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Pre-glacial sedimentary facies of the Point Thomas Formation (Eocene) at Cytadela, Admiralty Bay, King George Island, West Antarctica

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Abstract: New evidence of Eocene preglacial environments has been found on the southern coast of Ezcurra Inlet on King George Island, South Shetland Islands, West Antarctica. Plant remains (trunks, leaves, detritus) and carbonaceous seams and beds occur in sedimentary strata in a 4 km long Cytadela outcrop of the Point Thomas Formation. They are an evidence for the presence and diversity of terrestrial vegetation in the northern Antarctic Peninsula region. The forests were composed mostly of Podocarpaceae–*Araucaria*–*Nothofagus*, with an undergrowth of hygrophilous and thermophilous ferns, and grew on volcanic slopes and surrounding lowland areas of King George Island during breaks in volcanic activity. The succession that crops out at Cytadela provides a record of changing climatic conditions from a warm and wet climate with extensive vegetation to a much drier climate with limited vegetation and ubiquitous weathering of volcanic bedrock. The geochemical indices of weathering (CIA, PIA and CIW) have narrow and relatively high value ranges (76–88), suggesting moderate to high chemical weathering under warm and humid climate conditions. The decrease in humidity and the decline in plant life through the succession can be related to the gradually cooling climate preceding development of the Oligocene ice cover across the Antarctic continent.

Key words: Antarctic, King George Island, Point Thomas Formation, Eocene, preglacial environments, plant fossils, weathering.

Introduction

This paper concerns sedimentary sequences in the Point Thomas Formation that crop out in the Cytadela locality on King George Island (KGI), South Shetland Islands, West Antarctica (Fig. 1A). This formation has been known for decades and described as a Tertiary (Eocene to Early Oligocene) volcanic succession (Birkenmajer 1980, 1989, 2001). It is located on the Warszawa Block, on the

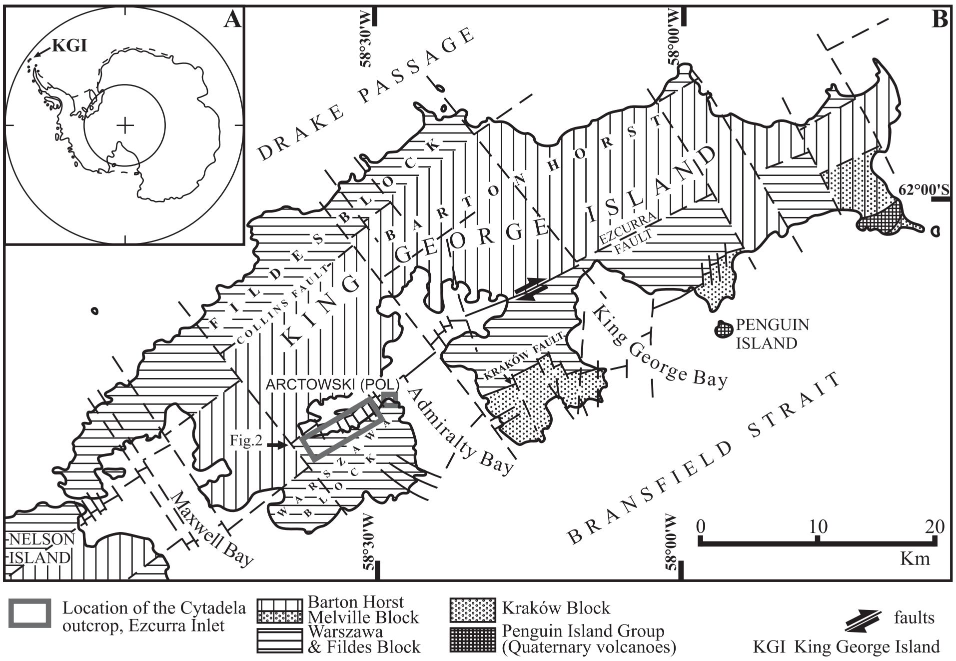

Fig. 1. **A**. Location of King George Island in Antarctica. **B**. Tectonic map of King George Island showing position of the Cytadela outcrop in Ezcurra Inlet. Map after Birkenmajer (1983).

southern coast of Ezcurra Inlet (Fig.1B) and belongs to the Ezcurra Inlet Group (Table 1). Plant fossils (petrified wood and fragments of leaves) known from this locality have been described (Orlando 1964; Stuchlik 1981; Birkenmajer 1989, 2001, 2003; Birkenmajer and Zastawniak 1989; Mohr 2001) and thought to have originated from a vegetation growing either near Eocene/Oligocene boundary or during the Early Oligocene (Birkenmajer *et al*. 1986; Birkenmajer and Zastawniak 1989; Askin 1992). New research in this area conducted during 34th and 35th Polish Antarctic Expeditions in 2009–10 and 2010–11 on KGI in conjunction with earlier work (Birkenmajer 2001, 2003; Birkenmajer *et al*. 2005) led to the discovery of new plant fossil sites to confirm the age of Point Thomas Formation.

This paper presents new descriptions of the volcanic and sedimentary sequence of the Point Thomas Formation at Mount Cytadela. The samples investigated here came from selected levels containing plant remains which were deposited in shallow lakes.

Geological setting

The Point Thomas Formation, part of the Ezcurra Inlet Group (Birkenmajer 1980, 2003) crops out along the southern coast of Ezcurra Inlet, between Zalewski

Table 1

Subdivision of the King George Island Supergroup (after Birkenmajer 2003)

Super group	Group	Formation	Member
King George Island Supergroup	Point Hennequin		
	Ezcurra Inlet	Point Thomas	Skua Cliff
		Arctowski Cove	Petrified Forest
			Hala
			Rakusa Point

Glacier and Point Thomas (Fig. 2). South of this coastal belt, the Ezcurra Inlet Group disappears under thick ice cover of Warszawa Icefield and its outflow, the Ecology Glacier (Birkenmajer 1980). The Group consists of two formations: (1) the Arctowski Cove Formation (lower unit), and (2) the Point Thomas Formation (upper unit), see Birkenmajer (2003).

The Arctowski Cove Formation is approximately 220 m thick. It begins with massive, thick basaltic lava flows that become thinner upwards (basalts and andesites) and alternate with pyroclastics and flow breccias (Birkenmajer 1980). The formation originally consisted of four members: the Rakusa Point Member, the Hala Member, the Petrified Forest Member, and the Skua Cliff Member. Between the lavas of the middle part of the Arctowski Cove Formation (AC Fm) are several conglomerates, agglomerates and shale intercalations. These lavas are often strongly zeolitised and weathered. The Skua Cliff Member (SC Mb) has originally been distinguished as the upper member of the Arctowski Cove Formation (Birkenmajer 1979, 1980, 2003), but taking into consideration that the SC Mb has an erosional unconformity at the boundary with the underlying Hala Member (Table 1) and top of SC Mb is conformable with lavas of Point Thomas Formation (PT Fm), it has been proposed by Birkenmajer *et al.* (2002) and Birkenmajer (2003) that the SC Mb should be excluded from the AC Fm and included as a basal unit to the PT Fm. The Petrified Forest Member contains plant fossils, generally as petrified wood.

The Point Thomas Formation is about 500 m thick and comprises the terrestrial volcanic and volcanoclastic upper unit of the Ezcurra Inlet Group. It is well

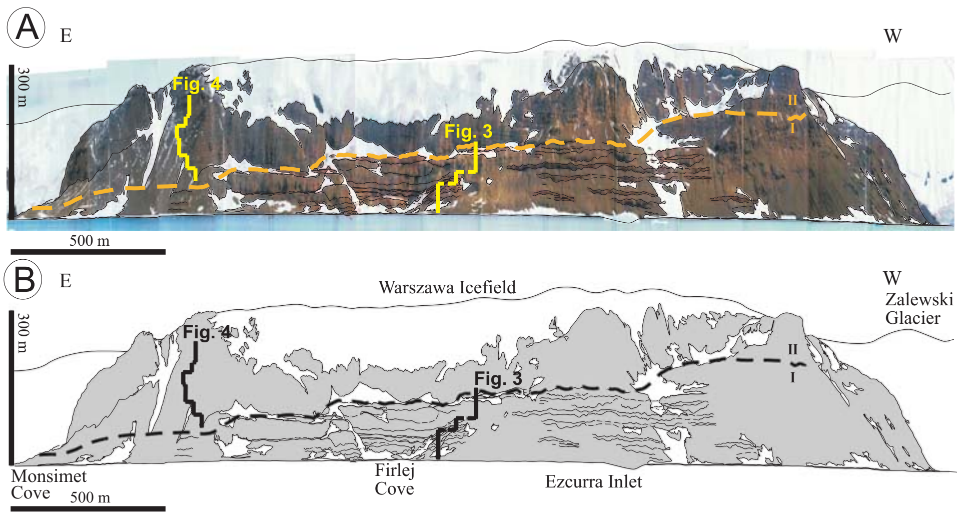

Fig. 2. **A**. Panoramic view of the southern coast of Ezcurra Inlet. **B**. Schematic drawing of Cytadela outcrop showing location of profiles described in this paper, dashed line – boundary between Lower (I) and Upper (II) Members.

exposed at Point Thomas (the type locality) and along the southern coast of the Ezcurra Inlet, between Italia Valley on the west and Zalewski Glacier on the east the Cytadela locality (Birkenmajer 1980). The area studied here included the section between Zalewski Glacier and Monsimet Cove (Fig. 2).

Two informal units were distinguished by Birkenmajer (1980) in the PT Fm: (1) a lower member (20–40 m thick) consisting of regular high-Al flow basalts 1–6 m thick, alternating with much thinner pyroclastics, and (2) an upper member (150–450 m thick) consisting of more irregular, lenticular basalt lavas alternating with feldspathic tuff (in the Point Thomas region), with coarse vent breccias (Hervé Cove area) and plant-bearing tuff interbeds (at Cytadela, west of Monsimet Cove).

Ongoing geochronological survey on the basis of andesite-basaltic and andesitic rock samples collected by the Polish Polar Research Expedition on King George Island in 2009 and 2010, indicate a Lower Eocene age (Zoltán Pécskay, personal communication).

Materials and methods

The material analyzed in this paper (volcanic and sedimentary rocks and plant fossils) was collected from the Cytadela area, a thick volcanic and volcanoclastic succession exposed on the southern coast of Ezcurra Inlet, King George Island.

Petrographic observations of sedimentary rocks were made using thin sections under transmitted and reflected light microscopy (TLM and RLM).

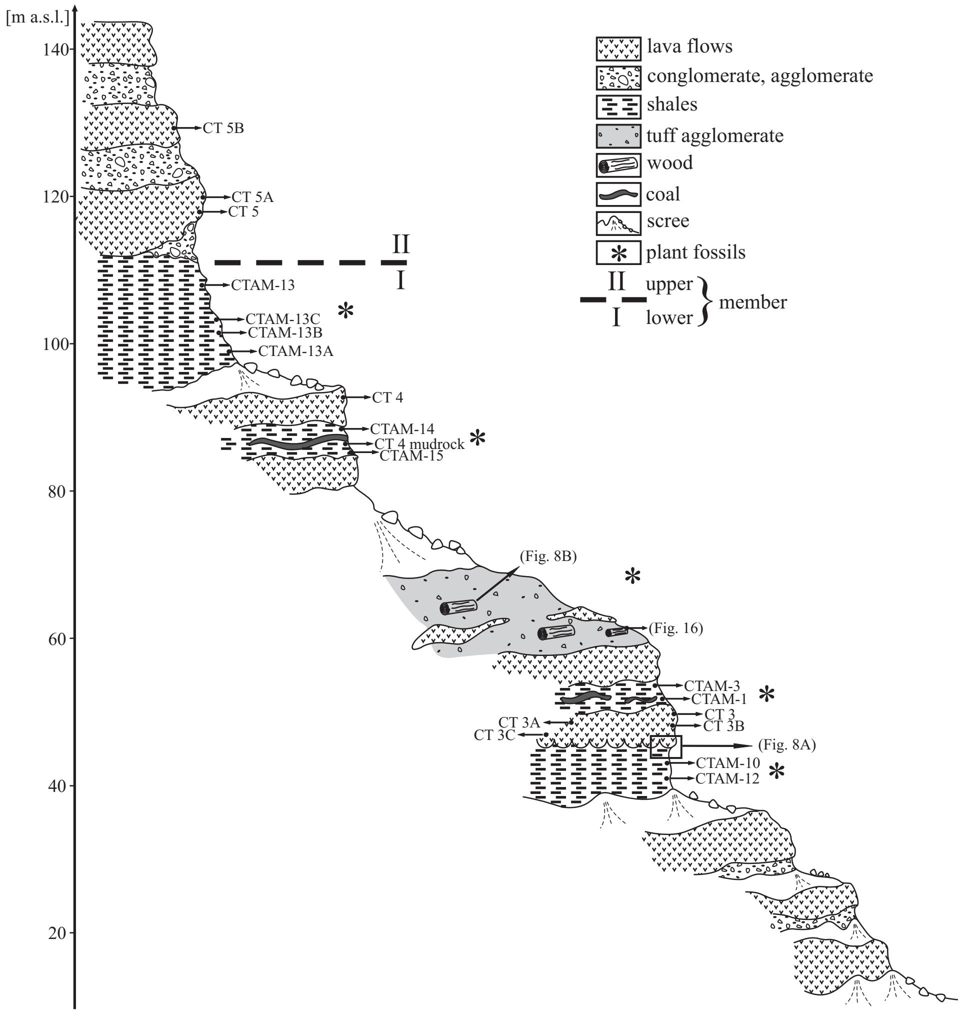

Fig. 3. Schematic field section of Lower Member of the Point Thomas Formation at Cytadela.

Thirty one rock samples were chosen for the X-ray diffraction (XRD), including 12 samples of volcanic and 19 samples of sedimentary rocks. The rock samples were crushed and powdered to the 5–10 μm fraction. X-ray diffraction patterns were recorded on a SIGMA 2070 diffractometer using a curved position sensitive detector in the range 2–120° 2θ with CoKα radiation and 20 hour analysis time. DIFFRACTIONEL software v. 03/93 was used to process the data obtained.

Geochemical analysis was undertaken on the same rock samples (lithogeochemical group 4A+4B: whole rocks major and trace element analysis). The base for this study were ICP-ES and ICP-MS results, taken in Acme Labs, Canada. Results obtained were subject to mathematical processing which enabled detailed data collection of the molar content of elements, ratio and enrichment factors, re-

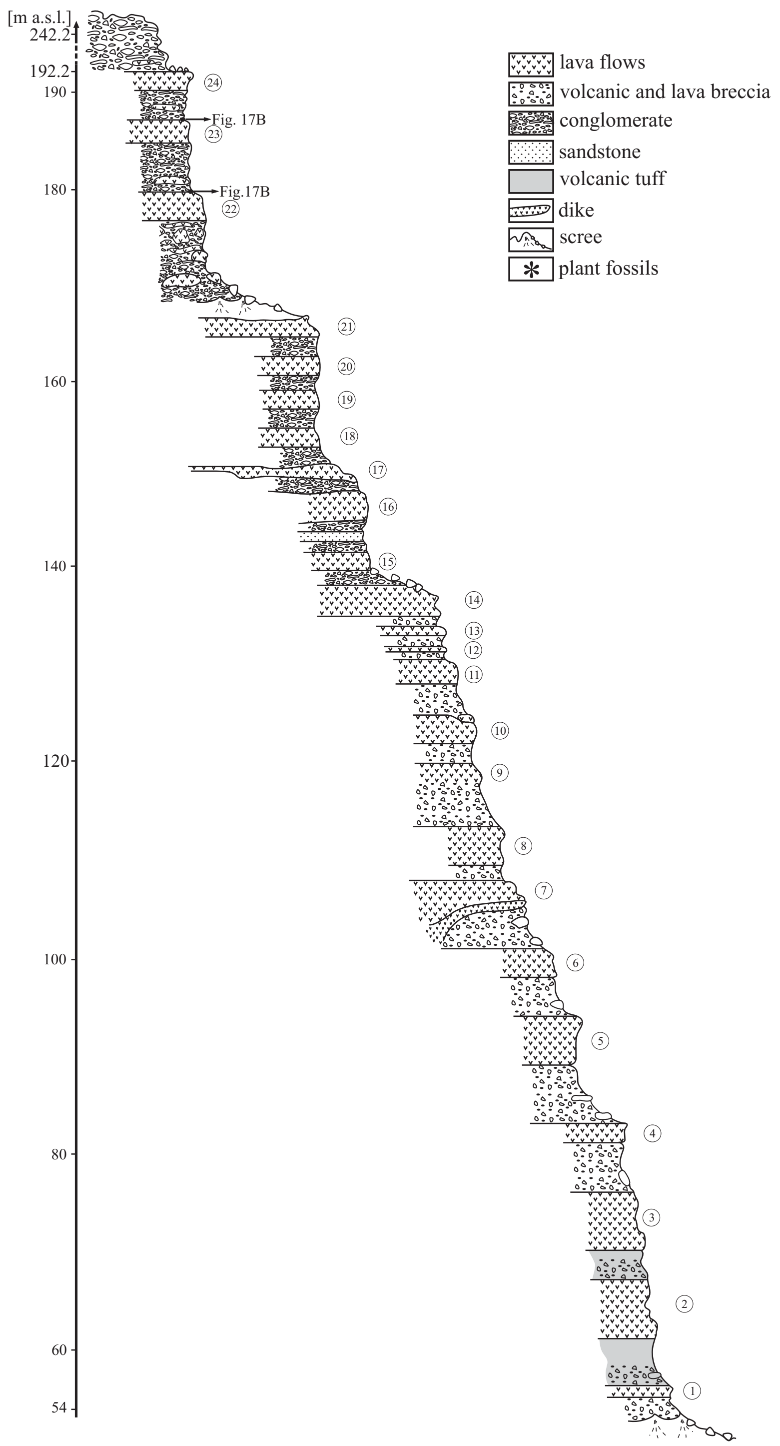

Fig. 4. Schematic field section of Upper Member of the Point Thomas Formation at Cytadela.

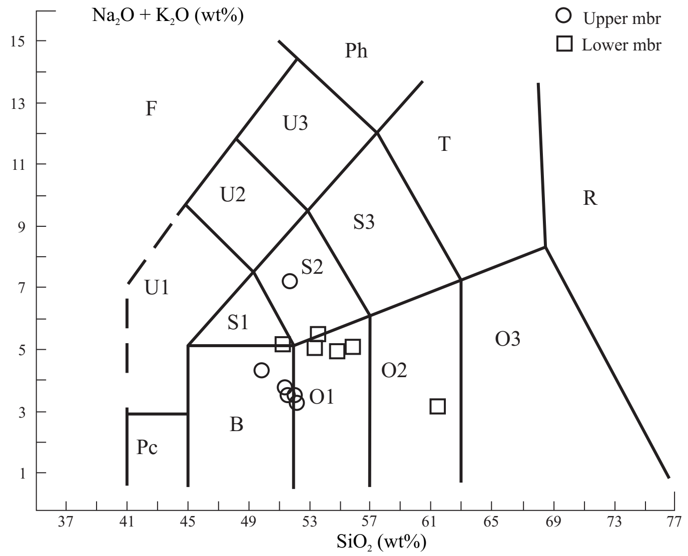

Fig. 5. Total alkali-silica diagram (TAS) from Lower and Upper Members of lava flows at Cytadela outcrop (diagram values and nomenclature according to Le Maitre *et al.* 1989).

lated to volcanic bedrock. These data were used to calculate weathering indices, such as the Chemical Index of Alternation (CIA), Chemical Index of Weathering (CIW) and Plagioclase Index of Alternation (PIA).

Furthermore, attempt of preliminary qualitative flora identification, which occurs in volcanoclastic sedimentary facies, was under taken.

All samples analyzed in this paper are housed at the Institute of Geological Sciences, Polish Academy of Sciences, in Warszawa.

Geology of the Point Thomas Formation at Cytadela

The Cytadela outcrop represents the upper unit of the Point Thomas Formation (Birkenmajer 1979). The outcrop is approximately 300 m high. The lower boundary is under the sea level, the upper boundary is partially hidden under icefalls of the Warszawa Icefield. Mount Cytadela is formed by numerous lava flows; the first 40 to 100 m of the section consist of lavas alternating with predominantly fine-grained, plant-bearing sedimentary rocks.

Two distinct episodes of volcanic activity were preserved in the lava pile, and these were used to establish two informal units: (1) the lower member (LM) and (2) the upper member (UM). The lower member is composed of a complex of andesitic lavas, conglomerates and volcanoclastic sediments with abundant fossil plants, whereas the upper member is composed mainly of andesitic lavas and conglomerates. The plant-bearing sediments appear primarily in the central part of outcrop, close to the Firlej Cove area. Wood, some of it permineralized (typically

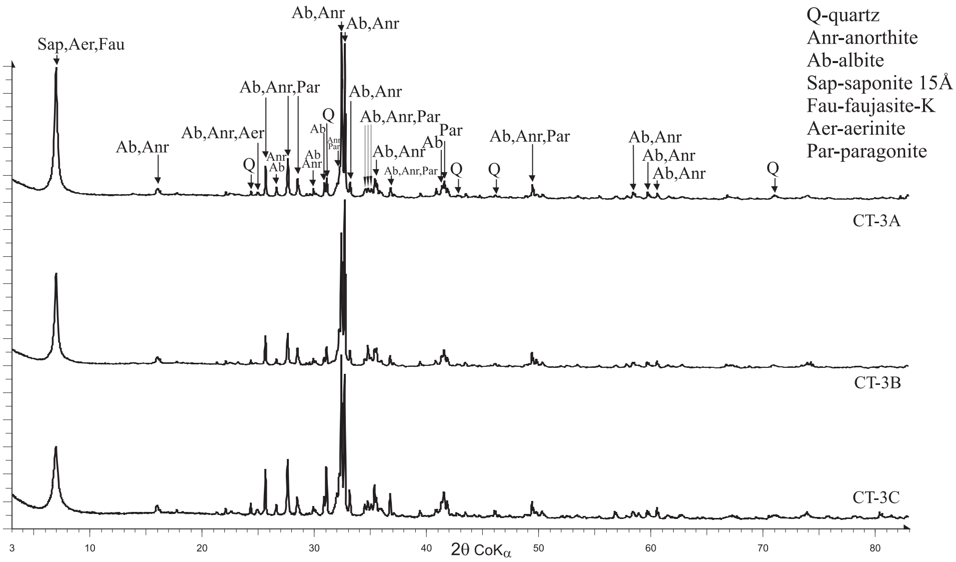

Fig. 6. X-ray diffraction (XRD) pattern of lava from Lower Member of the Point Thomas Formation at Cytadela. Location of samples in Fig. 3.

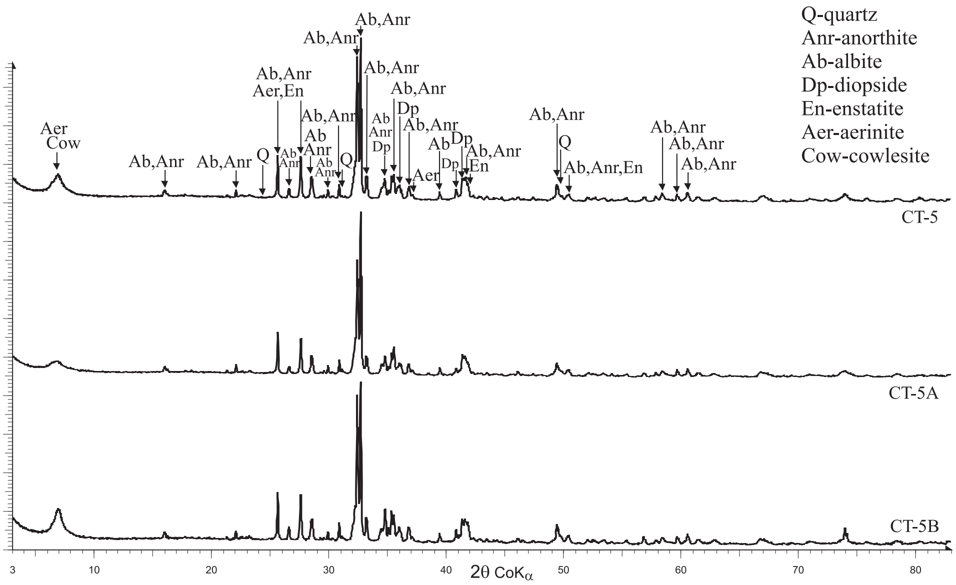

Fig. 7. X-ray diffraction (XRD) pattern of lava from Upper Member of the Point Thomas Formation at Cytadela. Location of samples in Fig. 3.

carbonate) and some coalified is relatively common and abundant in this part of exposure. The west part of Cytadela (near to Zalewski Glacier, which exposes

Fig. 8. Some details of Lower Member of the Point Thomas Formation (location in Fig. 3). **A**. Contact of andesitic lava flow with underlying mudstone/siltstone containing fossil plants. Note pillow structure in the bottom of lava (arrow). **B**. Partially petrified and charred wood incorporated in the lava flow, hammer as a scale.

more of the lower part of PT Fm), contains sedimentary plant-bearing beds, covered by scree and loose material. This western part of the outcrop is in close proximity to the Ezcurra Fault. Cracks, related to this fault underwent mineralization and metasomatic processes.

The LM is built up by continuous and thick (sometimes more than 15 m) lava flows, as compared to the UM, which consists of more lenticular lavas with volcanic breccias and tuffaceous deposits. The volcanoclastic, fine-grained beds with plant fossils were, in all probability, deposited under a more humid environment and in an aqueous environment, in contrast to subaerial UM tuffs and breccias. Details of both members are presented as schematic profiles in Fig. 3 (Lower Member) and Fig. 4 (Upper Member).

The LM lavas are basaltic andesites (passing to trachy-basalts and basaltic trachy-andesites), typical for intermediate arc lavas related to subduction zone. Only one lava sample among those analysed reveals a pure andesitic composition (Fig. 5).

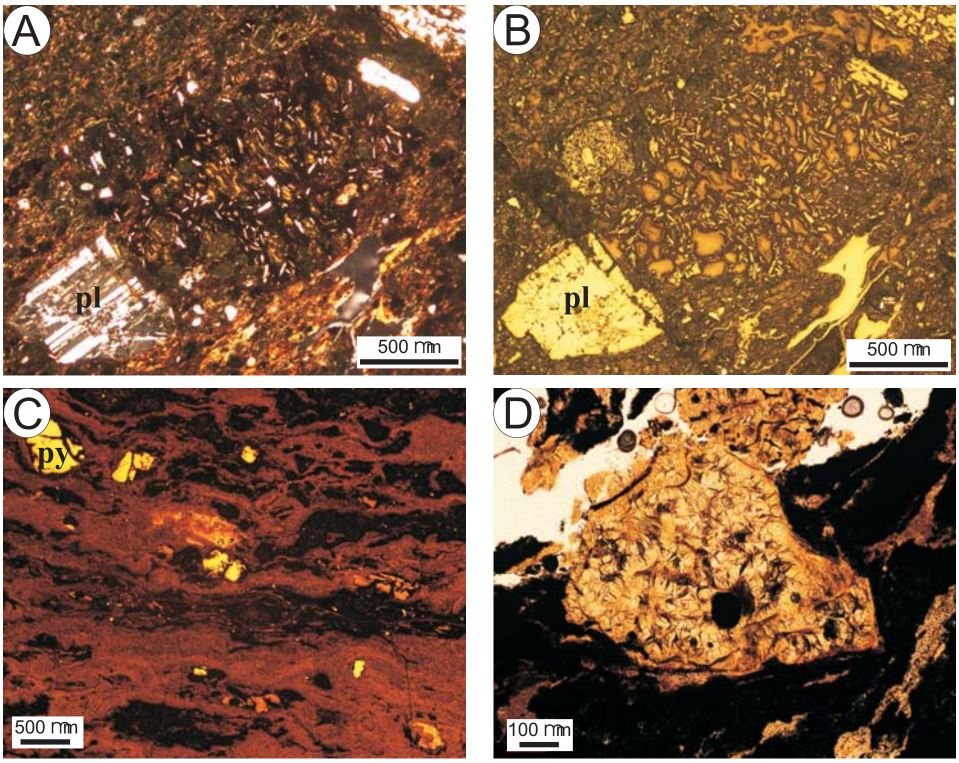

Fig. 9. Thin section of sedimentary rocks (I). **A**, **B**. Plagioclase, lithoclast (noticeable phenocrysts and volcanic glass within) and volcanic glass in plant-bearing tuffite, sample CTAM-13C. **C**. Clearly visible streaks of organic matter and impregnation of pyrite, sample CTAM-3. **D**. Recrystallized volcanic glass, sample CTAM-1. A–D TLM & RLM image, normal light, pl – plagioclase, py – pyrite, location in Fig. 3.

Results of X-ray analysis confirm that the lavas contain mostly plagioclase (albite to anorthite) and quartz, as well as clay minerals (saponite 15 Å) and zeolites (faujasite-K) (Fig. 6), as a products of subsequent weathering processes.

The lavas in the UM range from basaltic andesite to basalt, with only one sample showing trachy-andesite composition (Fig. 5). XRD analysis showed that the rocks are dominated by plagioclase (albite to anorthite), quartz and pyroxene (diopside and enstatite). Cowlesite and aerinite were detected in a small amounts (Fig. 7).

Sedimentary facies of the Lower Member of the Point Thomas Formation

Various plant foliage compressions and impressions have been found in volcanoclastic fine-grained sediments occurring on slopes on the south coast of Ezcurra Inlet. The fossils occur in sediments which represent lacustrine-bog and

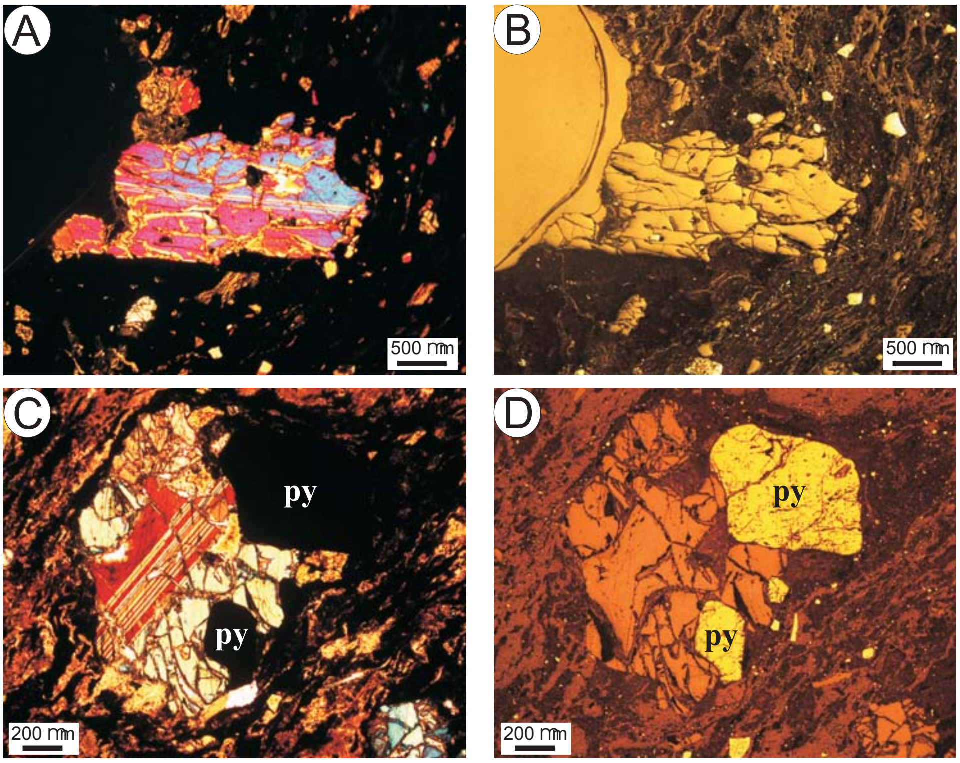

Fig. 10. Thin section of sedimentary rocks (II). **A**, **B**. Highly alkaline monoclinal pyroxene crystal in volcanic sediment. Note content of opaque minerals, single pyrite crystals and abundance of organic matter. **C**, **D**. Pyroxene, plagioclase and pyrite mineral. A–D TLM & RLM image, py – pyrite, sample CTAM-1, location in Fig. 3.

probably marsh facies. Above these sediments, there are lavas with pillow structures at the base, most likely formed as a result of lava cooling in shallow lakes or closed or stagnant basins, as well as fine-grained sediments with abundant leaf zones indicating a low energy environment (Fig. 8A). There are also large pieces of petrified or charred wood (30 cm in diameter by 150 cm in length), incorporated into tuffs or lava flows (Fig. 8B). The sediments were formed from the only available material at that time, that is, from deterioration, decay and weathering of local volcanic rocks. Also, ongoing volcanic activity periodically supplied bombs and ashes to fine-grained clastic material, probably subaqueus tuffs and tuffites.

Typical volcanoclastic deposits are presented in thin sections in Figs 9–11. All of the sediments contain high levels of amorphous minerals, mainly green or brown volcanic glass, sometimes beginning to recrystallize (Fig. 9A, B, D). Fragments of weathered feldspar crystals, plagioclases and pyroxenes are abundant (Fig. 10A–D). Pyrite occurs as pseudomorphs or euhedral crystals (Figs 9C, 10A–D, 11A, B). Other opaque minerals are magnetite and titanomagnetite. In some samples some pelagonitization and chloritization were observed. Small

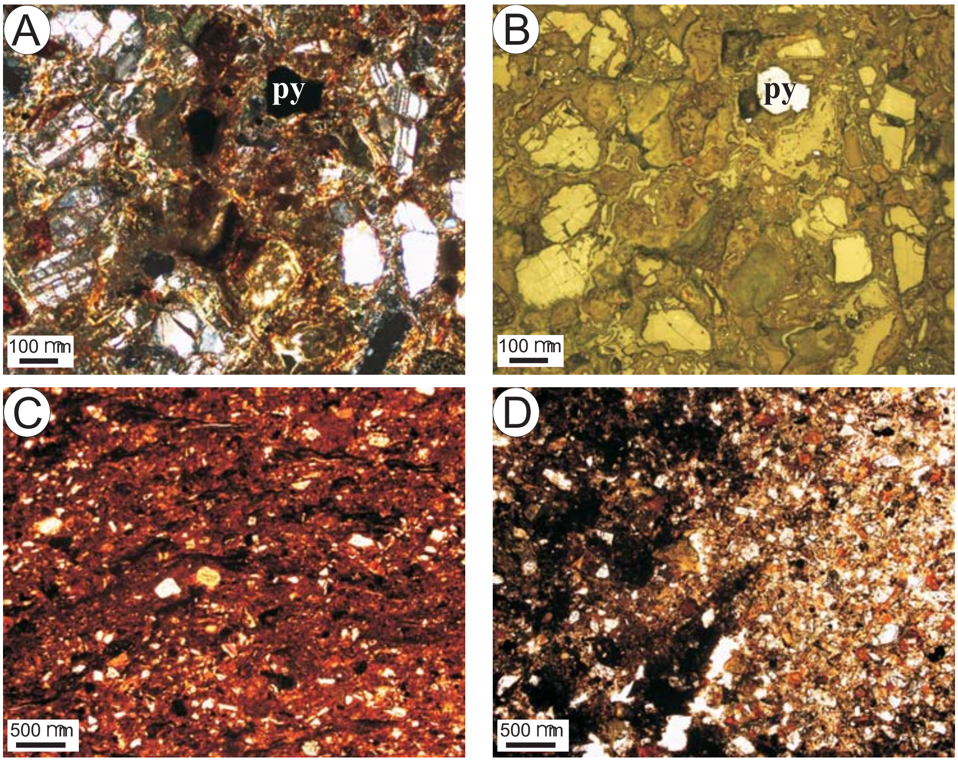

Fig. 11. Thin section of sedimentary rocks (III). **A**, **B**. Pyrite mineral in poorly-arranged organic matter, plagioclase and volcanic glass matrix, sample CTAM-15. **C**. Streaks of nearly horizontally arranged organic matter, plagioclase crystals, single pyroxene crystals and fragments of altered volcanic glass in plant-bearing tuffite, sample CTAM-10. **D**. Border of light and dark streaks contain less and more of organic matter and opaque minerals respectively, in tuffite, sample CTAM-15. A–D TLM and RLM image, py – pyrite, location in Fig. 3.

pieces of whole rock lithoclasts, such as andesite, were present in the shapes of volcanic bombs (Fig. 9A, B). Organic matter occurs as black or deep-brown streaks and represents more resistant humic and bituminous materials, such as waxes and lignins (Figs 9C, 11C, D).

The volcanic processes had a direct influence on preservation of fossils and vastly reduced the chance of leaf cuticle preservation, which makes correct identification of plant fossils difficult. At Cytadela, the leaves are poorly preserved, burned or charred.

The preservation quality of the fossil leaf material is variable and many specimens are fragmentary. The leaves are mostly preserved as impressions (Figs 12, 14).

The assemblage is made of angiosperms with broad-leaf types of *Nothofagus* (Fig. 12A, B), numerous ferns (Fig. 13A–D), and distinct gymnosperms dominated by podocarps.

One common leaf morphotype with delicate parallel venation is, probably a representative of the genus *Araucaria* (Fig. 14A). Another common leaf is

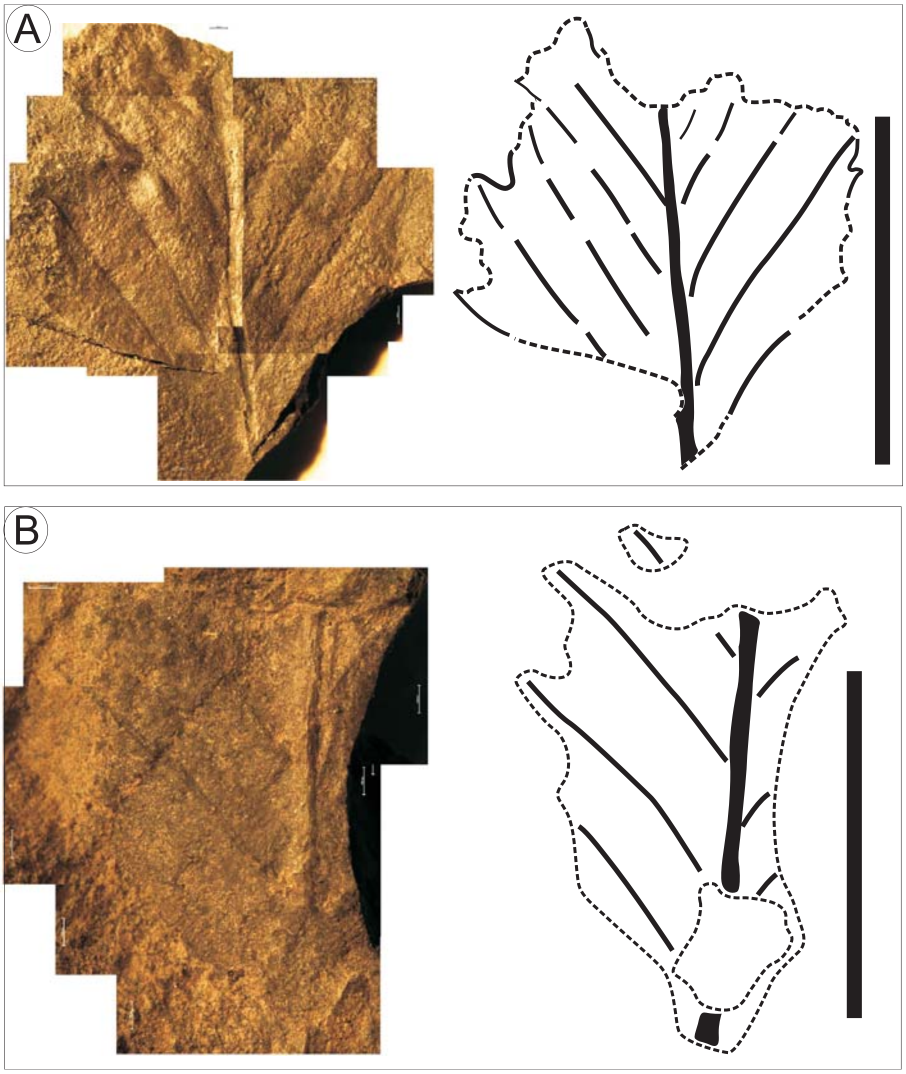

Fig. 12. Leaf impressions (I). **A**, **B**. Angiosperm form represented of *Nothofagus* type. **A**. Fragment of leaf 22 mm long and 21 mm wide. **B**. Fragment of leaf 14 mm long and 9 mm wide. Scale bars are 1 cm, sample CTAM-14, location in Fig. 3.

morphotype "A" with elongated, narrow (about 3 mm), entire-margin leaves (Figs 14B–D, 15B), has only one, thick, central vein. Plant-bearing interbedded tuffs yielded imprints of various ferns, occasionally with pinnate forms (Fig. 13A–D).

Fragments of dicotyledonous leaves with thick primary veins and well-defined secondary and tertiary veins that are arched and connected by loops (Fig. 15A). Toothed leaves with thick primary veins and arched lateral veins are often present (Fig. 15C, D). The apex and the base of the leaves are often missing. The assemblage also contains at least two unidentified type of seeds and woody fragments;

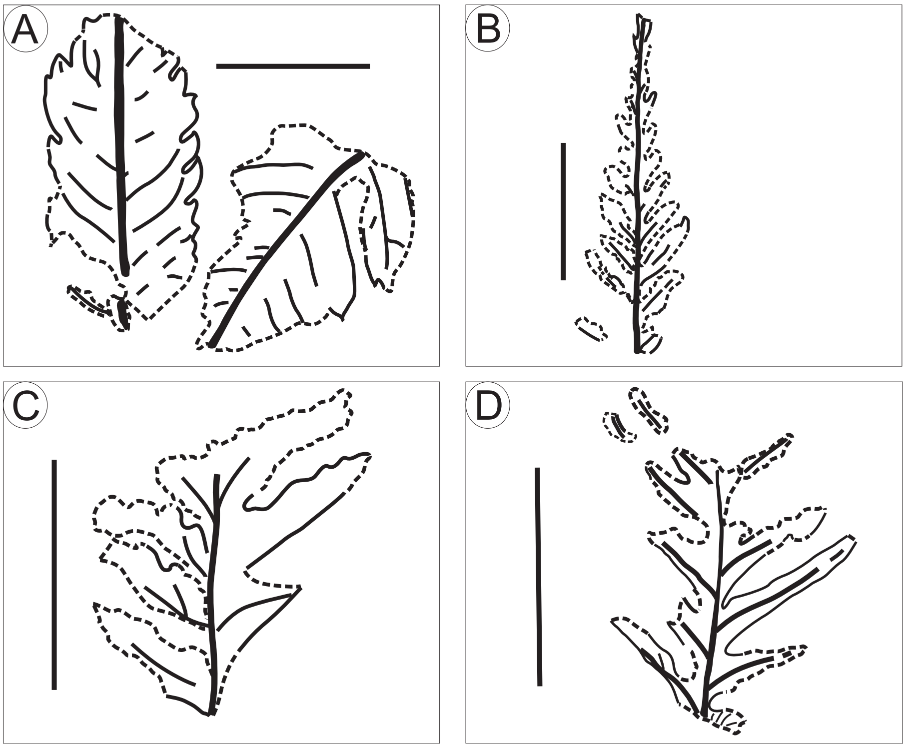

Fig. 13. Leaf impressions (II). **A–D**. Variety of fragments of fern impressions. Scale bars are 1 cm, A – sample CTAM-12, B – sample CTAM-13A, C, D – sample CTAM-13B, location in Fig. 3.

the latter appears in coal layers with well preserved, partially pyritized cell structures (Fig. 16A–D).

Although the volcanoclastic units have been already described (Birkenmajer 1980, 1989), the geochemical indicators of alternation have not been investigated until now. To measure weathering, the Chemical Index of Alternation (CIA, Nesbitt and Young 1982), Chemical Index of Weathering (CIW, Harnois 1988), and Plagioclase Index of Alternation (PIA, Fedo *et al.* 1995) were calculated from results of ICP-ES and ICP-MS geochemical analysis. These indices were chosen because they are sensitive to even slight changes such as hydrothermal alternation along fault and/or alternation at the water table, and also are common tools for indication of climatic conditions. Two typical examples of weathering indices for the sedimentary rocks and the underlying lava flows from the LM are presented in Fig. 17A.

High CIA (*i.e.* 76–83) and PIA (*i.e.* 77–87) point to moderate to intensive chemical weathering, possibly under warm and humid climate conditions, the underlying lava flows showing typically low values (*i.e.* 57–59). High values also indicate that most of the plagioclase has been converted to clay minerals, as confirmed by X-ray diffraction.

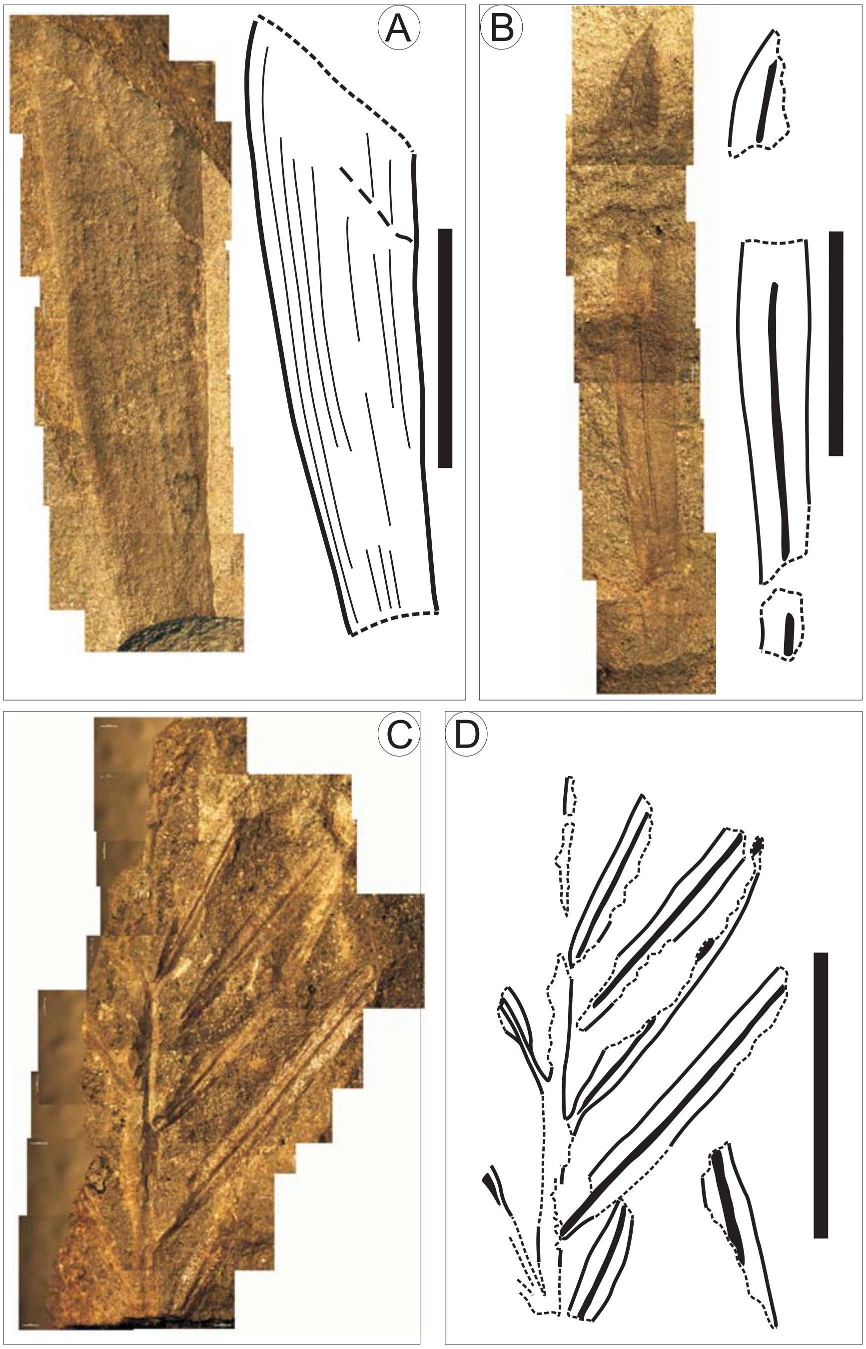

Fig. 14. Leaf impressions (III). **A**. Fragment of leaf impression of *Araucaria*, 34 mm long and 9 mm wide, parallel densely-arranged thin venation, sample CTAM-13A. **B**–**D**. Fragments of morphotype "A", with preserved shoot axis (C, D). Scale bars are 1 cm, B – sample CTAM-13C, C, D – sample CTAM-10, location in Fig. 3.

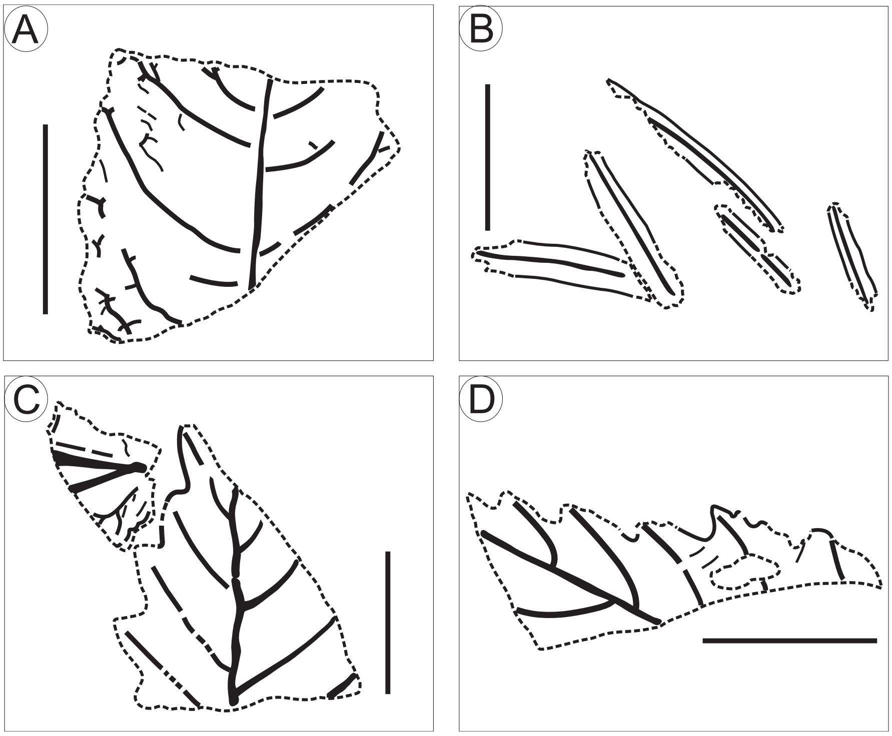

Fig. 15. Leaf impressions (IV). **A**. Fragment of dicotyledonous leaf 18 mm long and 26 mm wide with fragmentary preserved loops, sample CTAM-10. **B**. Randomly oriented fragments of morphotype "A", sample CTAM-12. **C**, **D**. Fragments of toothed leaves, sample CTAM-13A. Scale bars are 1 cm, location in Fig. 3.

The XRD results indicate the presence of clay minerals from the montmorillonite and smectite groups, such as stevensite (15 Å), volconskoite (15 Å), sauconite (15 Å), saponite (15 Å), nontronite (15 Å). The presence of minerals from the zeolite group, such as faujasite or chabasite was also stated (Figs 18, 19).

High values of geochemical indices of weathering and advanced weathering processes suggest warm and ice-free conditions during Early to Middle Eocene (PGS-1).

Discussion

Initially, the two members of the Point Thomas Formation were interpreted as indicating two different paleoclimatic conditions during the Eocene (Krajewski *et al*. 2010). The earlier climatic stage was distinguished by warm temperatures and high rainfall (Poole *et al*. 2003), local alpine glaciers may have formed on top of large stratovolcanoes (Birkenmajer *et al*. 2005; Krajewski *et al*. 2010). The younger climate stage was characterised by a mixed effusive-explosive style of volca-

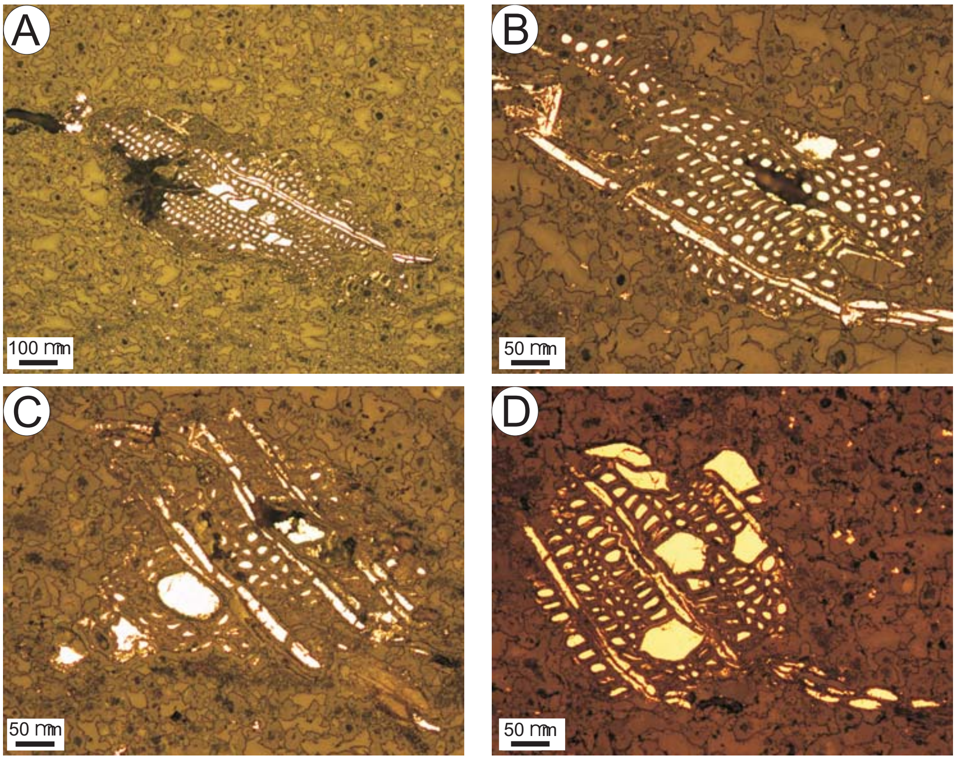

Fig. 16. Well preserved cell structures partially pyritized in coal from sedimentary facies of the Lower Member of the Point Thomas Formation at Cytadela. **A**–**D**. TLM & RLM image, normal light, location in Fig. 3.

nic activity, but under dry climate conditions, producing agglomerates and tuffaceous deposits with weathered lava surfaces and regoliths. Several well preserved regolith surfaces have locally been recognized in the Breccia Crag area (Birkenmajer and Łydka 1990; Birkenmajer *et al*. 2002). This episode of cooling is universally known and it is clearly visible in isotopic record in marine sediments (Zachos *et al*. 2001, 2003).

The diamictites and tillites at the base of the Point Thomas Formation (the Hervé Cove tillite on the east side of Cytadela – Birkenmajer *et al*. 2005) are related to a local Antarctic Peninsula mountain glaciation (Birkenmajer 1991; Askin 1992; Birkenmajer *et al*. 2005).

The palynoflora from the Cytadela outcrop represents a forest vegetation dominated by Podocarpaceae–*Araucaria*–*Nothofagus*, with an undergrowth of hygrophilous and thermophilous ferns, and other dicotyledonous plants. Similar plant assemblages were elsewhere dated as Early and Middle Eocene (Cao 1992; Mohr 2001). The plant material and lithologies correspond to the similar complex containing Cupressaceae and Araucariaceae described on Fildes Peninsula (Poole *et al*. 2001, 2003; Fontes and Dutra 2010). Cool temperature rainforest growing on the

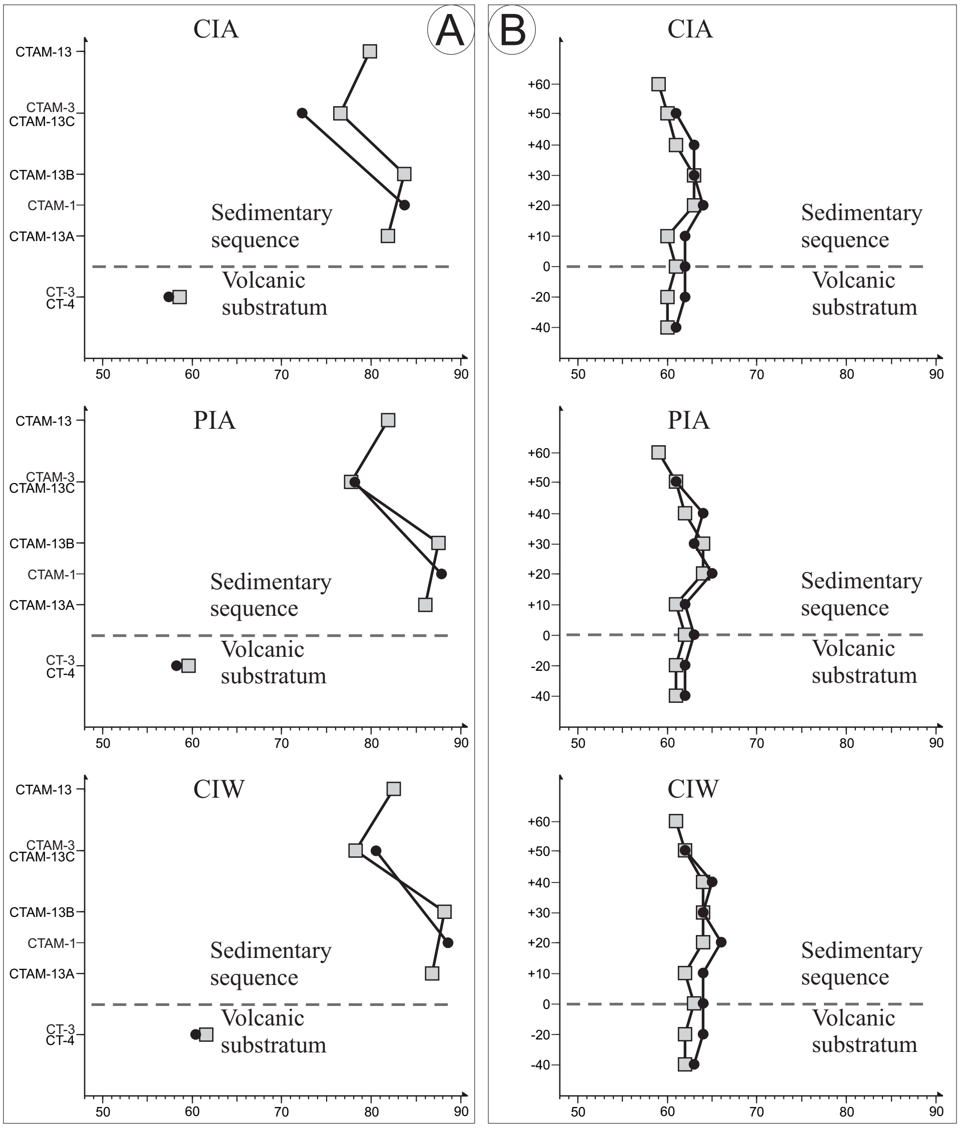

Fig. 17. **A**. Weathering indices for two short vertical profiles in lava and sedimentary facies from the Lower Member at Cytadela. **B**. Weathering indices for two short vertical profiles in lava and sedimentary facies from the Upper Member at Cytadela, CIA – Chemical Index of Alternation, PIA – Plagioclase Index of Alternation, CIW – Chemical Index of Weathering. Locations of samples in Figs 3, 4.

flanks of the Andes and along the Coastal Range in Valdivia (Chile) and Patagonian area today, provide the closest analogue for the fossil floras of Antarctica during Eocene (Orlando 1964; Poole *et al*. 2003). The fern communities are comparable with fern bush communities of the south oceanic islands such as the Gough and Auckland Islands (Birkenmajer and Zastawniak 1989; Mohr 2001).

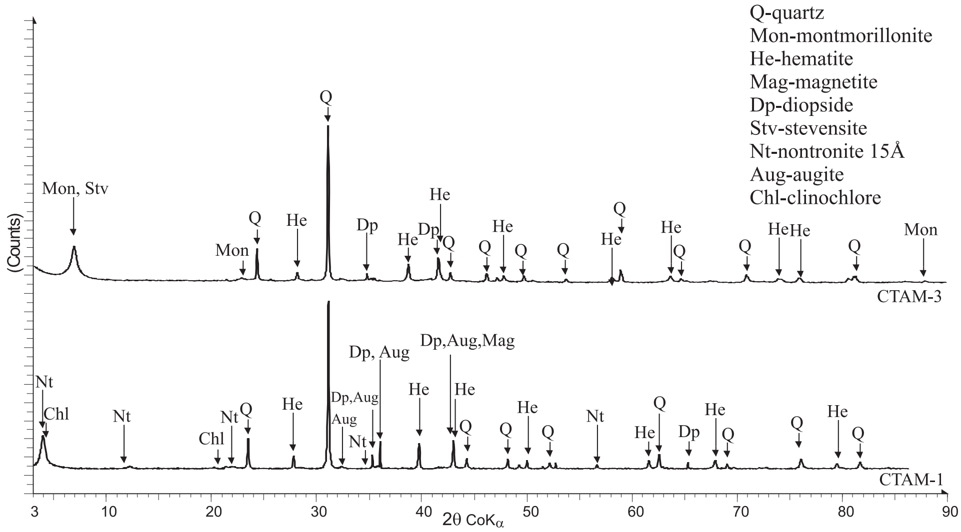

Fig. 18. X-ray diffraction (XRD) pattern of plant-bearing volcanoclastic facies at Cytadela (I). Note content of quartz. Locations of samples on Fig. 3.

Furthermore, low values of CIA (*i.e.* 59–64), PIA (*i.e.* 59–65) and CIW (*i.e.* 61–66) obtained from the weathering sections from the UM (Fig. 17B) point to mechanical weathering, possibly under dry and cool climate conditions. Beside disappearance of plant and shallow lakes, it is an another evidences for climate deterioration during Middle to Late Eocene (PGS-2).

Evidence from fossils, sediments and geochemistry indicates generally warm and ice-free conditions during the earliest part of the Eocene, followed by gradual cooling.

Conclusions

The volcanic and volcanoclastic succession of the Point Thomas Formation seems to represent the Eocene. Geochemical analysis indicates an arc-type basaltic-andesitic affinity as well as back-arc type basaltic-andesitic province. The Cytadela outcrop represents two paleoclimatic stages, recorded as two members (lower – LM, and upper – UM), separated by disconformity surface. Occurrence of the terrestrial floras has confirmed a warm (*i.e.* frost free) Eocene climate with general cooling trend up the succession (LM) cumulating in a significant cooling in the upper part (UM). The LM indicates humid climate, that supported abundance of flora and coal (marsh and peat bog environments) deposited in depressions on stratovolcanic slopes and surrounding lowlands, overgrown probably by forests dominated by *Nothofagus*.

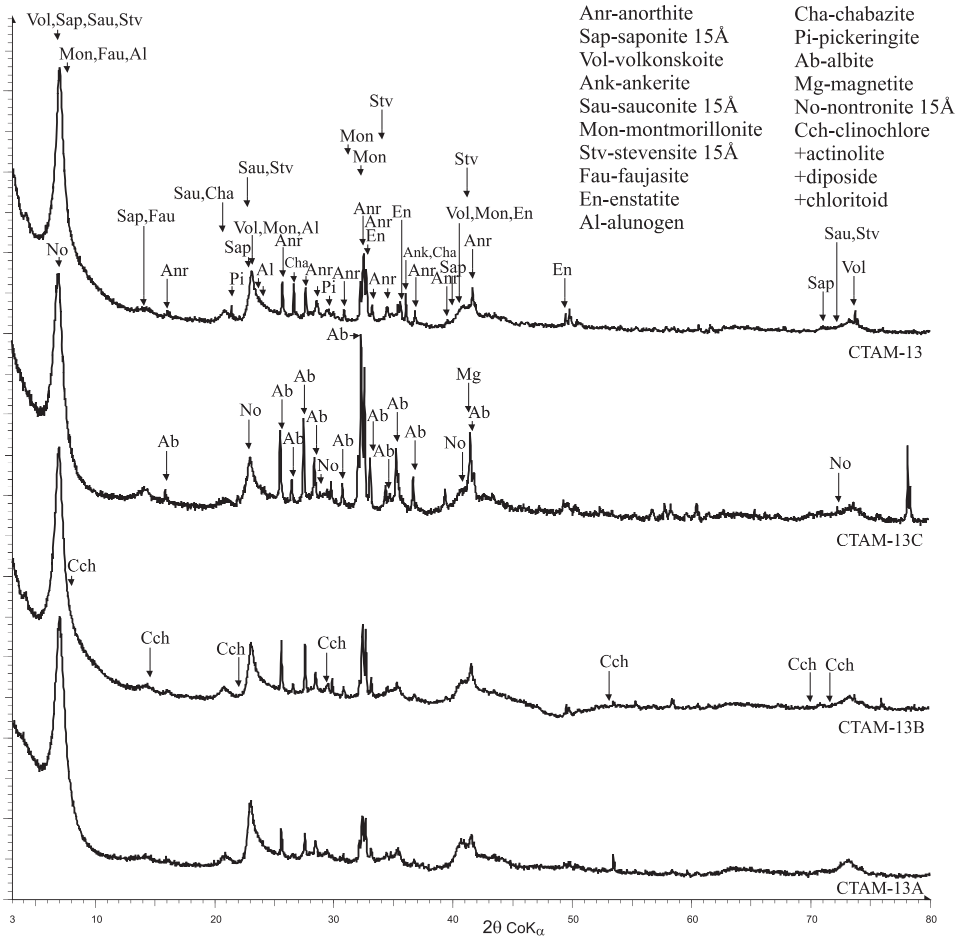

Fig. 19. X-ray diffraction (XRD) pattern of plant-bearing volcanoclastic facies at Cytadela (II). Note content of zeolites. Locations of samples in Fig. 3.

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