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Key Points:

- Precise U-Pb zircon ages from the Mount Flora Formation in Antarctic Peninsula constrain its classic fossil flora to late Middle Jurassic
- Similar but distinctly older Early Jurassic plant associations in Patagonia suggest paleoenvironmental control on geographic distribution
- Magmatic arc development, tectonic extension and continental break up dominated the evolution of southern Gondwana in the Middle Jurassic

Abstract

The spectacular fossil plant assemblage preserved in the non-marine Mount Flora Formation of the northern Antarctic Peninsula represents the diverse Jurassic flora that once covered the Gondwanan continents at high paleolatitudes. The depositional facies of the formation plays a key role in the tectonic interpretations and basin evolution models that attempt to reconcile large igneous province magmatism, continental break up, and magmatic arc development throughout the Jurassic and Cretaceous. Limited U-Pb *in situ* geochronology reported from the Mount Flora Formation and adjacent units lack the necessary resolution to overcome ambiguous correlations and biostratigraphic discrepancies. We present two high-precision U-Pb zircon ages (CA-ID-TIMS method) from a distinct tuffaceous interval of the Mount Flora Formation at Hope Bay, which document a terminal Middle Jurassic age (Callovian Stage) for the formation and its paleoflora. In excess of 1400 new collected fossil plant specimens exhibit a highly diverse Jurassic plant association that dominated the Antarctic Peninsula nearly 17 million years after its disappearance from northern Patagonia. This suggests similar paleoecological conditions were established diachronously throughout basins of southern Gondwana, possibly facilitating floral migrations in response to local climate change. The depositional facies

of the Mount Flora Formation, its age proximity to the marine Nordenskjöld Formation in the Antarctic Larsen Basin, and its coincidence with a regional unconformity in the northern Patagonia point out to a complex interplay among magmatic arc development, tectonic extension and continental break up that dominated the geologic and paleoenvironmental evolution of southern Gondwana near the end of the Middle Jurassic.

### Plain Language Summary

Highly diverse and exceptionally well-preserved Jurassic fossil plants are found in sedimentary rocks of Mount Flora, a classic geological localities of the Antarctic Peninsula, firstly discovered by a Swedish expedition in 1903. The geology indicates a dynamic landscape of lakes, emerging mountain chains and active volcanoes that harbored a diverse plant community of horsetails, ferns, seed ferns, conifers and cycads. Remarkably similar Jurassic flora once covered the northern Patagonia at a time when both regions were part of the Gondwana supercontinent and were dominated by a warm, humid climate. Our high-precision radioisotopic age determination by the U-Pb technique, along with a collection of more than 1400 new plant specimens indicate that this plant association dominated the Antarctic Peninsula in late Middle Jurassic, nearly 17 million years after it disappeared in Patagonia. Therefore, the composition of the Jurassic flora was strongly dependant on climatic and environmental conditions as the main driver of floral migrations, as opposed to the result of simple, simultaneous evolution of the plants throughout the southern hemisphere. Our results further portrait a period of tectonic upheaval that led to the formation of new sedimentary basins and culminated in the break-up of Gondwana in the Late Jurassic and Cretaceous.

### 1 Introduction

The Mount Flora of the Hope Bay area (Fig. 1) near the northern tip of the Antarctic Peninsula is one of the most famous geological and geographical localities of Antarctica, known for its diverse and remarkably well preserved Jurassic fossil flora, which is found in the strata of the Mount Flora Formation. Because of the historical, biostratigraphic and paleoecological significance of the flora, the plant-bearing outcrops are included in the Antarctic Specially Protected Area (ASPA) 148 of the Antarctic Treaty. The age of the paleoflora has been broadly assigned, ranging from the Early Jurassic (e.g., Rees, 1993a; Rees and Cleal, 2004) to the Early Cretaceous (e.g., Gee, 1989), on the basis of transcontinental correlations. Besides its biostratigraphic significance, the precise age of the paleoflora is critical to the depositional history of the Larsen Basin in the Antarctic Peninsula (Fig. 1). A latest Jurassic to earliest Cretaceous age interpretation (e.g., Farquharson 1984; Macdonald et al., 1988; Medina et al., 1989) would suggest that the Larsen Basin developed as a back arc to the emerging Early Cretaceous arc along the Proto-Pacific margin of Gondwana. On the other hand, an Early Jurassic age assumed by others (e.g., Hathway, 2000) would invoke tectonic linkage to the continental rift basins of similar age throughout southern South America. Recent U-Pb zircon geochronology by *in situ* tech-

niques (Pankhurst et al., 2000; Hunter et al., 2005) proposed a Middle Jurassic age for the Botany Bay Group, which incorporates the Mount Flora Formation, on the basis of ages from Hope Bay (Mapple Formation), Botany Bay (Camp Hill Formation) and Tower Peak (Tower Peak Formation) localities (Fig. 1). Although highly informative, these age data lacked the necessary resolution to distinguish among individual formations. No direct radioisotopic age has been reported from the Mount Flora Formation at Hope Bay in spite of the conspicuous tuffaceous intercalations in the lower part of the succession recognized since the pioneering work of Croft (1947) in Bibby (1966) and Elliot and Gracani (1983).

Here we report two high-precision U-Pb zircon dates by the chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS) from tuff deposits interbedded within the Mount Flora Formation, with clear stratigraphic relationship to the highly fossiliferous strata. The tuffs were sampled during the 2017 austral summer field season in the Hope Bay area together with a large collection of fossil plants (c. 1400 hand samples). The results yield a reliable temporal framework, though preliminary, for the Mount Flora Formation and its paleoflora, and allow a biostratigraphic and paleoecologic analysis of the flora in comparison to analogous Jurassic assemblages from Patagonia. Finally, the depositional history of the Botany Bay Group succession in the context of Jurassic tectonic evolution of southern Gondwana is discussed.

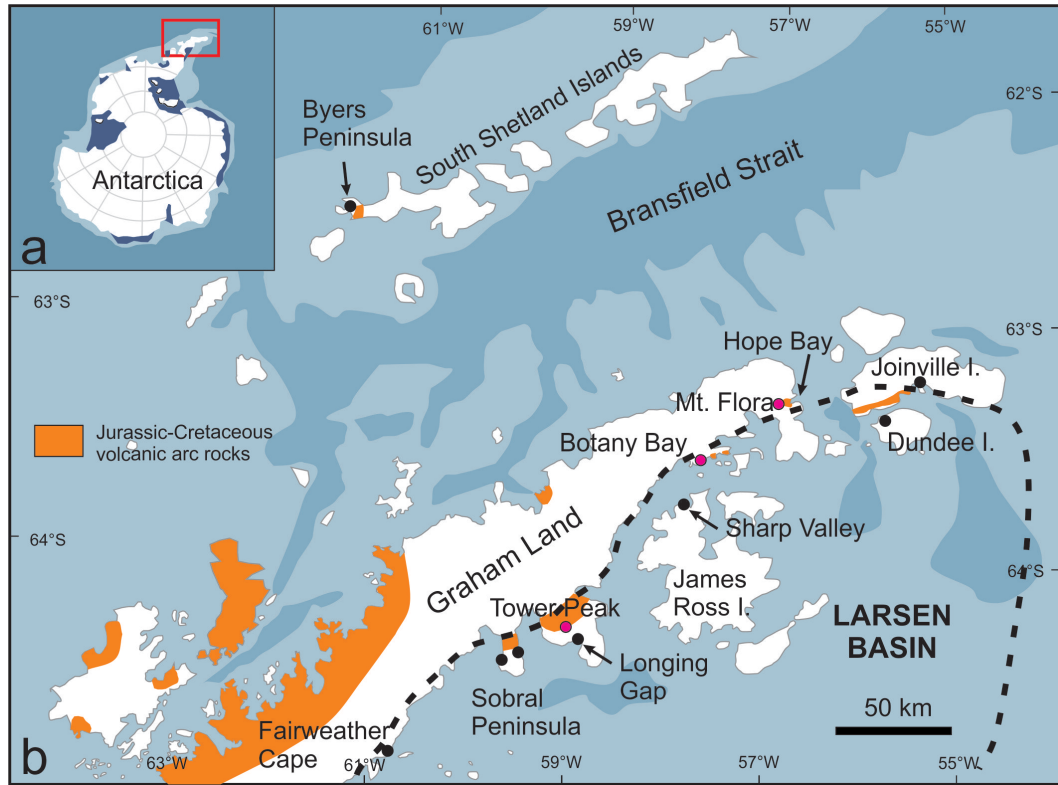


Figure 1. **a**, Location map of the Antarctic Peninsula. **b**, Main outcrop localities of the Jurassic marine (Ameghino/Nordenskjöld Formation) and terrestrial beds (Mount Flora Formation /Botany Bay Group) in the northern part of the Antarctic Peninsula.

## 2 Stratigraphy and geological setting

The Mount Flora Formation, together with its correlative Camp Hill and Tower Peak formations, are grouped under the non-marine Botany Bay Group, which is predominantly composed of basement-derived conglomerates exposed in discontinuous outcrops along the Antarctic Peninsula (Farquharson, 1984; Hathway 2000). The conglomeratic deposits are correlated on the basis of their lithology and stratigraphy; they were presumably accumulated in small, fault-bounded grabens as a product of debris flow and braided stream deposition in alluvial fans (Farquharson 1984). The Botany Bay Group unconformably overlies the (meta-) clastic sediments of the Trinity Peninsula Group (e.g., Hope Bay Formation) and is overlain by the volcanic and pyroclastic rocks of the Antarctic Peninsula Volcanic Group (e.g., Kenney Glacier and Mapple formations) (Fig. 2). Although early paleobotanical investigations suggested a Middle Jurassic age for the Botany Bay Group, a Late Jurassic to Early Cretaceous age was later adopted by many based on stratigraphic arguments and correlation to marine

fossil-bearing strata (see Farquharson 1984). Limited U–Pb zircon geochronology by the *in situ* secondary ion mass spectroscopy (SIMS) technique on the interbedded tuffs of the Botany Bay Group and the overlying volcanics from the Hope Bay, Botany Bay and Tower Peak outcrops (Fig. 1b) have yielded Middle to Late Jurassic ages ranging from  $168.9 \pm 1.3$  Ma (2 internal uncertainties) to  $162.2 \pm 1.1$  Ma (Pankhurst et al., 2000; Hunter et al., 2005). These radioisotopic dates have formed the basis of correlation of the Botany Bay and Antarctic Peninsula Volcanic groups to the presumed equivalent units throughout the Patagonian region of South America (Pankhurst et al., 2000).

The Mount Flora Formation (Caminos and Massabie, 1980) was originally studied by Andersson (1906), and later by Bibby (1966), Elliot and Gracani (1983), Farquharson (1984), Birkenmajer (1993), Montes *et al.* (2005) and Montes et al. (2019), with its fossil flora described originally by Halle (1913) and more recently by Birkenmajer and Ociepa (2008). It is a terrestrial clastic sedimentary unit in excess of 300 m in thickness, exposed to the SE of Hope Bay near the tip of the Antarctic Peninsula (Fig. 1a, b). The Mount Flora Formation is separated by an angular unconformity from the underlying Hope Bay Formation of Late Paleozoic/Triassic age and is overlain by the Kenney Glacier Formation (Birkenmajer, 1993), which is equivalent to the Mapple Formation of Riley and Leat (1999). A Late Jurassic U–Pb SIMS age of  $162.2 \pm 1.1$  Ma for a volcanic rock at Hope Bay (Pankhurst et al., 2000), whose exact location has not been documented, most likely belongs to the several-hundred-meter-thick Kenney Glacier Formation.

The Mount Flora succession is a fining-upward terrestrial clastic succession initially deposited as alluvial fans on a fault-controlled morphology. We follow here the two-fold lithostratigraphic subdivision of the Mount Flora Formation proposed by Montes et al. (2019). The stratigraphically lower member (Miembro Conglomerados), about 260 m thick, is composed of clast-supported conglomerates with large, rounded blocks of the Trinity Peninsula Group. Most beds show normal grading and may transition upward to thin, discontinuous sandstone beds. Towards the upper part of this member (140 – 190 meters above base) a ca. 50 m thick tuffaceous interval composed of light-coloured, hard beds is readily recognized. This interval is predominated by ash tuffs, lapilli tuffs, ignimbrites, and volcanic breccias. The upper member (Miembro Areniscas) consists of about 100 m of sandstones, thin-bedded conglomerates, siltstones and shales in beds up to 3 m thick. The conglomerates contain variable quantities of volcanic clasts, which are absent from those in the lower member below the tuffaceous interval. Sandstones may show cross-bedding and shales are well-laminated and may contain numerous, well-preserved, plant remains. Detailed facies analysis (Elliot and Gracani 1983; Birkenmajer 1993) suggest the succession represents a retrograding alluvial fan, where fluvio-deltaic and lacustrine beds overlie the coarse alluvial fan facies. The whole Mount Flora Formation contains abundant plant remains. Large logs are common at the top of the conglomerate beds, whereas small branches and leaf fragments in the sandstones. The well-preserved plants, together with rare fossil bivalves, beetles and fish

remains, were recovered from the lacustrine shales in the uppermost part of the unit and in blocks of recent moraine deposits (Andersson, 1906; Halle 1913; Rees and Cleal, 2004; Birkenmajer and Ociepa, 2008, Martínez et al., 2019). The latter probably eroded from the shale horizon and scattered along the NE pathway of the Flora Glacier (Martínez et al., 2019; Fig. 1).

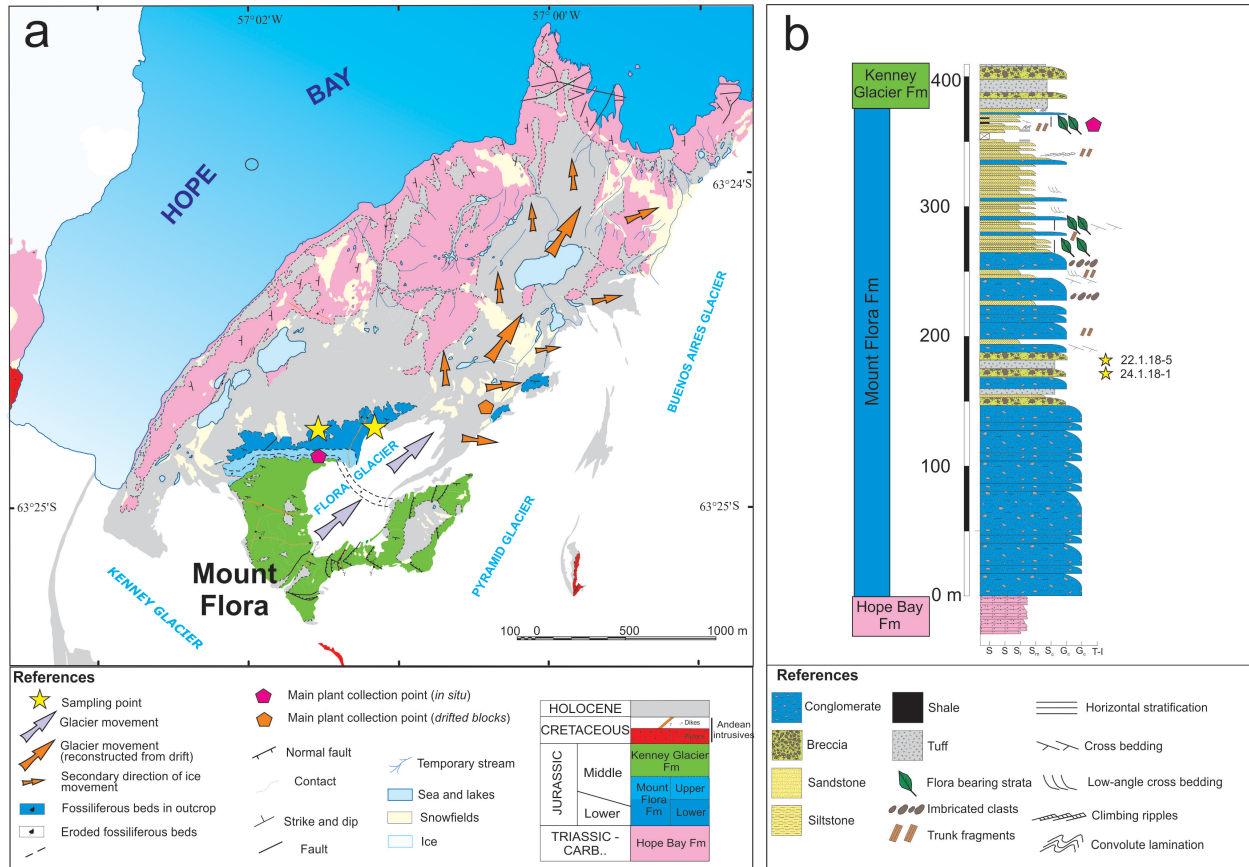


Figure 2. a, Geologic Map of the Hope Bay area (slightly modified from Montes et al., 2019) indicating the locations of the geochronology samples (stars) and of the main points for plant collection. b, Composite stratigraphic column of the Mount Flora Formation.

### 3 Materials and Methods

#### 3.1 Stratigraphy and sample collection

Stratigraphic measurements were made along multiple transects on the northern slopes of Mount Flora overlooking Hope Bay and were assembled into a single stratigraphic column (Fig. 2b). Bed thickness, sedimentary/volcanic structures and rock facies were described in the field and recorded along with GPS coordinates (Text S1; Fig. S1) Samples from the tuffaceous interval of the lower

member (Miembro Conglomerados) were collected for petrographic analysis in the lab (Fig. S2) and for U-Pb geochronology (Table S1). More than 1400 fossil plant specimens were collected from multiple locations throughout the Mount Flora area, from both *in situ* outcrops and drifted glacial blocks.

### 3.2 U-Pb Geochronology

Two samples from the tuffaceous interval (unidad 4a of the Miembro Conglomerados -Montes et al., 2019) of the Mount Flora Formation were chosen for U-Pb geochronology. Sample 22-1-18-5 was from a 16 meters-thick ignimbrite flow from the northeastern flank of Mount Flora, which exposes the most expanded section of the tuffaceous interval (Figs. 3; S1)). The tuffaceous interval thins out towards west and its lower part disappears laterally within a few tens of meters. Sample 24-1-18-1 is a crystal lithic lapilli tuff collected from approximately 290 meters to the west along strike from 22-1-18-5 and may be considered a lateral facies of the ignimbrite. Detailed stratigraphy of the tuffaceous interval and petrographic descriptions of the geochronology samples are given in the Supplementary Information.

High-precision U-Pb zircon analyses by the CA-ID-TIMS technique were conducted at the Massachusetts Institute of Technology Isotope Laboratory using procedures described in Ramezani et al. (2011). Samples were crushed and pulverized by standard techniques and heavy minerals were separated using a Frantz® isodynamic magnetic separator and high-density liquids. Final selection of zircons for analyses was made under a binocular microscope and based on morphological criteria including faceted prismatic habit, high aspect ratio and presence of elongated glass (melt) inclusions parallel to the crystallographic “C” axis (Fig. S3), which have proven effective in screening out reworked zircons. Selected grains were pretreated by a chemical abrasion technique modified after Mattinson (2005), which involved thermal annealing at 900°C for 60 hours before partial dissolution in 28M hydrofluoric acid at 210°C in a high-pressure digestion vessel for 12 hours. After thorough fluxing and rinsing to remove the leachates, the zircons were spiked with the EARTHTIME ET535 mixed U-Pb tracer solution (Condon et al., 2015; McLean et al., 2015) and completely dissolved in 28M HF at 210°C for 48 hours. Chemically purified Pb and U via anion-exchange column chemistry were subsequently analyzed on an Isotopx X62 thermal ionization mass spectrometer equipped with 9 Faraday detectors and a Daly ion counting system. Data reduction and error propagation were conducted using Tripoli and ET\_Redux software (Bowring et al., 2011; McLean et al., 2011). Complete data are given in Supplementary Table S1.

Tuff ages are derived from the weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  dates of the analyzed zircons after excluding visibly older analyses interpreted as xenocrystic or detrital (Fig. 4). No young zircon analysis has been excluded. Calculated age uncertainties are reported in the  $\pm X/Y/Z$  Ma format, where  $X$  is the internal 95% confidence interval uncertainty in the absence of all external errors,  $Y$  incorporates the tracer calibration errors and  $Z$  includes  $Y$  as well as the U decay constant uncertainties of Jaffey et al. (1971). Age results are summarized in

Figure 4.  $Y$  needs to be taken into account when U-Pb ID-TIMS dates are compared to those produced by *in situ* techniques such as SIMS. Similarly, the accuracy of the SIMS ages, derived from the reproducibility of mineral standard measurements, need to be considered in such comparisons (see Discussion).

## 4 Results

### 4.1 U-Pb Geochronology

Five single zircon grains were analysed from each sample. Excluding a slightly older analysis suspected of being detrital or xenocrystic in each case the remaining four analyses produced statistically coherent clusters of  $^{206}\text{Pb}/^{238}\text{U}$  dates from which weighted mean dates can be calculated (Fig. 4). These are  $163.541 \pm 0.052/0.090/0.20$  Ma (MSWD = 0.66) for the crystal lithic lapilli tuff 24-1-18-1 and  $163.555 \pm 0.071/0.10/0.20$  Ma (MSWD = 1.5) for the ignimbritic lapilli tuff 22-1-18-5. The two dates are statistically indistinguishable within uncertainty and are Middle Jurassic (Callovian) based on the latest calibration of the Jurassic time scale (Hesselbo et al., 2020), which places the Middle-Late Jurassic boundary at  $161.5 \pm 1.0$  Ma.



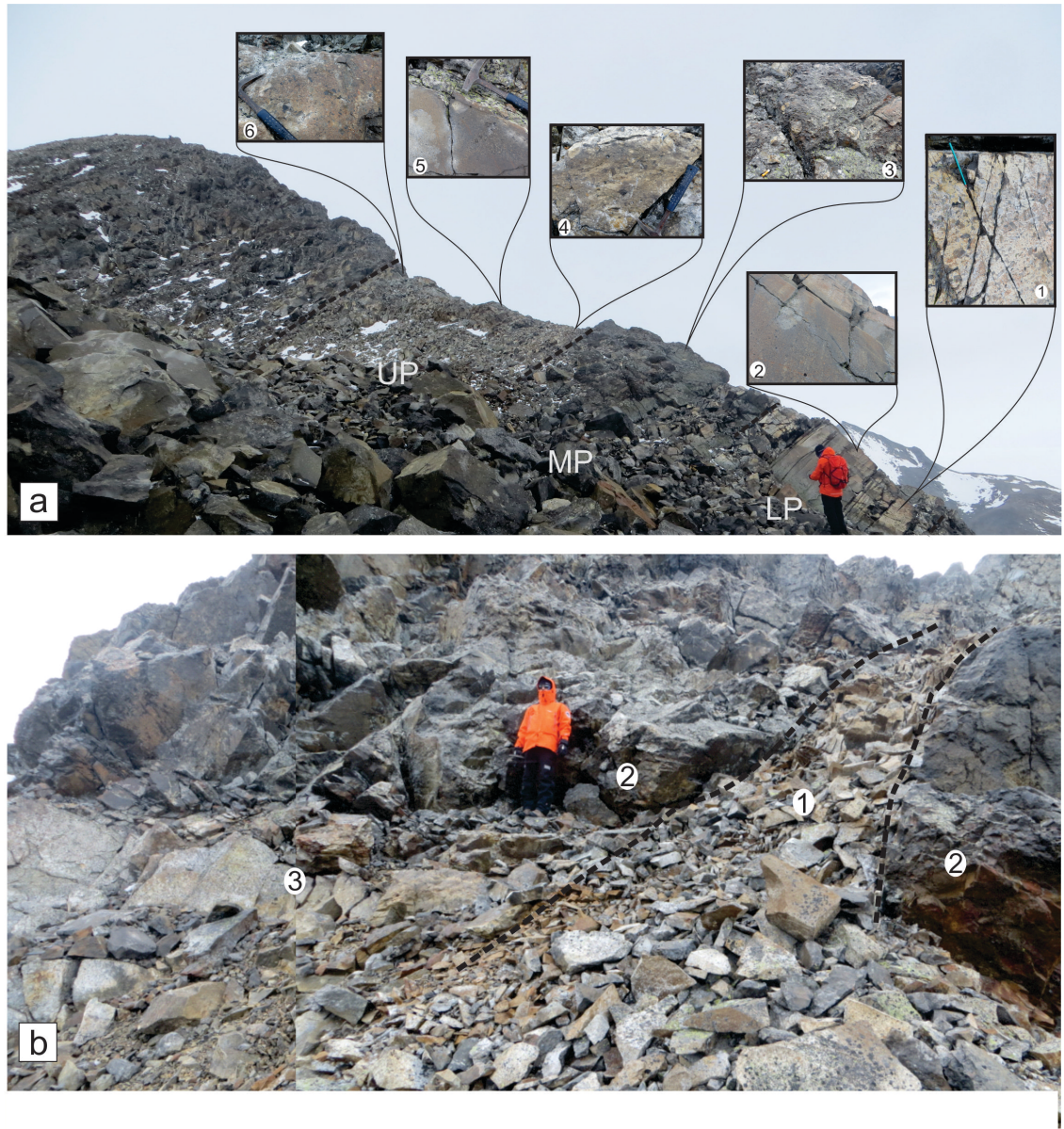


Figure 3. a, Tuffaceous interval in the Miembro Conglomerados of the Mount Flora Formation (section in Fig. 2b) subdivided into a lower part (LP), middle part (MP) and upper part (UP). From base to top: 1) Partially welded breccia deposited in energetic conditions of a pyroclastic density current; 2) Intercalated, lensoidal, ash and lapilli beds accumulated in fluctuating granular regime of the pyroclastic density current; 3) Clast-supported conglomerate with

whitish clasts of volcanic rocks representing the background sedimentation of the alluvial fan, interbedded with conglomerates with tuffaceous matrix and angular volcanic clasts interpreted as lahar deposits. 4) Reversely-graded, lithic-rich breccias deposited through the lower flow boundary of a pyroclastic density current. 5) Lapilli tuff and 6) Top Breccia forming the main body of the pyroclastic density current deposits. b, Dike (1) cutting across a conglomerate (2) and the uppermost breccia (3) in the upper part of the tuffaceous interval.

#### 4.2 Plants

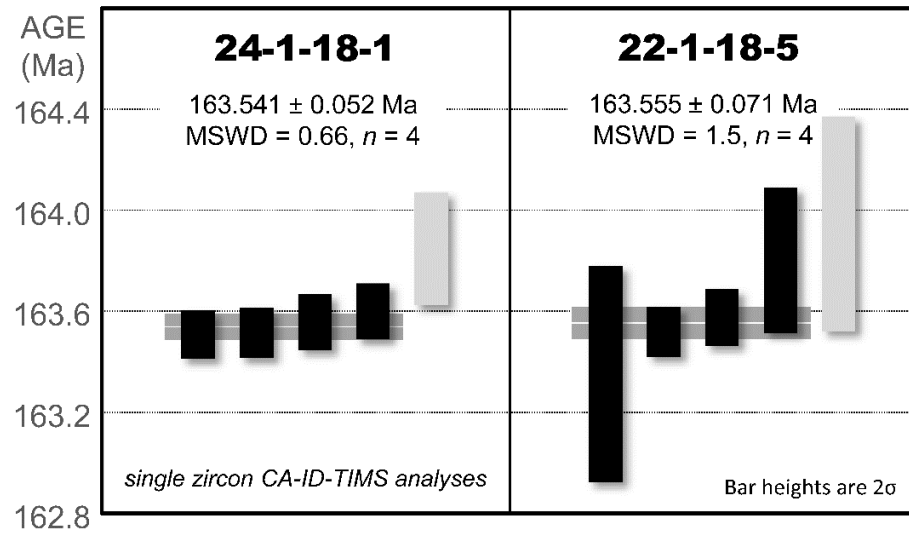


Figure 4. Date distribution plot of analyzed zircons from the inter-stratified tuffaceous samples of Mount Flora Formation. They show  $^{206}\text{Pb}/^{238}\text{U}$  dates of individual zircons with 2 analytical uncertainties (vertical bars) and their calculated weighted mean (horizontal line) with its 95% confidence error envelope (shaded band) for each sample. Grey bars are outliers excluded from date calculation.

The Mount Flora succession has produced one of the better understood fossil plant assemblages known for the Mesozoic of Gondwana (Halle 1913; Gee 1989; Rees and Cleal, 2004; Birkenmajer and Ociepa 2008). The new collection includes a little over 1400 specimens, collected at several points in the Mount Flora area, both from drifted blocks and *in situ* levels (Fig. 2).

The taphoflora is characterized by the coexistence of numerous lineages, including horsetails, ferns, cycads, bennettitales, conifers and seed ferns (e.g., Gee, 1989), constituting a highly diverse plant community. Horsetails are repre-

sented by vegetative remains, including axes, leaf whorls and isolated nodal diaphragms presenting no major morphological differences respect to extant *Equisetum* species, and therefore are included in this genus. Fern diversity at Mount Flora includes representatives of the families Dipteridaceae (*Hausmannia* and *Goeppertella*), Dicksoniaceae (*Coniopteris*), and Osmundaceae (*Todites*), together with taxa of uncertain systematic affiliation, such as the sterile fronds *Sphenopteris* and *Cladophlebis*. The seedferns are represented by Caytoniales, with leaves of the *Sagenopteris* genus being present as isolated leaflets, and hitherto unknown polliniferous organs of the *Caytonanthus* genus, with both genera thought to belong to the same plant. The presence of other seedfern families (e.g. Umkomasiaceae) is suggested by the occurrence of vegetative remains assigned to *Archangelskya* Herbst, in addition to possible seedfern taxa with uncertain affinities (e.g. *Pachypteris*, *Komlopteris*). Fronds of possible cycadales (e.g., *Ctenis*, *Pseudoctenis*) and bennettitales (e.g., *Zamites*, *Otozamites*, *Taeniopteris*) are also common in the plant associations, isolated scale leaves assigned to *Cycadolepis* are rare whereas probable megasporophylls of the *Cycadospadix* type are even rarer. Remains of the polliniferous organs of bennettitaleans such as *Weltrichia* previously mentioned by Gee (1989) weren't found, whereas the ovuliferous organ *Williamsonia* is represented by numerous newly collected specimens. Numerous conifer leaves and leafy twigs have been also described (e.g., *Brachyphyllum*, *Pagiophyllum*, *Elatocladus*), which are generalized morphologies that can potentially belong to different families during the Mesozoic (e.g., Araucariaceae, Podocarpaceae, Cheirolepidiaceae, Cupressaceae). Isolated ovuliferous complexes of various morphologies, all of them apparently bearing a single central seed covered by the tissues of the complex (i.e., *Araucarites*) strongly suggest the presence of Araucariaceae, although other families are still in debate. Reproductive organs subtended by branches with conifer-like leaves, previously assigned to *Schizolepidella* (Halle 1913) and *Sphenolepis* (Gee 1989) are also present on the new collections, but whether their affinities lie with modern or extinct conifer is still uncertain. Plant diversity at Mount Flora is completed by other genera of unknown systematic affiliation pending of a more detailed examination (e.g., *Scleropteris*, *Stachyotaxus*).

## 5 Discussion

### 5.1 Age and depositional history of the Mount Flora Formation

Elliot and Gracianin (1982) were the first to point out the presence of tuff interbeds in the Mount Flora Formation at Hope Bay. Their tuff dominated Unit 8 (Unit 4a of Montes et al., 2005; 2019) with a total thickness of 36 m matches the tuffaceous interval reported here. Correlative tuff intervals have been reported from the Tower Peak Formation, as well (Farquharson, 1984). Birkenmajer (1993) and Birkenmajer and Ociepa (2008, see their figs. 5 and 6) considered the interval as a sill. Dikes and sills intruding the Mount Flora Formation (Fig. 3b) differ from the tuffaceous beds in their petrography and field relationships.

The depositional facies of the tuffaceous interval of Mount Flora Fm. (Text

S1; Fig. S1) suggest widespread explosive volcanism during active alluvial (fan) deposition. The lower part of the tuffaceous interval (Fig. 3a) contain tuffs, lapilli tuffs and breccias. Coarser-grained breccias are interpreted as the coarse facies of ignimbrites, deposited in energetic conditions through the lower flow boundary of a pyroclastic density current (Branney and Kokelaar, 2004). The thick ash-lapilli intervals with lensoidal beds suggest accumulation in fluctuating granular regime of pyroclastic density currents (Sulpizio et al., 2014).

The middle part of the tuffaceous interval represents the typical background sedimentation of the alluvial fan combined with volcanic clasts and blocks eroded from loose or consolidated beds product of explosive volcanism exposed elsewhere in the highlands. Beds with tuffaceous matrix and volcanic clasts are interpreted as lahar deposits formed after the deposition of the pyroclastic density currents, when fresh, loose particles from the eruption were mixed with rainfall water and entrained in a lahar flow together with clasts from the TPG. Incipient rounding of the volcanic clasts pointing to reworking of the primary volcanic products in the sedimentary environment. The log remains within these conglomerates suggest well-vegetated highland and/or alluvial fan areas.

The lithic-rich, coarser grained breccias at the base of the upper interval (Figs. 3a; S1) are interpreted as deposited in energetic conditions through the lower flow boundary of a pyroclastic density current (Branney and Kokelaar, 2004). The 14 m thick lapillitic interval above capped by a 2 m thick, reverse-graded upper breccia (Fig 3a, b) constitute the main body of a pyroclastic flow deposit formed under a granular flow regime (Sulpizio et al., 2014). Wood pieces in the overlying sandstone and large logs concentrated at the base of the conglomerate bed above (Figs. 3; S1) reveal that explosive volcanism devastated a forested area and sourced abundant trunks of dead trees to the depositional system. Extensive reworking of volcanic material into the upper member (Miembro Areniscas) conglomerates further substantiates the syneruptive sedimentation. In addition, petrified wood indicates dense upstream vegetation in the form of a forested landscape.

The depositional facies of the Mount Flora Formation and its tuffaceous interval suggest at least two main episodes of explosive volcanism with associated pyroclastic density currents during active alluvial (fan) deposition heralding the widespread volcanism represented in the overlying Kenney Glacier Formation. Coarse-grained ignimbritic breccias suggest proximal to medial location with respect to the sources and broad lens shape of the tuffaceous interval topographically controlled sedimentation in valleys typical features of this kind of ignimbrites (Branney and Kokelaar, 2004)

Our new U-Pb geochronology constrains the peak volcanism of the Mount Flora Formation tuffaceous interval at  $163.55 \pm 0.10$  Ma (2 including tracer calibrations uncertainty). Hunter et al. (2005) reported tuff U-Pb SIMS ages (2 excluding any systematic uncertainties) of  $167.1 \pm 1.1$  Ma from the Camp Hill Formation at Botany Bay and  $168.9 \pm 1.3$  Ma from the Tower Peak Formation at Tower Peak. The volcanic rocks of the Antarctic Peninsula Volcanic Group

yielded U-Pb SIMS age of  $162.2 \pm 1.1$  Ma from Mount Flora and  $166.9 \pm 1.6$  Ma from Camp Hill (Pankhurst et al. (2000)). In the absence of any reported accompanying zircon standard measurements, the accuracy of the above *in situ* U-Pb dates cannot be directly evaluated. However, the reproducibility of the U-Pb dates measured by Sensitive High-Resolution Ion Microprobe (SHRIMP), in general, has been estimated to be no better than 1% at 2 (Ireland and Williams, 2003; Stern and Amelin, 2003). This translates to minimum uncertainties of  $\pm 1.7$  m.y. for the above SIMS ages. If the previously reported U-Pb SIMS age of  $162.2 \pm 1.1$  Ma from volcanic rocks overlying the Mount Flora Formation (presumably a Kenney Glacier Formation sample) is accurate, it implies that the upper half of the Mount Flora Formation with a thickness of nearly 200 m and including all of its plant remain was deposited in a relatively short time period of  $1.4 \pm 1.1$  m.y. in the Callovian.

The succession of the Mount Flora indicates that basin formation started with active, amagmatic tectonics triggering the formation of fault scarps and coarse-grained alluvial fans associated to them. Silicic to intermediate volcanism started shortly after the tectonic processes as is typical in many Jurassic-Cretaceous small basins from rift, back-arc or transtensional settings all over Patagonia (e.g. Uliana and Biddle, 1987; Figari et al., 2015; Di Capua and Scasso, 2020). Explosive volcanism leading to the deposition of tuffs, ignimbrites and other volcanoclastic products initiated when the alluvial fans were still in development, as these volcanic products are interbedded within the coarse-grained conglomerate successions in the northern part of the Antarctic Peninsula. The irregular relief product of formation of fault scarps and volcanic edifices led to the extended formation of endorheic fluvial networks in actively subsiding basins. Subsequently, small, sometimes deep, lakes were formed in humid climates (e.g. Di Capua and Scasso, 2020). These were rapidly filled with epiclastic and volcanoclastic sediments, producing thick columns that may thin out laterally in few kilometers. The primary or secondary (reworked by the sedimentary agents) products of the increasingly extensive volcanism finally buried the landscape and gave place to a succession with coarse-grained epiclastic beds underlying a thick volcanoclastic column. On the other hand these products are widely present as primary or reworked tuffs intercalated in the younger (Kimmeridgian onwards) of the Ameghino (Nordenskjöld) Fm. marine deposits formed after major subsidence in the northern Antarctic Peninsula (Kiessling et al., 1999; Scasso, 2001; Kietzmann and Scasso, 2019). Initiation of foreland basins in the Early Cretaceous also led to the formation of flexural marine basins showing similar successions elsewhere in Patagonia (Fosdick et al., 2014; Malkowski et al., 2016).

Both, the coarse-grained, terrestrial, Callovian Botany Bay Group and the radiolarian-rich, marine, Kimmeridgian-Early Berriasian Ameghino (Nordenskjöld) Fm. (Kiessling et al., 1999; Kietzmann and Scasso, 2019) crop out in several isolated localities along the northeastern part of the Antarctic Peninsula. Although these localities are, in some cases, few kilometres apart (Fig. 1b) both units have not yet found in contact. The lack of good radiometric ages

lead some authors in the 80's to consider both units coeval, representing different sedimentary environments in the Larsen Basin, a back-arc basin developed behind an Early Cretaceous arc emerging on the Antarctic Peninsula. While favoring a Lower Jurassic age for the Botany Bay Group, Hathway (2000) linked its deposition to localized, volcanically active, rift basins that developed across Patagonia and Antarctic Peninsula in response to lithospheric extension and crustal anatexis associated with the early stages of Gondwana breakup. The coarse-grained terrestrial sediments were buried by thick volcanic piles made of lavas and volcanoclastic sediments in areas close to the volcanoes (e.g. the Kenney Glacier Formation in Hope Bay). This 'syn-rift megasequence', which incorporated widespread ignimbrite-dominated volcanism (presumably mid-Jurassic) was followed in the northern Antarctic Peninsula by the Kimmeridgian-Early Berriasian, radiolarian-rich, mudstones of the Ameghino (Nordenskjöld) Formation and its marine equivalents ('post-rift transgressive megasequence'), although the contact relationships of the latter remain unclear. The Ameghino Formation represents deposition in a deep anoxic marine environment, with periodic fallout tuffs (Scasso 2001) on the inboard flank of an emerging magmatic arc, with the latter forming a barrier to ocean circulation (Hathway, 2000).

An unequivocal Callovian age for the Mount Flora Formation based on our U-Pb geochronology brings the non-marine Hope Bay Group and the Antarctic Peninsula Volcanic Group much closer in age to the marine Ameghino (Nordenskjöld) Formation and its correlatives throughout the Larsen Basin. In addition, this age proximity obscures the stated distinction between the syn-rift and magmatic arc-related depositional sequences associated with Gondwana break up and formation of the Antarctic Peninsula magmatic arc, respectively. High-precision radioisotopic ages from the Nordenskjöld Formation tuff interlayers will be necessary to untangle the regional tectonics and basin evolution histories.

Comparison with the high-resolution chronostratigraphy of the Jurassic basin fill in the Chubut River Valley region of Patagonia (Cúneo et al., 2013; Pol et al., 2020) indicates that the Mount Flora Formation was deposited subsequent to the Cañadón Asfalto Formation and prior to the deposition of the Cañadón Calcáreo Formation. Both of these formations are non-marine successions with tuff interbeds and abundant vertebrate and plant fossils (see floral comparisons below); their contact is characterized by an unconformity. It has been postulated that a post-Aalenian (Middle Jurassic) tectonic event resulted in down-cutting into the Cañadón Asfalto and older formations, followed by the onset of deposition of the predominantly fluvial and lacustrine Cañadón Calcáreo Formation prior to ca. 158 Ma (Cúneo et al., 2013). This suggests that the Mount Flora formation either coincides with a period of Middle Jurassic non-deposition or correlates with the basal conglomerates of the Cañadón Calcáreo Formation, in central Patagonia.

## 5.2 Middle Jurassic Flora of Mount Flora and biostratigraphic implications

The Mount Flora succession has been assigned a broad range of ages, from the

Early Jurassic to the Early Cretaceous, with the same floristic elements -at generic and specific level- being used to support alternative age assignments. Taking into consideration its overall paleobotanical content, the plant association in Mount Flora can undoubtedly be assigned to the Jurassic, and this was observed as early as the flora was initially studied (Nathorst 1904; Halle 1913). In this sense, most recent paleobotanical studies have constrained the taphofloras of Mount Flora and Botany Bay to the Early Jurassic (e.g., Rees, 1993a, b; Rees and Cleal, 2004) based on the presence of an association of taxa related to this age. Those taxa include the dipteridaceous ferns *Goeppertella* and *Dictyophyllum*/*Clathropteris*, seed ferns like *Sagenopteris nilssoniana* and *Dicroidium feistmantelli*, and other possible seed ferns such as *Archangelskya furcata* and *Pachypteris indica*. The utility of these taxa as biostratigraphic indicators of Lower Jurassic are discussed in detail below.

*Goeppertella woodii* and *G. jeffersonii* are present at Mt. Flora and Botany Bay plant assemblages, and were regarded as being most similar to Early Jurassic species from South America (Rees 1993a; Rees & Cleal 2004). Species of this genus from the Northern Hemisphere are mostly Late Triassic, while those of the Southern Hemisphere are mostly Late Triassic-Early Jurassic, suggesting the same age for Mt. Flora. However, Rees (1993b) also reported fossils of *G. cf. woodii* from Clent Hills, New Zealand, which are almost indistinguishable from the Antarctic remains. Since the New Zealand fossils come from an assemblage now regarded as Middle-Late Jurassic (Kamp 2001; Pole 2009), then although the majority of records from South America suggest that *Goeppertella* is a good index fossil for Late Triassic-Lower Jurassic, the records from New Zealand point to a younger age.

*Dictyophyllum* is often found in localities dated as Lower to middle Jurassic from South America (Herbst 1975). However, *Dictyophyllum* is not present at Mt. Flora, but Rees and Cleal (2004) argued that fragmentary fronds of the genus can't be distinguished from *Goeppertella* fragments, which is present at Mt. Flora. Nevertheless, since despite intensive field work done at Mt. Flora there still aren't fossils that can be confidently assigned to *Dictyophyllum* (Halle 1913; Morel et al., 1994; Rees & Cleal 2004; Birkenmajer & Ociepa 2008; this study), its use as an argument in favour of a Lower Jurassic age is not supported, and as they are not readily identifiable when fragmentary, their usefulness as a marker for Lower Jurassic results quite limited.

*Sagenopteris nilssoniana* (and its synonym *S. rhoifolia*) is present on numerous Lower Jurassic localities from South America and Europe (Halle 1913; Bonetti 1963; Quattrocchio et al., 2007), and its presence on Mt. Flora was used to argue for a Lower Jurassic age for the plant assemblage (Rees and Cleal 2004). However, it has been argued that *S. nilssoniana* display a vast amount of contrasting features that suggest that its records may be attributable to more than a single species, and that they should be carefully revised (Elgorriaga et al., 2019). More importantly, some of the specimens from Mt. Flora and Botany Bay display at least one feature that do not conform with neither *S. nilssoniana*



nor any species of the genus (i.e. leaflets with numerous deep lobes on their margins), casting doubts on the specific and perhaps even generic attribution of those specimens (Pattemore et al., 2015).

*Archangelskya furcata* is one of the two species of the genus, the other one being *A. proto-loxsoma* from the Lower Jurassic of Mendoza, Argentina (Herbst 1964). Since *A. furcata* was also reported from the Lower Jurassic of Patagonia (Herbst 1964 and Harbst and Anzoátegui 1968), it was suggested that the presence of the genus could be used as a good indicator for a Lower Jurassic age (Rees and Cleal 2004). However, since *A. furcata* remains were also found on Cretaceous rocks from Livingston Island (Parica et al., 2007) then the species has a longer biochron than initially thought, and hence it is no longer advisable to use its presence as an indicator for Lower Jurassic. .

Three specimens assigned to *Dicroidium feistmantelli* were found on Botany Bay (Rees & Cleal 2004), and since the genus rarely surpasses the Late Triassic (although see Bomfleur et al., 2018), its presence suggested a Late Triassic/Lower Jurassic age for Mt. Flora plants. But, as Rees (1990) argues, the remains from Botany Bay lack cuticular features and are too fragmentary to confidently place them on the *Dicroidium* genus, lacking one of the features that characterizes the genus (i.e.. basal dichotomy), and they may be better placed in other genera that possess similar morphology (e.g. *Thinnfeldia*).

The remains of *Pachypteris indica* from Mt. Flora resemble those of India, which are of probable Lower Cretaceous age (Bose and Banerji 1984). Additionally, as noted by Rees & Cleal (2004), they also resemble the fronds described as *Sphenopteris bagualensis* by Menendez (1956) from Bajo de los Baguales, Argentina, that is dated as Middle Jurassic. Therefore, the presence of *P. indica* suggests a Middle Jurassic minimum age for the Mt. Flora assemblage, which agrees with the late Middle Jurassic age determination of this study. In summary, the taxa that were previously used to estimate the age of Mt. Flora and the Botany Bay Group do not provide unequivocal support for a Lower Jurassic age for the plant assemblage as a whole, and as will be discussed below, their presence in the terminal Middle Jurassic of Antarctica may have a paleoecological explanation instead.

Our new U-Pb CA-ID-TIMS geochronology, along with the U-Pb SIMS data of Pankhurst et al. (2000) and Hunter et al. (2005), strongly support a Middle Jurassic (Callovian) age for the entire plant associations at Hope Bay. By direct correlation, this age assignment can be extended to the floral associations at Botany Bay and Tower Peak (Fig. 1), as well. The calibrated age of this paleoflora has important biostratigraphic implications. It has been demonstrated that some of the genera used to date Mt. Flora have a broad biochron, including several stages within the Jurassic and, in some cases, reaching the Triassic or the Cretaceous (e.g. *Goepertella*, *Pachypteris*). Also, in the absence of cuticular or anatomical information, many species-level taxa are defined by characters that are highly homoplastic and, therefore, their biostratigraphic or biogeographic relevance is questionable. The Middle Jurassic floras of the Antarctic Peninsula



are remarkably similar to the floras in some localities in Patagonia (Argentina) in terms of their most characteristic elements (e.g., *Sagenopteris*, *Geoppertella*, *Archangeliskya*) and some other floristic components (Escapa 2009). The Cerro Taquetrén locality in the Jurassic Cañadón Asfalto Basin (Chubut River Valley, Chubut Province, Argentine Patagonia), for instance, shows a high degree of similarity in plant composition with respect to the Hope Bay floras (Bonetti, 1963; Herbst and Anzótegui, 1968; Escapa et al., 2008; Escapa, 2009). However, the Cerro Taquetrén flora occur in the basal Lonco Trapial Formation, which has an Early Jurassic (Pliensbachian-Toarcian) age on the basis of CA-ID-TIMS geochronology (Cúneo et al., 2013; Pol et al., 2020), indicating at least a 17 m.y. age difference between the two. The fossil flora of Piedra Pintada in the province of Neuquén is another Patagonian assemblage with a Lower Jurassic age (based on ammonite biostratigraphy), which contains *Sagenopteris* and *Goeppertella* among other elements also present at Mt. Flora (Herbst 1966). In addition to these key elements, the Patagonian Early Jurassic floras are similar to their Antarctic Middle Jurassic counterparts in the presence of Equisetum-like equisetals, bennettitales, and other conifer and fern remains (e.g. *Elatocladus*, *Osmundopsis*).

In the Cañadón Asfalto Basin, the diverse Pliensbachian-Toarcian floras were replaced by relatively less diverse ones by the end of the Toarcian (i.e., Cañadón Asfalto Fm.), which are dominated by conifers (e.g., *Brachyphyllum*) and small leaf ferns (e.g., *Cladophlebis*) (Escapa 2009). The permineralized flora of the overlying Cañadón Calcáreo Formation with an unambiguous Late Jurassic based on U-Pb geochronology (Cúneo et al., 2013) are dominated by conifer seed cones of the families Araucariaceae and Cheirolepidiaceae. Thus, Mount Flora exhibits stark differences with its coeval successions in South America in terms of paleofloral associations, indicating the low value of macrofossil plant associations in establishing biochronologic stages for the Jurassic.

The large age disparity between near-identical South American and Antarctic flora is of particular paleoecologic significance. In the case of Dipteridaceae, one of the most conspicuous taxa of the Gondwanic floras mentioned here, a similar pattern of distribution in the Northern Hemisphere has been interpreted to reflect migration from Southeast Asia (Late Triassic) to Europe (Early Jurassic) as a function of climate change (Barale, 1990; van-Konijnenburg-van Cittert, 2002). The response of the vegetation to changes in the Jurassic climate has been also documented at a finer scale by measuring the effect of the Toarcian Anoxic Event on the continental environments of Yorkshire (Slater et al., 2019). The scheme seems to be similar: the same basic lineages, without major changes in composition throughout the Jurassic, comprised associations that were strongly correlated with temperature and humidity. In contrast with the Northern Hemisphere, well-described Gondwanic Jurassic associations with well-documented ages are scarce. However, the available information suggests that a similar ecologic plant mosaic could have been present in the Jurassic of Gondwana. It is also possible that tectonically controlled inception of foreland basins established the paleoecological conditions for similar plant associations to flourish at sepa-

rate locations and at different times during the Jurassic. More complete plant concepts with broader geographic distributions and precise ages are needed in order to decrease the probability of homoplasy biases in the biotic comparisons and to better understand complex patterns of vegetation change in time and space.

### 5.3 Mount Flora and the Gondwana extensional history

The tectonic evolution of the Antarctic Peninsula has been traditionally interpreted by correlation of its magmatic and sedimentary rocks to presumed equivalent units throughout the South American Patagonia. Pankhurst et al. (2000) divided the ca. 35 m.y. regional Jurassic silicic volcanism into three episodes (V1-V3), with the Early Jurassic V1 (188-178 Ma) influenced largely by the Karoo-Ferrar magma plume and the Middle Jurassic V2 (172-162 Ma) reflecting a progressive trend towards rifting and break-up along the proto-Pacific margin of Gondwana. The Late Jurassic V3 volcanism (157-153 Ma) and associated granitoids were interpreted to have an active-margin affinity and to represent a precursor to the intrusion of the Andean and Antarctic Peninsula arc batholiths. In this scheme, the volcanic rocks at Mount Flora would correlate with those of the Chon Aike Formation of central Patagonia and fall within the V2 episode of Pankhurst et al. (2000). Riley et al. (2017) recognized a ca. 185-181 Ma episode of granitoid emplacement throughout Patagonia and (southern) Antarctic Peninsula, which although coincided with the V1 episode, but had a subduction genetic affinity. This shifted the onset of subduction along the proto-Pacific margin of Gondwana to Early Jurassic, in contrast to the earlier interpretation of Pankhurst et al. (2000). Finally, Bastias et al. (2021) added a yet earlier episode of active margin magmatism of Triassic age (V0) to the geologic history of Antarctic Peninsula and Patagonia and concluded, based on a compilation of age, geochemical and isotopic data, that the entire Triassic-Jurassic magmatic evolution can be explained by subduction-related processes involving a westward migrating slab. In their view, a mantle plume need not be invoked and the disassembly of southern Gondwana followed the Late Jurassic episode (V3) of back-arc extension and rifting (Bastias et al., 2021).

The above interpretations have been derived to a large extent from temporal correlations of magmatic rocks throughout the Antarctic Peninsula and Patagonia based on *in situ* U-Pb geochronology using SIMS (Pankhurst et al., 2000; Riley et al., 2017) or LA-ICPMS (Bastias et al., 2021) methods with limited precision and accuracy. Recent high-precision U-Pb geochronology by the CA-ID-TIMS technique has demonstrated distinct and short-lived, Early Jurassic magmatic episodes for the Karoo (e.g., Sell et al., 2014) and Ferrar (e.g., Burgess et al., 2015) large igneous provinces of South Africa and Antarctica, as well as for the Lonco Trapial Formation of northern Patagonia (Pol, et al., 2020), all of which were once considered to be contemporaneous and associated with rifting. Such high resolution temporal constraints nevertheless remain sparse in the region. Untangling the complex geologic evolution of southern Gondwana driven by protracted magmatic arc-rift interactions requires an integrated approach that

would include detailed depositional histories of its sedimentary successions, in addition to precise age calibration of its magmatic episodes.

The chronostratigraphy and depositional facies of the Mount Flora succession indicates rapid deposition in a continental landscape characterized by high topographic relief and dense vegetation proximal to centers of active felsic volcanism near the end of the Middle Jurassic. The high relief may have been the result of a regional uplift event during the development of the Jurassic arc, which was also responsible for a regional unconformity in the northern Patagonian foreland basin(s).

## 5 Conclusions

Two high-precision U-Pb zircon ages (CA-ID-TIMS method) from a distinct tuffaceous interval in the lower conglomerate member of the Mount Flora Formation at Hope Bay produced statistically coherent clusters of  $^{206}\text{Pb}/^{238}\text{U}$  dates of  $163.541 \pm 0.052/0.090/0.20$  Ma (MSWD = 0.66) for crystal lithic lapilli tuff and  $163.555 \pm 0.071/0.10/0.20$  Ma (MSWD = 1.5) for an ignimbritic lapilli tuff indicate a Middle Jurassic (Callovian) age

The succession of the Mount Flora indicates that basin formation started with active, amagmatic tectonics triggering the formation of fault scarps and coarse-grained alluvial fans associated to them. In this setting, silicic to intermediate volcanism started shortly after the tectonic processes, as is typical in many Jurassic-Cretaceous small basins from rift, back-arc or transtensional settings all over Patagonia.

The depositional facies of the Mount Flora Formation, its age proximity to the marine Ameghino (Nordenskjöld) Formation in the Antarctic Larsen Basin, and its coincidence with a regional unconformity in the northern Patagonia point out to a complex interplay among magmatic arc development, tectonic extension and continental break up that dominated the geologic and paleoenvironmental evolution of southern Gondwana near the end of the Middle Jurassic.

The highly diverse Jurassic plant association that dominated the Antarctic Peninsula nearly 17 million years after its disappearance from northern Patagonia suggests similar paleoecological conditions were established diachronously throughout foreland basins of southern Gondwana, possibly facilitating floral migrations in response to local climate change.

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