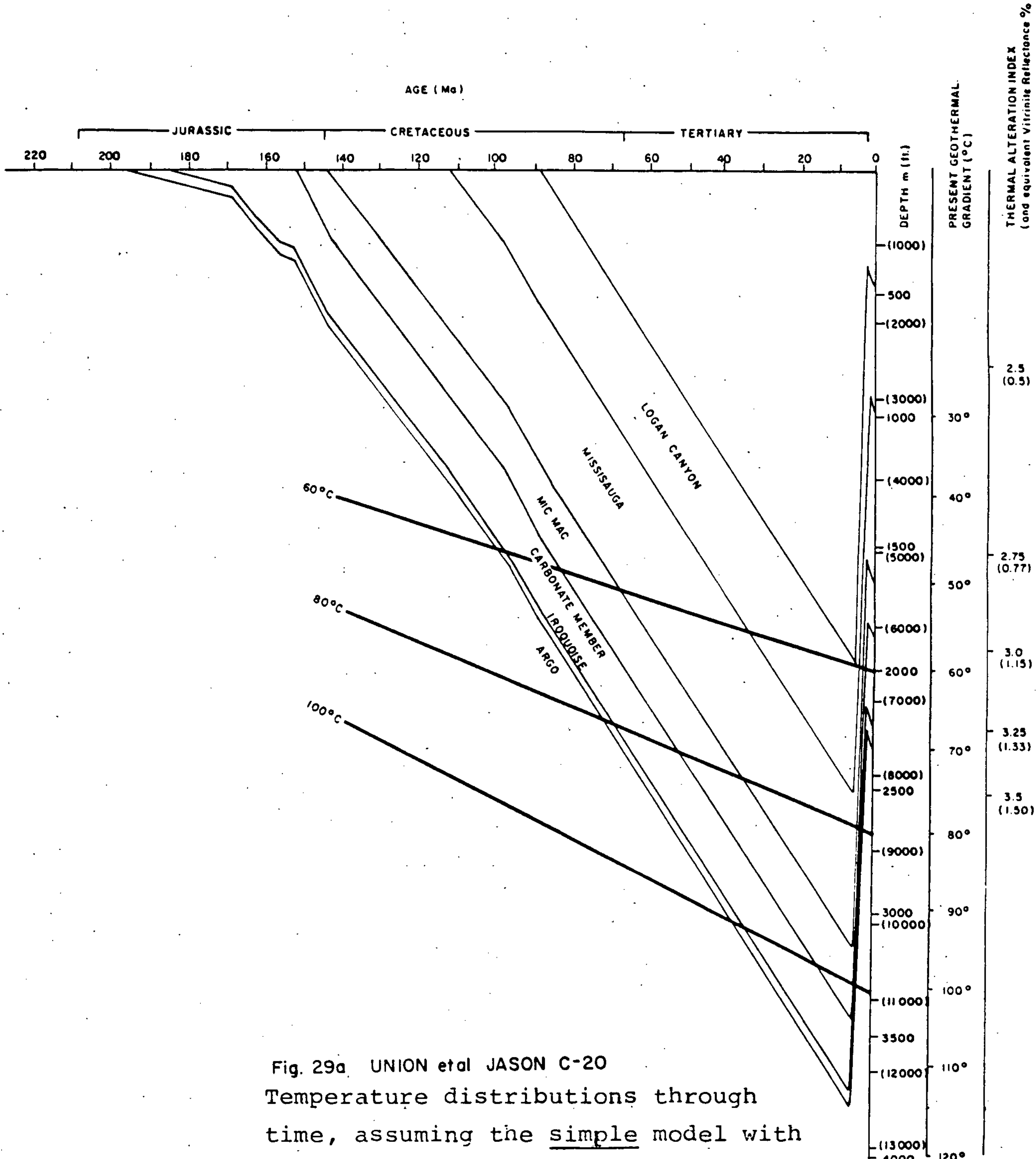

Fig. 29a UNION etal JASON C-20
Temperature distributions through time, assuming the simple model with some 2000m of Tertiary deposition

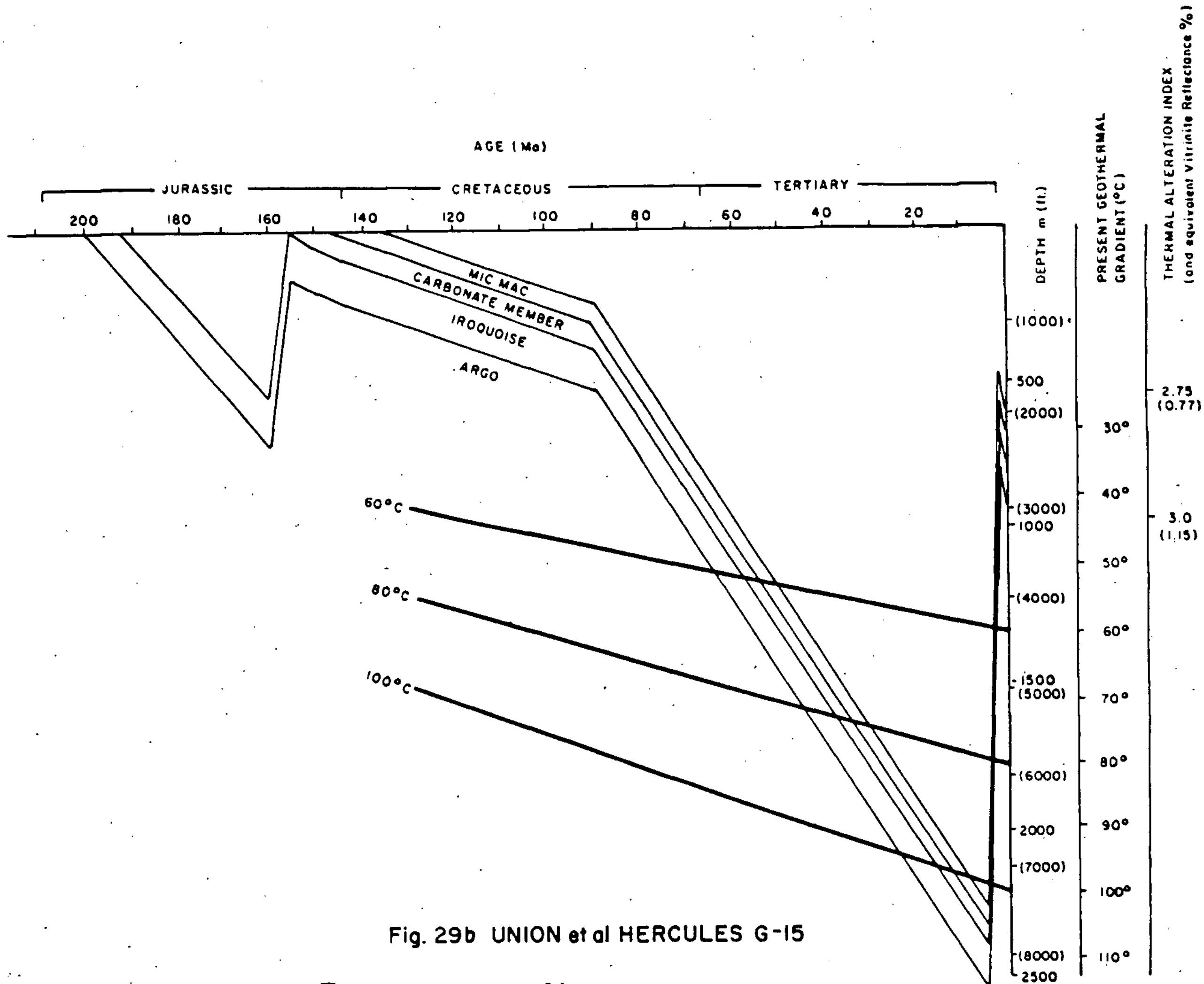

Fig. 29b UNION et al HERCULES G-15

Temperature distributions through time, assuming the simple model with some 2000m of Tertiary depostion

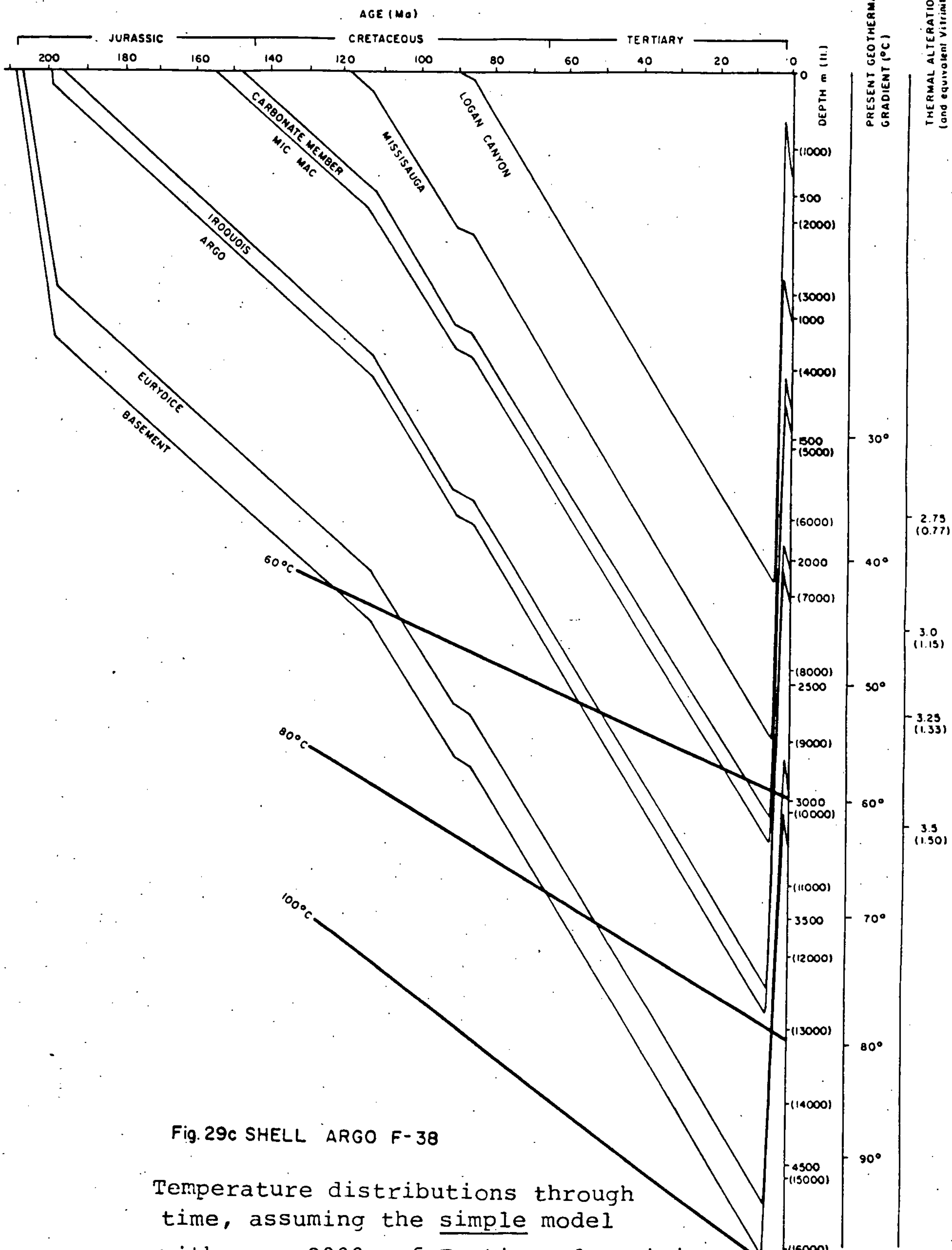

Fig. 29c SHELL ARGO F-38

Temperature distributions through time, assuming the simple model with some 2000m of Tertiary deposition

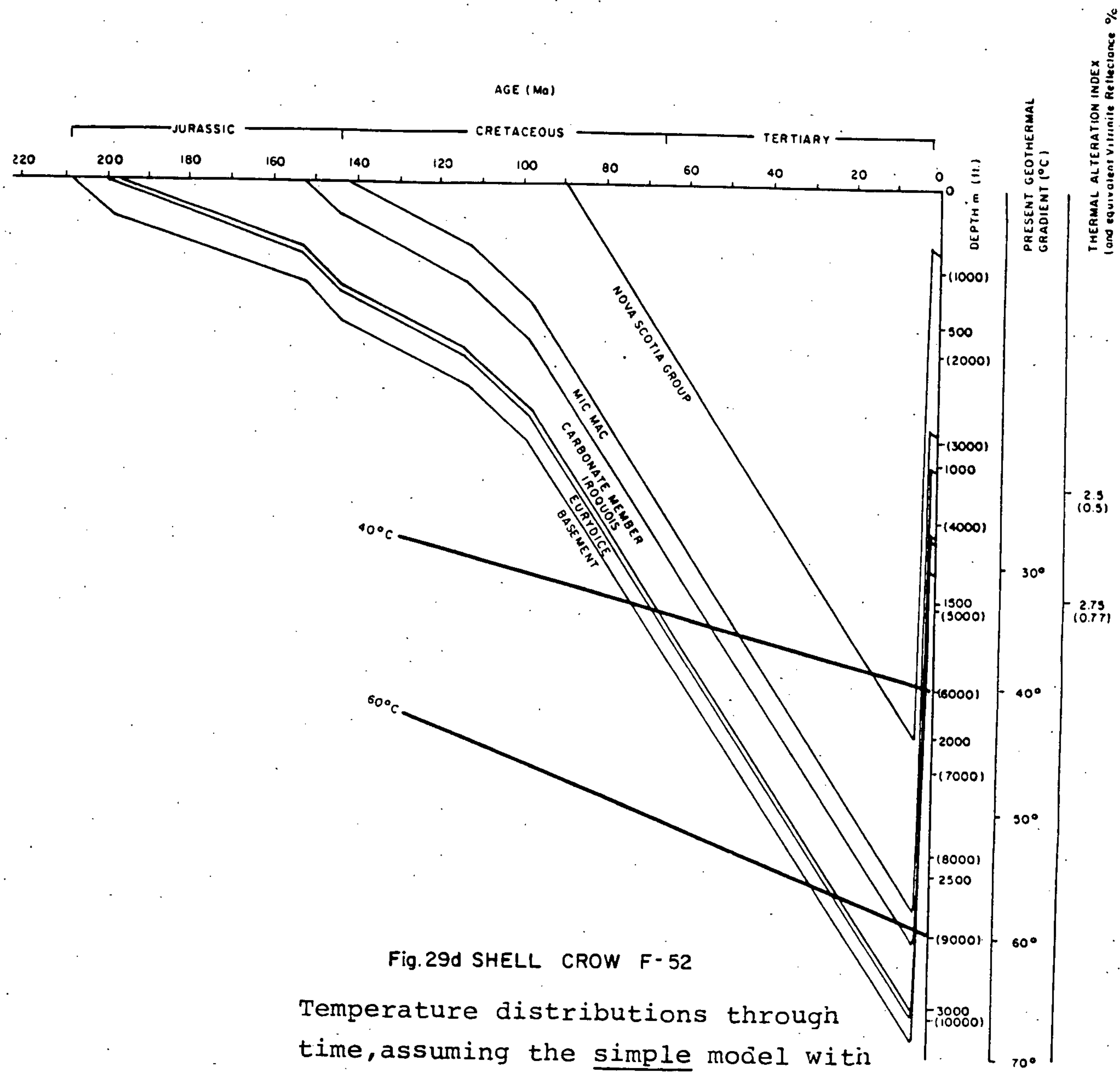

Fig.29d SHELL CROW F-52

Temperature distributions through time, assuming the simple model with some 2000m of Tertiary deposition

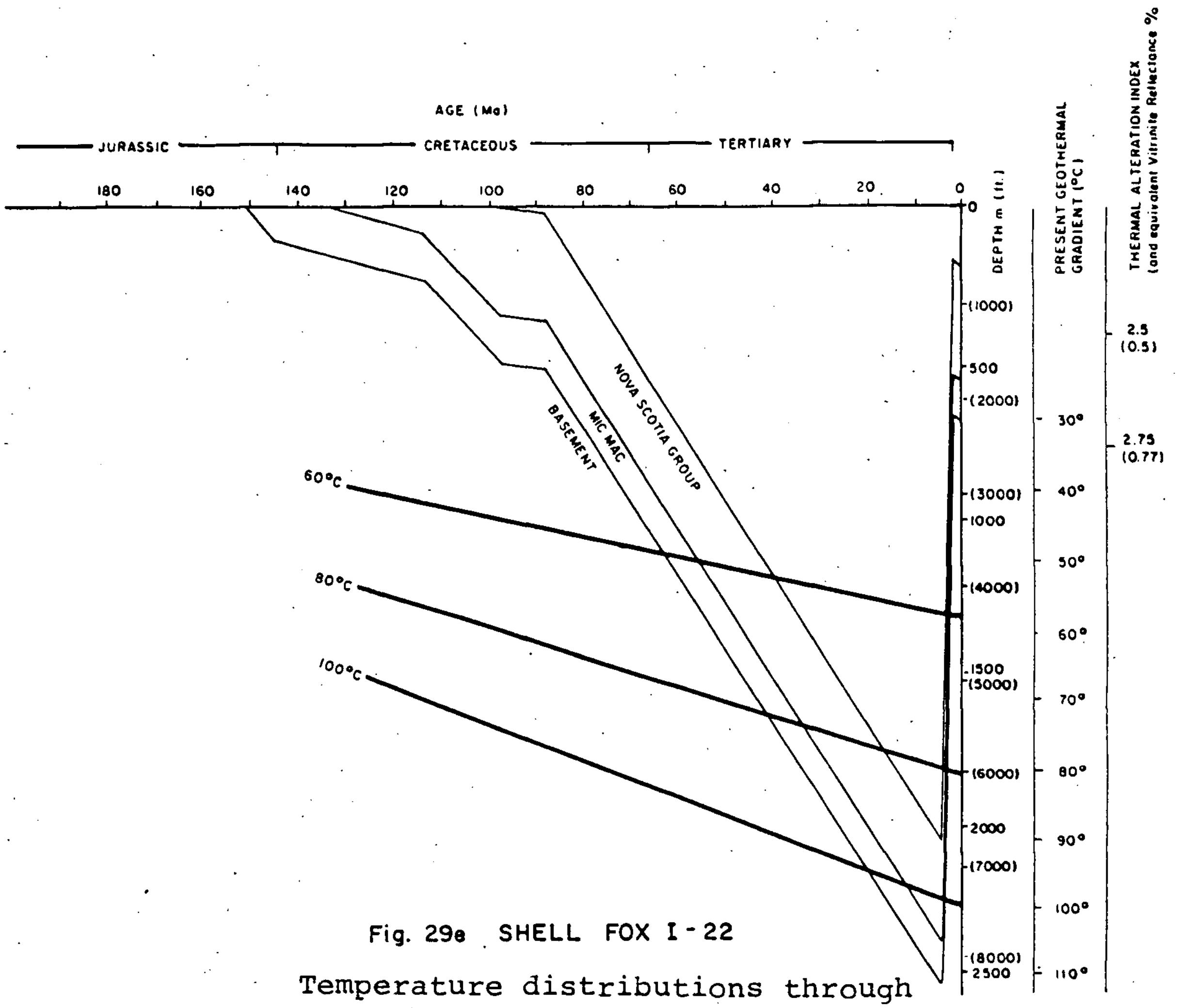

Fig. 29e SHELL FOX I-22

Temperature distributions through time, assuming the simple model with some 2000m of Tertiary deposition

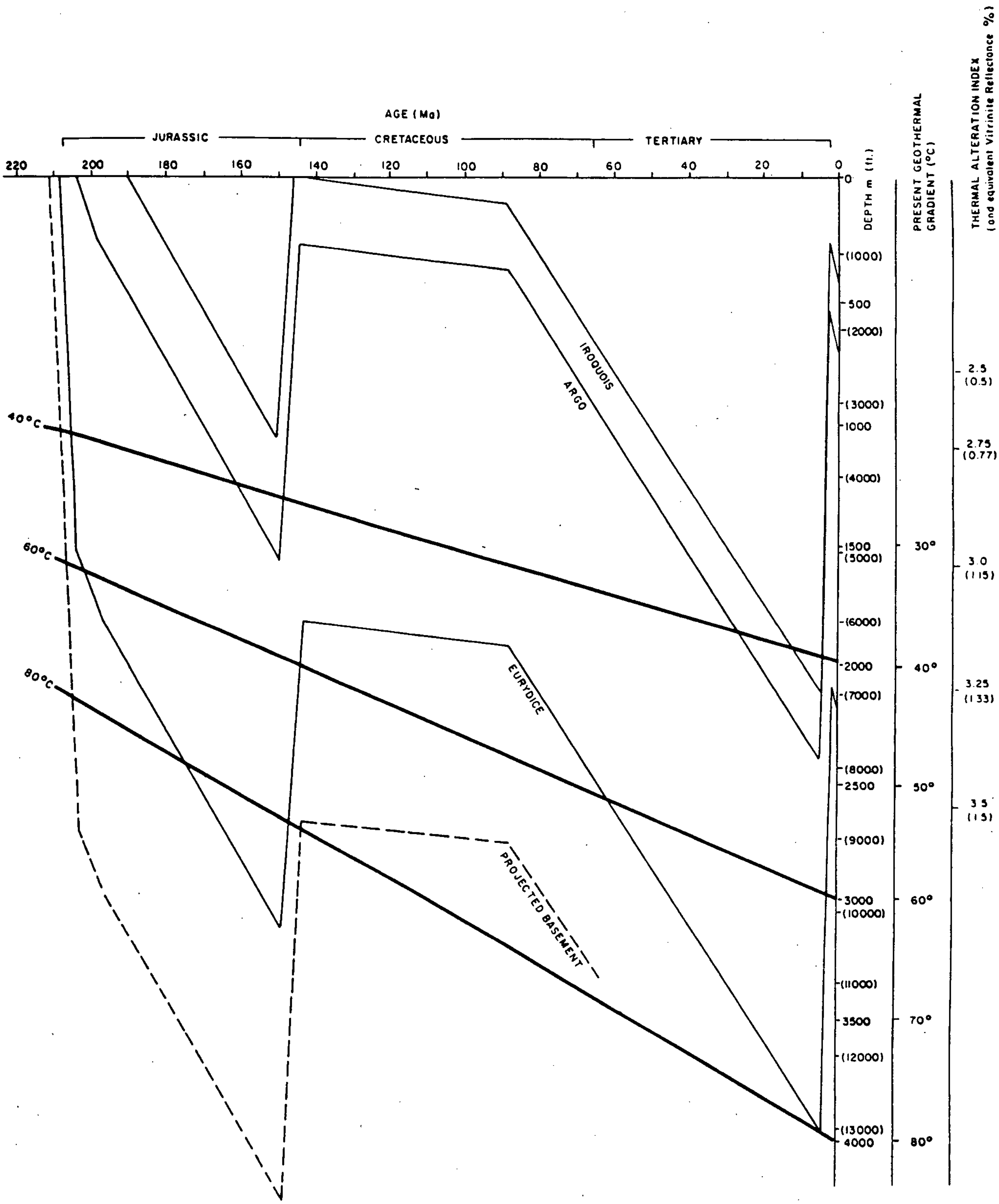

Fig. 29f SHELL EURYDICE P-36

Temperature distributions through time, assuming the simple model with some 2000m of Tertiary deposition

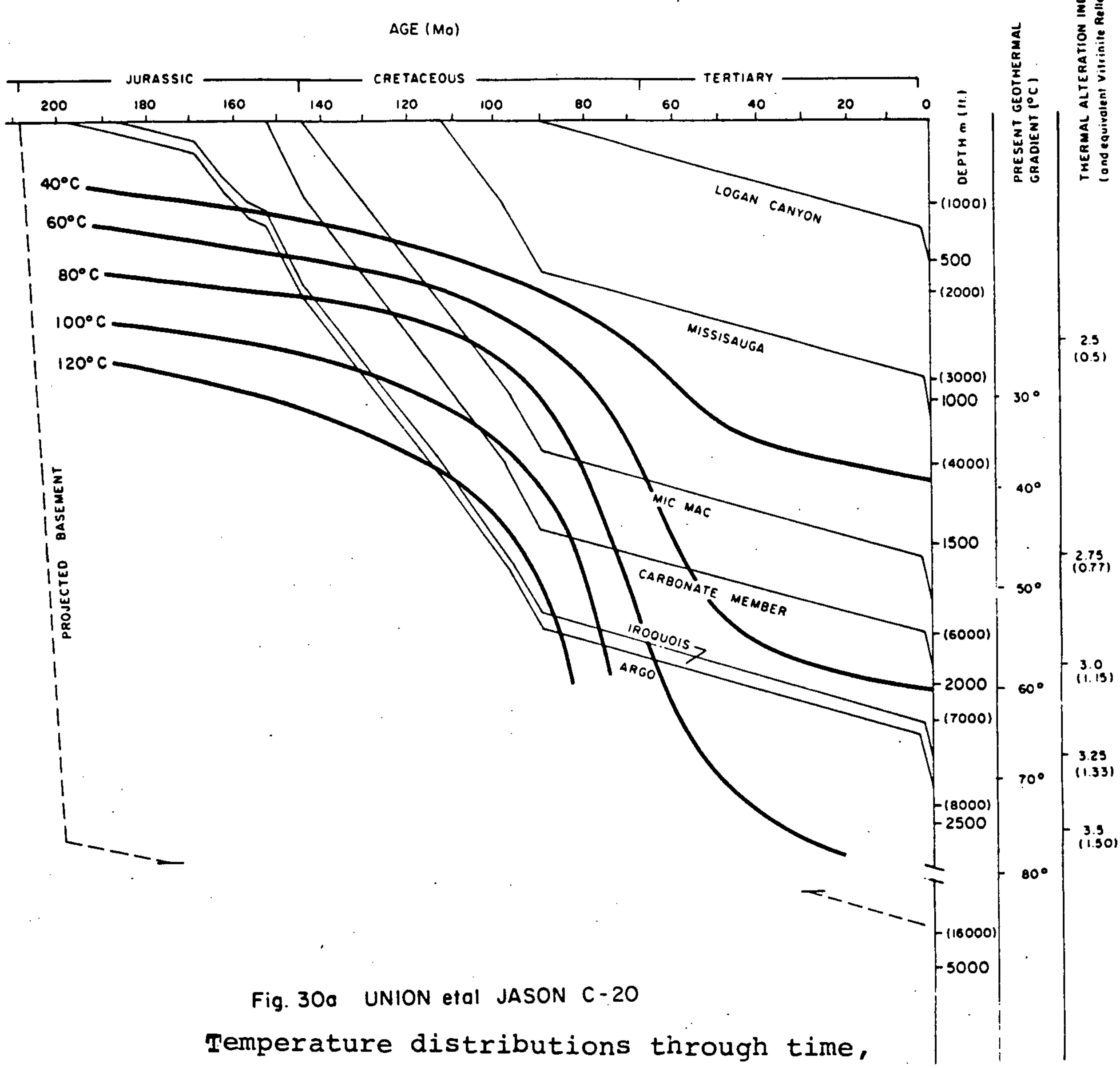

Fig. 30a UNION etal JASON C-20

Temperature distributions through time, assuming the <u>complex</u> model with minimal Tertiary deposition

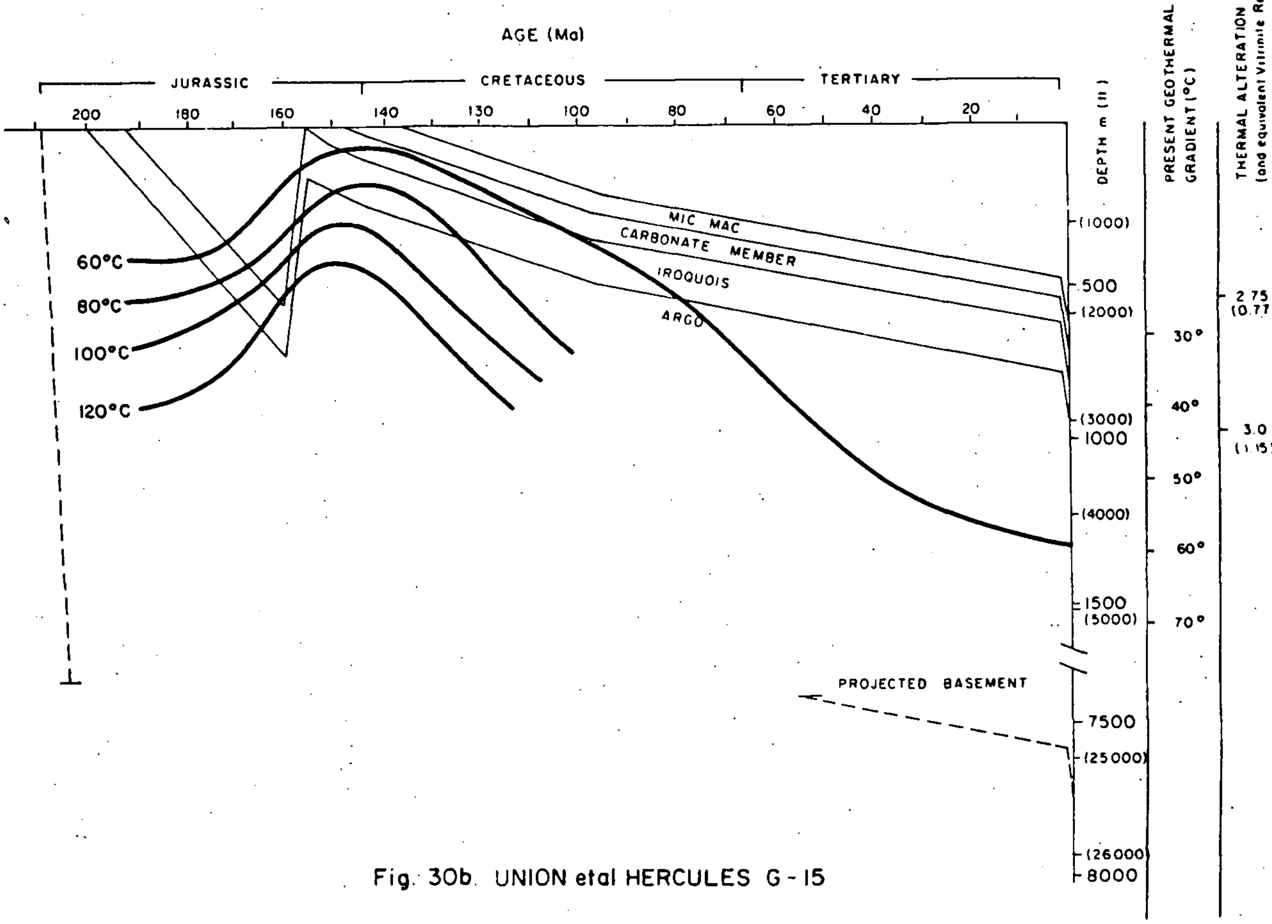

Fig. 30b. UNION etal HERCULES G-15

Temperature distributions through time, assuming the complex model with minimal Tertiary deposition

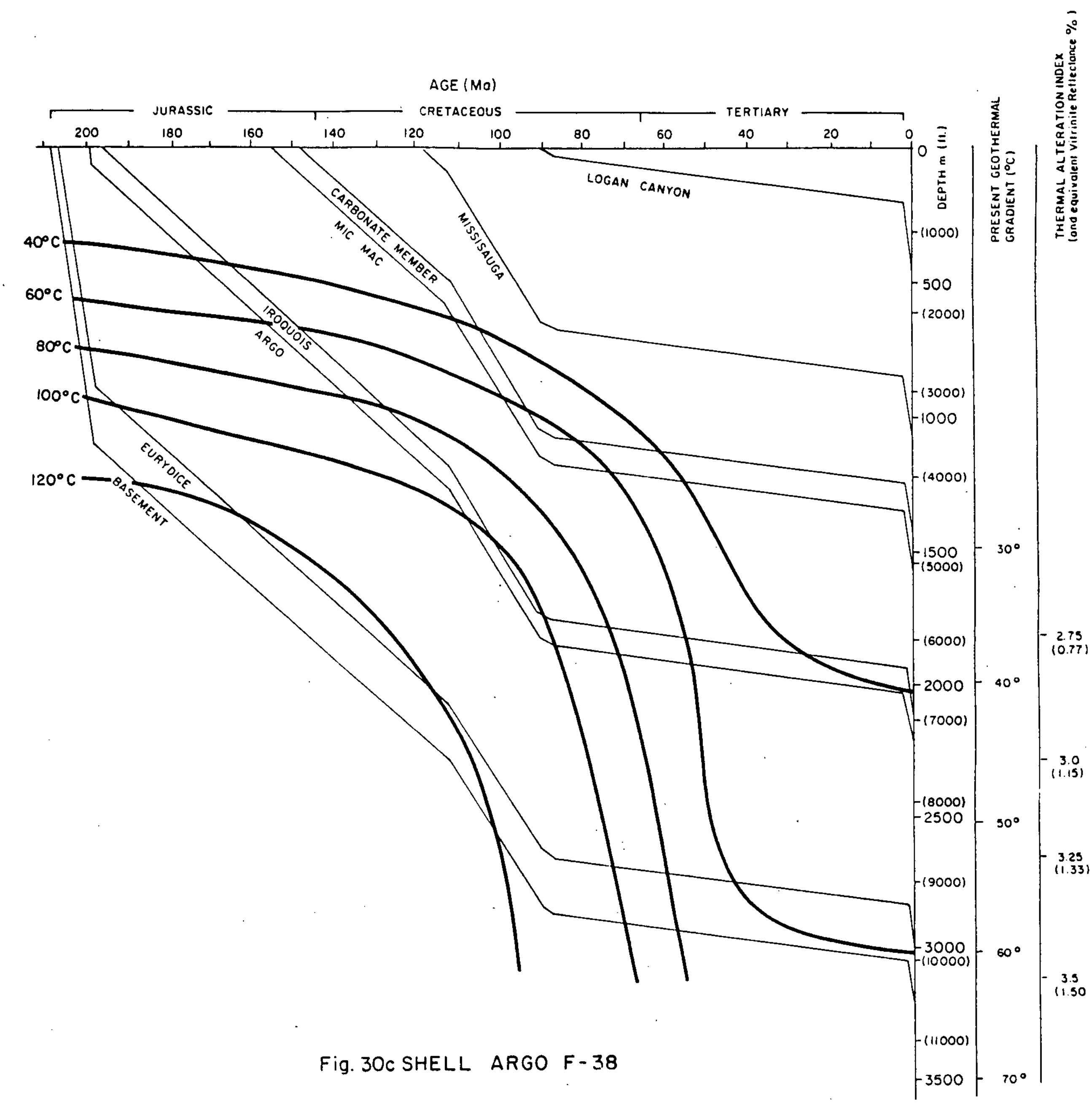

Fig. 30c SHELL ARGO F-38

Temperature distributions through time assuming the <u>complex</u> model with minimal Tertiary deposition

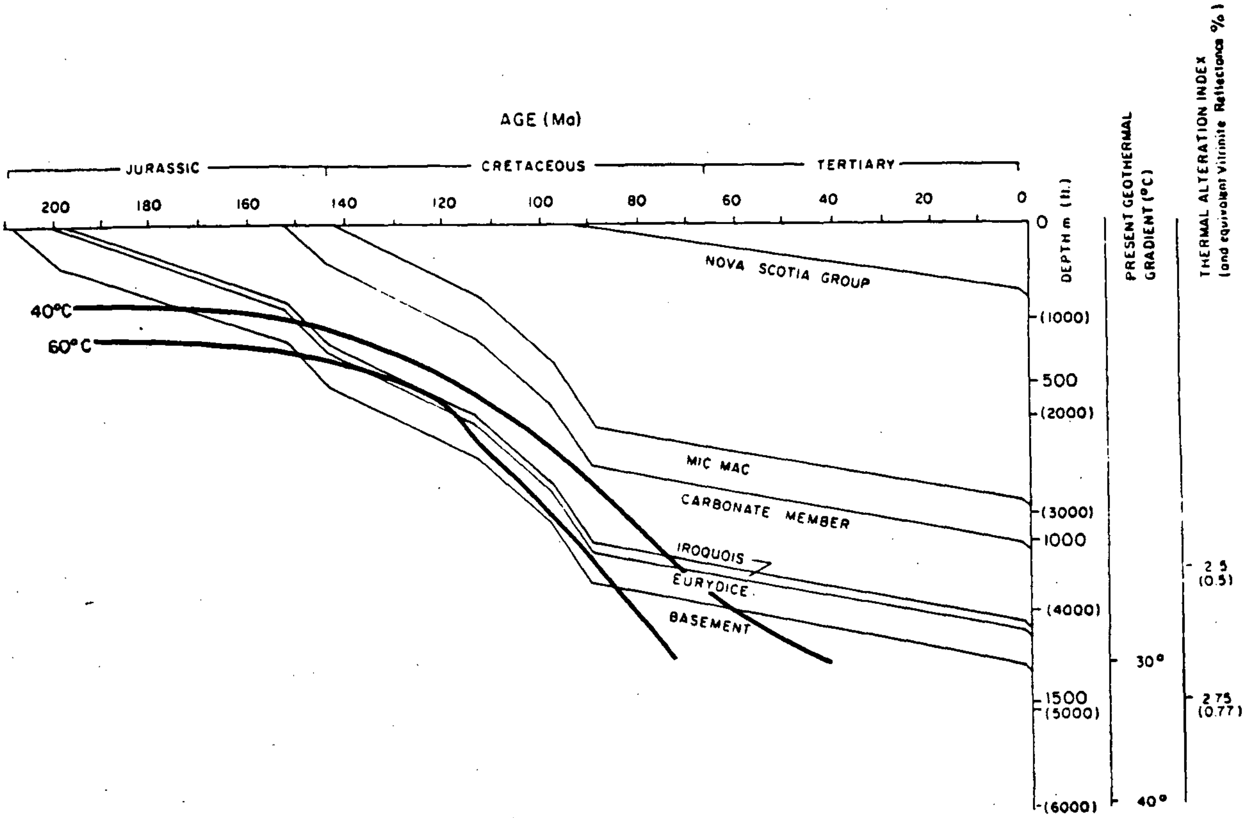

Fig. 30d SHELL CROW F-52

Temperature distributions through time, assuming the <u>complex</u> model with minimal Tertiary deposition

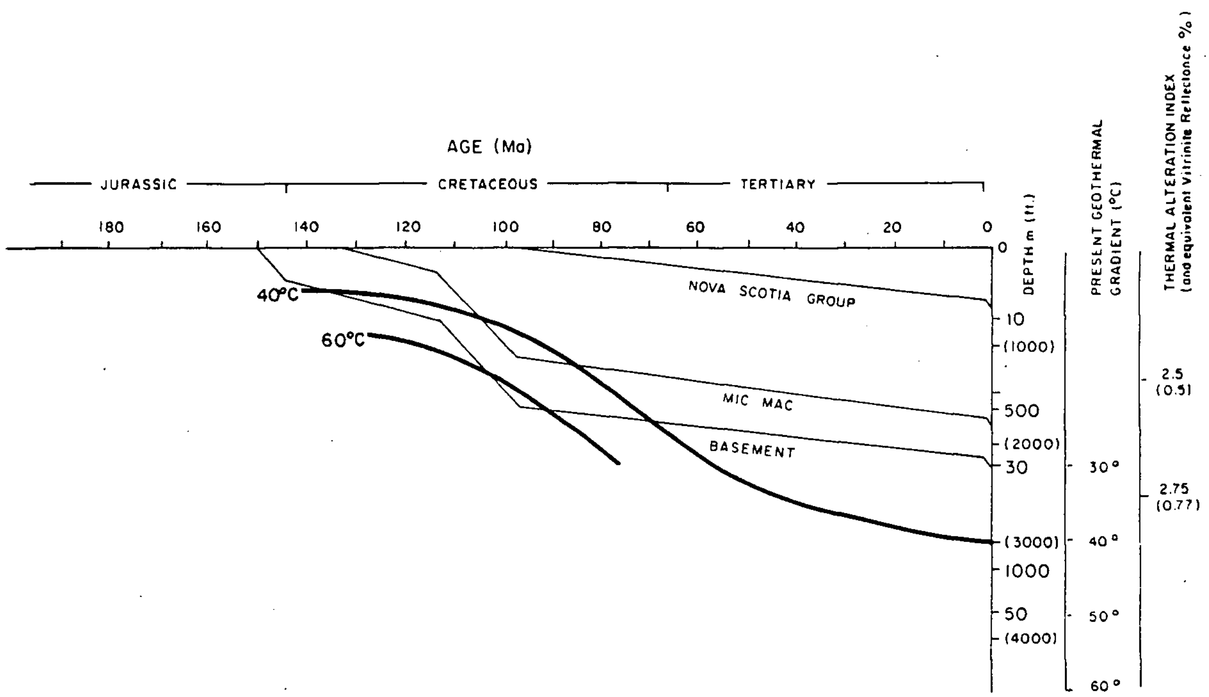

Fig. 30e SHELL FOX I-22

Temperature distributions through time, assuming the complex model with minimal Tertiary deposition

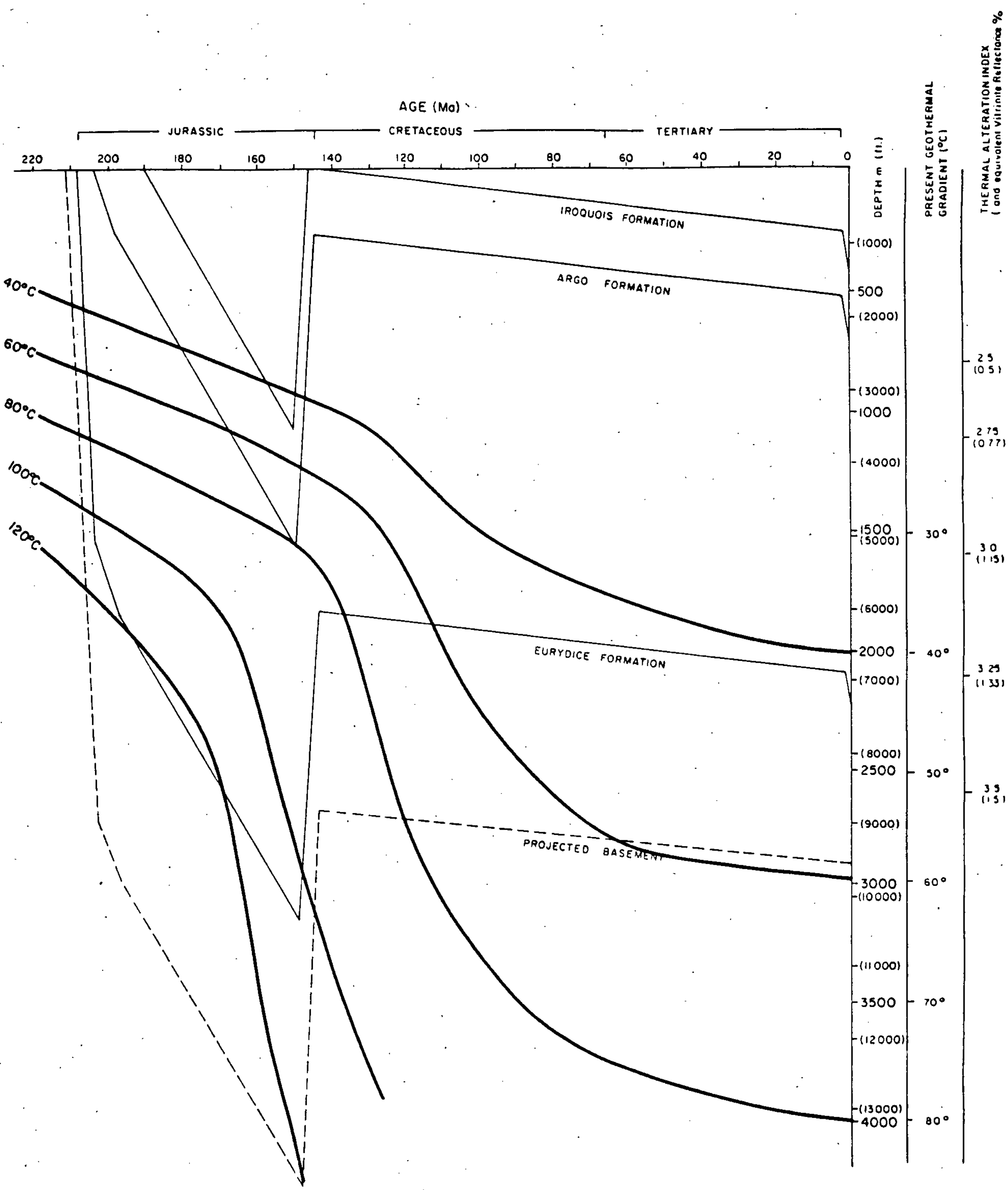

Fig. 30f SHELL EURYDICE P-36

Temperature distributions through time, assuming the <u>complex</u> model with minimal Tertiary deposition

The initial geothermal gradient is dependent on how the basin cooled. Different thermal models will have a different temperature distribution through time.

Table VII compares the calculated T.T.I. to the observed maturity for the two temperature histories. When the simple temperature history from increased Tertiary burial (Figures 29 a-f) is used to calculate the Time-Temperature Index, the calculated maturity (T.A.I.) is lesser than the observed maturity (except for Fox I-22). Hence, increased depth of burial in the Tertiary cannot account for the observed maturity in Eurydice, Crow, Argo, Hercules and Jason.

The proposed complex temperature history (Figures 30 a-f) provides T.T.I. values that are closer to observed maturity, for some strata (See Table VI). However, the calculated T.T.I. for the Cretaceous tends to be slightly less thermally mature than is observed. The amount of time spent in the hottest temperature interval appears to have influenced the Time-Temperature Index the most.

Jason (Fig. 30a), Argo (Fig. 30c), Hercules (Fig.30b) and Eurydice (Fig. 30f) all show that the temperature decay was probably influenced by the Argo salt, which tended to elevate and prolong the length of time an isotherm occupied a particular horizon. Fox and Crow, both relatively shallow wells over the Canso Ridge, exhibit temperature distributions influenced by proximity to basement. This is reflected in the maturation

TABLE VII

COMPARISON OF CALCULATED T.T.I. TO OBSERVED MATURITY FOR TWO TEMPERATURE HISTORYS

Well	Model	Formation	Calculated T.T.I. (T.A.I.)	Observed Maturity T.A.I. (T.T.I.)
Jason	I*	Argo	62 (2.8-2.9)	3.25 (170)
		MicMac	10 (2.6)	2.75 (30)
	II*	Argo	170 (3.25)	3.25 (170)
		MicMac	36 (2.75-2.8)	2.75 (30)
Hercules	I	Argo	41 (2.8)	3.0 (110)
		MicMac	10 (2.6)	2.75 (30)
	II	Argo	44 (2.8)	3.0 (110)
		MicMac	immature <1 (2.25)	2.75 (30)
Argo	I	Eurydice	28 (2.75)	3.5 (300)
		Argo	immature <1 (2.25)	2.9 (75)
		MicMac	immature <1 (2.25)	2.7 (20)
	II	Eurydice	320 (3.5)	3.5 (300)
		Argo	43 (2.8)	2.9 (75)
		MicMac	1.3 immature	2.7 (20)
Crow	I	Eurydice	2.6 (2.5)	2.75 (30)
	II	Eurydice	7 (2.6)	2.75 (30)
Fox	I	MicMac	18 (2.7)	2.6 (10)
	II	MicMac	1.2 immature	2.6 (10)
Eurydice	I	Eurydice	18 (2.7)	3.25 (170)
		Argo	immature	2.5 (3)
	II	Eurydice	164 (3.2)	3.25 (170)
		Argo	2 (2.4)	2.5 (3)

*Model I - Simple Temperature history, subsidence and uplift in Tertiary.

*Model II - Complex Temperature history, slow Tertiary deposition.

curves by a more rapid increase in maturation within 200 m of basement. The sedimentary rocks immediately overlying the more thermally conductive basement rocks may have served as a thermal insulator, resulting in enhanced temperatures at and near the basement sediment interface.

Figures 31 a-d and 32 a-c show the depositional and temperature history of the basin at 200 Ma., 144 Ma., 66 Ma. and the present respectively for both simple and complex temperature histories. The salt diapirs and the basement-sediment interface are the major influences on the temperature distribution. Comparison of the isomaturation lines (Fig. 25) to temperature distribution over the basin (Fig. 31d) shows a similar influence by the diapirs especially over the Hercules diapir. The peak oil generating temperatures, 90°C to 110°C occur in salt for Argo F-38, Eurydice, P-38, Hercules G-15, and Jason C-20. The more organically rich Cretaceous has experienced lower temperatures. The initial stages of hydrocarbon generation would be expected to have occurred in the Cretaceous.

Comparison of T.T.I. to a maturation profile shows that to reach a higher level of maturity, either a short period of time at a high temperature or a longer period of time at a lower temperature is required.

The process of modeling the temperature history to fit observed maturation data is dependent upon the predetermined limits that will influence the temperature distribution. By

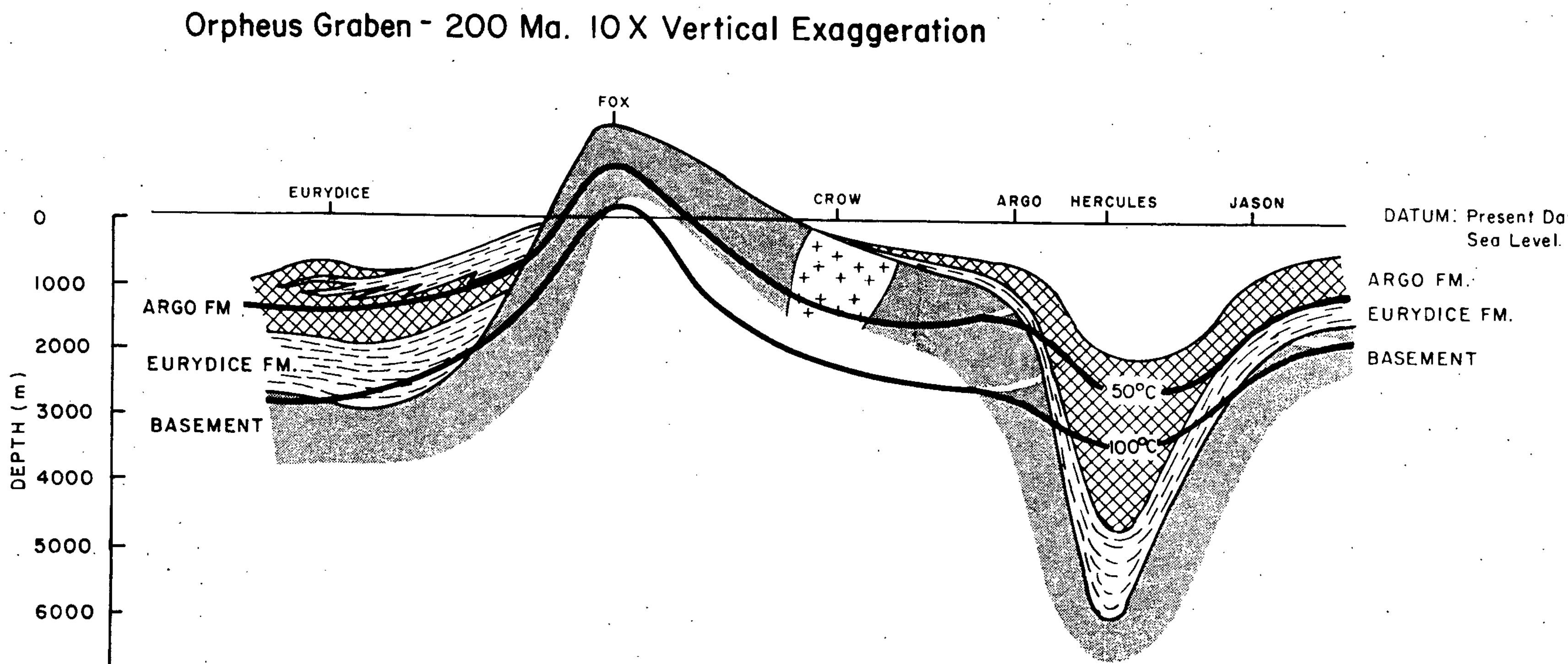

Fig. 31a Temperature distribution for the Orpheus Graben during the early Jurassic, assuming the <u>simple</u> temperature model

Orpheus Graben - 144 Ma. 10X Vertical Exaggeration

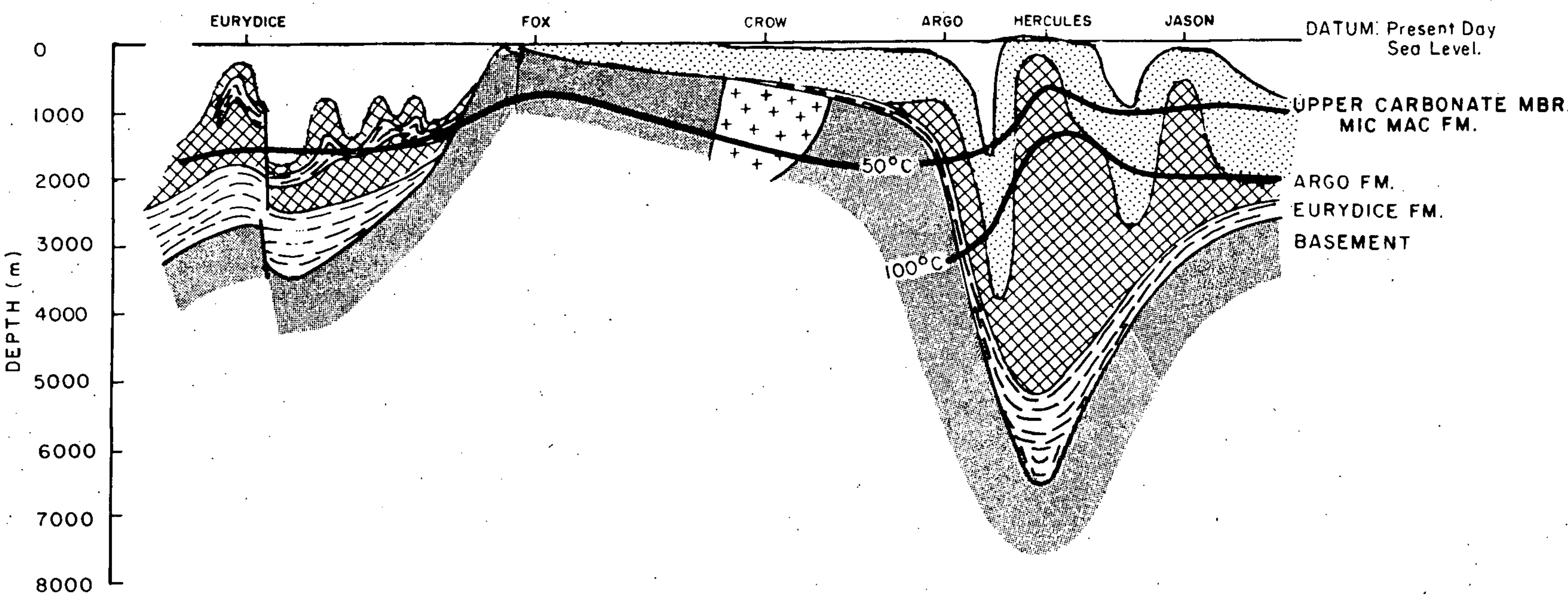

Fig. 31 b Temperature distribution for the Orpheus Graben at the Jurassic-Cretaceous boundary, assuming the simple temperature model

Orpheus Graben - 66 Ma. 10X Vertical Exaggeration

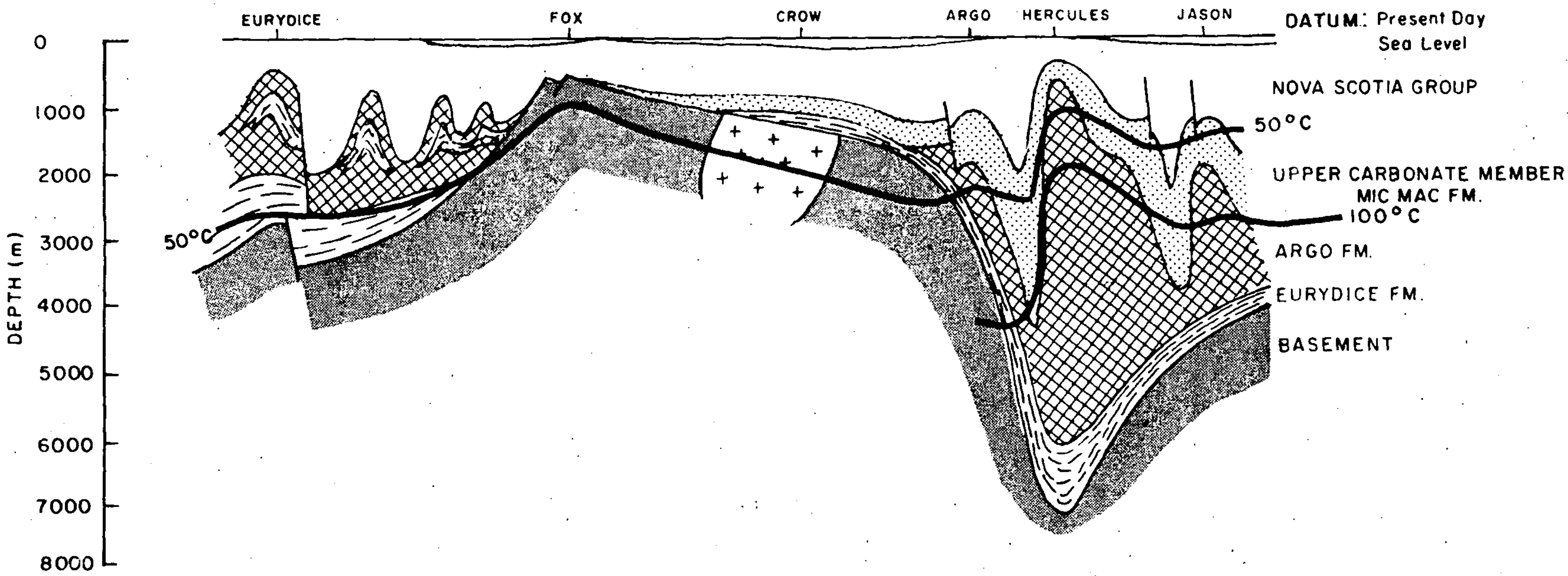

Fig. 31c Temperature distribution for the Orpheus Graben at the Cretaceous-Tertiary boundary, assuming the simple Temperature model

Orpheus Graben - Present Day 10X Vertical Exaggeration

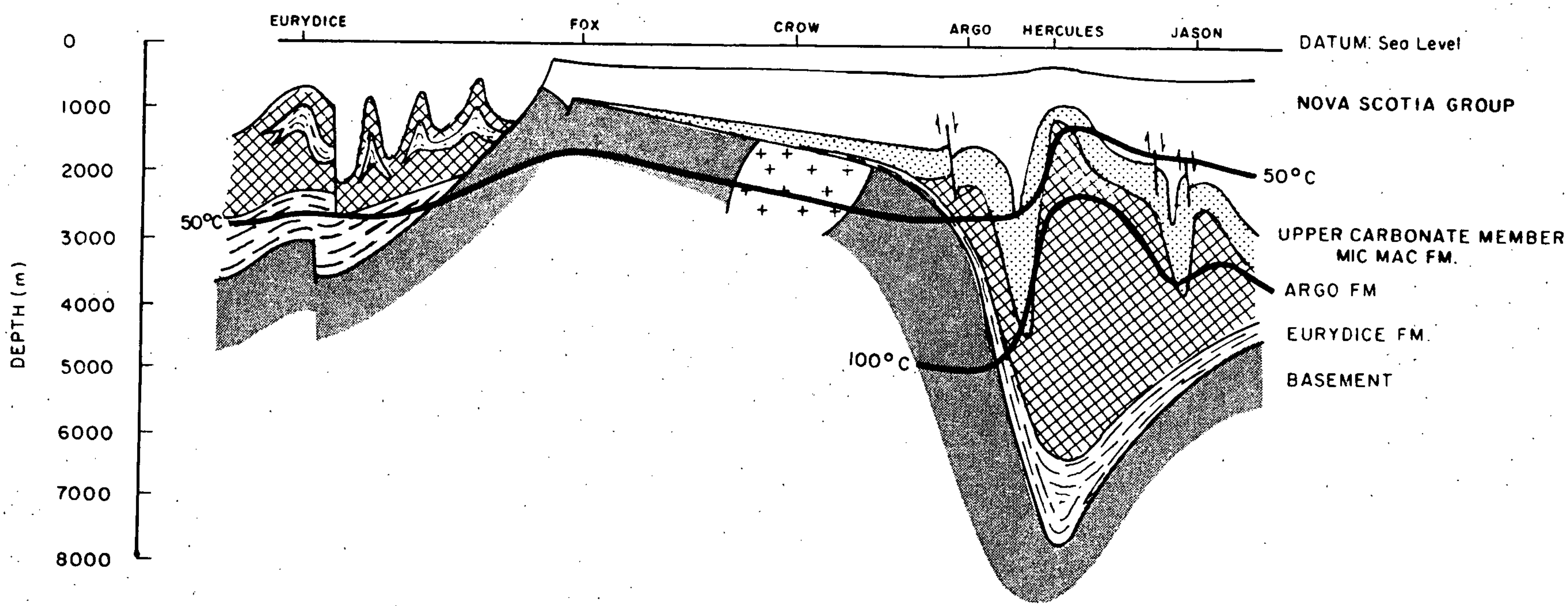

Fig. 31d Temperature distribution for the Orpheus Graben at present

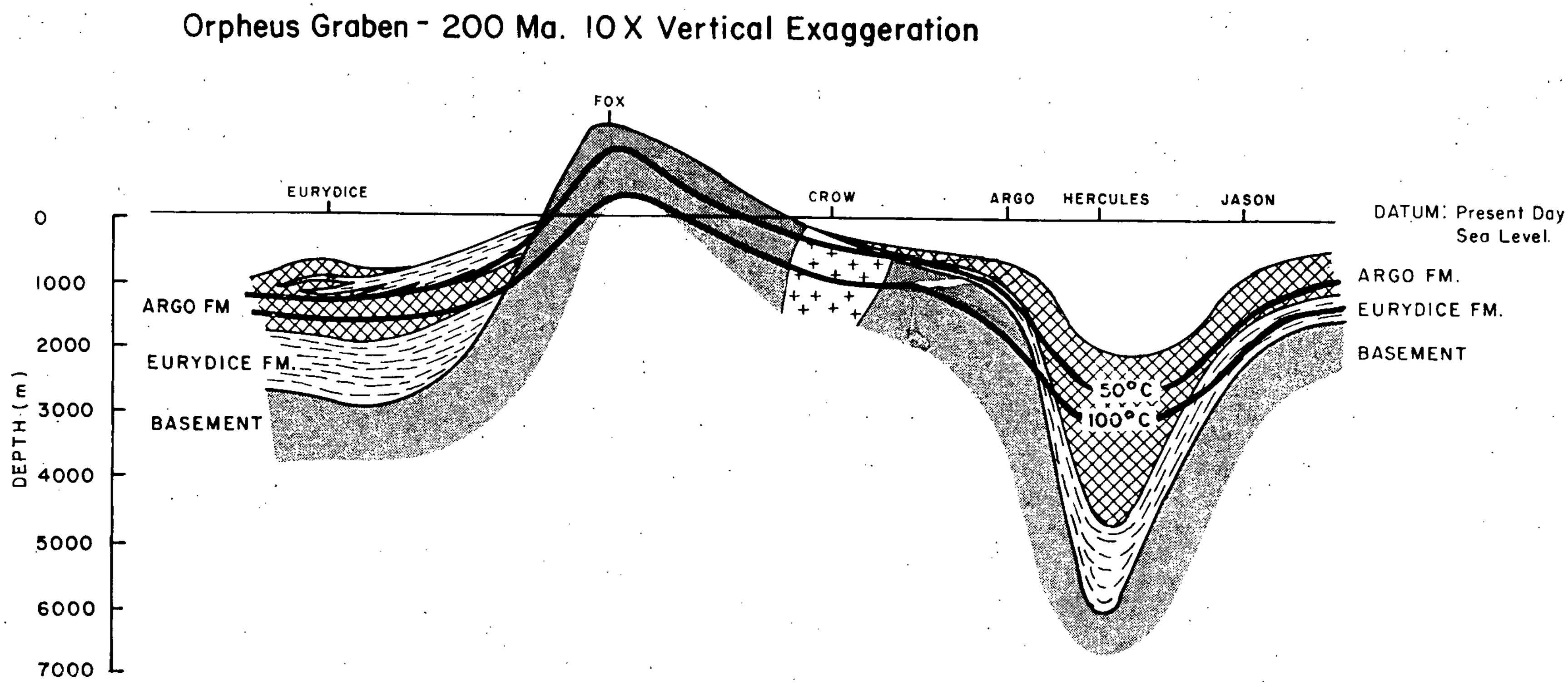

Fig. 32a Temperature distribution for the Orpheus Graben during the early Jurassic, assuming the complex temperature model

Orpheus Graben - 144 Ma. 10X Vertical Exaggeration

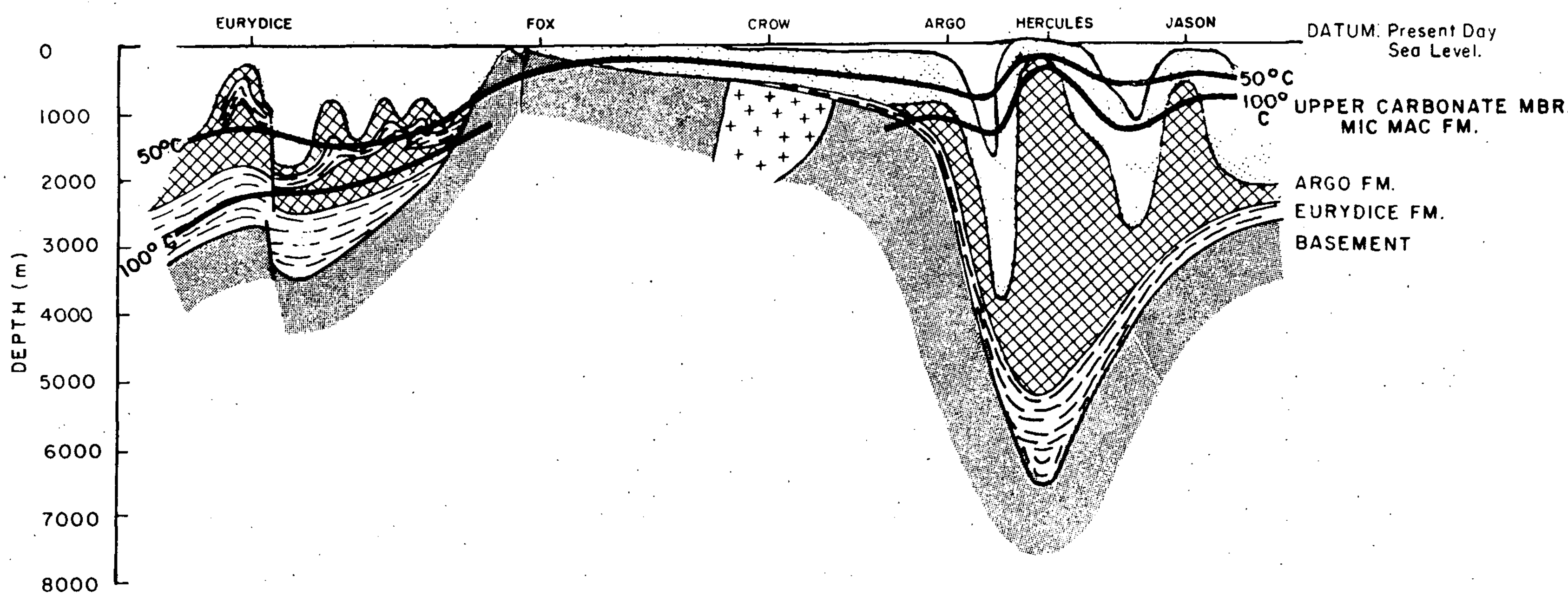

Fig. 32b Temperature distribution for the Orpheus Graben at the Cretaceous-Tertiary boundary, assuming the complex temperature model

Orpheus Graben - 66 Ma. 10X Vertical Exaggeration

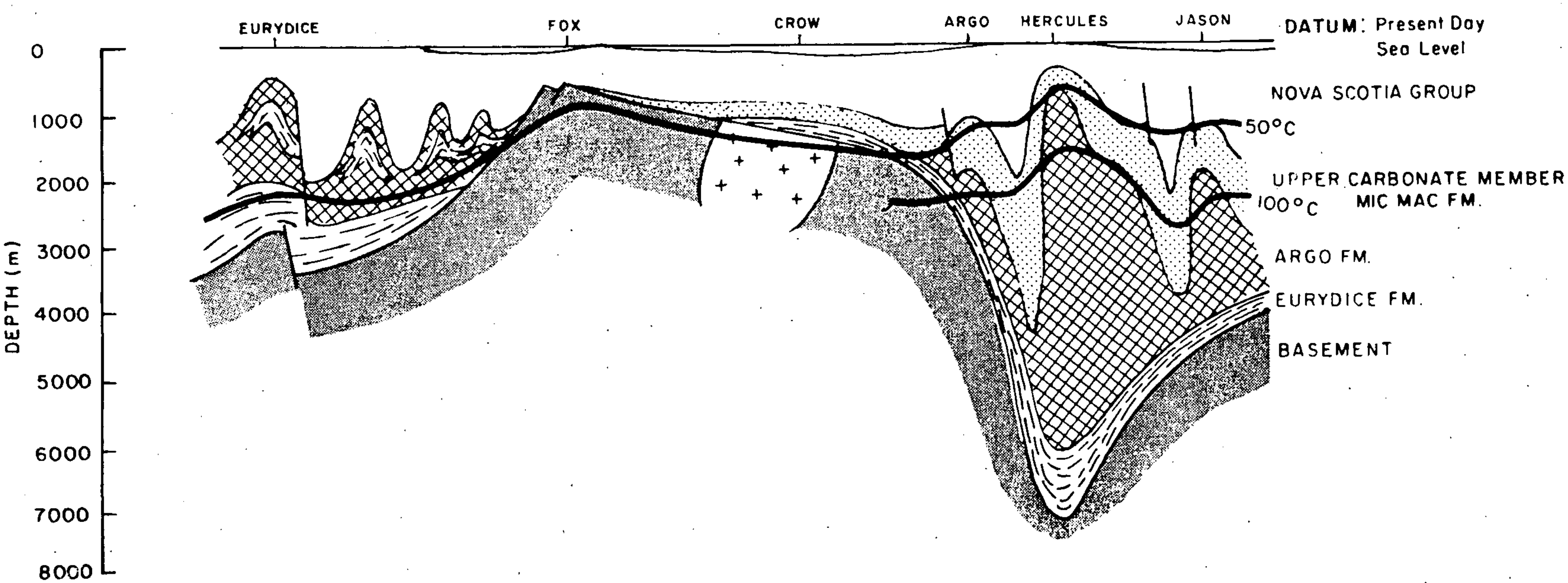

Fig. 32c Temperature distribution for the Orpheus graben at the Cretaceous-Tertiary boundary, assuming the <u>complex</u> temperature model

specifying the thermal characteristics of a rifting model and taking into account conductivity contrasts, subjectivity in the temperature distribution can be minimized. The method of temperature modeling presented here is an attempt intended to provide a technique for studies in other basins. More refined methods can be expected when the relationships among time-temperature distribution, vitrinite reflectance, and spore colour are better defined.

CONCLUSIONS

1. The temperature history of the Orpheus Graben can be inferred by combining the Time Temperature Index and maturation data.
2. If a simple temperature history is specified for the Orpheus Graben the T.T.I. is too low for the observed maturity. If a more complex temperature distribution is specified, the calculated T.T.I. is closer to the observed maturity.
3. The observed maturity indicates that the initial geothermal gradients were higher than the present geothermal gradients.
4. The critical hydrocarbon generating temperature occurred in the salt. Except for thermal anomalies developed over salt structures, the overlying sediments experienced temperatures too low for oil generation.

B. HYDROCARBON POTENTIAL OF THE ORPHEUS GRABEN

Drilling in the Orpheus Graben centred on three structure types: 1) faulted anticlines over salt structures; 2) basement highs and; 3) structural and stratigraphic traps on the flanks of the basement highs. Failure to encounter commercial hydrocarbon accumulations was a result of geologic and thermal environments not being conducive to hydrocarbon generation and accumulation.

Potential source rocks occur in the Iroquois, Mohican, Micmac, Logan Canyon and Dawson Canyon Formations. The richer source rocks occur in the marine intervals, specifically in the Upper Jurassic and Middle Cretaceous. As the Jurassic source rocks are humic, gas would most likely be generated. However, Middle Jurassic salt tectonism may have influenced bottom topography forming small anoxic basins that could accumulate and preserve oil prone material such as algal remains.

The time temperature relations suggest that the oil generation stage of maturity was reached in Jurassic strata, but migration pathways may not have existed to allow hydrocarbons to accumulate. There are localized zones of enhanced maturity over salt structures but their areal extent may not have been sufficiently large to generate sufficient hydrocarbons to fill a large reservoir. The oil prone organic matter in the Dawson and Logan Canyon formations occurs in the marginally mature zone, so that only small quantities of hydrocarbons would be generated.

Since no traps are known to occur in association with these two formations, no hydrocarbon accumulation should be expected.

To summarize, hydrocarbons were not encountered in the Orpheus Graben because the space - time relationships of source rocks, migration pathways, and traps were not conducive to hydrocarbon generation and accumulation. However, comparison of the North Sea Graben System to the Orpheus Graben suggests potential exploration objectives that could be considered for the Orpheus Graben.

The North Sea Graben System is a result of Triassic rifting on a foundered continental crust. The stratigraphy is similar to that of the Orpheus Graben in that Triassic redbeds and evaporites are present in the southern part of the North Sea. The Jurassic contains shallow marine clastics (Zeigler, 1982). In the Orpheus graben a similar redbed, evaporite, shallow marine clastic section occurs, although it is younger than that in the North Sea. The major source rock of the North Sea is an organically rich deep - water Kimmeridgian shale which has no known equivalent on the Scotian shelf. The Lower Cretaceous of the northern North Sea is largely deep marine shale, whereas carbonates comprise the Upper Cretaceous (Zeigler, 1980).

In the North Sea, several structural and depositional environments trap hydrocarbons: 1) anticlines over salt structures: eg. Ekofisk (Van den Bark and Thomas, 1980); 2) Paleocene submarine fans: eg. Frigg Gas Field (Heritier et al., 1980), and Forties Oil Field (Hill and Wood, 1980); and 3) Jurassic sands structurally draped over basement fault blocks (The fault blocks were tilted after the deposition of the Jurassic sands); eg. Statfjord and Brent Oil Fields (Kirk, 1980), Beatrice Oil Field (Lindsey et al., 1980), Piper Oil Field (Maher, 1980), Ninian Oil Field (Albright et al., 1980).

If future exploration is undertaken in the Orpheus Graben consideration should be given to targets eastward along the axis of the graben from the original exploration area. A more marine environment, that could have provided richer oil prone source rocks may have occurred in the late Jurassic and Cretaceous farther east in the Orpheus Graben.

From the subsidence data of Chapter 4 it is clear that the major period of subsidence occurred in the Jurassic. It is reasonable to assume that basement block faulting, which could provide traps for hydrocarbon accumulation developed along the margin and axis of the Orpheus Graben. If a thick Tertiary section exists it is possible that Cretaceous and Jurassic source rocks could be in the oil generating zone of thermal maturity and could have generated hydrocarbons for accumulation in traps within the sands of the Missisauga Formation.

SUMMARY

Jurassic - The suture separating the Avalon platform from the Meguma platform was reactivated during the early Jurassic, resulting in the formation of the Orpheus Graben. Initial deposition consisted of a red bed-evaporite sequence formed under hot arid conditions. Basin subsidence was rapid and geothermal gradients were high. A marine phase began in the middle Jurassic and culminated in the Upper Jurassic with the deposition of carbonates of the Abenaki Formation. Salt diapirism began in the Middle Jurassic, and in some locations (eg. Hercules) salt reached the surface, creating local reef environments. The flora during the Jurassic consisted of Classopollis pollen-producing plants occupying the uplands and near-coast environments, with Cycadopites pollen-producing plants further inland. The dominance of a single plant type is reflected in the organic matter deposited at the time; an abundance of humic matter with local concentrations of exinite. During the Middle to Upper Jurassic marine phase, however, there may have been small anoxic basins that could have had local accumulations of algal organic matter. By the end of the Jurassic, thermal cooling had lowered the geothermal gradient, although elevated temperature conditions probably existed over salt structures.

Cretaceous - Sedimentation during the Early Cretaceous consisted of a regressive deltaic sequence (the Missisauga Formation likely the fluvial portion that is in the Orpheus region) which graded upward into restricted marine shales and sands (the Dawson Canyon Formation), in the Albian. A marine phase began in the Aptian and continued until the Upper Cretaceous, culminating in the deposition of shales and mudstones of the Dawson Canyon Formation. During the Albian a second phase of increased subsidence occurred, related to the separation of the Grand Banks from Europe. Thermal cooling continued, reducing the geothermal gradient to its present value. The organic matter, primarily humic in the Lower Cretaceous progressively, became richer with a higher exinite and amorphous component in the Upper Cretaceous. During the Cretaceous the flora changed from a *Classopollis* dominated flora, to a flora dominated by plants producing *Taxodiaceaepollenites* pollen, and *Cyathidites* and other fern spores indicative of a subtropical to tropical environment.

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APPENDIX I

STRUCTURAL GEOLOGY OF EACH WELL

APPENDIX I

Structural Geology of each well based upon Shell Canada Resources Ltd. reports.

Shell Argo F-38: The Argo structure is a faulted anticline overlying salt, with primary objectives in the Cretaceous and Jurassic sandstones.

Shell Crow F-52: The Crow Well tested stratigraphic and structural traps flanking a plunging anticlinal ridge (Canso Ridge) with objectives in the Cretaceous and Jurassic sandstones.

Shell Fox I-22: The Fox well tested Jurassic and Cretaceous stratigraphic and structural objectives in a thinning and flanking sedimentary wedge associated with the regional culmination of the Canso ridge.

Shell Eurydice P-36: The Eurydice structure is an anticline located in the western portion of the Orpheus Basin over a basement horst block. Objectives were the Cretaceous and Jurassic sandstones and limestones.

Union et al Hercules G-15: This well was located on the flank of a salt diapir, to test stratigraphic and structural traps in the Jurassic and Cretaceous sandstones and limestones.

Union et al Jason C-20: The Jason structure overlies the up-thrown side of a fault block and associated salt pillow. Stratigraphic and structural objectives were in the Jurassic and Cretaceous sandstones and limestones.

APPENDIX II

SUMMARY OF STRATIGRAPHY

APPENDIX II

Summary of Stratigraphy, from well logs

BASEMENT: Argo F-38, 3331.5m (10930') - quartzite
Crow F-52, 1504m (4935') - granite
Fox I-22, 784m (2572') - sericitic schist

Eurydice Formation: Eurydice P-36 - type section between 2392.7m - 2965.1m (7850' - 9728') underlying the Argo Salt (Jansa and Wade, 1975a) - orange to red brown anhydritic siltstones and shales

Argo F-38 - 3112m - 3331.5m (10210' - 10930') - as above

Crow F-52 - conglomerate and arkosic sandstone underlying Iroquois Formation, may be equivalent to Eurydice Formation

Argo Formation: Type section Argo F-38, 2304.3m - 3112.0m (7560'-10210') massive white halite with a few shale and anhydrite interbeds.

Hercules G-15, 1054.6m (3460')
Jason C-20, 2449.4m (8036')
Eurydice P-36, 798.6m (2620'). In Eurydice P-36, the Argo is divisible into 2 units, an interbedded, red brown to olive shale and halite 798.6m - 1932.4m (2620' - 6340') and a massive halite section 1932.4m - 2392.7m (6340' - 7850').

Iroquois Formation: Eurydice P-36, 538m - 798.6 (1765' - 2620') varicoloured to red massive anhydritic mudstone, capped by a microsucrosic anhydritic dolomite, possible updip clastic facies of Iroquois Formation (Unpublished Shell Technical Report, 1975)

Crow F-52, 1376.2m - 1402.1m (4515' - 4600')
Argo F-38, 2212.8m - 2304.3m (7260' - 7560')
Jason C-20, 2406.1m - 2449.4m (7894' - 8036') - argillaceous anhydritic dolomite with mudstone interbeds. The Iroquois is divisible into 3 units (unpublished Shell Technical Report, 1973), an upper unit of microcrystalline dolomite siltstone shale and sandstone; a middle unit of massive microcrystalline dolomite and oolitic grainstone and a lower unit of orange red shale with siltstone and anhydrite. Given (1977) considered the upper unit to represent deposition in a restricted marine environment, locally on supratidal flats, while the middle unit represented a higher energy regimen.
Hercules G-15, 911.4m - 1054.6m (2990' - 3460') massive dolomite overlying green to brown shale.

Mohican Formation: Argo F-38, 2104.6m - 2212.8m (6905' - 7260') interbedded sequence of arkosic sand, red to brown argillaceous mudstone and shale with occasional dolomite or limestone beds. The Mohican Formation was defined by Given (1977) for the "texturally less mature sands that tended to be poorly sorted and dolomitic, with locally inter-bedded varicoloured shale, "conformably overlying the Iroquois and underlying the Scatarie Member of the Abenaki Formation, or Mohawk Formation.

WESTERN BANK GROUP

Abenaki Formation; The Abenaki Formation is divisible into four members (Eliuk 1978), the Scatarie, Misaine, Baccaro and Artimon. In the Orpheus Graben, the Abenaki equivalents are two carbonate members that occur in the MicMac Formation. The Scatarie marks the beginning of the middle to late Jurassic marine trangression. The anhydritic limestone and dolomite of Argo F-38, 2060.4m - 2104.3m (6760' - 6905') is probably the equivalent to the Scatarie (Eliuk, 1978). The middle member of the Abenaki Formation, the Misinaine shale is not present in the Orpheus Graben. Eliuk (1978) considers the Baccaro, a relatively pure, oolitic grainstone, to be the primary Abenaki unit. On near shore ridges, tongues of the Baccaro interfinger with the MicMac Formation (Eliuk 1978). The time equivalent deposits in the Orpheus Graben are oolitic to algal mat carbonates formed in lagoonal to shallow marine conditions:

> Jason C-20, 2084.8m - 2164.7m (6840' - 7102') oolitic packstone
> Hercules G-15, 832.7m - 911.4m (2732' - 2990') cyclic limestone with algal mat limestone alternating with oolitic to oncolitic lime packstone, Eliuk (1978) also interpreted this to represent a condensed section due to salt diapirism. The initial environment was supratidal grading to subtidal.
> Argo F-38, 1627.6m - 1673.4m (5340' - 5490') pellitic limestone with occasional oolites
> Crow F-52, 1130.8m - 1176.5m (3710' - 3860') - grainstone

MicMac Formation:

> Jason C-20, 1815.1m - 2406.1m (5955' - 7894'), variegated shales with sandstone interbeds
> Hercules G-15, 774.2m - 911.4m (2540' - 2990') - bentonitic siltstones and quartzose sandstones
> Argo F-38, 1530.1m - 2104.6m (5020' - 6905') - greyish green shales with the occasional coaly sections
> Crow F-52, 998.2m - 1376.2m (3275' - 4515') - silty mudstone grading to a quartzose sandstone near the base
> Fox I-22, 658.4m - 783.9m (2160' - 2572') - shale with sandstone and coaly beds

The MicMac Formation underlies the Missisauga Formation of the Nova Scotia Group (defined below), and is in part the lateral time equivalent to the Baccaro Member of the Abenaki Formation. The common lithologies of the MicMac include medium to dark brown to olive grey silty shales, often calcareous (McIver, 1972). The upper contact was placed at the base of the lowermost massive sandstone of the overlying Missisauga Formation. The MicMac represents an influx of sediment from the north and northwest either as a coastal plain environment or shallow marine nearshore (Jansa and Wade, 1975a). In the Orpheus Graben, deposition was primarily of a continental and fluvial deltaic nature.

Nova Scotia Group: The three formations that form the Nova Scotia Group are the Missisauga, Naskapi and the Logan Canyon Formations (McIver, 1972). These represent the Sable Island Delta, a regressive sequence that covered the carbonate facies (Given, 1977) during the Late Jurassic and Early Cretaceous. Jansa and Wade (1975) relate the Sable Island delta to the Avalon uplift. The upper contact of the Missisauga Formation is either the Naskapi shale (where present) or the top-most massive sand unit (McIver, 1972). The Logan Canyon Formation overlies the Missisauga and Naskapi formations (McIver, 1972) and consists of continental to restricted marine sands and shales (Given, 1977).

Argo F-38 - Missisauga Formation - 1121.7m - 1530.1m (3680' - 5020'), massive arkosic sandstone with occasional variegated shale beds
Naskapi Formation - 1079m - 1121.6m (3540' - 3680'), shale

Logan Canyon - 487.7m - 1079.0m (1600' - 3540'), interbedded quartzose to arkosic sandstone with shale and mudstone

Jason C-20 - Missisauga Formation - 1178.4m - 1815.1m (3866' - 5955') massive quartzose sandstone and shaley sandstone and coaly interbeds
Logan Canyon Formation - 641.3m - 1178.4m (2104' - 3866') massive mudstone, siltstone with quartzose sandstone and coaly interbeds

Where the Missisauga and Logan Canyon cannot be distinguished, the term Nova Scotia Group is used (McIver 1972)

Hercules G-15,	317m - 774.2m	(1040' - 2540')
Crow F-52,	335.3m - 998.2m	(1100' - 3275')
Fox I-22,	289.6m - 658.4m	(950' - 2160')
Eurydice P-36,	289.6m - 538.0m	(950' - 1765')

A volcanic unit is present in Argo 1024.1m (3360'), Hercules 757.7m (2486'), Jason 1366.7m (4484').

Dawson Canyon Formation - Jason C-20, 262.1m - 641.3m (860' - 2104')
Argo F-38, 281.0m - 487.7m (922' - 1600')
Hercules G-15, 289.6m - 317.0m (950' - 1040')
Fox I-22, 121.9m - 335.3m (400' - 1100')

The Dawson Canyon Formation overlies and is partly a lateral equivalent to the Logan Canyon (Given, 1977), and represents a transgressive marine phase. Mudstone and shale are the common lithologies. The upper contact of the Dawson Canyon Formation was not observed in any of the wells.

APPENDIX III

A. SUMMARY OF SOME SPORE-PLANT AFFINITIES

B. PARTIAL LIST OF REWORKED SPORES

APPENDIX III

A. Summary of Some Spore-Plant Affinites

Jurassic

Araucariacites sp. - Coniferophyta, Araucariaceae

Alisporites sp. - Coniferophyta, Podocarpaceae, Tschudy and Scott, 1969

Baculatisporites sp. - Pteridophyta, Osmundaceae, Tschudy and Scott, 1969

Callialasporites sp. - (Tsugaepollenites) Coniferophyta, Podocarpaceae, Taylor, 1981

Classopollis sp. - Coniferophyta Cheirolepidaceae, with affinities to Araucariaceae, Voltziaceae Gnetaceae, S.K. Srivastava, 1976

Couperisporites sp. - Hepaticae, Tschudy and Scott, 1969

Densoisporites sp. - Lycophyta, Lycopodiales, Selaginellales, Dettman, 1963

Laevigatosporites sp. - Pteridophyta, Polypodiaceae, Kremp and Kawasaki, 1972

Leptolepidites sp. - Pteridophyta, Kremp and Kawasaki, 1972

Podocarpidites sp. - Coniferophyta, Podocarpaceae

Verrucosisporites sp. - Pteridophyta, Taylor, 1981

Cycadopites sp. - Cycadophyta, Bennettitales, Cycadales, Tschudy and Scott, 1969

Neoraistrickia sp. - Similar to modern *Selaginella*, Dettman, 1963

Osmundacidites sp. - Pteridophyta, Osmundaceae

Rouseisporites sp. - Hepaticae, Tschudy and Scott, 1969

Stereisporites sp. - similar to *Sphagnum*, Dettman, 1963

Todisporites sp. - Pteridophyta, Osmundanceae, Tschudy and Scott, 1963

Tsugaepollenites sp. - *Tsuga* (hemlock) - Coniferophyta, Potonie, p.2, 1958.

Vitreisporites sp. - Pteridospermophyta, Caytoniales, Taylor, 1981

Gleicheniidites sp. - Pteridophyta, Gleicheniaceae, Taylor, 1981

Cyathidites sp. - Pteridophyta, Cyatheaceae, Taylor, 1981

Taxodiaceaepollenites sp. - Coniferophyta, Taxodiaceae, Tschudy and Scott, 1969

Upper Cretaceous

Aequitriradites sp. - Hepaticae, Dettman, 1963

Appendicisporites sp. - Pteridophyta, Schizaeaceae, Tschudy and Scott, 1969

Cirratriradites sp. - Lycophyta, Selaginellales, Taylor, 1981

Ephedripites sp. - Gnetales, Taylor, 1981

Ericipites sp. - Ericaceae, Tschudy and Scott, 1969

Parvisaccites sp. - Coniferophyta, Tschudy and Scott, 1969

Rugubivesiculites sp. - Coniferophyta, Podocarpaceae?, Tschudy and Scott, 1969

Lower Cretaceous, Albian-Aptian

Acanthotriletes sp. - Pteridophya, Kemp, 1972

Appendicisporites sp. - Pteridophyta, Schizaeaceae, Tshudy and Scott, 1969

Baculatisporites sp. - Pteridophyta, Osmundaceae, Dettman, 1963

Ceratosporites sp. - Lycophyta, Lycopodiales, Tschudy and Scott, 1969

Cicatricosisporites sp. - Pteridophyta Schizaeaceae (Pelletieria, Schizaeopsis), Tschudy and Scott, 1969

Concavissimisporites sp. - Pteridophyta, Schizaeaceae, Cyatheaeceae (Cyathea, Dicksonia), Dettman, 1963

Deltoidospora sp. - Pteridophyta Gleicheniaceae, Matoniaceae, Cyatheaceae, Tschudy and Scott, 1969

Densoisporites sp. - Lycophyta, Lycopodiales, Selaginellales, Dettman, 1963

Eucommiidites sp. - Coniferophyta - Gnetales?, Doyle, et al., 1975

Foveosporites sp. - Lycophyta, Lycopodiales, Dettman, 1963

Klukisporites sp. - Pteridophyta, Schizaeaceae (Klukia, Stachypleris), Dettman, 1963

Lycopodiumsporites sp. - Lycophyta, Lycopodiales?

Matonisporites sp. - Pteridophyta, Matoniaceae (Phlebopteris?), Tschudy and Scott, 1969

Sequoiapollenites sp. - Coniferophyta, Taxodiaceae, Tschudy and Scott, 1969

B. Reworked Spores

Krauselisporites sp.

Murospora sp.

Waltzispora albertensis

Leiotriletes sp.

Dictyotriletes sp.

Punctatisporites sp.

Lycospora sp.

Verrucosisporites sp.

PLATE 1

All figures at 1000X unless otherwise stated

Figure 1. *Ctenidodinium panneum*

2. *Systematophora sp.*

3. *Gonyaulacysta sp.* 500X

4. *Meiourogonyaulax sp.*

5. *Lanterna sportula*

6. *Pareodinia ceratophora*

7. *Valensiella vermiculata*

8. *Callialasporites turbatus*

9. *Callialasporites trilobatus* 500X

10. *Echinitospites cf. iliacoides*

11. *Cycadopites subgranulosus*

12. *Cycadopites sp.*

13. *Classopollis meyeriana*

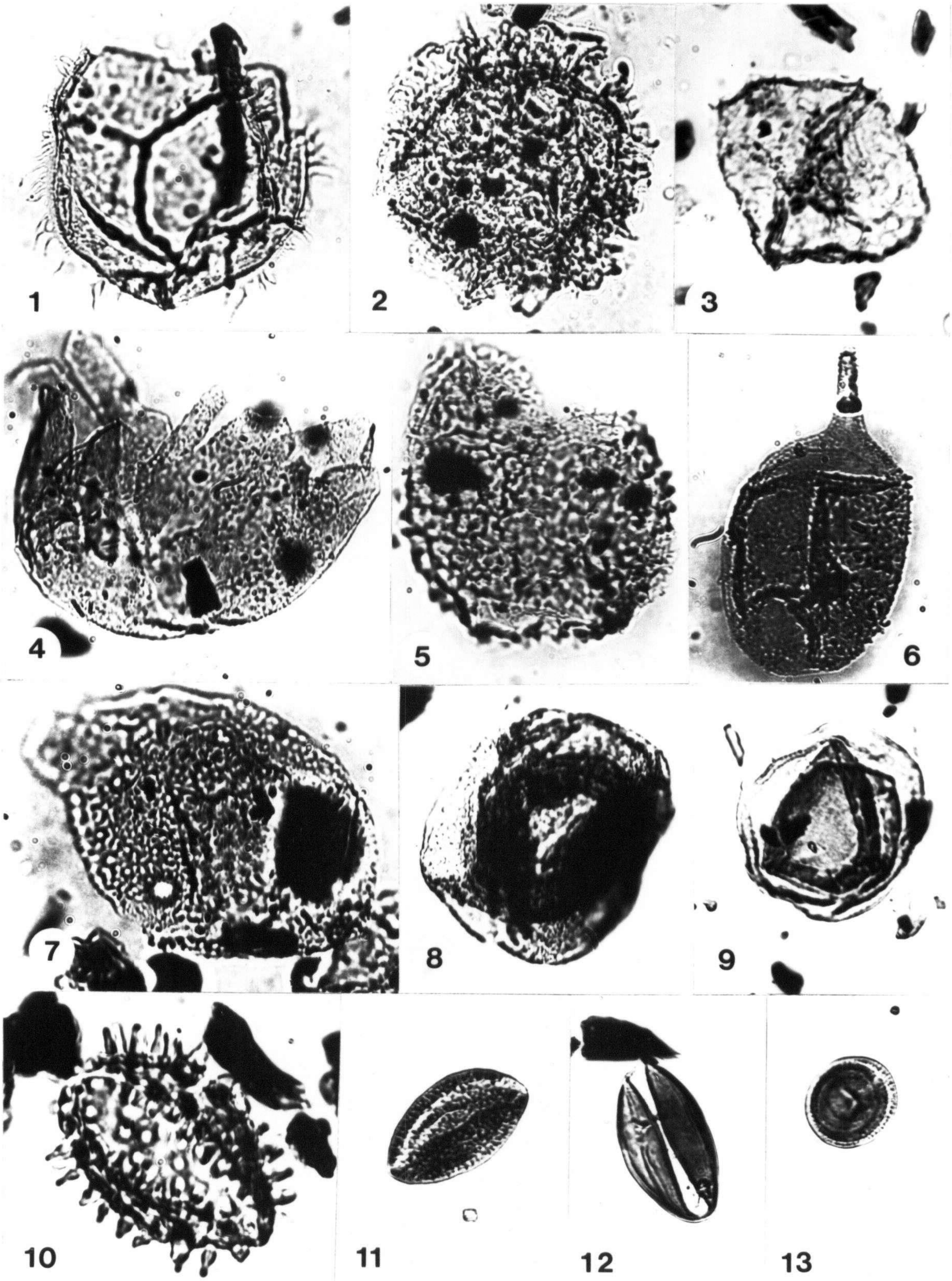
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PLATE 2

All figures at 1000X unless otherwise stated

Figure 14. *Chatangiella victoriesis* 400X

15. *Diconodinium glabrum*

16. *Alterbia acuminata*

17. *Cleistosphaeridium polypes* 400X

18. *Cyclonephelium distinctum* 400X

19. *Cyclonephelium vannophorum* 400X

20. *Dinogymnium acuminatum*

21. *Cribroperidinium sp.* 400X

22. *Spinidinium vestitum*

23. *Pareodinia kondratjevii*

24. *Spiniferites ramosus*

25. *Pterospermopsis australiensis*

26. *cf. Hemicystodinium sp.*

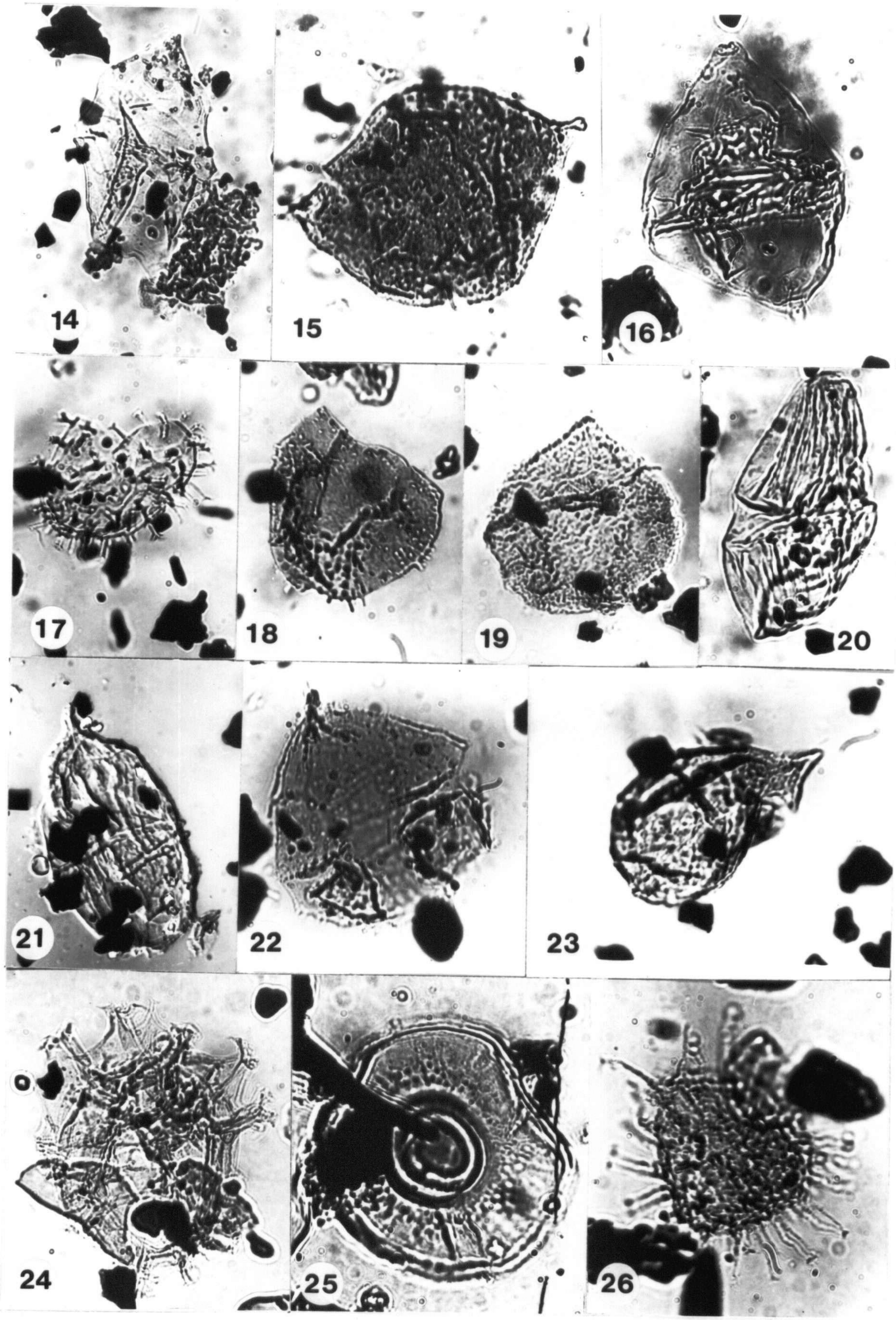
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PLATE 3

All figures at 1000X unless otherwise stated

Figure 27. *Cyathidites australis*

28. *Gleicheniidites senonicus* 400X

29. *Deltoidospora juncta*

30. *Liliacidites dividuus*

31. *Stereisporites antiquasporites*

32. *Rotaspora rugulata*

33. *Matonisporites sp.*

34. *Liliacidites peroreticulatus*

35. *Appendicisporites potomacensis* 400X

36. *Cicatricosisporites hallei*

37. *Cicatricososporites auritus*

38. *Ceratatosporites equalis*

39. *Ericipites sp.*

40. *Laeviatosporites ovatus*

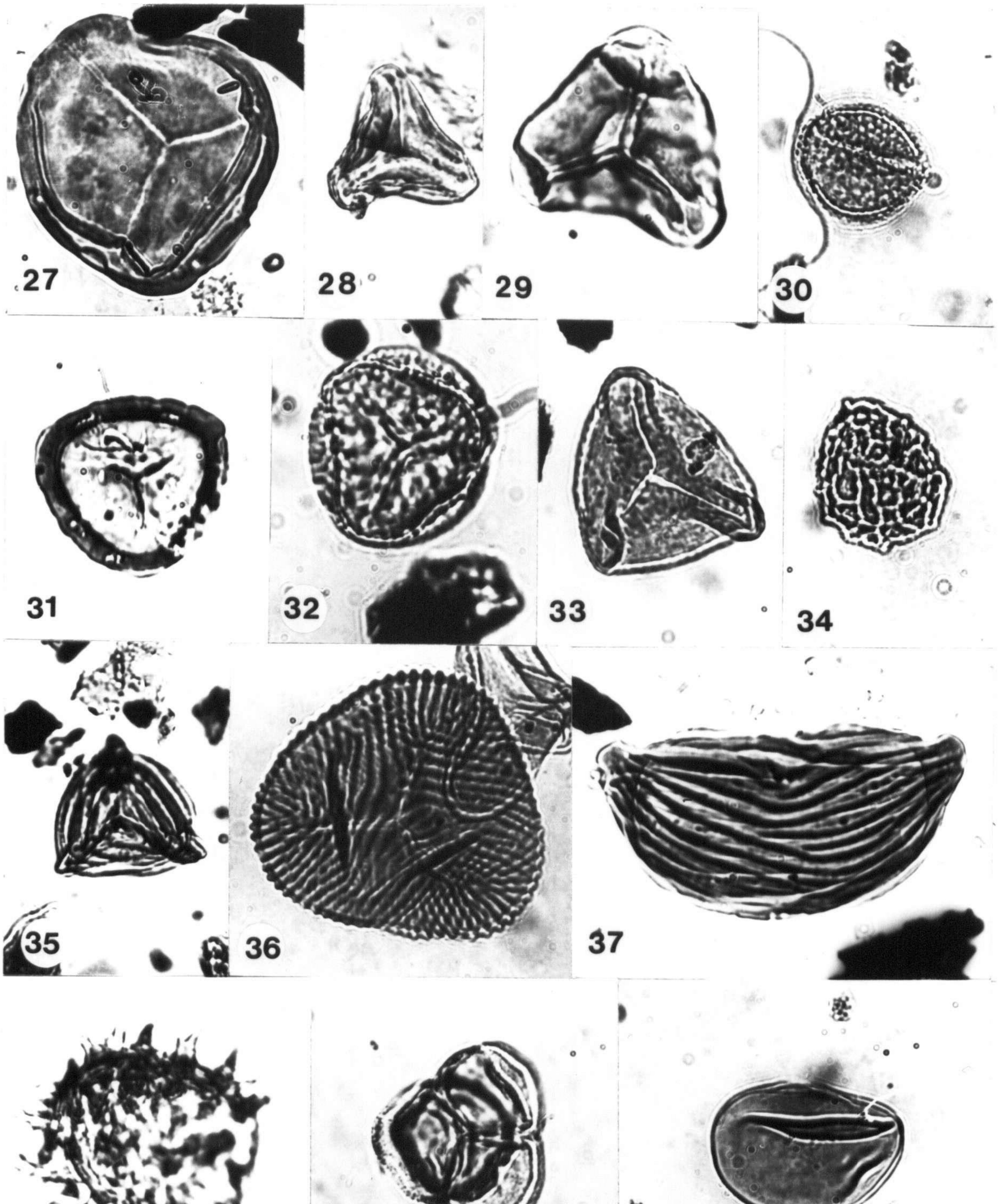
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PLATE 4

All figures at 1000X unless otherwise stated

Figure 41. *Eucommiidites minor*

42. *Kraeuselisporites sp.*

43. *Undulatisporites fossulatus*

44. *Pfugipollenites lucidus*

45. *Costatoperforosporites sp.*

46. *Trilobosporites humilis*

47. *Densoisporites microrugulatus* 500X

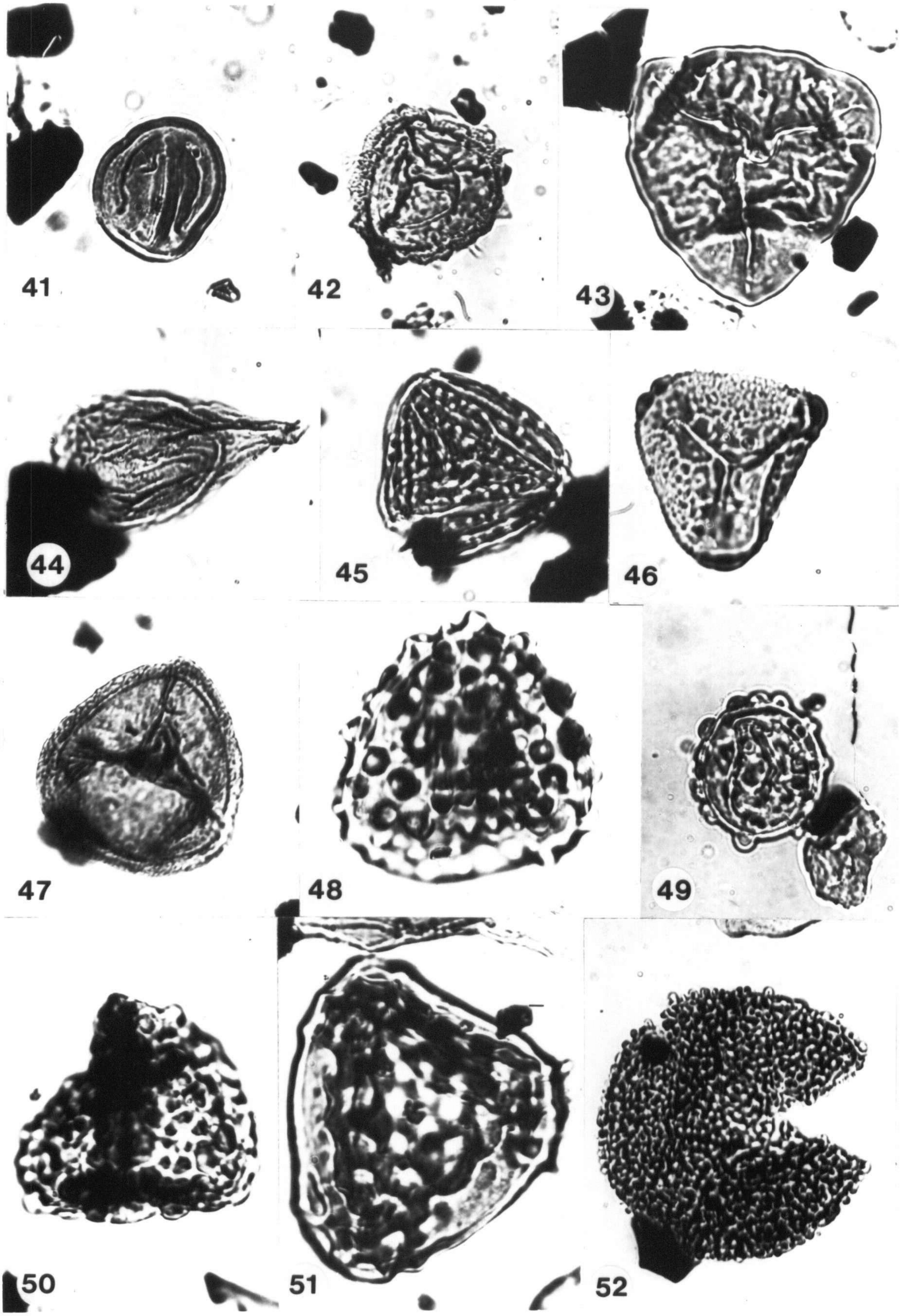
48. *Leptolepidites verrucatus*

49. *Leptolepidites minor*

50. *Leptolepidites magor*

51. *Klukisporites sp.*

52. *Osmundacidites wellmanii*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