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Recycled palynofloras from the Bransfield Strait, Antarctic Peninsula, and their climatic implication

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ABSTRACT: Recycled terrestrial palynomorphs recorded from surficial glaciomarine sediments of the Bransfield Strait, Antarctic Peninsula, help to enhance our understanding of Cretaceous to early Tertiary vegetation and climate history of the Antarctic Peninsula. Climate data determined from palynofloras, together with published multi-proxies of fossil plants, sediments and geochemical indicators, show a distinct pattern of warming and cooling through Late Cretaceous into early Tertiary. Cooler climates during the Early Cretaceous were followed by a warming, ever-wet, phase which peaked during the Coniacian to Early Campanian. The climate cooled during the Maastrichtian and Early Paleocene and cold, wet and probably seasonal environments prevailed. Late Paleocene/Early Eocene was once again warm but conditions subsequently deteriorated through the latter part of the Eocene, when cold seasonal climates developed. The cooling temperatures ultimately led to the onset of the Cenozoic ice sheets and the elimination of vegetation from mainland Antarctica.

Introduction

One of the most curious geological features between late Paleozoic and early Cenozoic is the preservation of plentiful fossil forests at high paleolatitudes. Polar temperatures were warmer than at present and vascular plants grew in the highly variable annual light regime characteristic of the polar regions (Frakes, 1979; Thorn, 2001). Today, the southern latitudinal limit of conifer's growth is coincident with the lowermost tip of South America (Creber and Chaloner, 1984). Flora on the Antarctic Peninsula at present includes non-vascular plants such as lichens, liverworts, bryophytes and only two species of flowering vascular plants: a herb, *Colobanthus quietensis* and a grass, *Deschampsia antarctica* (Ahmadjian, 1970; Bliss, 1979; Longton, 1985).

The surficial glaciomarine sediments distributed in the Antarctic yield abundant organic microfossils that have been recycled from older sedimentary rocks by glacial or submarine processes (e.g., Truswell, 1983; Truswell and Drewry, 1984; Byun *et al*., 1996). The recycled palynofloras, recovered in sea floor sediments, played the potential value for determining the age of rock hidden beneath the ice around Antarctica (Kemp 1972; Truswell, 1983, 1990; Truswell and Drewry, 1984). The Cretaceous and early Tertiary palynological data were known from the eastern side of the Antarctic Peninsula, where outcrop sequences had been studied in James Ross and Vega Islands (Askin, 1983b), Seymour Island (Askin, 1988a, b, 1989, 1990a, b, 1997) and James Ross Island Basin (Dettmann and Thomson, 1987). The Antarctic Cretaceous and early Tertiary terrestrial palynofloras are considered to be endemic or provincial. Also, some species have their earliest occurrence from Antarctica, suggesting that the region acted as a site of origin for these taxa (Askin, 1989). This study aims to reconstruct the Cretaceous-early Tertiary climate based on the terrestrial palynomorphs records, with aid of previous published diverse data sets (fossil plant, sediment and geochemistry), from the surficial glaciomarine sediment of the Bransfield Strait, Antarctic Peninsula.

Physiographical setting

The Antarctic Peninsula is predominantly an ensialic Mesozoic and Cenozoic magmatic arc related to subduction of the proto-Pacific and Pacific Ocean floors (Storey and Garrett, 1985). Late Cretaceous and Cenozoic marine sediments in the Bransfield Strait area were deposited in back-arc basins related to subduction along the SE edge of the Pacific Plate, accompanied by arc volcanism and magmatism, and Neogene continental rifting (Pirrie *et al.*, 1991; Birkenmajer, 1992).

The Bransfield Strait is a semi-enclosed basin limited to the south by the Antarctic Peninsula and the South Shetland Islands to the north. The Bransfield Basin consists of 3 subbasins that are separated by sills about 500 m deep. The Western Subbasin, in which Core S7 was drilled, is relatively shallow (1000 m) and irregularly shaped, and lies south and west of Livingston and Deception Islands. The Central Subbasin that contains cores S4 and AB2 sites and locates south of King George Island is deeper (up to 2000 m) and shows a more regular shape than the others. The Eastern Subbasin extends north-eastward, is narrower than the Central Subbasin, and reaches a depth of 2500 m (Fig. 1).

Today, surface circulation in the Bransfield Strait has two primary sources, the Bellingshausen Sea and Weddell Sea Currents (Fig. 1). Current coming from the Bellingshausen Sea is warm and relatively fresh, whereas current from the Weddell Sea is colder and denser (García *et al.,* 2002). These currents meet in the vicinity of Trinity Island and form a front of biological significance (Amos, 1987). Advection of circumpolar

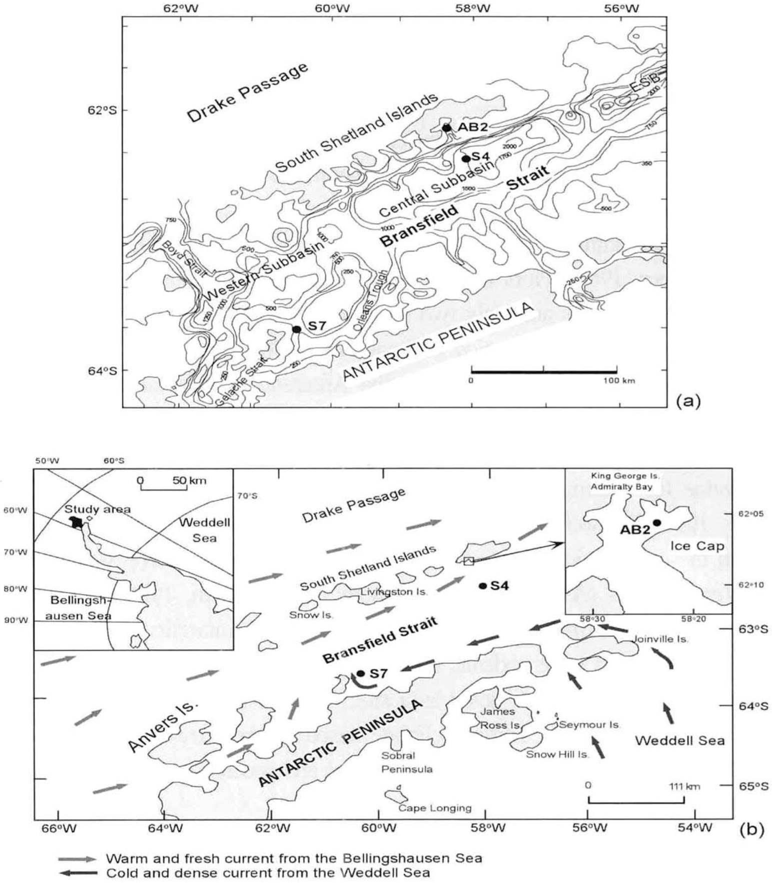

Fig. 1. Bathymetric map (a) of the Bransfield Strait (from Jeffers and Anderson, 1990) with the location of cores (b). Contours in meters. ESB: Eastern Subbasin.

deep water into the Strait from the Drake Passage is prevented by the presence of shallow sills. Gordon and Nowlin (1978) suggested the indication of in situ deep and bottom water formation through the sinking of surface waters of the Bransfield Strait. These waters are characterized by having lower temperatures and salinity, high oxygen and lower nutrient concentrations in comparison with deep waters outside the basin (García *et al.*, 2002).

The sediment distribution in the Bransfield Strait is related to the morphology of the sea floor. Jeffers and Anderson (1990) reported that the characteristic sediments of the deepest basin consists of 3 main components. In order of abundance, these are: (1) biosiliceous material, mostly diatoms; (2) terrigenous silt-sized quartz; and (3) volcanic ash.

Materials and method

Core S7 (Latitude 63°30’05″S, Longitude 60°26’06″W), cored in the Western Subbasin, is 523 cm long and consists of clay, silt, sand and gravel. The samples were not taken from the lower section due to high abundance of gravel and sand contents (Fig. 2a). Core S4 (Latitude 62°30’58″S, Longitude 58°05’58″W), cored in the Central Subbasin, is 537 cm long, and consists mainly of clay, silt, and a small amount of sand (Fig. 2b). Core AB2 (Latitude 62°05’09″S, Longitude 58°23’06″W), cored in the Admiralty Bay on King George Island, is 256 cm long and comprises mainly mud (Park *et al.*, 1992).

Three piston cores (S7, S4 and AB2) were taken for palynological studies. A total 68 samples by 10~20 cm intervals were collected from three cores: 10 samples on S7, 31 samples on S4, and 27 samples on AB2. About 30 g of dried samples were processed for palynological studies using standard procedures (Moore *et al.*, 1991) involving HCl (30%) and HF (45%) for the removal of calcareous and siliceous minerals. The organic matter recovered was oxidized with NaClO (3%) to remove fine humic matter, and then sieved through screens of 10 μm mesh. The sieved residue was strew mounted on glass slides using glycerine jelly. Raw data were converted into percentages using TILIA v2.0 (Grimm, 1993). TILIAGRAPH v1.25 (Grimm, 1991) was used to generate the pollen diagrams. The percentages of younger pollen and recycled palynofloras (spores, gymnosperm and angiosperm pollen) were calculated from the total palynomorph sum (Fig. 2).

Palynofloral assemblages

In all, the fossil microflora recorded is relatively diverse in assemblage consisted of younger (Fig. 3) and recycled sporomorphs (Pl. I-II). The younger taxa are composed of cryptogam spores (*Cyathea* and Polypodiaceae) and herb pollen grains (Chenopodiaceae, Compositae, Ericaceae and Poaceae). The recycled sporomorphs are characterized by diverse biostratigraphic ranging taxa that have been reported in the Antarctic (Askin, 1981, 1983a, b, 1988a, b, 1990a, b, 1992, 1997; Truswell, 1983, 1990; Dettmann and Thomson, 1987; Dettmann and Jarzen, 1988; Dettmann, 1989). Late Jurassic-Early Cretaceous species are spore of *Baculatisporites comaumensis*, *Ceratosporites equalis*, *Cicatricosisporites cuneiformis*, *C. hughesii*, *Contignisporites cooksonii*, *Cyathidites australis*, *C. concavus*, *Cyatheacidites annulatus*, *Leptolepidites verrucatus*, *Matonisporites agatonensis* and *Todisporites minor*, and gymnosperm pollen of *Alisporites bilateralis* and *Zonalapollenites dampieri*. But the forms known to be confined to the Jurassic were not recorded. Taxa known as Late Cretaceous and/or early Tertiary time involve spores of *Appendicisporites distocarinus*, *Camerozonotriletes ambigens*, *Clavifera triplex*, *Gleicheniidites circinidites*, *Osmundacidites wellmanii* and *Retitriletes eminulus*, and pollen grains of *Lygistepollenites florinii*, *Microcachryidites antarcticus*, *M. australiensis*, *Phyllocladidites mawsonii*, *P. paleogenicus*, *Podocarpidites marwickii*, *Beaupreaidites elegansiformis*, *Nothofagidites emarcidus*, *N. flemingii*, *N. incrassatus*, *Periporopollenites polyoratus*, *Proteacidites adenanthoides*, *P. kopiensis*, *P. rectomarginis*, *P.*

tenuiexinus, *Tricolpites reticulatus* and *Tubulifloridites antipodica*.

In S7, the recycled pollen including *Phyllocladidites mawsonii*, *P. paleogenicus*, *Pinuspollenites* sp., *Lygistepollenites florinii* and *Tricolpopollenites crassimurus*, together with younger Poaceae dominate (>20%) throughout the section. Common taxa involve the recycled spores such as *Cyathidites australis* and *Baculatisporites comaumensis*, and the recycled pollen, *Nothofagidites incrassatus*. A younger spore, *Cyathea* is also common (Fig. 2a).

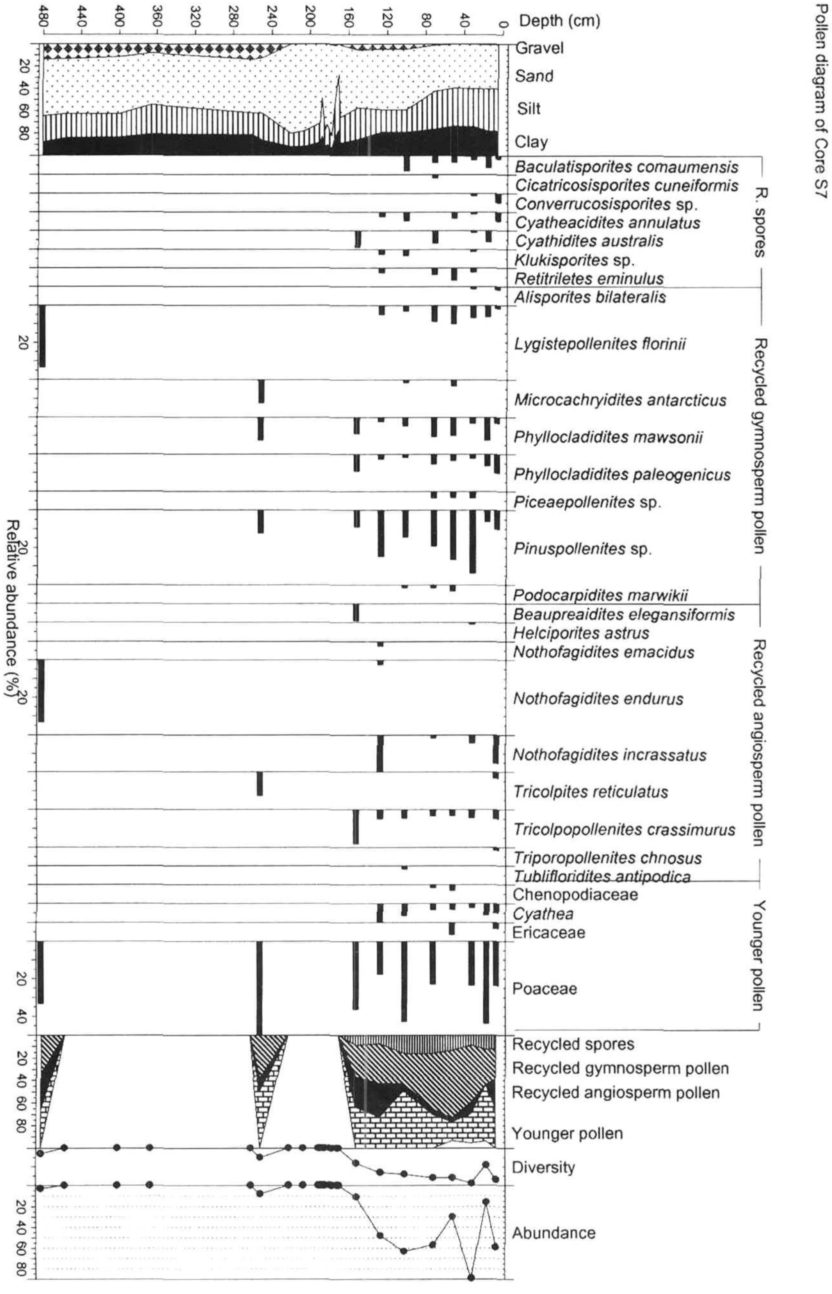

Fig. 2. Pollen diagram of S7 (a), S4 (b) and AB2 (c) cores from the Bransfield Strait. Grain size analysis is from Park *et al.* (1992), but that of AB2 is not shown.

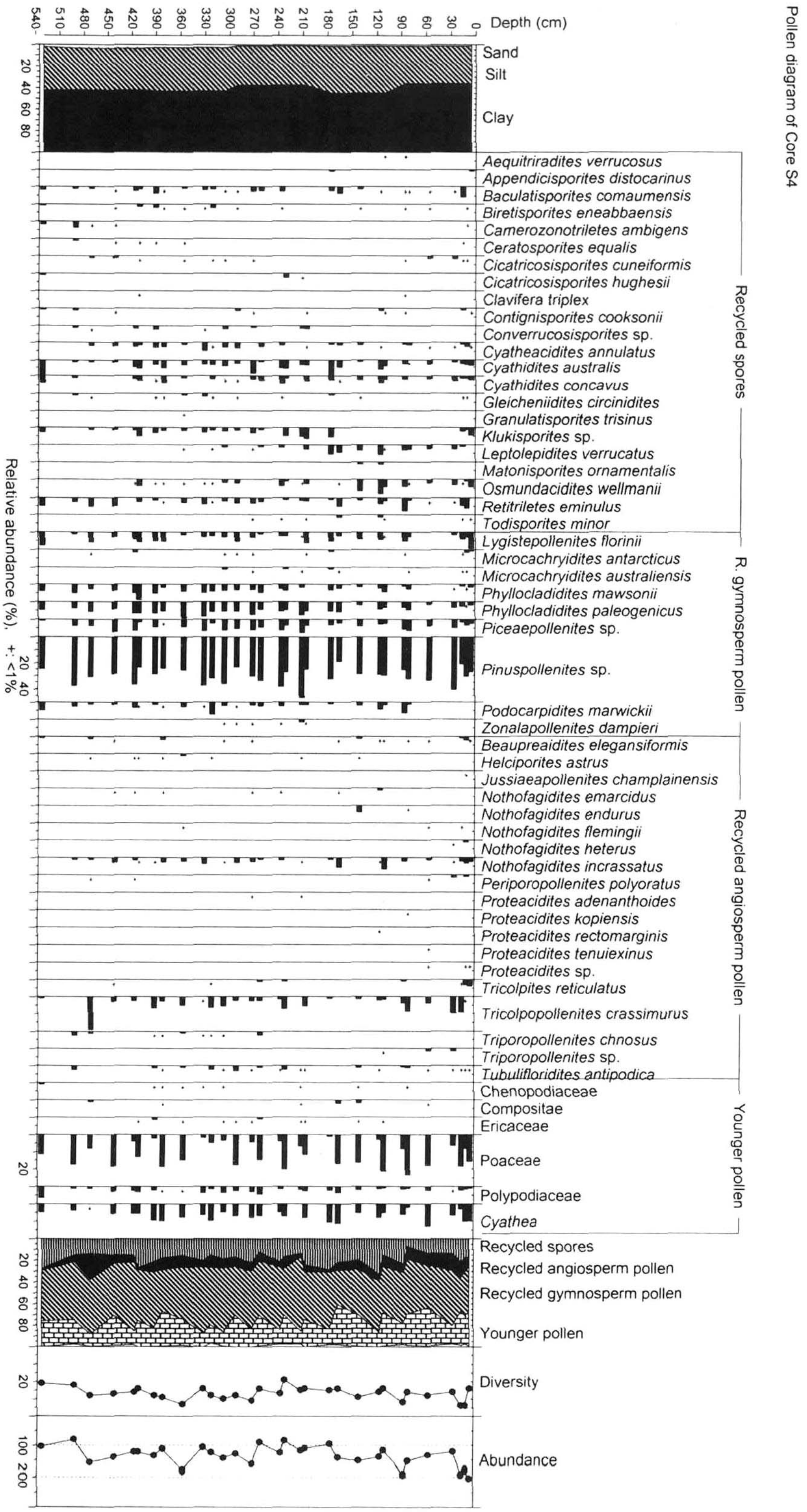

Fig. 2. *Continued.*

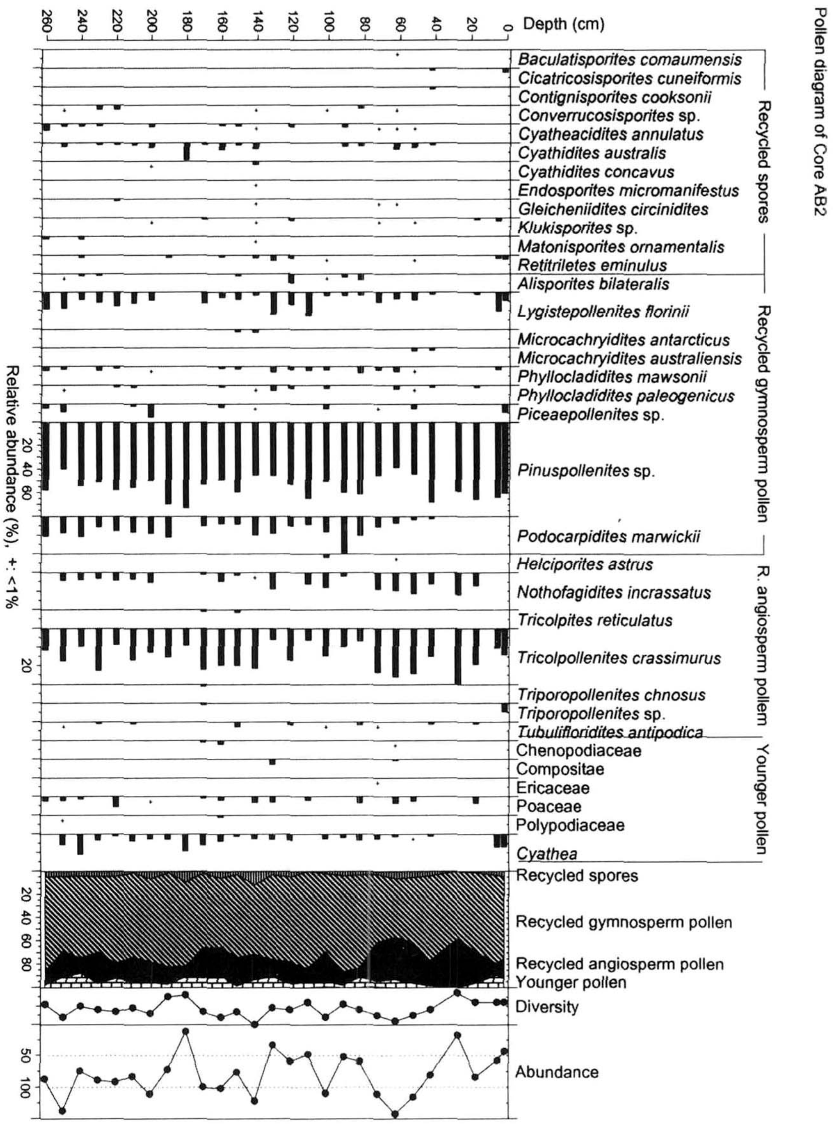

Fig. 2. *Continued.*

In S4, the palynofloral assemblages are characterized by predominance (5-40%) of a recycled gymnosperm pollen (*Pinuspollenites* sp.) and an younger pollen (Poaceae), combined with common (<5%) recycled spores of *Cyathidites australis*, *Osmundacidites wellmanii* and *Retitriletes eminulus* and a *Cyathea* younger spore. Also the recycled pollen, such as *Lygistepollenites florinii*, *Phyllocladidites mawsonii*, *P. paleogenicus*, *Nothofagidites incrassatus* and *Tricolpopollenites crassimurus*, are common throughout the section (Fig. 2b).

In AB2, the recycled pollen representatives of *Pinuspollenites* sp. and *Tricolpopollenites crassimurus* dominate (20-60%) throughout the section. Common taxa consist of the recycled pollen of *Lygistepollenites florinii*, *Phyllocladidites mawsonii*, *P. paleogenicus*, *Podocarpidites marwickii*, *Nothofagidites incrassatus*, in combination with younger taxa such as *Cyathea* and Poaceae (Fig. 2c).

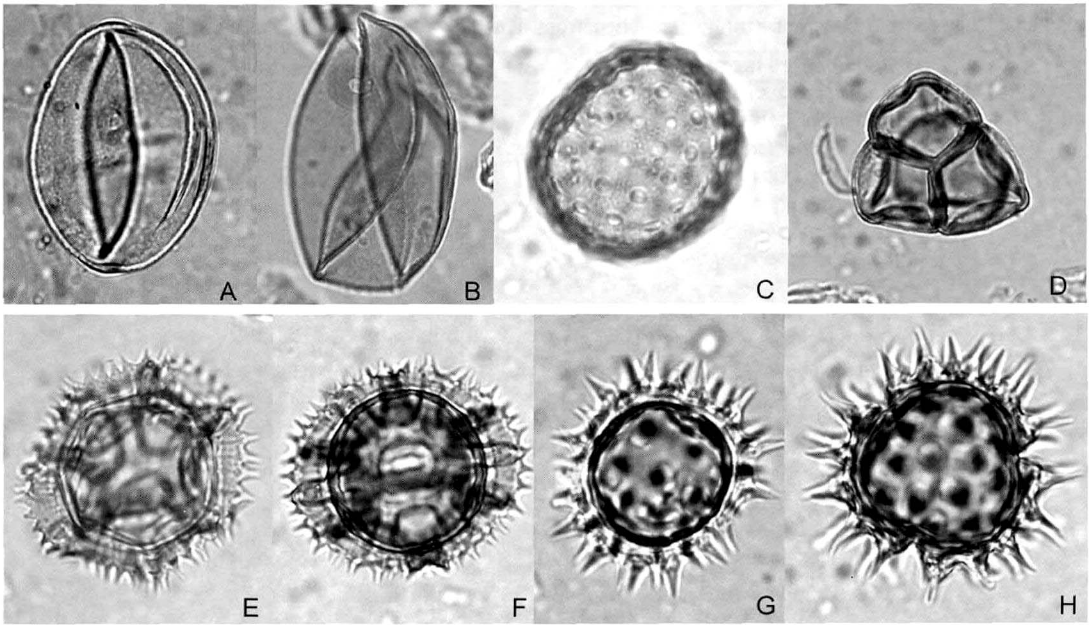

Fig. 3. Younger (recent) angiosperm pollen (x900): A, B, Poaceae. A, Core S4, 55-60, F27/3+4; B, Core S4, 55-60, F27/3+4; C, Chenopodiaceae. Core S4, 210-220, F17/3+4; D, Ericaceae. Core S4, 270-280, E20/3; E, F, G, H, Compositae. E, Core S7, 30-35, B42/2; F, Core S4, 320-325, F44/4; G, Core S4, 320-325, G17/2; H, Core S4, 55-60, N37/1+3.

Vegetation and paleoclimate history

The diversity of palynoflora is moderate, suggesting that the assemblages are probably a mixture of inland and coastal taxa brought in by both wind and water action. The palynomorph assemblages, therefore, can reflect the in situ inland and coastal vegetation. The botanical affinities of the majority of Cretaceous terrestrial spore and pollen appear to be linked to extinct taxa. It, therefore, is difficult to make precise paleovegetation and paleoclimate implications on the basis of such forms. Nevertheless, some assumptions may be suggested by comparisons to the morphologically similar modern taxa (Table 1).

Cretaceous Period

Bryophyte taxon present includes *Aequitriradites* belonging to the Family Hepaticae. The spores belonging to genera *Ceratosporites*, *Leptolepidites* and *Retitriletes* may be placed within the order Lycopodiales. The following pteridophyte fern spores, *Cyathidites*, *Cicatricosisporites*, *Gleicheniidites*, *Osmundacidites*, *Contignisporites* and *Cyatheacidites* are related to particular families (see Table 1). These taxa, present in three cores (S7, S4 and AB2), are all significant components of the Early Cretaceous floral assemblage of the Southern Hemisphere (Australia: Dettmann, 1963, 1981, 1989; Helby *et al.*, 1987; southern South America: Archangelsky and Gamerro, 1967; Antarctica: Domack *et al.*, 1980; Askin, 1981, 1983a; Truswell, 1990; Duane, 1996). Although many of these taxa have broad climatic tolerance, the majority generally indicates temperate and high humidity conditions, especially *Cyathidites*, *Cyatheacidites*, *Gleicheniidites*, *Osmundacidites* and *Cicatricosisporites* (Dettmann, 1989). The data that have accumulated from recycled palynomorphs assemblages suggest an Early Cretaceous vegetation in Antarctica that was very similar to that of Australia today. The schizaeaceous ferns, today in Australia, are more prevalent in subtropical and tropical with high humidity areas. The gymnosperm taxa *Alisporites* and *Podocarpidites* are similar to the pollen shed by podocarps growing at southern high altitudes today (Nandi, 1990). The pollen grains may have been transported some distance from source and may not reflect the in

Table 1. Pollen and spores recorded in Bransfield Strait, Antarctic Peninsula, with their probable botanical affinity (complied from Truswell, 1990; Specht *et al.*, 1992).

	Pollen/spore taxon	**Probable botanical affinity**
Spore	*Aqeuitriradites verrucosus*	Hepaticae
	Appendicisporites distocarinus	Schizaeaceae
	Baculatisporites comaumensis	Osmundaceae
	Camerozonotriletes ambigens	Pteridaceae (*Pteris*)
	Ceratosporites equalis	Selaginellaceae (*Selaginella*)
	Cicatricosisporites cuneiformis	Schizaeaceae
	Cicatricosisporites hughesii	Schizaeaceae
	Clavifera triplex	Gleicheniaceae
	Contignisporites cooksonii	Pteridaceae
	Cyatheacidites annulatus	Lophosoriaceae (*Lophosoria*)
	Cyathidites australis	Cyatheaceae/Dicksoniaceae
	Gleicheniidites circinidites	Gleicheniaceae (*Gleichenia*)
	Klukisporites sp.	Schizaeceae (cf. *Klukia*)
	Leptolepidites verrucatus	Selaginellaceae?
	Matonisporites ornamentalis	Dicksonioideae?
	Matonisporites agatonensis	Dicksonioideae?
	Osmundacidites wellmanii	Osmundaceae
	Retitriletes eminulus	Lycopodiaceae (*Lycopodium*)
	Todisporites minor	*Sphagnum*
Gymnosperm pollen	*Alisporites bilateralis*	Podocarpaceae
	Lygistepollenites florinii	Podocarpaceae (*Dacrydium*)
	Microcachryidites antarcticus	Podocarpaceae (*Microcachrys*)
	Microcachryidites australiensis	Podocarpaceae (cf. *Microcachrys*)
	Phyllocladidites mawsonii	Podocarpaceae (*Lagarostrobus*)
	Phyllocladidites paleogenicus	Podocarpaceae (*Lagarostrobus*)
	Piceaepollenites sp.	Pinaceae
	Pinuspollenites sp.	Pinaceae
	Podocarpidites marwickii	Podocarpaceae (*Podocarpus*)
	Zonalapollenites dampieri	Araucariaceae
Angiosperm pollen	*Beaupreaidites elegansiformis*	Proteaceae (*Beauprea*)
	Helciporites astrus	Fagaceae
	Jussiaeapollenites champloainensis	Fagaceae
	Nothofagidites emarcidus	Fagaceae (*Nothofagus*)
	Nothofagidites endurus	Fagaceae (*Nothofagus*)
	Nothofagidites flemingii	Fagaceae (*Nothofagus*)
	Nothofagidites heterus	Fagaceae (*Nothofagus*)
	Nothofagidites incrassatus	Fagaceae (*Nothofagus*)
	Periporopollenites polyoratus	Trimeniaceae
	Proteacidites adenanthoides	Proteaceae (*Adenanthos*)
	Proteacidites kopiensis	Proteaceae
	Proteacidites rectomarginis	Proteaceae
	Proteacidites tenuiexinus	Proteaceae
	Proteacidites sp.	Proteaceae
	Tricolpites reticulatus	Gunneraceae (*Gunnera*)
	Triporopollenites chnosus	Proteaceae (*Telopea*)
	Triporopollenites sp.	Proteaceae
	Tubulifloridites antipodica	Ranunculaceae

situ paleoclimatic conditions. Accordingly, the land vegetation probably consisted of a coniferous forest with abundant podocarps and araucarians, a fern understory and minor amounts of lycopods and bryophytes under the warm, humid conditions during the Early Cretaceous.

The Albian-Cenomanian flora is a temperate gymnosperm (especially podocarp and conifers)-cryptogam rainforest association (Dettmann, 1989). The spore *Appendicisporites distocarinatus*, which has a range from Late Cretaceous (Cenomanian to Turonian) in eastern Australia and around the Antarctic Peninsula, is present in this study. The gymnosperm pollen, *Podosporites marwickii* and *Phyllocladidites mawsonii* may have derived from Late Cretaceous (Campanian) source. Angiosperm pollen grains are present in all samples, and specimens of *Proteacidites*, *Nothofagidites* and *Tricolpites* may be derived as readily from Late Cretaceous sedimentary rocks. Although angiosperms appeared during Turonian-Maastrichtian time, in the early part, the rainforest was coniferous. By latest Cretaceous age, however, angiosperms such as Proteaceae (*Proteacidites* spp.) and Fagaceae (*Nothofagidites* spp.) had become dominant and many of the original cryptogams and gymnosperms had disappeared (Askin, 1992). *Nothofagus* first appeared in the Santonian-?early Campanian Santa Marta Formation, but was a relatively unimportant component (Francis, 1986). Late Cretaceous floras suggest warm to cool temperate, high rainfall conditions (Francis, 1986; Askin, 1992), with water-logged coastal lowlands in the latest Maastrichtian-earliest Paleocene (Askin and Jacobson, 1996). The climate condition of Early Paleocene is assumed to be cold period indicated by increased tree-ring densities in fossil logs (Francis, 1991). The bulk of the Late Cretaceous data come from the James Ross Island area, but tuffaceous, plant bearing strata, interbedded with volcanoclastic rocks occur on King George Island, and these contain similar floras (Birkenmajer and Zastawniak, 1989; Askin, 1992; Cao, 1992) (Fig. 4).

The paleoclimate implication during the Cretaceous Period can be supported by the following previous geochemical data sets. Between Albian and Turonian times were relatively cool temperate and wet following a warmer Aptian episode, based on geochemical analyses and stable oxygen isotope (Ditchfield *et al.*, 1994; Huber *et al.*, 1995; Dingle and Lavelle, 1998a). δ^{18}O data indicate cool sea surface temperatures for the South Atlantic for this period (Huber *et al.*, 1995) and these data were calculated values of 10-12℃ by Ditchfield *et al.* (1994) for the nearshore marine areas. The δ^{18}O data that estimates paleotemperatures of marine waters in James Ross and Seymour Islands area suggest that a Late Cretaceous maximum (18.5℃) occurred in Coniacian-early Santonian time, following an Aptian-Albian period of cooler conditions (10-12℃) (Ditchfield *et al.*, 1994; Dingle and Lavelle, 1998a). Ditchfield *et al.* (1994) report a cooling trend through Campanian-Maastrichtian time to values 12℃ in the late Maastrichtian. Partly contemporaneous data from the Snow Hill Island-López de Bertodano formations (Barrera *et al.*, 1987) suggest a short-term temperature increase in the lowermost López de Bertodano Formation, and a further increase in the upper part of the same formation (earliest Paleocene), superimposed on the overall Late Cretaceous cool record (Fig. 4).

Warm and humid climatic conditions, during the Turonian through Campanian, coincide with a time of long-term change in the temperature regime from cool to warm and could be related to climatic instability as oceanic circulation adjusted to the rapidly altering paleogeography of the southern South Atlantic/Weddell Sea area (Dingle and Lavelle, 2000). During this time period, the most significant paleogeographical development in the area was the initiation at 90 Ma of direct surface and mid water access for South Atlantic equatorial waters into the Weddell Basin (Dingle, 1999), whereas shortly before, the transpolar shallow seaway had closed (Lawver *et al.*, 1992) (Fig. 4). Also, this period was the acme of the trans-equatorial Tethyan seaway and was a time when the planktonic foraminiferal faunas of the paleo-Southern Ocean (Weddell Basin) were characterized by tropical elements (Huber, 1992).

The chemical index of alteration (CIA) curve and isotope studies for latest Cretaceous to mid-Paleogene reflect that there is relatively large paleotemperature changes with a decline from the mid-Campanian optimum, although minor Late Maastrichtian perturbations to cool-cold conditions by mid-Paleogene times (Barrera *et al.*, 1987; Ditchfield *et al.*, 1994; Dingle and Lavelle, 1998b). The only major paleogeographical change that occurred during this time interval was the separation of the New Zealand-Lord Howe Rise complex from Antarctica/Australia between 80-70 Ma (Lawver *et al.*, 1992). This have generated a new, more-polar circulation route along the southern edge of the Pacific Ocean and may have brought colder surface currents to the western side of the Antarctic Peninsula.

Early Tertiary Period

Nothofagaceae (*Nothofagidites*) is considered to be of critical importance as an indicator of paleoclimate

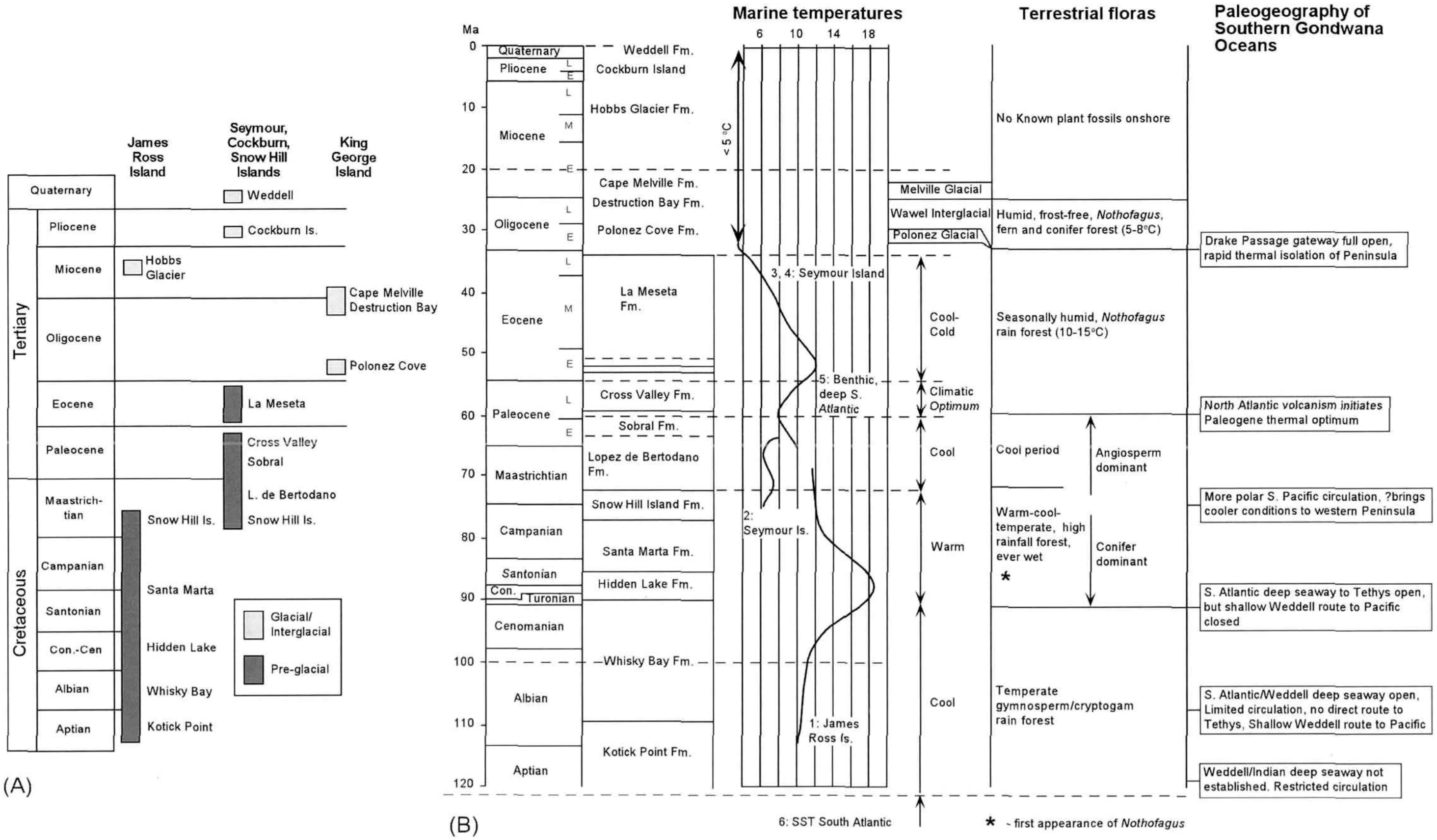

Fig. 4. (A) Summary stratigraphical relationships of sedimentary sequences and formations (after Dingle and Lavelle, 1998a). (B) Schematic diagram of Cretaceous-Tertiary paleoclimatic proxies for northern Antarctic Peninsula. Marine water $\delta^{18}O$ paleotemperature variations (℃) compiled from data in: 1, 3= Ditchfield *et al.* (1994); 2= Barrera *et al.* (1987); 4= Pirrie *et al.* (1998); 5= Zachos *et al.* (1993); 6= Huber *et al.* (1995). Stratigraphical position of Melville Glacial, Wawel Interglacial and Polonez Glacial after Dingle and Lavelle (1998b). Summary of terrestrial floras compiled from data in Francis (1986, 1991); Case (1988); Dettmann (1989); Birkenmajer and Zastawniak (1989); Askin (1992); Cao (1992); Doktor *et al.* (1996). Major paleoceanographic changes in southern Gondwana during the Late Cretaceous-Cenozoic times (modified from Dingle and Lavelle, 2000).

(Reguero *et al.*, 2002). *Nothofagidites* is the predominant to common angiosperm taxon in each of the three cores from the Bransfield Strait (Fig. 2).

Late Paleocene-Eocene forests on Seymour and King George Islands were mixed broadleaved angiosperm (*Nothofagidites*, *Proteacidites* and *Tricolpites*) and podocarps conifer associations with a reduced diversity compared to earlier floras (Case, 1988; Askin, 1992). Doktor *et al.* (1996) compared them to those of southern Chile and Argentina today, and suggested ambient paleotemperatures of 10-15℃ and a rainfall of 600-1200 mm, whereas Askin (1992) suggested that the climate was strongly seasonal. Gandolfo *et al.* (1998) reported several species belonging to *Nothofagidites* from the late-Early Eocene La Meseta Formation of Seymour Island. *N. serrulata* is now restricted to southern South America, where it grows in a cool temperate climate (Reuero *et al.*, 2002). Paleofloral data show that the Middle-Late Eocene was warmer than present, but not as warm as the Late Paleocene through Early Eocene (Reguero *et al.*, 2002). Askin (1992) had already suggested that an element of rainfall seasonality in the Seymour Island Eocene terrestrial floral signal without specifying any particular stratigraphical interval. A further decline in diversity was recorded in the Late Oligocene King George Island Wawel Interglacial floras, which are essentially *Nothofagidites*, fern and podocarp associations. Angiosperm diversity was greatly reduced compared to Eocene time, and modern analogues suggested cool (5-8℃), moist, frost-free paleoclimates (Birkenmajer and Zastawniak, 1989). The palynofloras become less diverse, which probably reflects the cooling temperatures (Askin, 1997) that ultimately led to the onset of the Cenozoic ice sheets and the elimination of vegetation from mainland Antarctica (Francis and Poole, 2002) (Fig. 4).

On the basis of CIA evidence from the upper section of Cross Valley Formation (Late Paleocene) and the lowermost section of La Meseta Formation (Early Eocene) on Seymour Island, Dingle and Lavelle (1998a) considered that the extended period of warm, wet climate conditions was prevailed during the Early Eocene, although the relatively large hiatus between these two formations. Antarctica experienced the start of the Paleogene global thermal optimum (Robert and Kennett, 1994). Southern Ocean deep water temperature was as high as 15 ℃ (Zachos *et al.*, 1994) and sea surface temperature was 18-22℃ (Robert and Kennett, 1994). However, during the Late Eocene, cold-cool conditions were indicated by falling in smectite/kaolinte ratios upward the La Meseta succession (Dingle and Lavelle, 1998a). This is in general agreement with oxygen isotope temperature data for the adjacent areas, which give mean values of 7-9℃(Ditchfield *et al.*, 1994; Pirrie *et al.*, 1998). Between South America and the Antarctic Peninsula, the Drake Passage remained closed to deep circulation until slightly later; but by 30 Ma, deep and shallow circumpolar circulation had been established and the thermal isolation of Antarctica was completed (Lawver *et al.*, 1992; Dingle and Lavelle, 2000).

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남극 브랜스필드 해협의 재동된 화분-포자화석에 기록된 고기후 변화

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요 약: 남극 브랜스필드해협의 해빙양성퇴적물에서 산출된 백악기-제3기 초기의 재동된 화분-포자화석기록은 그 당시의 식생과 기후변동을 나타냈다. 화분-포자 분석 자료와 기존 다중지시자료(식물화석, 퇴적물, 지화학)를 이용하여 백악기-제3기 초기동안 뚜렷한 고기후변동을 알 수가 있었다. 한랭했던 백악기 초기의 기후는 백악기 후기에 접어들면서 계절변화가 없는 온난한 기후조건으로 변하였으며, 특히 코니아시안(Coniacian)-캄파니안 초기(Early Campanian)에는 고온기(hypsithermal)였던 것으로 생각된다. 백악기 최후기(Maastrichtian)와 팔레오세 초기동안에는 다시 한랭하였으며, 이 시기에는 계절적 변화가 존재하는 기후 조건이었던 것으로 생각된다. 팔레오세 후기와 에오세 초기에는 다시 한번 온난하였지만, 에오세 후기에 접어들면서 다시 한랭하였던 것으로 판단된다. 계속되는 한랭기후는 남극대륙에 신생대(마이오세)의 빙상이 만들어지는 시기로, 이로 인해 목본식물이 더 이상 존재 할 수 없는 환경으로 바꾸었던 것으로 판단된다.

References

Ahmadjian, V., 1970 : Adaptation of antarctic terrestrial plants. in: M. W. Holdgate (ed.), *Antarctic Ecology*, vol. 2. Acad. Press, New York, NY, pp. 801-811.

Amos, A. F., 1987 : Racer: physical oceanography of the western Bransfield Strait. *Antarc. J. US.*, v. 22, p. 137-140.

Archangelsky, S. and Gamerro, J. C., 1967 : Spore and pollen types of the Lower Cretaceous in Patagonia (Argentina). *Rev. Palaeobot. Palynol.*, v. 1, p. 211-217.

Askin, R. A., 1981: Jurassic-Cretaceous palynology of Byers Peninsula, Livingston Island, Antarctica. *Antarc. J. US.*, v. 16, p. 11-13.

Askin, R. A., 1983a : Tithonian (uppermost Jurassic)-Barremian (Lower Cretaceous) spore, pollen and microplankton from the South Shetland Islands, Antarctica. in: R. L. Oliver, P. R. James and J. B. Jago (eds.), *Antarctic Earth Science*. Austral. Acad. Sci., Canberra, pp. 295-297.

Askin, R. A., 1983b : Campanian palynomorphs from James Ross and Vega Island, Antarctic Peninsula. *Antarc. J. US.*, v. 18, p. 63-64.

Askin, R. A., 1988a : Campanian to Paleogene palynological succession of Seymour and adjacent islands, northern Antarctic Peninsula. *Geol. Soc. Amer., Mem.*, v. 169, p. 131-153.

Askin, R. A., 1988b : The palynological record across the Cretaceous/Tertiary transition on Seymour Island, Antarctica. *Geol. Soc. Amer., Mem.*, v. 169, p. 155-162.

Askin, R. A. 1989 : Endemism and heterochroneity in the Late Cretaceous (Campanian) to Paleocene palynofloras of Seymour Island, Antarctica: implications for origins, dispersal and paleoclimates of southern floras. in: J. A. Crame (ed.), *Origins and evolution of the Antarctic Biota*. Geol. Soc. Spec. Publ. 47, pp. 107-119.

Askin, R. A., 1990a : Campanian to Paleocene spore and pollen assemblages of Seymour Island, Antarctica. *Rev. Palaeobot. Palynol.*, v. 65, p. 105-113.

Askin, R. A., 1990b : Cryptogam spores from the upper Campanian and Maastrichtian of Seymour Island, Antarctica. *Micropaleont.*, v. 36, p. 141-156.

Askin, R. A., 1992 : Late Cretaceous-early Tertiary Antarctic outcrop evidence for past vegetation and climates. *Antarc. Res. Ser.*, v. 56, p. 61-73.

Askin, R. A., 1997 : Eocene-?Earliest Oligocene Terrestrial palynology of Seymour Island, Antarctica. in: C. A. Ricci (ed.), *The Antarctic Region: Geological Evolution and Processes*. Terra Antarc. Publ., Siena, pp. 993-996.

Askin, R. A. and Jacobson S. R., 1996: Palynological change across the Cretaceous-Tertiary boundary on Seymour Island, Antarctica: environmental and depositional factors. in: N. MacLeod and G. Keller (eds.), *Cretaceous-Tertiary Mass Extinctions: Biotic and Environmental Changes*. Norton, New York, pp. 7-25.

Barrera, E., Huber, B. T., Savin, S. M. and Webb, P. N., 1987: Antarctic marine temperature: late Campanian through early Paleocene. *Paleoceanography*, v. 2, p. 21-47.

Birkenmajer, K., 1992 : Evolution of the Bransfield Basin and rift, West Antarctica. in: Y. Yoshida, K. Kaminuma and K. Shiraishi (eds.), *Recent Progress in Antarctic Earth Science*. Terra, Tokyo, pp. 405-410.

Birkenmajer, K. and Zastawniak, E., 1989 : Late Cretaceous-early Tertiary floras of King George Island, West

Antarctica: their stratigraphic distribution and palaeoclimatic significance. *Geol. Soc. London, Spec. Publ.,* v. 47, p. 227-240.

Bliss, L. C., 1979 : Vascular plant vegetation of the Southern Circumpolar Region in relation to Antarctic, alpine, and arctic vegetation. *Can. J. Bot.,* v. 57, p. 2167-2178.

Byun, H., Yun, H., Yi, S. and Chang, S.-K., 1996 : Reworked dinocysts from the Bransfield Strait, Antarctica. *J. Paleont. Soc. Kor.,* v. 12, p. 22-56.

Cao, L., 1992 : Late Cretaceous and Eocene palynofloras from Fildes Peninsula, King George Island (South Shetland Islands) Antarctica. in: Y. Yoshida, K. Kaminuma and K. Shiraishi (eds.), *Recent Progress in Antarctic Earth Science.* Terra, Tokyo, pp. 363-369.

Case, J. A., 1988 : Paleogene floras from Seymour Island, Antarctic Peninsula. in: R. M. Feldmann and M. O. Woodburne (eds.), *Geology and Paleontology of Seymour Island, Antarctic Peninsula.* Geol. Soc. Amer., Mem., 169, pp. 523-530.

Creber, G. T. and Chaloner, W. G., 1984 : Influence of environmental factors on the wood structure of living and fossil trees. *Bot. Rev.,* v. 50, p. 357-447.

Dettmann, M. E., 1963 : Upper Mesozoic microfloras from south-eastern Australia. *Proc. Royal Soc. Vict.,* v. 77, p. 1-148.

Dettmann, M. E., 1981 : The Cretaceous flora. in: A. Keast (ed.), *Ecological Biogeography of Australia.* The Hague, pp. 355-375.

Dettmann, M. E., 1989 : Antarctica: Cretaceous cradle of austral temperate rainforests? in: J. A. Crame (ed.), *Origins and Evolution of the Antarctic Biota.* Geol. Soc., Spec. Publ. 47, pp. 89-105.

Dettmann, M. E. and Jarzen, D. M., 1988 : Angiosperm pollen from uppermost Cretaceous strata of southeastern Australia and the Antarctic Peninsula. *Assoc. Australasian Palaeont., Mem.,* v. 5, p. 217-237.

Dettmann, M. E. and Thomson, M. R. A., 1987 : Cretaceous palynomorphs from the James Ross Island area-a pilot study. *Brit. Antarc. Surv., Bull.,* 77.

Dingle, R., 1999 : Walvis Ridge barrier: its influence on palaeoenviroments and source rock generation deduced from ostracod distributions in the early South Atlantic Ocean. in: N, Cameron, R. H. Bate and R. Clure (eds.), *Hydrocarbon Habitats of the South Atlantic.* Geol. Soc. London, Spec. Publ. 153, pp. 293-302.

Dingle, R. and Lavelle, M., 1998a : Late Cretaceous-Cenozoic climatic variations of the northern Antarctic Peninsula: new geochemical evidence and review. *Palaeogeogr. Palaeoclimat. Palaeoecol.,* v. 141, p. 215-232.

Dingle, R. and Lavelle, M., 1998b : Antarctic Peninsula cryosphere: Early Oligocene (c. 30 Ma) initiation and a revised glacial chronology. *J. Geol. Soc. London,* v. 155, p. 433-437.

Dingle, R. and Lavelle, M., 2000 : Antarctic Peninsula Late Cretaceous-Early Cenozoic palaeoenvironments and Gondwana palaeogeographies. *J. Afri. Earth Sci.,* v. 31, p. 91-105.

Ditchfield, P. W., Marshall, J. D. and Pirrie, D., 1994 : High latitude palaeotemperature variation: new data from the Tithonian to Eocene of James Ross Island, Antarctica. *Palaeogeogr., Palaeoclimat., Palaeoecol.,* v. 107, p. 79-101.

Doktor, M., Gazdzicki, A., Jerzmanska, A., Porebski, S. J. and Zastawniak, E., 1996 : A plant- and -fish assemblage from the Eocene La Meseta Formation of Seymour Island (Antarctic Peninsula) and its environmental implications. *Palaeontology,* v. 55, p. 127-146.

Domack, E. W., Fairchild, W. W. and Anderson, J. B., 1980 : Lower Cretaceous sediment from the East Antarctic continental shelf. *Nature,* v. 287, p. 625-626.

Duane, A. M., 1996 : Palynology of the Byers Group (Late Jurassic-Early Cretaceous) of Livingston and Snow Islands, Antarctic Peninsula: its biostratigraphical and palaeoenvironmental significance. *Rev. Palaeobot. Palynol.,* v. 91, p. 241-281.

Frakes, L. A., 1979 : *Climates throughout Geological Time.* Elsevier, Amsterdam.

Francis, J. E., 1986 : Growth rings in Cretaceous and Tertiary wood from Antarctica and their palaeoclimatic implications. *Palaeontology,* v. 29, p. 665-684.

Francis, J. E., 1991 : Paleoclimatic significance of Cretaceous-early Tertiary fossil forests of the Antarctic Peninsula. in: M. R. A. Thomson, J. A. Crame and J. W. Thomson (eds.), *Geological Evolution of Antarctica.* Cambr. Univ. Press, Cambridge, pp. 623-628.

Francis, J. E. and Poole, I., 2002 : Cretaceous and early Tertiary climates of Antarctica: evidence from fossil wood. *Palaeogeogra. Palaeoclimat. Palaeoecol.,* v. 182, p. 47-64.

Gandolfo, M. A., Marenssi, S. A. and Santillana, S. N., 1998 : Flora y paleoclima de la Formación La Meseta (Eoceno medio), isla Marambio (Seymour), Antartida. in: S. Casadio (ed.), *Paleógeno de América del Sur y de la Peninsula Antártica.* Asoc. Paleont. Argentina, Publ. Especial 5, pp. 155-162.

García, M. A., Castro, C. G., Ríos, A. F., Doval, M. D., Roson, G., Gomis, D. and López, O., 2002 : Water masses and distribution of physico-chemical properties in the Western Bransfield Strait and Gerlache Strait during Austral summer 1995/96. *Deep-Sea Research II,* v. 49, p. 585-602.

Gordon, A. L. and Nowlin, W. D., 1978 : The basin waters of the Bransfield Strait. *J. Physi. Oceanogra.,* v. 8, p. 258-264.

Grimm, E., 1991 : TILIAGRAPH v1.25 (computer software) Illinois State Museum, Research and Collections Center, Springfield, IL, USA.

Grimm, E., 1993 : TILIA v2.0 (computer software) Illinois State Museum, Research and Collections Center, Springfield, IL, USA.

Helby, R., Morgan, R. and Partridge, A. D., 1987 : A palynological zonation of the Australian Mesozoic. in: P. A. Jell (ed.), *Studies in Australian Mesozoic Palynology. Assoc. Australasian Palaeont., Mem.,* v. 4, pp. 1-94.

Huber, B. T., 1992 : Palaeobiogeogrphy of Campanian-Maastrichtian foraminifera in the southern high latitudes. *Palaeogeogr. Palaeoclimat. Palaeoecol.,* v. 92, p. 325-360.

Huber, B. T., Hodell, D. A. and Hamilton, C. P., 1995 : Middle-Late Cretaceous climate of the southern high latitudes: stable isotope evidence for minimal equator-to-pole thermal gradients. *Geol. Soc. Amer., Bull.,* v. 107, p. 1164-1191.

Jeffers, J. D. and Anderson, J. B., 1990 : Sequence stratigraphy of the Bransfield Basin, Antarctica: implications for tectonic history and hydrocarbon potential. in: B. S. John (ed.), *Antarctica as an exploration frontier-hydrocarbon potential, Geology, and hazards.* Amer. Assoc. Petro. Geol., Studies in Geology 31, pp. 13-29.

Kemp, E. M., 1972 : Reworked palynomorphs from the West Ice Shelf area, East Antarctica, and their possible geological and palaeoclimatological significance. *Mar. Geol,.* v. 13, p. 145-157.

Lawver, L. A., Gahagan, L. M. and Coffin, M. F., 1992 : The development of palaeoseaways around Antarctica. *Amer. Geophysi. Union, Antarc. Res. Ser.,* v. 56, p. 7-30.

Longton, R. E., 1985 : Terrestrial habitats-Vegetation. in: W. N. Bonner and D. W. H. Walton (eds.), *Key Environment: Antarctica.* Pergamon Press, Oxford, pp. 73-105.

Moore, P. D., Webb, J. A. and Collinson, M. E., 1991 : *Pollen Analysis (2nd ed.).* Blackwell Science, Oxford, 216 p.

Nandi, B., 1990 : Palynostratigraphy of Upper Cretaceous sediments, Meghalaya, northeastern India. *Rev. Palaeobot. Palynol.,* v. 65, p. 119-129.

Park, B. K., Choi, M. Y., Chang, S. K., Cheong, D. K., Shin, D. H., Park, J. K., Ju, Y. and Kang, C. Y., 1992 : Sedimentological and geoengineering characteristics of cores drilled from the Bransfield Strait, Antarctic Peninsula. Antarctic environments and natural resource exploration. *Report of KORDI,* pp. 89-135 (in Korean).

Pirrie, D., Marshall, J. D. and Crame, J. A., 1998 : Marine high Mg calcite cements in Teredolites-bored fossil wood; evidence for cool palaeoclimates in the Eocene La Meseta Formation, Seymour Island, Antarctica. *Palaios,* v. 13, p. 276-286.

Pirrie, D., Whitham, A. G. and Ineson, J. R., 1991 : The role of tectonics and eustacy in the evolution of a marginal basin: Cretaceous-Tertiary Larsen Basin, Antarctica. in: D. I. M. Macdonald (ed.), *Sedimentation, Tectonics and Eustacy.* Spec. Publ., Intl. Assoc. Sediment. 12, pp. 293-305.

Reguero, M. A., Marenssi, S. A. and Santillana, S. N., 2002 : Antarctic Peninsula and South America (Patagonia) Paleogene terrestrial faunas and environments: biogeographic relationships. *Palaeogeogr. Palaeoclimat. Palaeoecol.,* v. 179, p. 189-210.

Robert, C. and Kennett, J. P., 1994 : Antarctic subtropical humid episode at the Palaeocene-Eocene boundary: clay mineral evidence. *Geology,* v. 22, p. 211-214.

Specht, R. L., Dettmann, M. E. and Jarzen, D. M., 1992 : Community associations and structure in the Late Cretaceous vegetation of southeast Australasia and Antarctica. *Palaeogeogr. Palaeoclimat. Palaeoecol.* v. 94,

p. 283-309.

Storey, B. C. and Garrett, S. W., 1985 : Crustal growth of the Antarctic Peninsula by accretion, magmatism and extension. *Geol. Magazine,* v. 122, p. 5-14.

Thorn, V., 2001 : Vegetation communities of a high palaeolatitude Middle Jurassic forest in New Zealand. *Palaeogeogr. Palaeoclimat. Palaeoecol.,* v. 168, p. 273-289.

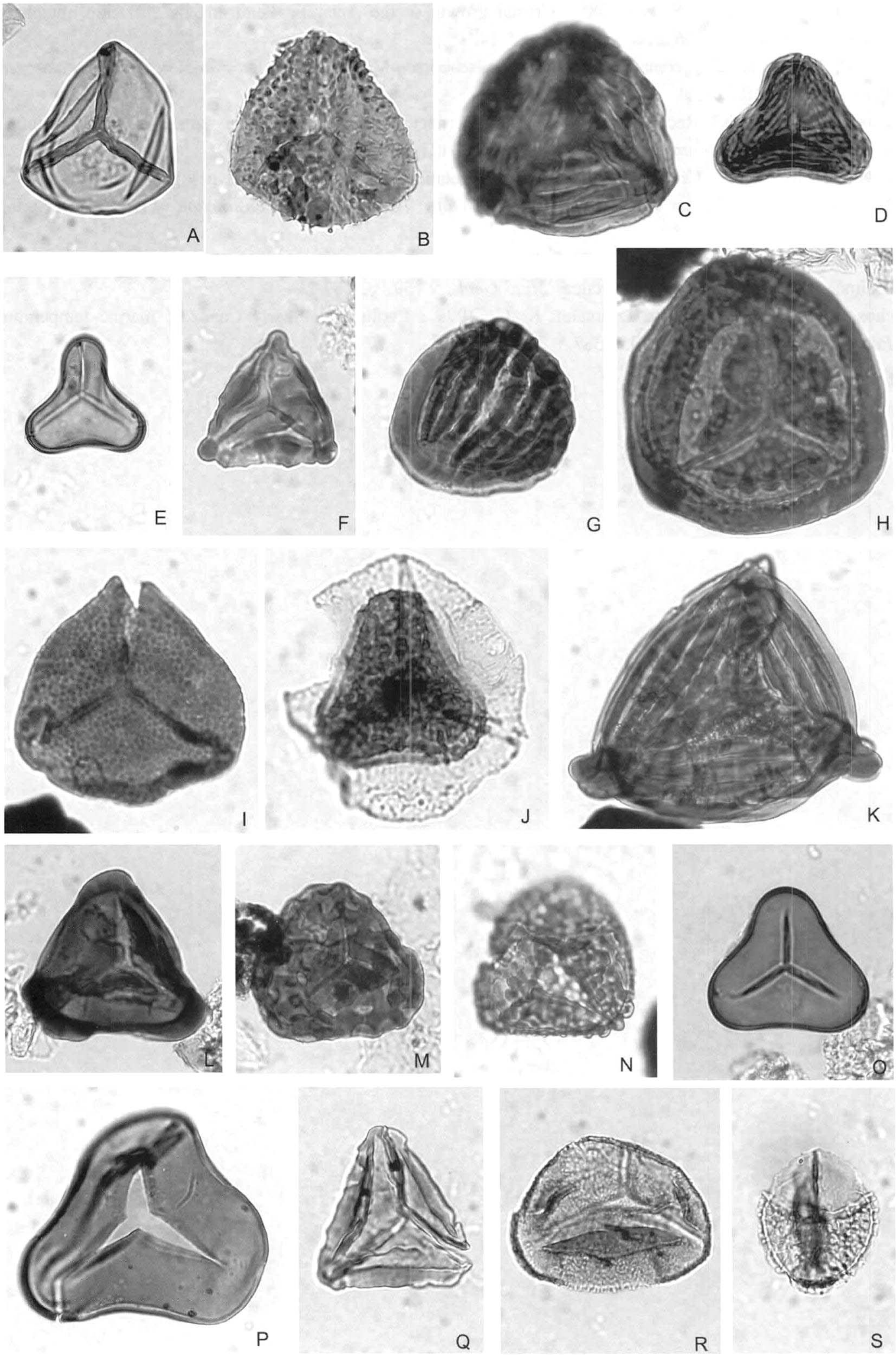
Truswell, E. M., 1983 : Recycled Cretaceous and Tertiary pollen and spores in Antarctic marine sediments: a catalogue. *Palaeontographica Abt. B,* v. 186, p. 121-174.

Truswell, E. M., 1990 : Cretaceous and Tertiary vegetation of Antarctica: a palynological perspective. in: T. N. Taylor and E. L. Taylor (eds.), *Antarctic Paelobiology: Its role in the reconstruction of Gondwana.* Springer, New York, NY, pp. 71-88.

Truswell, E. M. and Drewry, D. J., 1984 : Distribution and provenance of recycled palynomorphs in surficial sediments of the Ross Sea, Antarctica. *Mar. Geol.,* v. 59, p. 187-214.

Zachos, J. C., Stott, L. D. and Lohmann, K. C., 1994 : Evolution of early Cenozoic marine temperatures. *Palaeoceanography,* v. 9, p. 353-387.

[Plate 1]



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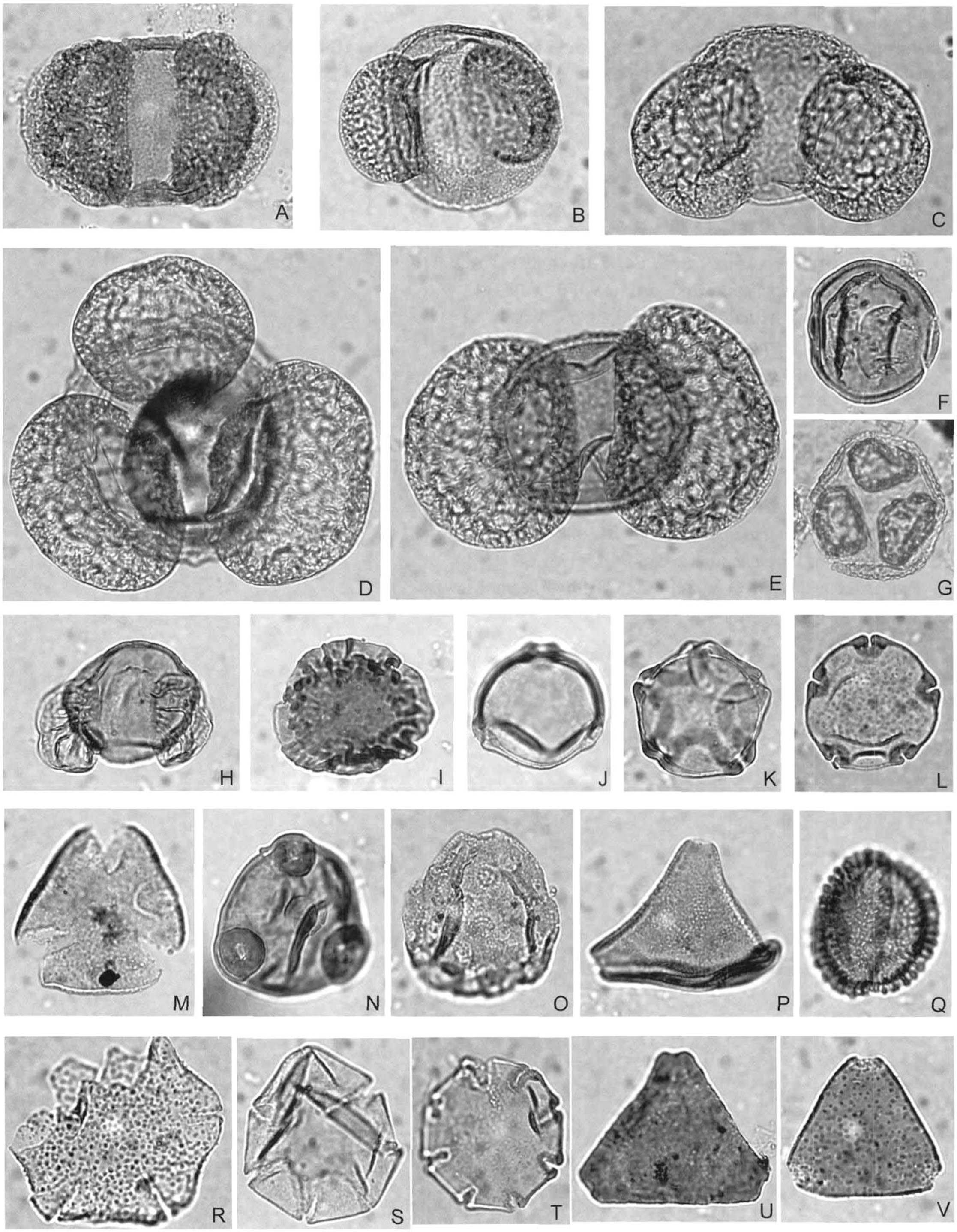
Jurassic to Late Cretaceous spores (A-N); Jurassic to early Tertiary spores (O-S). Magnification x900, unless otherwise stated. Specimens are identified by core/sample depth (cm) and England Finder reference.

A. *Biretisporites eneabbaensis*. Core S4, 290-295, E43/3.
B. *Ceratosporites equalis*. Core S4, 355-360, D14.
C. *Cicatricosisporites hughesii*. Core S4, 210-220, D20/1.
D. *Cicatricosisporites cuneiformis*. Core S4, 55-60, X18/4.
E. *Cyathidites concavus*. Core S4, 115-125, Q30/4.
F. *Clavifera triplex*. Core S4, 410-415, N18/1+3.
G. *Contignisporites cooksonii*. Core S4, 5-10, X50/3+4 (distal view).
H. *Cyatheacidites annulatus*. Core S4, 165-170, V40/3+4.
I. *Granulatisporites trisinus*. Core S4, 355-360, V30/1.
J. *Aequitriradites verrucosus*. Core S4, 530-537, O48/3.
K. *Appendicisporites distocarinus*. Core S4, 175-185, X43/3.
L. *Matonisporites agatonensis*. Core AB2, 240-245, E43/4.
M. *Klukisporites* sp. Core AB2, 17-22, L41/1+3.
N. *Leptolepidites verrucatus*. Core S4, 55-60, P19/3.
O. *Cyathea*. Core S4, 230-235, Q26/2.
P. *Cyathidites australis*. Core S4, 175-185, S38.
Q. *Gleicheniisporites circinidites*. Core S4, 140-145, Y27/3+4.
R. *Osmundacidites wellmanii*. Core S4, 115-125, Q21/2+4.
S. *Retitriletes eminulus*. Core S4, 10-15, E14/4 (lateral view).

[Plate 2]



←

Early Cretaceous to early Tertiary gymnosperm pollen (A-K) and Late Cretaceous to early Tertiary angiosperm pollen (L-V). Magnification x900, unless otherwise stated. Specimens are identified by core/sample depth (cm) and England Finder reference.

A. *Alisporites bilateralis*. Core AB2, 82-86, U13/4.
B. *Lydistepollenites florinii*. Core S4, 175-185, Q21.
C. *Pinuspollenites* sp. Core S4, 25-35, D11/4.
D. *Microcachryidites australiensis*. Core S4, 210-220, C24/2.
E. *Podocarpidites marwickii*. Core S4, 305-315, O29/1+2.
F. *Phyllocladidites paleogenicus*. Core S4, 110-115, H21/3.
G. *Microcachryidites antarcticus*. Core S4, 5-10, D28/3.
H. *Phyllocladidites mawsonii*. Core S4, 410-415, X34.
I. *Zonalapollenites dampieri*. Core S4, 205-210, 21/2.
J. *Triporopollenites chnosus*. Core S4, 55-60, F30/4.
K. *Helciporites astrus*. Core AB2, 101-106, B26.
L. *Nothofagidites flemingii*. Core AB2, 17-22, X13.
M. *Beaupreaidites elegansiformis*. Core S4, 115-125, Y36/3.
N. *Jussiaeapollenites champlainensis*. Core S4, 10-15, Q44/3.
O. *Periporopollenites polyoratus*. Core S4, 25-35, X26/1.
P. *Proteacidites adenanthoides*. Core S4, 210-220, C21/4.
Q. *Tricolpites reticulatus*. Core S4, 320-325, D30/3.
R. *Nothofagidites emarcidus*. Core S4, 55-60, O41/4.
S. *Nothofagidites heterus*. Core S4, 380-385, W24/4.
T. *Nothofagidites incrassatus*. Core S4, 140-145, G36.
U. *Proteacidites rectomarginis*. Core S4, 115-125, K33/1.
V. *Proteacidites tennuiexinus*. Core S4, 55-60, W34/3.