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# The Chon Aike province of Patagonia and related rocks in West Antarctica: A silicic large igneous province

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**Abstract**

The field occurrence, age, classification and geochemistry of the Mesozoic volcanic rocks of Patagonia and West Antarctica are reviewed, using published and new information. Dominated by rhyolitic ignimbrites, which form a bimodal association with minor mafic and intermediate lavas, these constitute one of the largest silicic igneous provinces known, equivalent in size to many mafic LIPs. Diachronism is recognized between the Early–Middle Jurassic volcanism of eastern Patagonia (Marifil and Chon Aike formations) and the Middle Jurassic–earliest Cretaceous volcanism of the Andean Cordillera (El Quemado, Ibañez and Tobífera formations). This is accompanied by a change in geochemical characteristics, from relatively high-Zr and -Nb types in the east to subalkaline arc-related rocks in the west, although the predominance of rhyolites remains a constant factor. All of the associated mafic rocks are well fractionated compared to direct mantle derivatives. Petrogenetic models favour partial melting of immature lower crust as a result of the intrusion of basaltic magmas, possibly with some hybridisation of the liquids and subsequent fractionation by crystal settling or solidification and remelting. The formation of large amounts of intracrustal silicic melt acted as a density barrier against the further rise of mafic magmas, which are thus rare in the province. © 1998 Elsevier Science B.V.

*Keywords:* large igneous province (LIP); volcanic rocks

## 1. Introduction

The term large igneous province (LIP) has become almost synonymous with continental flood basalt fields, partly because there have been many published accounts of such *mafic* LIPs (Macdougall, 1988; Storey et al., 1992a; Coffin and Eldholm, 1994, for reviews and references). Debate has centred on the relative roles of lithospheric and asthenospheric mantle sources in their petrogenesis and on their relationship to mantle plume models (White and McKenzie, 1989). Silicic rocks are commonly present as a minor component in mafic LIPs (Cleverly et al., 1984; Lightfoot et al., 1987; Milner et al.,

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Table 1
Estimated volumes of silicic rocks in some large igneous provinces

| Province | Location | Age | Volume ($km^3$) | Reference |
|---|---|---|---|---|
| Sierra Madre Occidental | Mexico | mid-Tertiary | 296,000 | Cameron et al. (1980) |
| Chon Aike/West Antarctica | South America and Antarctic Peninsula | Jurassic | 235,000 | This study |
| Lebombo | South Africa | Jurassic | 35,000 | Cleverly et al. (1984) |
| Parana | Brazil | Cretaceous | 16,000 | Garaland et al. (1995) |
| Taupo | New Zealand | Pleistocene | 10,000 | Cole (1981) |
| Yellowstone | USA | Pliocene | 6000 | Hildreth et al. (1991) |
| Deccan | India | Paleocene | 500 | Lightfoot et al. (1987) |

1992; Garaland et al., 1995), and silicic plutonic rocks of batholithic proportions could properly be regarded as silicic LIPs in their own right, although usage has concentrated on volcanic provinces. Large volcanic fields in which silicic rocks predominate, although relatively rare, sometimes occur on the same scale as mafic LIPs (see Table 1). In these cases, there are even wider questions concerning the nature and origin of the primary magmas, the relative roles of fractional crystallization and partial melting of crustal rocks, and the mechanisms of transfer of magmas to the surface. One such silicic LIP is described in this paper, by means of a review of published and unpublished information concerning its geological setting, age range, petrology and geochemistry; some constraints on its petrogenesis are considered. Much of the relevant literature is in Spanish and in South American sources not well known or easily obtained elsewhere.

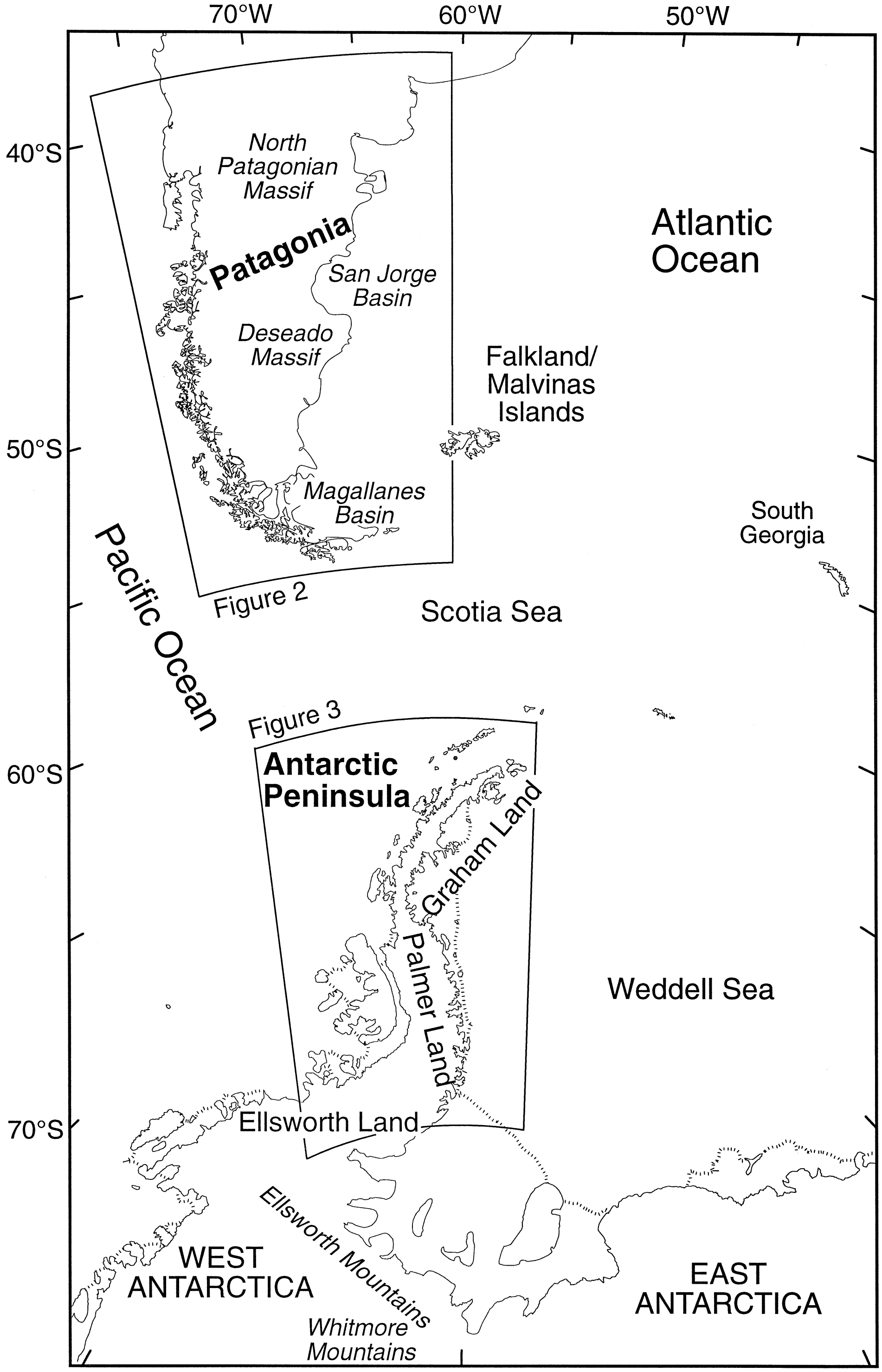
## 2. Geological setting

The mainly Jurassic volcanic rocks of southern South America are predominantly rhyolitic and form one of the world's most voluminous silicic provinces (Pankhurst and Rapela, 1995). The province comprises several now geographically separated formations in Patagonia, and possibly extends into West Antarctica (Fig. 1).

The silicic volcanic field of Patagonia (Fig. 2) extends from the Atlantic Coast to the Chilean side of the Andes. Eastern Patagonia is geologically divided into stable areas in which the volcanic rocks are now exposed (North Patagonian and Deseado massifs), and the intervening subsided areas in which they are present beneath Cretaceous and Tertiary marine and lacustrine sedimentary rocks (San Jorge and Magallanes basins). Here, the volcanic rocks are predominantly flat-lying and undeformed; they overlie crystalline basement rocks of Precambrian to earliest Jurassic age and, locally, Liassic rift-related sedimentary rocks. In contrast, silicic volcanic rocks of the same general age in the Andean Cordillera are locally deformed, tilted and strongly affected by hydrothermal alteration. They form relatively narrow outcrops parallel to the trend of the Andes. Where their base is seen, they overlie highly deformed greywackes of the Pacific margin, which are of Palaeozoic age, at least in part (Hervé, 1988).

It is usually considered that the silicic volcanic rocks of Patagonia are Early-to-Middle Jurassic in age, but recent evidence suggests a rather wider range. Rb–Sr dating in the northeastern part of the province (Rapela and Pankhurst, 1993; Pankhurst and Rapela, 1995) indicates that eruption there occurred locally in short, paroxysmal episodes of $< 2$–3 Ma, with a probable southward migration over the interval 190–170 Ma (Toarcian–Bajocian; Gradstein et al., 1994), a range essentially confirmed by new

Fig. 1. Geographical sketch map of southern South America and part of West Antarctica, covering the areas in which the mainly Jurassic silicic volcanic rocks described in this paper crop out; more detailed maps of Patagonia and the Antarctic Peninsula are shown in Figs. 2 and 3, respectively.


70°W
60°W
50°W
40°S
50°S
60°S
70°S
North Patagonian Massif
Patagonia
San Jorge Basin
Deseado Massif
Magallanes Basin
Figure 2
Atlantic Ocean
Falkland/ Malvinas Islands
South Georgia
Scotia Sea
Pacific Ocean
Figure 3
Antarctic Peninsula
Graham Land
Palmer Land
Weddell Sea
Ellsworth Land
Ellsworth Mountains
Whitmore Mountains
WEST ANTARCTICA
EAST ANTARCTICA

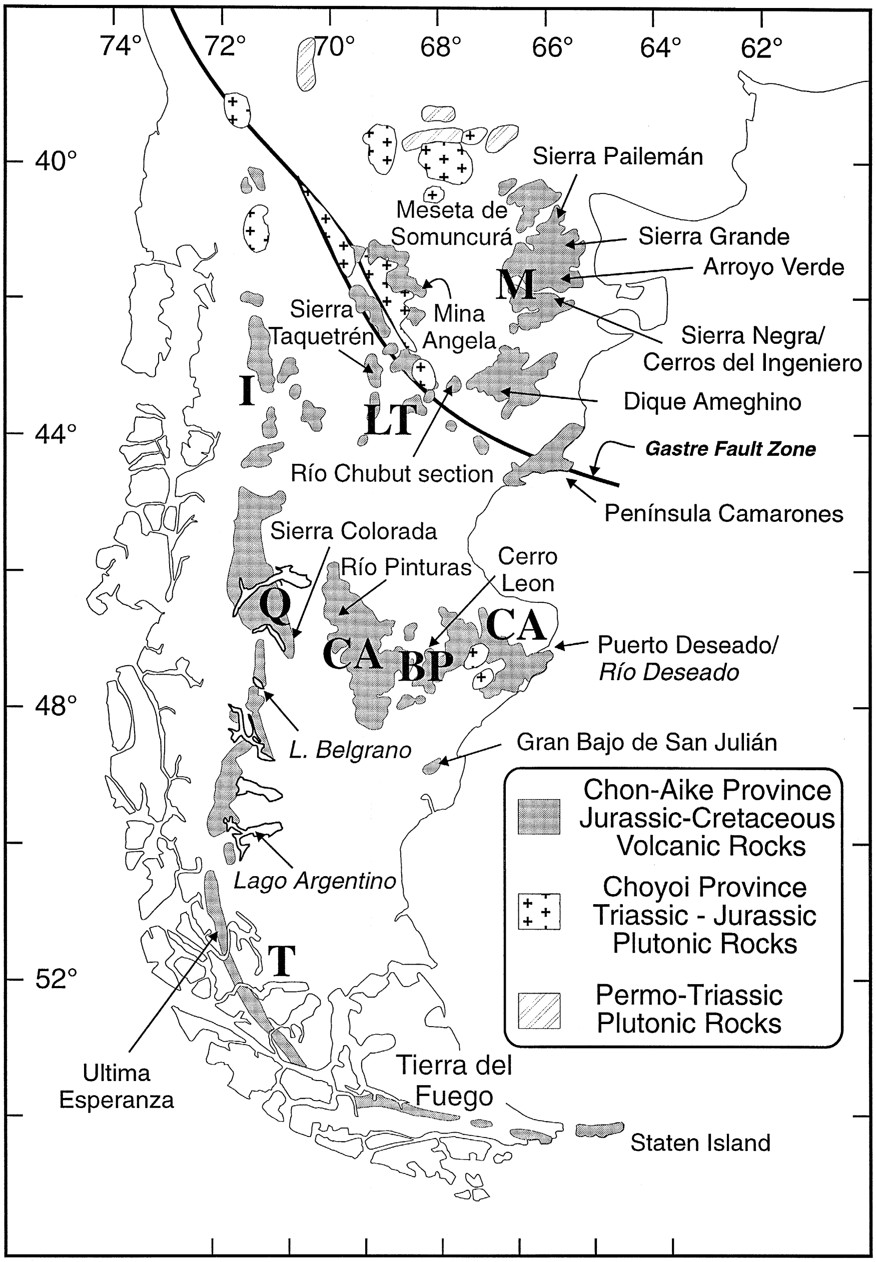



Fig. 2. Sketch map of Patagonia showing the main outcrop areas of the Jurassic–lowermost Cretaceous Chon Aike province, after Gust et al. (1985) and Pankhurst and Rapela (1995), and other geographical and geological features mentioned on the text. The areas of the principal formations of the province are indicated: M = Marifil, LT = Lonco Trapial, I = Ibañez, CA = Chon Aike, BP = Bajo Pobre, Q = El Quemado and T = Tobífera. The most southerly outcrops ascribed to the earlier Choiyoi volcanic and plutonic magmatism (Kay et al., 1989) are also shown.

Ar–Ar data (Alric et al., 1996). Although the precise chronology of magmatism in the southern and western parts of Patagonia is not clear, there is reasonable stratigraphic evidence for late Jurassic to early Cretaceous ages, particularly for the Ibañez Formation in Chile (Suárez and de la Cruz, 1994), recently supported by K–Ar biotite geochronology (Suárez and de la Cruz, 1997). This implies an extended period of eruption for the province as a whole, with significant westward diachronism.

As noted by Kay et al. (1989) and Storey and Alabaster (1991), similar volcanic rocks, of dominantly Middle Jurassic age, occur along the eastern side of the Antarctic Peninsula, and contemporaneous granites occur in the Ellsworth–Whitmore mountains area of West Antarctica and in South Georgia.

## 3. Chon Aike province (Patagonia)

### *3.1. Nomenclature*

Since the pioneering description of Feruglio (1949), varied usage has resulted in a maze of conflicting and overlapping formations, groups and complexes for the Jurassic volcanic province of Patagonia and its associated sedimentary intercalations, and there is no consensus on an overall name. Bruhn et al. (1978) used 'Tobífera' (literally 'tuffaceous strata') in this general sense, but this is inappropriate for the majority of lithologies. Gust et al. (1985) used the descriptive, but now chronologically too restrictive, term 'mid-Jurassic volcanic rocks', and Pankhurst and Rapela (1995) broadened this to 'Jurassic volcanic province'. In order to avoid problems with the as yet undated sequences, a nondescriptive name seems preferable. Rapela and Kay (1988) referred to the Chon Aike Group, but the Chon Aike Formation is already a component member of the Bahía Laura Group according to the nomenclature of Lesta and Ferello (1972) and De Giusto et al. (1980). We therefore follow Kay et al. (1989) in using the name Chon Aike province. The principal silicic volcanic units in extra-Andean Patagonia are referred to as the Marifil (in part subvolcanic) and Chon Aike formations, and those of the Andean Cordillera as the El Quemado (Argentina), Ibañez (Chile), and Tobífera formations, although other smaller formations have also been identified (see Gust et al., 1985). It is considered that the more andesitic rocks of central Patagonia (Lonco Trapial and Bajo Pobre formations), as well as the equivalent silicic and andesitic volcanic rocks of West Antarctica, should also be included, at least for the moment, within the overall concept of the province. The geological setting of the province is described below.

### *3.2. Pre-Jurassic basement*

Outcrops of basement to the volcanic rocks are confined to relatively small areas within the massifs of Patagonia and in the Andean Cordillera. They exhibit a wide variety of crystalline and sedimentary sequences.

In the Deseado massif, a number of small windows in the Jurassic sequence (De Giusto et al., 1980) reveal micaceous and amphibolitic schists, possibly of very late Precambrian or Cambrian age (K–Ar age of $549 \pm 20$ Ma for amphibolite, Pezzuchi, 1978). Permo-Triassic conglomerates fill small basins and represent the oldest evidence for an extensional regime that became more pronounced during Triassic times, with the regional formation of NNW–SSE-trending graben throughout Patagonia (Uliana and Biddle, 1987). The basement is intruded by earliest Jurassic monzonitic plutons (Márquez et al., 1993; Rapela and Pankhurst, 1996).

Basement rocks occupy a greater area in the North Patagonian Massif. The oldest crop out along its western margin, where relatively high-grade schists and gneisses (Rb–Sr ages of up to 1190 Ma, Linares et al., 1988) are intruded by Palaeozoic granites. Rifted basins contain Triassic silicic volcanic rocks of the Choiyoi Formation, and Liassic marine and pyroclastic rocks. Granitoids ascribed to the 'Gondwanian' cycle (Llambías et al., 1984) form extensive plutonic-volcanic complexes of wide-ranging composition beneath the Tertiary plateau basalts of the Meseta de Somuncurá. Rb–Sr dating indicates that this activity began mainly in Permian times and extended into the earliest Jurassic (Pankhurst et al., 1992, 1993a). East of 68°W, the Marifil Formation overlies a deformed Silurian sedimentary sequence, itself deposited on a previous meta-igneous basement, and Devonian granite (Giacosa, 1994). In the southwestern part of the massif, gneisses of possible Carboniferous and Permian age are succeeded by the batholith of central Patagonia, with Triassic granodiorites and leucogranites emplaced at $220 \pm 3$ Ma and $208 \pm 1$ Ma (Rapela et al., 1992). The leucogranites are associated with the Gastre Fault, a major strikeslip fault active during the Triassic–Jurassic rifting of Gondwana.

Basement to the Jurassic volcanic rocks in the south western Andean region is represented by highly deformed and folded metasedimentary rocks, known in Argentina as the Río Lacteo and Bahía de la Lancha formations. These consist of interbedded quartzites and black shales/phyllites of turbiditic aspect, which were tentatively assigned a Devonian–Carboniferous age by Riccardi and Rolleri (1980), partly on the basis of correlation with rocks in the Falkland/Malvinas Islands and Chile. On the Chilean side of the Andes, similar rocks form the basement to the Ibañez Formation. Fossil evidence for a mid-Palaeozoic age is extremely limited and somewhat inconclusive.

### 3.3. Chon Aike Formation

The Chon Aike Formation covers an area of some 100,000 $km^2$ in the Deseado Massif (Fig. 1). A general stratigraphical account was given by Lesta et al. (1980). In the Río Pinturas section (Fig. 2), where the base is not seen, outcrop thickness is $>300$ m. K–Ar dating has generally yielded Upper Jurassic ages in the range 140–160 Ma (Spalletti et al., 1982). Concordant Rb–Sr whole-rock isochrons of $162 \pm 11$ Ma (recalculated) for the western section of the plateau (De Barrio, 1993) and $168 \pm 2$ Ma for the eastern exposures around Puerto Deseado (Pankhurst et al., 1993b) are more indicative of eruption during Middle Jurassic (?Bajocian) times, whereas the accompanying fossil flora is consistent with a Middle to Late Jurassic age (De Barrio et al., 1982).

The lithological characteristics of different areas have been described by Sruoga and Palma (1984, 1986), Sruoga and Irigoyen (1987) and Sruoga (1989, 1994). The main plateau consists of volcanic and volcaniclastic rocks, cut by dykes and overlain by rhyolitic domes. Pyroclastic rocks predominate; ignimbrites form ca. 85% of the outcrop, with subordinate epiclastic deposits, air-fall tuffs and intercalated lavas. Nine successive ignimbrite units have been identified in the estuarine area of Río Deseado alone (Fig. 2), but it is difficult to establish correlations between distant ignimbrite outcrops due to poor exposure, localised block faulting, and the facies variations that characterise such pyroclastic volcanism.

The ignimbrites include simple and complex cooling units. Individual flows vary in thickness from 10 cm to tens of metres, exceptionally reaching 100 m or more (e.g. at Río Pinturas). The degree of welding is variable: in the Gran Bajo de San Julián, poorly welded and highly altered ignimbrites predominate (Sruoga and Irigoyen, 1987), whereas farther north in the Río Deseado estuary, both perlitic vitrophyres and unwelded pumice flows occur. The better-welded ignimbrites are massive and frequently show coarse columnar jointing. There are fiamme flattened to aspect ratios of 4–5:1, up to 10:1 in some units, and at least one flow unit has a basal autobreccia. Parataxitic and other rheomorphic textures are rare. Some features suggest emplacement over wet sediments or subaqueously, but fine-grained tuff horizons intercalated with the ignimbrites are attributed to air-fall.

The sequence is associated with lacustrine epiclastic rocks (referred to as the La Matilde Formation), which are locally fossiliferous. These laminated tuffs and tuffaceous sediments interdigitate with the ignimbrites and do not represent a significant hiatus in volcanic activity, but rather the reworking of pyroclastic material between eruptions. Very rarely, they include 10 m thick, coarse, matrix-supported breccias, interpreted as debris-flow deposits.

Rhyolitic dykes up to 20 m wide cross-cut the pyroclastic and epiclastic sequences of the formation. The dykes are sometimes zoned, being more feldspar-phyric in the core than at the margin, and are considered as feeders to the rest of the sequence. Rhyolite domes (Sruoga and Palma, 1986) stand out above the local volcaniclastic plateau. They exhibit flow-banding, sometimes highly contorted, whilst upper parts of the domes are auto-brecciated.

The pyroclastic and lava facies are petrographically similar. Modally, the ignimbrites are phenocryst-poor rhyolites or leucocratic dacites. Devitrification is a common phenomenon and results in a variety of textures: axiolitic, spherulitic, micro- and crypto-crystalline. The vitrophyres are characterised by perlitic texture. The proportions of ash and pumice vary, although ash-rich deposits predominate.

The principal minerals are quartz, K-feldspar, plagioclase and biotite; accessories are magnetite, ilmenite, apatite and zircon with associated monazite. The alteration assemblage is quartz, sericite, calcite, albite and clay minerals. Alteration is widespread and often obvious from the pervasive pink to dark red colour of the rocks. Silicification and vein-like deposits of Fe and Mn oxides are common, especially in the rhyolite domes. Locally, hydrothermal alteration was succeeded by bleaching along joints and fractures. The feldspars are generally highly altered; remnants of unaltered K-feldspar are slightly more potassic than is normal for such rocks ($Or_{75}$). Lithic clasts in the ignimbrites can be classified as cognate (perlitic glass and microfelsites), accessory (ignimbrites, silicic lavas, vitroclastic tuffs), and accidental (tuffaceous sediments).

### *3.4. Marifil Formation*

Named by Malvicini and Llambías (1974) and described in more detail (as the 'Marifil Complex') by Cortés (1981) and Haller et al. (1990), this comprises the silicic volcanic sequences northeast of the San Jorge Basin (Fig. 2), from the Atlantic Coast to about 68°W. The name 'complex' was largely due to an earlier belief that these rocks extended in age from Middle Triassic to Middle Jurassic (K–Ar ages of 210–150 Ma). However, Rb–Sr whole-rock geochronology in four central outcrops (Rapela and Pankhurst, 1993) has indicated essential contemporaneity in Toarcian–Aalenian times and justifies the original title of 'formation': 183 ± 2 Ma (Arroyo Verde), 181 ± 7 Ma (Sierra Negra), 181 ± 4 Ma (Dique Ameghino) and 178 ± 1 Ma (Península Camarones). Three further isochrons were presented by Pankhurst and Rapela (1995) which do, however, support the idea of southward diachronism: 188 ± 1 Ma for Sierra Pailemán, 174 ± 2 Ma for Sierra Grande (interpreted as due to hydrothermal resetting postdating original eruption at 182 ± 3 Ma) and 169 ± 2 Ma for Río Chubut.

As in the Chon Aike Formation, pyroclastic deposits predominate over tuffs and lavas, although the latter are volumetrically significant. Ignimbrites form cooling units up to 100 m thick, in which welding is often strong, and commonly have a massive red–brown aspect. They cover an area of over 50,000 $km^2$ in the east of the Marifil Formation, where flat lying ignimbrite sheets predominate and are believed to have been erupted from large (100 km diameter) calderas (Aragon et al., 1996). Lavas occur at Península Camarones and Cerros del Ingeniero, where many of the flows are porphyritic. Tuffs, lapilli-tuffs and volcanic agglomerates are interbedded with the ignimbrites, and the sequence is cut by subvolcanic intrusions, including dacitic and andesitic dykes, which, according to their isotopic composition, are comagmatic with the ignimbrites (Rapela and Pankhurst, 1993). Clastic sedimentary intercalations in the Marifil Formation are much less common than in the Chon Aike Formation.

In the Río Chubut section, flow-banded rhyolites interdigitate with the significantly more mafic rocks of the Lonco Trapial Formation (Demichelis et al., 1996). This, and their younger Rb–Sr age, casts some doubt over inclusion of these rhyolites in the Marifil Formation s.s.

### *3.5. Bajo Pobre Formation*

Although the Chon Aike province is largely composed of silicic volcanic and hypabyssal rocks, associated and possibly cogenetic mafic and intermediate rocks (basaltic andesites and andesites) form extensive outcrops in the central part of the Deseado Massif. These rocks are collectively assigned to the Bajo Pobre Formation (Lesta and Ferello, 1972), although discontinuity of exposure and subdued relief make the stratigraphy difficult to define. De Giusto et al. (1980) suggested overall thicknesses for the formation of 200 m and 600 m (the latter partly tectonically thickened).

The base of the formation is rarely exposed, but in the central, anticlinal part of the massif, it overlies epiclastic and pyroclastic rocks with a well preserved Toarcian–Aalenian fossil flora (Roca Blanca Formation: Stipanicic and Bonetti, 1970). Lithologically similar sedimentary horizons are also interbedded with the volcanic rocks. The mafic rocks are generally considered to be overlain by the Chon Aike ignimbrites, perhaps with angular unconformity. Alric et al. (1996) report an Ar–Ar age of 156 ± 2 Ma for plagioclase from a basalt, rather younger than the Ar–Ar and Rb–Sr ages obtained for the Chon Aike Formation.

The formation consists dominantly of subhorizontal lavas and tuffs. Basaltic andesite lava flows, up to 30 m thick, are aphanitic to slightly porphyritic, with plagioclase phenocrysts. Mafic clastic deposits interbedded with the lavas are up to 100 m thick and are dominated by locally palagonitized epiclastic debris-flow units. The upper parts of some sections are formed of coarse agglomerates, with 0.5 m blocks of pyroxene andesite. Some coarser-grained dolerites or diorites occur as intrusive bodies, as at Cerro Leon. Most of the rocks of the Bajo Pobre Formation are hydrothermally altered and they occasionally exhibit disseminated sulphide mineralization.

### *3.6. Lonco Trapial Formation*

The Lonco Trapial Formation is a sequence of lavas and volcaniclastic rocks with sedimentary intercalations which crop out across the western and southern margins of the North Patagonian Massif (Fig. 2) and continue sporadically to the north and east, although exposure is restricted by the overlying Cretaceous sediments. The areal extent of the Lonco Trapial Formation is difficult to estimate, although in Chubut province alone it has a surface area of 40,000 $km^2$ (Page and Page, 1993), and a total thickness of 500–800 m can be estimated by summing the thicknesses of different facies reported by various authors. Reported K–Ar radiometric ages (summarised by Nullo, 1983) cover a wide range of 176–146 Ma (Middle to Late Jurassic).

Lavas in the formation are mostly thin flows ($< 1$ m) of basic composition. In contrast, the breccias and agglomerates are mainly intermediate in composition and crop out in thick beds with poor stratification. The hypabyssal facies is abundant and consists of intraformational dykes and small stocks that extend to rhyolitic composition. Volcanic structures locally define central volcanic edifices, as in the northern Río Chubut section. The largest andesite masses are spatially associated with polymetallic, Au-bearing, mineralised veins that have been classified as subvolcanic (Márquez et al., 1988). The rhyolitic dykes produce similar vein mineralization in the area of Mina Angela, and the intermediate dykes are associated with small zones of hydrothermal alteration of siliceous and carbonate type in the Sierra de Taquetrén (Márquez, unpublished). In the zone of Las Plumas, which is the eastern border of the intermediate rocks, where they are intercalated with the rhyolites of the Río Chubut section, Haller et al. (1990) reported the presence of small domes of trachyte, trachyandesite and trachybasalt.

The sedimentary facies, which appears to be intercalated with the volcanic rocks, is red, violet, green and yellow in colour and is composed of conglomerates, sandstones and rare pelites that have plant remains (*Otozamites*). The conglomerates have tuffaceous matrices, and clasts up to 0.4 m across have broadly andesitic compositions.

Mineralogically, the intermediate rocks contain phenocrystal plagioclase and amphibole; in the basic varieties pyroxene, olivine and biotite are additionally present. Groundmass minerals are generally the same as the phenocrysts. Rhyolites are commonly flow-banded, with quartz and K-feldspar phenocrysts. Amygdales are common and in some areas celadonite is abundant.

### *3.7. El Quemado and Ibañez formations*

The El Quemado Formation consists of mainly silicic volcanic rocks, comparable to those of the Chon Aike Formation, that have been faulted, tilted and thrust as a result of Andean (Cretaceous–Tertiary) deformation. On the western slopes of the Andes, in Chile, the Ibañez Formation has usually been regarded as a direct equivalent.

These formations are traditionally thought of as penecontemporaneous with the Chon Aike, albeit more andesitic in character due to the increasing influence of subduction at the Pacific margin (Gust et al., 1985; Sruoga, 1989). The upper part of the Ibañez Formation at least is Berriasian (Suárez and de la Cruz, 1994; Covacevich et al., 1994). Suárez and de la Cruz (1997) have recently presented six K–Ar biotite ages in the range $144 \pm 3$ to $150 \pm 4$ Ma (with two further values of $132 \pm 3$ and $134 \pm 3$ Ma that were considered unrepresentative), corresponding to eruption within the Kimmeridgian–Berriasian interval. Descriptions of the El Quemado Formation in its type area north of Lago Argentino have also suggested that it is interbedded with sedimentary rocks bearing Upper Jurassic or Cretaceous fauna (Feruglio, 1949; Nullo, 1978; Riccardi and Rolleri, 1980). The type section consists of a 235-m sequence of six massive ignimbrites tilted at about 40° and cut by subhorizontal thrusts, which may indicate some repetition. According to our observations, the nearby sedimentary rocks could be in either slump or thrust contact with the volcanic rocks, and do not provide direct age control. Suárez et al. (1997) have reported four K–Ar biotite ages in the range $142 \pm 4$ to $159 \pm 4$ Ma, implying an eruptive span comparable to that of the Ibañez Formation. Rb–Sr data for the El Quemado Formation at Sierra Colorada have given an errorchron of $136 \pm 26$ Ma (Pankhurst et al., 1993b), which may well reflect post-eruption alteration. On the basis of currently available data, therefore, no part of the El Quemado and Ibañez formations can be shown to be older than Callovian, suggesting a westward younging of the Patagonian part of the province as a whole, possibly progressive, as suggested by Ramos et al. (1982).

Throughout its exposure along the eastern flank of the Andes, there is evidence of imbrication and tectonic thickening of the El Quemado Formation. Nevertheless, the thickness of its incomplete sequences approaches 1100 m in the peninsula of Lago Belgrano and on the northern flank of Sierra Colorada (Fig. 2), and in the latter case tectonic disturbance seems minimal. Thicknesses of 290 and 1000 m have been reported for the Ibañez Formation (Baker et al., 1981). Individual ignimbrite cooling units are also generally thicker than in the Chon Aike Formation. Sierra Colorada is interpreted as a dissected caldera complex (Sruoga, 1994). One tuff within this complex is locally 400 m thick and is interpreted as an intra-caldera deposit, and a polymict, crudely bedded and poorly sorted breccia with blocks up to 1 m across is possibly a near-vent co-ignimbrite breccia (viz. Walker, 1985). Rhyolite dykes with eutaxitic texture parallel the caldera walls and dip at ca. 70° away from the centre of the complex.

Overall, the lithological types of the El Quemado and Ibañez formations are similar to those of the Chon Aike Formation: rhyolitic ignimbrites associated with epiclastic sequences, air-fall tuffs, breccias of various origins and some intercalated andesitic lava flows. Mafic and intermediate rocks are scarce in the El Quemado Formation, but they occur as lavas, clastic deposits similar to the Bajo Pobre ones, and as a component in at least one mixed mafic-silicic lava flow. The ignimbrites of the El Quemado Formation have a high content of lithic clasts (quartzites, Río Lacteo schists, granites and andesites), and mineralogically a high content of plagioclase and Fe-rich biotite (Sruoga, 1989). In general, the degree of hydrothermal alteration, propylitic and chloritic, is significantly higher than in the Chon Aike Formation.

### 3.8. *Tobífera Formation*

This formation largely lies beneath the sedimentary cover of the Magallanes basin, but limited exposures occur along the southeastern margin of the Patagonian ice cap in the Ultima Esperanza district of Chile (Wilson, 1991) and in Tierra del Fuego (Fig. 2). The easternmost outcrops are on Staten Island (Hanson and Wilson, 1993). In most drill holes it is overlain by marine sandstones of the Springhill Formation, regarded as Tithonian–Berriasian in age (Riccardi, 1988), and mudstones interbedded with the volcanic rocks have yielded Late Jurassic fauna (Allen, 1982; Fuenzalida and Covacevich, 1988), so that it appears to be at least partly correlative with the El Quemado and Ibañez formations farther north.

The Tobífera Formation is predominantly composed of subaqueous pyroclastic and volcano-sedimentary rocks, the latter including bedded ash fall tuffs and thin tuff turbidites composed of rhyolitic debris that locally accumulated to form 9-m-thick composite beds (Wilson, 1991). Massive polymict debris-flow deposits contain blocks of rhyolite and mudstone rip-up clasts. Penecontemporaneous rhyolitic intrusions occur both as cross-cutting hypabyssal bodies and peperite breccias emplaced into wet sediments (Hanson and Wilson, 1993). Pillowed basaltic bodies are also documented. Wilson (1991) deduced a volcanic environment associated within a deep marine trough immediately preceding and overlapping with opening of the Sarmiento back-arc basin (Bruhn et al., 1978).

## 4. The Jurassic volcanic province of West Antarctica

### 4.1. *The Antarctic Peninsula volcanic group*

The Antarctic Peninsula is dominated by the products of a Triassic to Cenozoic magmatic arc system formed in response to east-directed subduction of the Pacific and proto-Pacific plates. Batholithic granitoids, magmatic arc volcanic rocks, fore-arc complexes and back-arc sedimentary sequences are all present (Storey and Garrett, 1985). Pre-Mesozoic crystalline basement is proven only at one locality in the Antarctic Peninsula, at Target Hill (Fig. 3), where foliated orthogneiss have yielded Rb–Sr whole-rock ages of 410 ± 15 and 426 ± 12 Ma (Milne and Millar, 1989).

The volcanic rocks of this magmatic arc are collectively known as the Antarctic Peninsula volcanic group (APVG: Thomson and Pankhurst, 1983). They mainly consist of calc-alkaline basic, intermediate and silicic lavas, volcaniclastic deposits, and ignimbrites (Saunders et al., 1980; Storey and Alabaster, 1991; Leat and Scarrow, 1994). Along the eastern (back-arc) coast of the northern peninsula (Graham Land), volcanic sequences dominated by silicic ignimbrites appear to have a more restricted, mid-Jurassic, age.

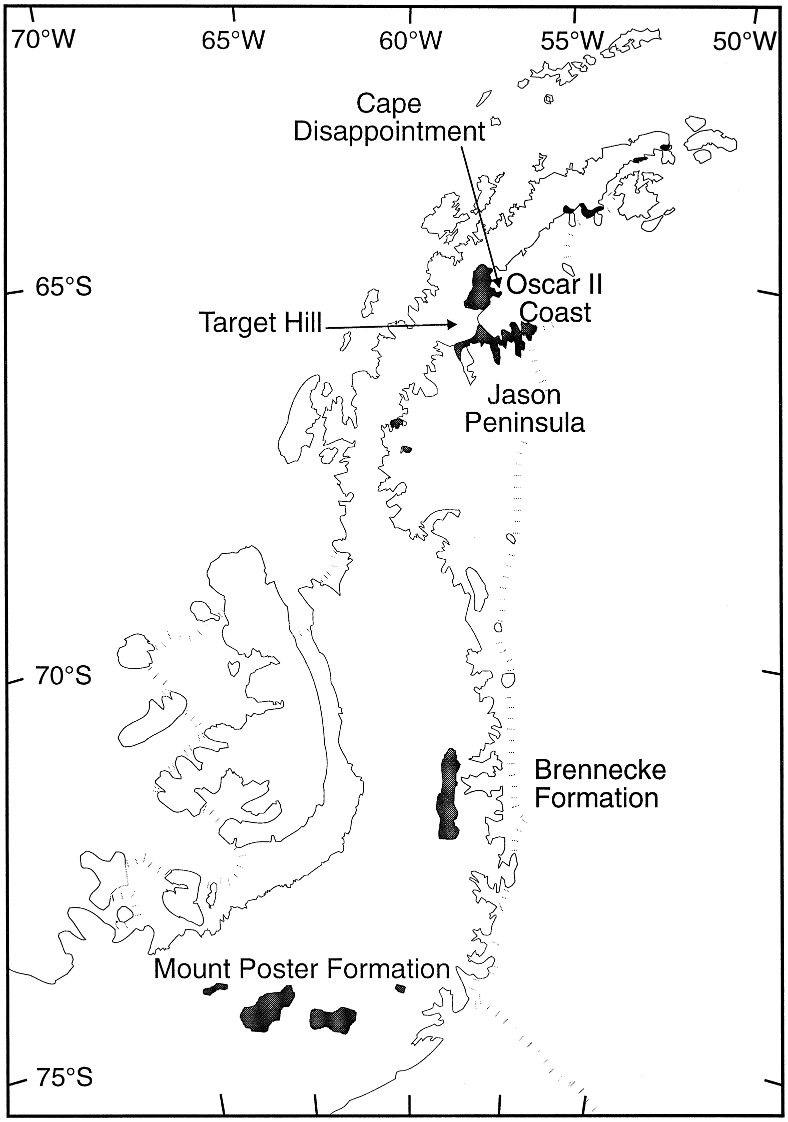



Fig. 3. Sketch map of the Antarctic Peninsula showing the main outcrop areas of Jurassic volcanic rocks described in the text.

*4.1.1. Oscar II Coast, Graham Land*

The region around Cape Disappointment, and scattered localities farther north on the east coast of Graham Land (Fig. 3), probably exhibits the greatest range of silicic volcanic rocks in the Antarctic Peninsula. Rhyolitic ignimbrite flows, $< 0.5$ m to 70 m thick, conformably overlie up to 600 m of interbedded siltstones and mudstones (Fleet, 1968; Riley and Leat, 1996). It is difficult to correlate ignimbrite units over any distance, due to within-flow facies variations and significant faulting, but a maximum observed thickness of 1000 m is estimated, providing a volume of approximately 2100 $km^3$.

The sedimentary and volcanic rocks are intruded by granitoid plutons and quartz–feldspar porphyritic dykes. The granites provide the only age constraint of the region; one has yielded a Rb–Sr whole-rock age of $160 \pm 4$ Ma (Milne, 1990), whereas similar plutons to the south are dated at $167 \pm 2$ and $163 \pm 2$ Ma (Pankhurst, 1982). Andesitic tuffs and flow banded rhyolites just north of Jason Peninsula (Fig. 3) have yielded a Rb–Sr whole-rock age of $174 \pm 2$ Ma (Pankhurst, 1982).

Ignimbrite units dominate the volcanic pile and vary in degree of welding and lithic content. The most strongly welded ignimbrites have fiamme flattening ratios of 7:1, and are typically lithic-free. Extreme welding is exhibited in rare, high-grade rheomorphic ignimbrites with parataxitic textures. The volcanic rocks are largely subaerial ignimbrite flows, although siliceous nodules and chert horizons within some units imply localised subaqueous emplacement. Eruptive centres have not been identified, although close proximity to source can be inferred from mass-flow deposits and co-ignimbrite breccias. Rare xenoliths of granoblastic granulite within ignimbrites indicate a deeper-seated source for acidic magmatism than would be anticipated from central caldera complexes. The rhyolitic ignimbrites and lavas have a mineral assemblage of embayed quartz, K-feldspar, plagioclase, and minor biotite, magnetite, ilmenite and zircon, in a fine-grained matrix.

Plant-bearing volcaniclastic deposits, mostly 1–2 m thick but occasionally up to 10 m, are commonly interbedded with the ignimbrites. These are thought to represent lacustrine facies similar to that of the epiclastic sedimentary rocks intercalated in the Chon Aike Formation.

*4.1.2. Jason Peninsula, Graham Land*

Jason Peninsula, with an area of approximately 3000 $km^2$, extends eastwards from Graham Land (Fig. 3). Its geology is dominated by relatively flat-lying rhyolitic lava flows and ignimbrites, with rare occurrences of interbedded basic lavas and sills, forming a bimodal assemblage (Smellie, 1991; Riley and Leat, 1996). The rocks are intensely frost-shattered and stratigraphical interpretations are difficult. The volcanic rocks on Jason Peninsula attain a maximum thickness of 450 m, which translates to a volume of approximately 1500 $km^3$, not allowing for probable offshore extension.

Rex (1976) determined K–Ar whole-rock ages of $160 \pm 6$ Ma and $190 \pm 8$ Ma on basic volcanic rocks from the north coast of Jason Peninsula, and a minimum age of Kimmeridgian–Tithonian is provided by overlying fossiliferous, arc-derived sandstones at the eastern extremity of the peninsula (Riley et al., 1997).

Mineralogically, the rhyolites are very similar to those from the Oscar II Coast, and are dominated by quartz, K-feldspar and plagioclase, set in a fine-grained matrix.

*4.1.3. Brennecke Formation, Palmer Land*

This forms a large area of silicic metavolcanic rocks in eastern Palmer Land, comprising dacitic and rhyolitic lava flows and welded ignimbrites (Wever and Storey, 1992). A bimodal assemblage is recognized, with a ca. 150-m-thick succession of basaltic lavas called the Hjort Formation (Wever and Storey, 1992). Interbedded metasedimentary rocks (Mount Hill Formation) were correlated with the Middle to Late Jurassic Latady Formation of southeastern Palmer Land by Singleton (1980). However, it is probable that the Brennecke Formation predates the Late Jurassic Palmer Land regional deformation event (Storey et al., 1996) so that at present its correlation with the Chon Aike province is only tentative. Wever and Storey (1992) suggested that it formed in an extensional back-arc basin related to the Antarctic Peninsula arc.

*4.1.4. Mount Poster Formation, Ellsworth Land*

The Mount Poster Formation crops out in the southern Antarctic Peninsula and eastern Ellsworth Land (Fig. 3) and comprises dacitic and rhyodacitic pyroclastic rocks and lava flows. It is dominated by an intracaldera sequence of rhyodacitic lavas and poorly welded ignimbrites, which reach a minimum thickness of ca. 500 m, although a thickness of at least 2 km has been estimated for the entire formation (Rowley et al., 1982). Outside the caldera limits, a bimodal assemblage of welded ignimbrite units and amygdaloidal and pillowed basaltic rocks, interdigitates with back-arc, fossiliferous rocks of the Latady Formation. The faunal assemblages are Middle to Late Jurassic (Thomson, 1980), the only age constraint on the Mount Poster Formation.

The geology, field relationships and chronology suggest overlaps between the Mount Poster and Brennecke Formations, and mark a continuation of the largely silicic, and explosive style of volcanism along the east coast of the Antarctic Peninsula.

### *4.2. Jurassic granites of the Ellsworth–Whitmore mountains*

The Ellsworth–Whitmore Mountains block (Fig. 1) consists of deformed Cambrian to Permian sedimentary strata (Webers et al., 1992), intruded locally by Jurassic granites and modest-volume mafic intrusions, some of which probably also are of Jurassic age (Vennum and Storey, 1987). Isolated granitic plutons also occur in the area between here and the Transantarctic Mountains (just off the southern limit of Fig. 1). Rb–Sr whole-rock analyses yielded an Early Jurassic age in one case ($195 \pm 21$) and Middle Jurassic ages ($173 \pm 3$ to $176 \pm 8$) for the rest (Millar and Pankhurst, 1987). The granites are dominantly peraluminous, coarse- to medium-grained biotite ($\pm$muscovite) granites, which are S-like in many characteristics, e.g. high but restricted $SiO_2$ (mostly $>71$ wt%) and moderate K contents, as well as variably high initial $^{87}Sr/^{86}Sr$ ratios; Storey et al. (1988) suggested a petrogenetic relationship to the Ferrar mafic magmas of the Transantarctic Mountains. Their Middle Jurassic ages and crust-dominated, silicic compositions are typical of the Chon Aike province; the deeper erosional level may be a result of Early Cretaceous and younger uplift identified by Fitzgerald and Stump (1991).

### *4.3. Trendall Crag granite, South Georgia*

The Trendall Crag granite is intruded into metasiliciclastic rocks of the Drygalski Fjord Complex on South Georgia (Macdonald et al., 1987; Fig. 1). It has been dated at $181 \pm 30$ Ma (Rb–Sr: Tanner and Rex, 1979). It is slightly potassic in composition and isotopic characteristics suggest it is a crustal partial melt, related to the break-up of Gondwana (Storey and Alabaster, 1991). Since South Georgia is normally placed between the Antarctic Peninsula and South America in Gondwana reconstructions, the granite is tentatively regarded as part of the Chon Aike province.

## 5. Geochemistry

Geochemically, the Chon Aike province is relatively poorly documented. We have compiled geochemical data from the following formations: Chon Aike (Sruoga, 1989; De Barrio, 1993; Pankhurst et al., 1993b; authors' unpublished data, 1996), Marifil (Rapela and Pankhurst, 1993; Pankhurst and Rapela, 1995), El Quemado (Sruoga, 1989; Pankhurst et al., 1993b; authors' unpublished data, 1996), Ibañez (Baker et al., 1981), Lonco Trapial (Page and Page, 1993), Tobífera (Storey and Alabaster, 1991) and Bajo Pobre (Pankhurst and Rapela, 1995; authors' unpublished data, 1996). Comparative Antarctic Peninsula data are available from the Oscar II Coast and Jason Peninsula (Fleet, 1968; Smellie, 1991; authors' unpublished data, 1996), Brennecke Formation (Wever and Storey, 1992) and the Mount Poster Formation (Laudon, 1982).

### *5.1. General observations*

Major-element variations are presented in Figs. 4 and 5. The rocks are dominantly rhyolites (ca. 65%), with many fewer dacites and trachydacites, a moderate number of andesites and trachyandesites (14%), fewer basaltic andesites and basaltic trachyandesites, and rare basalts. Because of their relative rarity in the province, mafic rocks are probably overrepresented in the sample set (Fig. 4), but the province is clearly dominated by silicic compositions. Overall, there is a paucity of samples between 63 and 70 wt% $SiO_2$, so forming a bimodal association. Considerable overlap exists between different formations in Fig. 4, but there is a marked distinction between the

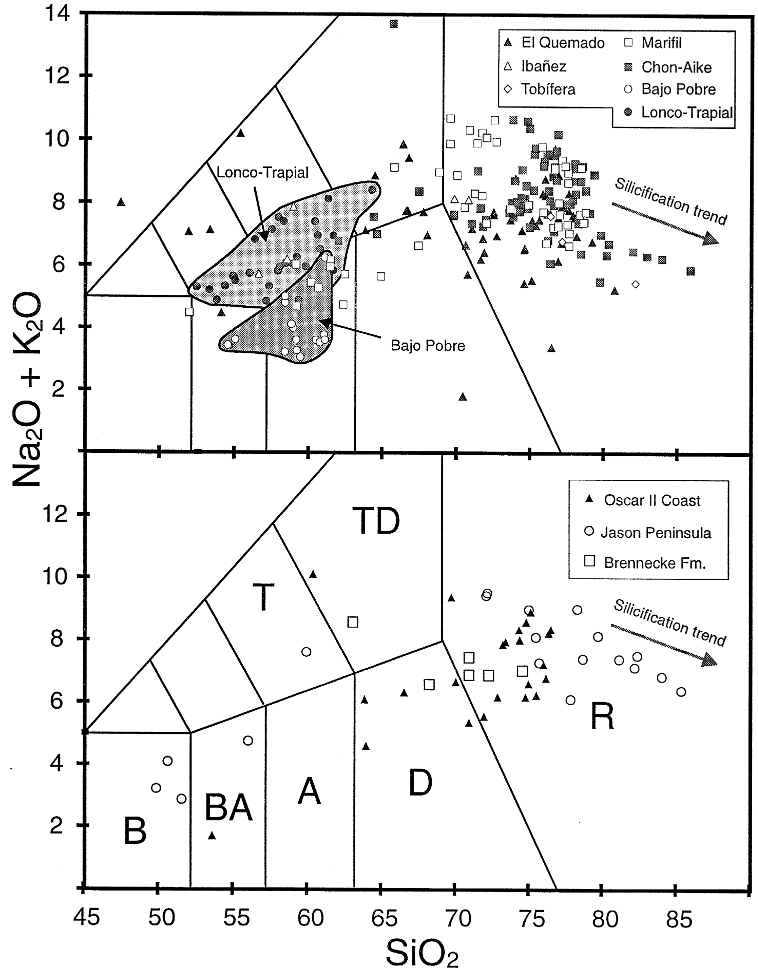



Fig. 4. Total alkali vs. silica plot (Le Maitre et al., 1989) for the Jurassic rocks of the Chon Aike and West Antarctic volcanic provinces. All data are recalculated to volatile-free totals of 100%.

entirely intermediate compositions of the Lonco Trapial and Bajo Pobre formations, and the overwhelmingly rhyolitic compositions of the Marifil and Chon Aike formations. Sruoga (1989) observed comparatively lower Ti contents (and higher Fe, Ca) in Chon Aike rhyolites from the northern part of the El Quemado outcrop than in rhyolites from around Puerto Deseado.

The similarities between the Patagonian and Antarctic Peninsula volcanic rocks are also clear from these plots; both have bimodal silica distributions, and are dominated by silicic compositions. Most samples in both Patagonia and the Antarctic Peninsula are very evolved, having $< 1$ wt% MgO, whereas two relatively high-MgO samples occur on Jason Peninsula (Fig. 5). Nearly all samples fall on calc-alkaline trends without iron-enrichment, although one sample from Oscar II Coast is a ferrobasalt.

Many of the rhyolites have been chemically altered by post-emplacement processes (Gust et al., 1985; Sruoga, 1989; Smellie, 1991). Several samples, notably from the Chon Aike formation and on Jason Peninsula, have $SiO_2$ abundances significantly above the normal maximum for fresh glass of ca. 78 wt%, implying post-emplacement silicification (Fig. 4). In a plot of $Na_2O + K_2O$ versus $100 \times K_2O/(K_2O + Na_2O)$ (Hughes, 1973), most samples

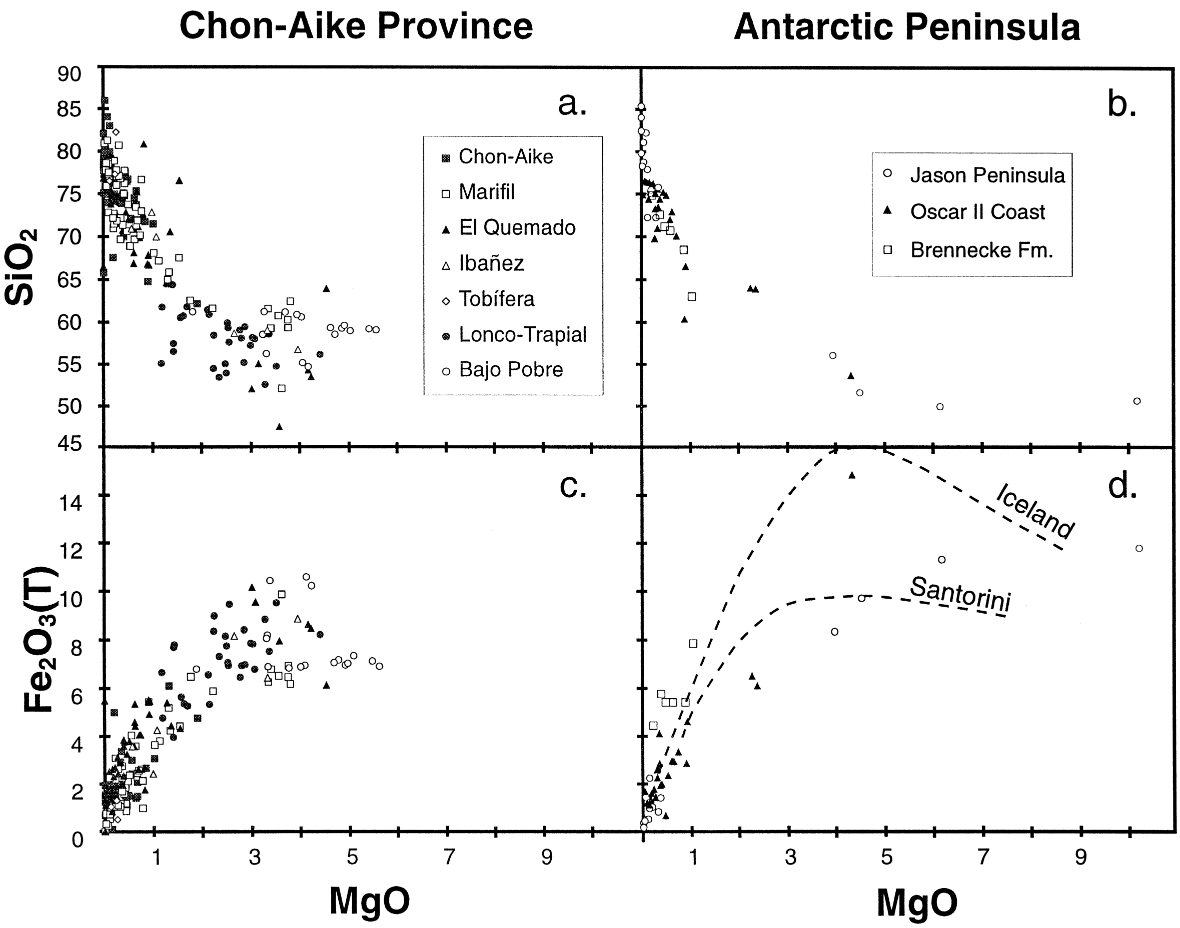



Fig. 5. Major-element distribution (vs. MgO) for the Jurassic rocks of the Chon Aike and West Antarctic volcanic provinces. $SiO_2$ is recalculated to volatile-free totals of 100%. Typical trends for tholeiitic (Iceland: Wood, 1978) and calc-alkaline (Santorini: Nicholls, 1971) volcanic sequences are shown.

fall within the igneous spectrum or in the field of K-enrichment, implying some post-emplacement K-gain and/or Na-loss. Smellie (1991) thought that alteration of rhyolites of Jason Peninsula was dominantly hydrothermal or deuteric, and this is also apparent from the mineral parageneses of the Andean outcrops (Sruoga, 1989). On the other hand, both low-temperature hydration of glassy rhyolite and devitrification are associated with gains in K and losses in Na, and devitrification is associated with mobility of Si (Lipman, 1965; Stewart, 1979). Such processes are more evident in the ignimbrites around Puerto Deseado. It would thus be unwise to attempt to classify the rhyolites, or comment on their petrogenesis, through uncritical use of alkali element abundances, normative compositions, or ratios derived from them.

Trace element concentrations of the rhyolites are variable. In the Y versus Nb plot (Fig. 6) of Pearce et al. (1984), intended as a granite discrimination plot, the Patagonian samples scatter between the fields for volcanic arc granites, syncollision granites and within-plate granites. There is large overlap in Y concentrations between the formations, and the diagram does not help in determining the tectonic setting of eruption, nor petrogenesis of the rhyolites.

Nb abundances do successfully discriminate between the formations: Ibañez, El Quemado and

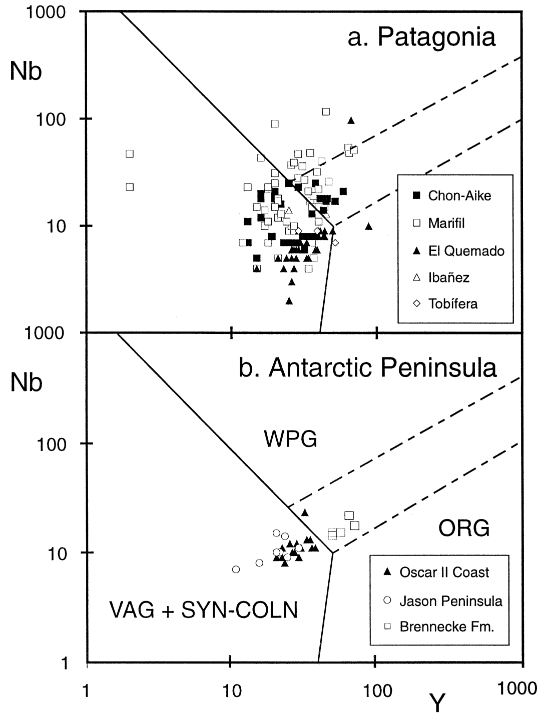



Fig. 6. Comparative Nb–Y plot for volcanic rocks in the Chon Aike and West Antarctic Jurassic provinces with > 60% $SiO_2$. The fields characteristic of within-plate granites (WPG), ocean ridge granites (ORG), and volcanic arc/syncollisional granites (VAG + SCOLN) are those defined by Pearce et al. (1984).

Tobífera have lower Nb abundances than Chon Aike and Marifil. A Zr versus Nb plot (Fig. 7) shows large variations in the Patagonian rhyolites as a whole. Most of the samples have Zr in the range 80–350 ppm, appropriate for subalkaline silicic liquids. Of these, most Chon Aike, and all Ibañez, El Quemado and Tobífera samples have < 20 ppm Nb, characteristic of island-arc and continental margin rhyolites rather than the rhyolites of continental interiors and oceanic rifts (Macdonald et al., 1992). On the other hand, a significant portion of the Marifil samples have > 20 ppm Nb, a continental interior signature. Antarctic Peninsula rhyolites have similar low Nb and Zr contents to the Ibañez and El Quemado formations, suggesting that these Cordilleran outcrops are close geochemical correlatives, and distinct from the extra-Andean Chon Aike and Marifil formations.

Several samples from different Patagonian formations, but especially the Marifil, have > 350 ppm Zr. Zr abundance in rhyolites of different composition correlates with alkalinity, and the progression from subalkaline to peralkaline compositions normally occurs in the Zr range of 350–500 ppm Zr (Leat et al., 1986). Samples with over ca. 500 ppm Zr were thus probably erupted as peralkaline liquids. The presence of originally peralkaline rhyolite within the Chon Aike province does not, however, define the setting of eruption, as such magmas occur associated with flood basalts (e.g. the high-Ti rhyolites of Garaland et al., 1995), as well as in continental rifts and magmatic arcs (Macdonald, 1974).

### 5.2. Geochemical characteristics of the individual formations

The Chon Aike Formation is overwhelmingly dominated by rhyolites, with a few dacites and trachydacites. The rhyolites appear to be mostly high-Si varieties (Sruoga, 1989; Pankhurst and Rapela, 1995) with < ca. 1 wt% MgO. They form a bimodal suite with the basaltic andesite and andesite of the Bajo Pobre Formation (Fig. 4).

The relatively low MgO, Ni (2–41 ppm) and Cr (7–117 ppm) abundances of the Bajo Pobre rocks indicate that the magmas were far removed from primitive mantle melts. Incompatible trace-element abundances are appropriate for Si-saturated intraplate mafic rocks (Zr = 88–250 ppm; Zr/Y = 6.2–8.4). Pankhurst and Rapela (1995) found that Bajo Pobre lavas from the eastern outcrops have similar initial $^{87}Sr/^{86}Sr$ ratios to the Chon Aike and Marifil ignimbrites (ca. 0.7067 on average), suggesting a similar source region, but our unpublished analyses of lavas from the central Deseado massif have lower initial $^{87}Sr/^{86}Sr$ ratios in the range 0.705–0.706, as do the mafic intrusive rocks of Cerro Leon.

The Marifil Formation also consists dominantly of rhyolite, but with some dacite, andesite, and basalt, suggesting a bimodal distribution (Fig. 4). The basalt-andesite samples have < 3.8 wt% MgO, and are generally more fractionated than basaltic andesites and andesites of the Bajo Pobre Formation. The rhyolites have a large range of trace-element abundances, encompassing almost the entire range of compositions for the whole Chon Aike province

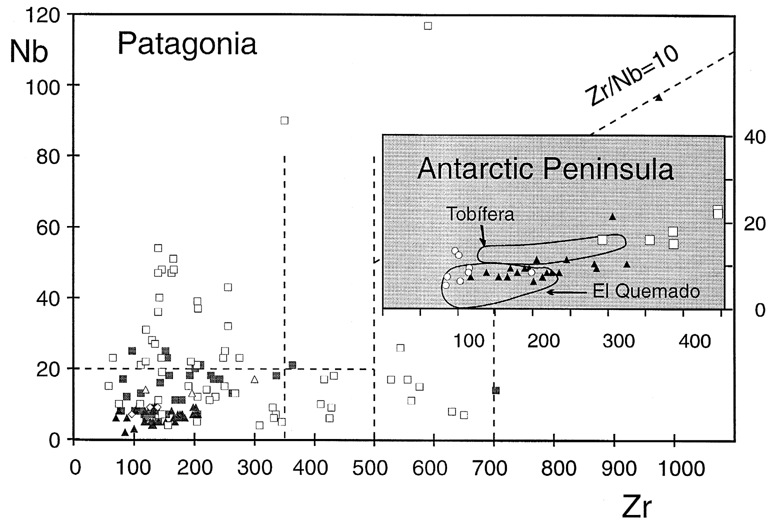



Fig. 7. Nb–Zr plot for the silicic volcanic rocks (> 63% $SiO_2$) of the Chon Aike province (contemporaneous silicic volcanic rocks of the Antarctic Peninsula shown in inset).

(Fig. 7). Several chemical subgroups of rhyolite can be distinguished within the formation. High-Zr (ca. > 400 ppm) peralkaline varieties occur in the western part of the formation (Demichelis et al., 1996), notably at Península Camarones (Pankhurst and Rapela, 1995). Subgroups may be identified within the dominant, low-Zr, subalkaline varieties of the formation, including low-Y (< 20 ppm), high Sr/Y (42–61) adakite-like types, and high-Y (64–70 ppm), high-Nb (48–54 ppm) types.

The Lonco Trapial Formation consists almost entirely of basaltic andesite, andesite and trachyandesite (Fig. 4), with relatively few dacites and rhyolites. The formation is less Si-saturated than the Bajo Pobre Formation (Fig. 4) and has many features of calc-alkaline orogenic andesites (Page and Page, 1993), but nevertheless follows a trend of minor Fe-enrichment (Fig. 5). All samples are strongly fractionated with respect to MgO (< 4.3 wt%), and have been substantially modified from mantle-derived liquids. Trace-element abundances are normal for andesites of destructive margins, having moderate enrichment in LIL elements relative to HFS elements compared to MORB, and variable Ce/Nb ratios (Page and Page, 1993).

The El Quemado Formation consists of basaltic andesite, andesite, dacite and rhyolite (Fig. 4). Available data are again strongly suggestive of bimodality, with no samples in the range ca. 57 to 62 wt% $SiO_2$. All but one of the silicic samples have low-Zr, low-Nb compositions appropriate for subalkaline rhyolites of magmatic arcs (Fig. 7). The relatively small ranges in composition are striking, given the geographically large sample area: 2–10 ppm Nb, and 75–206 ppm Zr. One exceptionally high-Zr sample (970 ppm) is interpreted as originally peralkaline. The mafic rocks are moderately fractionated from likely mantle-derived melts, having 2.8–4.2 wt% MgO, 5–116 ppm Ni and 15–179 ppm Cr. They have diverse incompatible trace-element contents, e.g. Nb from 4 to 31 ppm, and Zr/Y ranging from 4.2 to 9.6 (ranges appropriate for tholeiitic to mildly alkaline rocks). Some may have undergone post-emplacement Na-gain, and one of the samples was evidently carbonated, resulting in basanitic apparent composition in Fig. 4.

At present there are few published geochemical data for the Ibañez Formation. Six samples analysed by Baker et al. (1981) form an apparently bimodal assemblage of rhyolitic and intermediate (basaltic andesite to andesite) compositions. The rhyolites are low-Nb, low-Zr types, similar to those of the El Quemado Formation.

The Tobífera Formation is also poorly documented geochemically. According to Hanson and Wilson (1991), the formation is bimodal, comprising rhyolites and minor basalts. Three rhyolite analyses presented by Storey and Alabaster (1991) are low-Zr, low-Nb, subalkaline varieties similar to those of the El Quemado Formation.

The Oscar II Coast area of the Antarctic Peninsula is dominated by rhyolites, with subordinate dacites, one (K-enriched) andesite, and one basaltic andesite (Fleet, 1968; authors' unpublished data, 1996). The distribution of compositions is similar to that of the El Quemado Formation, and the rhyolites are of the same low-Zr, low-Nb type.

The Jason Peninsula association is bimodal, dominated by rhyolite, with small volumes of basalt and basaltic andesite. The rhyolites are strongly altered with respect to Si and alkali elements, and have low-Zr, low-Nb, subalkaline compositions (Smellie, 1991) similar to those of the El Quemado Formation. The basalts are more primitive than any rocks in the Chon Aike province, having 4.5–9.7 wt% MgO, 109–191 ppm Cr and 26–46 ppm Ni, values consistent with moderate fractional crystallisation from parental mantle-derived melts. The basalts show no significant Fe-enrichment (Fig. 5), but plot in the tholeiitic field of the $SiO_2$ versus Fe/Mg diagram of Miyashiro (1974): they are enriched in LIL elements relative to HFS elements, and may be classified as transitional between calc-alkaline and tholeiitic (Smellie, 1991).

The dominantly silicic (dacite–rhyolite) metavolcanic rocks of the Brennecke Formation comprise a bimodal assemblage with the basic greenstones of the Hjort Formation (Wever and Storey, 1992). The silicic volcanic rocks are dominated by high $K_2O$ rhyodacites, and show more Fe-enrichment than most of the other rocks (Fig. 5). They have high concentrations of Zr (290–450 ppm), Y (50–72 ppm) and to a lesser extent, Nb (15–22 ppm), and extend into the subalkaline field (Fig. 7).

Available geochemistry indicates that dacite and rhyodacite are the dominant lithologies in the Mount Poster Formation (Fig. 4; Laudon, 1982). Rare basaltic and basaltic andesite rocks are also present, and complete a bimodal assemblage, as is common along the east coast of the Antarctic Peninsula.

## 6. The size of the province

Our tentative calculation of the volume of the Chon Aike and West Antarctic volcanic provinces is compared to other large-volume rhyolite volcanic fields in Table 1. The figure of 235,000 $km^3$ is probably conservative and comprises the following formation volumes (thousands of $km^3$): Chon Aike, 23; Marifil, 30; Lonco Trapial, 16; Tobífera, 80; El Quemado–Ibañez, 20, San Jorge basin subsurface,

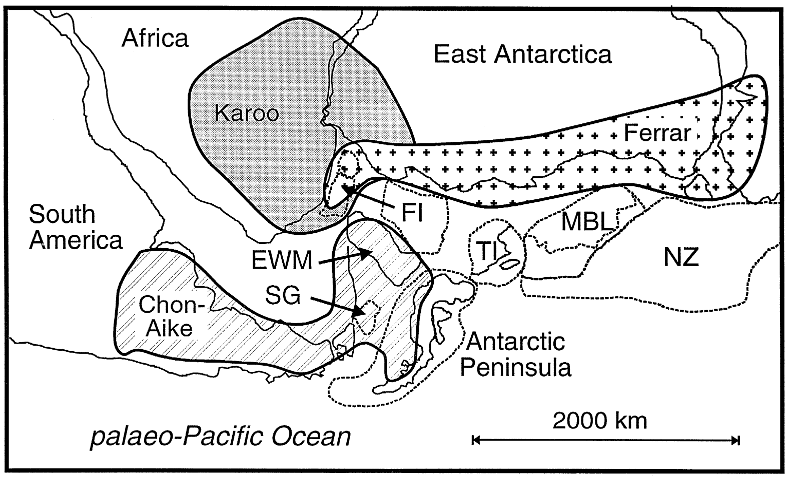



Fig. 8. Reconstruction of the prebreak up western Gondwana (after Storey et al., 1992b), showing the areas of the main Jurassic magmatic provinces. Dotted lines surround microplates whose limits are not all well defined. Those microplates that are identified are EWM = Ellsworth–Whitmore mountains, SG = South Georgia, FI = Malvinas/Falkland Islands, TI = Thurston Island, MBL = Marie Byrd Land, NZ = New Zealand continental platform.

10; Magallanes basin subsurface, 32; Antarctic Peninsula, 24. The total volume is similar to that calculated for the Sierra Madre Occidental volcanic field, Mexico (Table 1), the most widely cited analogue for the Chon Aike province. Other large, well documented silicic volcanic provinces are an order of magnitude less voluminous. Nevertheless, the figures for the Chon Aike and Sierra Madre Occidental provinces are within an order of magnitude of volumes for extrusive parts of mafic LIPs such as Columbia River (173,000 $km^3$; Hooper and Hawkesworth, 1993), Etendeka–Parana (800,000 $km^3$; Turner et al., 1994) and Deccan (1,500,000 $km^3$; Coffin and Eldholm, 1994). By this token, the Chon Aike/West Antarctic Jurassic volcanic field should be classified as a large igneous province, although its exposed part is predominantly silicic: it covers an area of at least 702,000 $km^2$, 675,000 $km^2$ in South America and 27,000 $km^2$ in the Antarctic Peninsula. In Gondwana reconstructions for Middle Jurassic times (Fig. 8), the province occupies continental areas then adjacent. Parts of the province may be buried beneath ice, water and sediment in the Weddell Sea and its continental margins.

## 7. Petrogenesis

Undoubted mantle-derived mafic rocks are rare in the province, having been identified only in the Antarctic Peninsula. This is unlikely to be a result of sampling bias, as mafic and intermediate rocks tend to be over-sampled owing to their rarity. The basaltic andesites and andesites that are prominent in the Bajo Pobre, Lonco Trapial and El Quemado formations are significantly modified from mantle-derived liquids, and have been suggested to be remelts of mafic lower crust (Pankhurst and Rapela, 1995).

The absence of mafic rocks over large parts of the province requires explanation in those models that relate the origin of the rhyolites to intrusion of mafic magmas into the crust. Most authors who have discussed petrogenesis in the province have concluded that the silicic rocks were generated by partial fusion of continental crust as a result of heat transported by voluminous mafic magmas. Bruhn et al. (1978) suggested that the Patagonian rhyolites were generated by partial melting of continental crust, but they did not specify the depth at which the anatexis took place. They suggested that the mafic magmas were derived from a mantle diapir that provided the thermal energy to melt the crust. Baker et al. (1981) thought that the intermediate rocks of the Ibañez Formation represented mantle-derived magmas generated in a magmatic arc related to easterly subduction of Pacific plate, and that the associated rhyolites were generated by crustal fusion. Gust et al. (1985) also favoured an origin for the Patagonian rhyolites by partial melting of continental crust. They noted that some relatively fresh rhyolites plot near minimum melt compositions for pressures between 1 and 5 kbar, although such relationships should be treated with caution, given the evidence for alteration from the alkali elements. They thought that the crustal protolith was sedimentary, in view of the supposed S-type characteristics of the rhyolites, and that melting was a response to ponding of hot, mantle-derived mafic magma at the base of the crust; a similar model was preferred for the Patagonian rhyolites by Kay et al. (1989) and De Barrio (1993). Wever and Storey (1992) suggested that rhyolites of the Brennecke Formation were generated dominantly by partial melting of crust in order to explain Nd isotopic differences between rhyolite and contemporaneous basalt. Nevertheless, trace-element similarities between some mafic rocks and the rhyolites led them to suggest that the rhyolites also contained a component derived from mafic magma by fractional crystallisation. Storey and Alabaster (1991) further suggested that the Patagonian rhyolites might contain significant components derived from mafic magmas. In their model, isotopic and trace element characteristics of the rhyolites were inherited, via mafic parents, from lithospheric mantle that was 'enriched' with respect to incompatible elements. They emphasised that similar models were widely accepted for the Sierra Madre Occidental volcanic field, regarded as the closest analogue for the Chon Aike province. In the case of the Sierra Madre Occidental, a model in which the silicic volcanic rocks are products of fractional crystallisation from basaltic magmas has been consistently proposed (Cameron et al., 1980; Bagby et al., 1981; Lanphere et al., 1980; Cameron and Hanson, 1982). Because the silicic and mafic

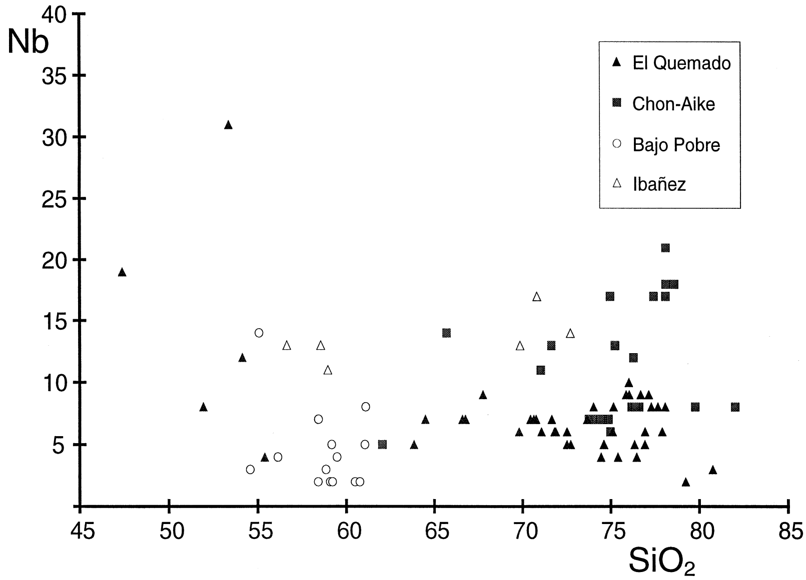



Fig. 9. Nb vs. $SiO_2$ plot for the silicic volcanic rocks (> 63% $SiO_2$) of the Chon Aike and West Antarctic Jurassic provinces.

rocks have similar initial $^{87}Sr/^{86}Sr$ ratios, in the range 0.7042 to 0.7050, the amount of crust assimilation was thought to be small (Lanphere et al., 1980). Similar conclusions have been reached, by different workers, for silicic volcanic rocks of the related San Juan volcanic field, where correlation of isotopic ratios with indices of differentiation has been interpreted as indicating progressive interaction with crust (Riciputi and Johnson, 1990; Colucci et al., 1991; Johnson, 1991).

Rapela and Pankhurst (1993) and Pankhurst et al. (1993b) found that initial $^{87}Sr/^{86}Sr$ ratios were relatively constant throughout the Marifil and eastern parts of the Chon Aike formation, with values of close to 0.7067, even for the local intermediate and mafic rocks. They argued that this ruled out a significant contribution to the rhyolites from heterogeneous upper crust, but did not help to discriminate between mantle and lower crustal sources. Pankhurst and Rapela (1995) interpreted the rhyolites as generated from andesitic parent magmas by a process that could be chemically modelled as fractional crystallisation, but in fact involved several cycles of partial melting, crystallisation and partial remelting. They further argued that the andesitic magmas were produced by partial melting of basaltic lower crust.

The chemical diversity of the rhyolites, notably in the Marifil Formation, demands that different processes of rhyolite production occurred within the province. In plots of trace elements that are incompatible during fractional crystallisation of subalkaline magmas, such as Nb, against silica (Fig. 9), some suites, such as Ibañez and the Chon Aike/Bajo Pobre association, display generally rising Nb contents with increasing $SiO_2$, consistent with the fractionation models of Storey and Alabaster (1991) and Pankhurst and Rapela (1995). But Nb abundances of El Quemado rhyolites are generally lower than in the associated andesites, implying that these rocks cannot be related simply by fractional crystallisation. Global petrogenetic schemes for the whole province are probably not meaningful.

In view of the lack of reasonable alternatives, it is nevertheless likely that generation of the rhyolites was ultimately related to intrusion of basalt into the crust, and that this transported sufficient heat to produce widespread partial melting of the lower crust. Both partial melts and liquids derived from the mafic magmas may have contributed to the rhyolites. A difference between the Chon Aike province and basaltic LIPs may have been the availability of crustal lithologies susceptible to partial melting — a relatively immature crust dominated by schists and low-grade metasedimentary rocks accreted and/or deposited along the Palaeozoic–Mesozoic active continental margin. Much of this crust had undergone no significant previous magmatism since stabilisation, although granites occur locally. Intrusion of voluminous basalt as a sill complex could have generated layers of silicic melt, which in turn could have formed a density trap impenetrable to ascent of basalt. Pankhurst and Rapela (1995) suggested, on the basis of Sm–Nd isotopes, that the protolith for the eastern rhyolites was broadly Grenvillian in age (1150–1600 Ma), although it is not certain whether this represents the age of the crustal source or merely that of its sedimentary provenance.

Rhyolites everywhere in the Chon Aike province are dominated by ignimbrites. These are associated locally with calderas in the El Quemado, Marifil and Mount Poster formations and it is likely that further calderas await discovery. The ignimbrites are typically of low welding grade, and strongly welded types are rare. The silicic magmas were apparently stored in upper crustal magma chambers and erupted at normal or low temperatures. The generally phenocryst-poor character of the rhyolites suggests that the magmas had at least moderate volatile contents.

## 8. Tectonic setting

The emplacement of the province during Early Jurassic to earliest Cretaceous times was coincident with extension in this part of Gondwana during early stages of Gondwana break-up (Storey et al., 1996), and with emplacement of at least parts of the Karoo and Ferrar basalt provinces at about 184 Ma (Encarnación et al., 1996). It is likely that the generation of the Chon Aike rhyolites was related to the lithospheric extension, and it is possible that there may be a link between the rhyolite generation and impact of mantle plumes on the base of the lithosphere. However, given the relatively long time of emplacement of the province, between Early Jurassic and earliest Cretaceous times (ca. 188–140 Ma) according to current data, a simple mantle plume model for the Chon Aike province is unlikely.

A further aspect of the tectonic setting that requires consideration is the probability that there was an active subduction system operating along the Pacific margin contemporaneously with rhyolite volcanism. Calc-alkaline batholiths were emplaced in the Andes and in the Antarctic Peninsula from mid-Jurassic times, and the tendency to arc-related geochemical characteristics in the Andean and Antarctic Peninsula outcrops has been noted by Gust et al. (1985) and Saunders et al. (1980), respectively. The high-MgO andesites of the latter area (Storey and Alabaster, 1991) require an active margin, and Storey et al. (1992b) highlighted subduction roll-back and plate-boundary forces as an alternative to plume models in the break-up of Gondwana. Finally, throughout the Late Palaeozoic and Mesozoic history of southernmost South America, bimodal volcanic suites alternated with calc-alkaline (batholith) emplacement related to the Pacific margin, probably due to cyclic changes in the subduction regime (Rapela et al., 1996).

## 9. Conclusions

The Chon Aike province and related rocks in West Antarctica constitute a silicic large igneous province (LIP), comparable in volume to continental flood basalt provinces. It comprises numerous formations in Argentina and Chile and volcanic rock outcrops in the Antarctic Peninsula, together with granitic rocks in Ellsworth–Whitmore Mountains and South Georgia, emplaced between Early Jurassic and earliest Cretaceous (Berriasian) times (ca. 188–140 Ma). The province is dominated by low-grade, phenocryst-poor ignimbrites, for which source calderas have been identified locally. These relationships imply that the silicic magmas were erupted from magma chambers within the upper crust. The province is chemically dominated by rhyolite, although it exhibits consistent bimodality between rhyolite and andesite/basaltic andesite. Undisputed mantle-derived mafic rocks are rare: the basaltic andesites and andesites are strongly modified from mantle-derived compositions. Most authors have favoured generation of the rhyolites by partial melting of crust as a result of intrusion of basalt, although many of the rhyolites can be successfully modelled by fractionation from associated andesites (fractional crystallisation and/or multi-stage remelting), a petrogenesis that agrees with conclusions of more detailed studies of the analogous Sierra Madre Occidental volcanic field of Mexico, and its outliers in the southwestern United States. However, rhyolite geochemistry within the province is varied, including subalkaline and peralkaline varieties, and no single petrogenetic model can be applied to the province as a whole. The volcanic rocks were erupted through immature continental crust formed at the Gondwana continental margin. The easy fusibility of such crust may provide an explanation for why this LIP differs so dramatically from basaltic LIPs: basalt intruding such crust is likely to generate zones of partially melted crust that are impassable to ascending basalt, but which can develop to magma chambers within which available magmas can fractionate to rhyolite. The ultimate origin of the province probably is related to contemporary lithospheric extension caused by break-up of Gondwana. A simple mantle plume origin for the province is unlikely, and subduction dynamics at the Pacific margin seem to have played a significant role.

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