Geodynamic evolution of the Antarctic Peninsula during Mesozoic times and its bearing on Weddell Sea history

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Abstract: This review of the tectonic evolution of the Antarctic Peninsula during Mesozoic times highlights four main events: (1) Late Triassic–Late Jurassic extension, (2) Late Jurassic–Early Cretaceous dextral transpression, (3) Early Cretaceous extension and (4) mid-Cretaceous compression. Magmatism was virtually continuous during much of this period with the exception of possible breaks in the known record in Early Jurassic and Late Jurassic–Early Cretaceous times. The second of these breaks corresponded to the first compressional event. There was no apparent hiatus in the magmatic record during the mid-Cretaceous compressional event, although there was a significant change in the pattern of sedimentation in the Larsen basin on the eastern margin of the Weddell Sea at about that time.

The tectonic evolution of the peninsula is compared to, and puts some constraints on, existing Weddell Sea models. The Late Triassic–Late Jurassic arc extension correlates with initial rifting in the Weddell Sea region during sinistral motion between East and West Gondwana. However, there is no known record of large-scale pre-Mid-Jurassic transcurrent deformation in the Antarctic Peninsula that would have been consistent with rotation of West Antarctic crustal blocks in the initial rifting period. The peninsula-wide Late Jurassic–Early Cretaceous compressional event may correlate with the major change in Gondwana plate motions from E–W to N–S (African reference frame) separation of East and West Gondwana. This change probably resulted in formation of an ocean–continent boundary along the northern margin of the Weddell Sea embayment and initial seafloor spreading. Geological data do not seem to support subduction of southwestern proto-Weddell Sea oceanic lithosphere beneath the eastern margin of the peninsula at that time. Cretaceous arc extension was coeval with the initial seafloor spreading phase in the Weddell Sea. Mid-Cretaceous arc compression, linked to a global increase in ocean floor spreading rates and a superplume event, correlates with a change from NE–SW to NW–SE spreading in the Weddell Sea.

Subduction-related processes dominated the Mesozoic evolution of the Antarctic Peninsula (Suárez 1976; Storey & Garrett 1985). Prior to Mid-Jurassic times, the peninsula formed part of the palaeo-Pacific margin and one of five crustal blocks (Fig. 1) within Gondwana. Subsequently, during continued subduction, it separated from Gondwana by crustal extension and seafloor spreading in the Weddell Sea region either as an independent microplate or as part of a larger West Antarctic crustal block termed Weddellia by some authors (e.g. Grunow et al. 1987a). This uncertainty in the status of the Antarctic Peninsula block is linked primarily to uncertainties in the seafloor spreading history and tectonic evolution of the Weddell Sea region due to its remoteness. Difficult ice conditions have also limited the acquisition of ship data. This has been partly offset in recent years by access to satellite radar altimetry data (Bell et al. 1990), although much of the key area is covered by year-round sea ice. This paper sets out to compare the timing (using the timescale of Harland et al. 1990) of tectonic events in the Antarctic Peninsula determined from structural geological mapping and radiometric dating, with events in the Weddell Sea determined from marine geology and geophysics, and look for correlations that may improve our understanding of the history of both areas.

The location of the Antarctic Peninsula along the western margin of the Weddell Sea (Fig. 1) makes it likely that the effects of seafloor spreading and the movement of West Antarctic microplates in the Weddell Sea region could be recorded in the geodynamic evolution of the

Antarctic Peninsula. Some links have been suggested, e.g. the Late Jurassic Palmer Land deformation event (Kellogg & Rowley 1989) has been tied with both collision of the Ellsworth–Whitmore mountains crustal block with the eastern margin of the Antarctic Peninsula (Grunow et al. 1991), and with subduction of proto-Weddell Sea floor beneath the peninsula (Grunow 1993a, b). As previous work has shown, the Weddell Sea and the Antarctic Peninsula are not mutually isolated, and the effects of possible changes in subduction parameters or subduction forces are important in trying to understand the history of the Weddell Sea region. This new synthesis of Antarctic Peninsula geodynamic evolution presented here, may consequently increase our understanding of the evolution of the Weddell Sea region and the initial break-up history of Gondwana.

Geodynamic evolution of the Antarctic Peninsula

The Antarctic Peninsula is an ensialic Mesozoic arc that formed on Palaeozoic (Milne & Millar 1989), or possibly older (Storey et al. 1994) Gondwana basement from eastward subduction of proto-Pacific and Pacific oceanic lithosphere. It contains a deeply dissected magmatic province and, in some places, a broad subduction-accretion complex (Storey & Garrett 1985), with thick sequences from inverted fore- and back-arc basins (Suárez 1976; Macdonald & Butterworth 1990). Age data from the magmatic arc show that it contains Late Triassic–Early Jurassic (236–199 Ma), Mid-Jurassic (c. 180–160 Ma), and Early and Late Cretaceous magmatic episodes (Pankhurst 1982, 1990; Hole et al. 1991; Storey et al. 1992). The arc was deformed by ductile shear zones with complex kinematic histories involving strike-slip, compressional and extensional deformational episodes, some of which were coeval with magmatic events (Meneilly et al. 1987; Storey & Nell 1988; Vaughan & Millar in press). The breaks in the magmatic record may be due either to a sampling bias, or to changes from plutonic to volcanic emplacement (Glazner 1991; Grocott et al. 1994) during arc compression (see below) or perhaps more likely they corresponded to periods of inactivity. The main events we have recognized to date, and that may be related to Weddell Sea history, are outlined below (Figs 2 & 3). As far as the evidence suggests, eastward subduction of oceanic lithosphere was continuous throughout these events, although Storey & Alabaster (1991) suggested that subduction may have ceased due to ridge–trench collision during the Late Jurassic break in magmatism.

Late Triassic to Early Jurassic extension

Magmatism, sedimentation and ductile deformation provide evidence for a prolonged period of extension during Late Triassic to Late Jurassic times. Within the magmatic arc, a K-feldspar megacrystic granite gneiss at Welch Mountains, (NE Palmer Land, Fig. 2a), dated at 221 ± 14 Ma by Rb–Sr whole rock (Wever et al. 1994), shows a relict syn- magmatic foliation. This foliation dips moderately to steeply W and is predominantly defined by aligned K-feldspar phenocrysts with steeply plunging long-axes. ‘Tiling’ of these phenocrysts (Paterson et al. 1989) suggests extensional shearing during
Fig. 2. Summary diagrams for the Antarctic Peninsula illustrating relevant geological events for (a) Late Triassic–Late Jurassic; (b) Late Jurassic–Early Cretaceous; (c) Early Cretaceous and (d) mid-Cretaceous time periods. ’σ1’ represents palaeostress, although we assume that in most cases this approximates closely to palaeostress, particularly for kinematic data derived from Early Jurassic and Early Cretaceous syn-kinematic intrusions, and the relatively brief mid-Cretaceous shortening event. North is at top of diagram.

magma-emplacement. A foliated granodiorite (U–Pb zircon age of 205 ± 3 Ma) and mafic dykes within a long-lived and large-scale crustal shear zone at Auriga Nunataks (NW Palmer Land, Fig. 2, Vaughan & Millar, unpublished data) were also emplaced synkinematically. In the granodiorite, a weak, feldspar, preferred-orientation, magmatic foliation dips moderately to steeply S. Asymmetric diorite and amphibolite xenoliths are aligned subparallel to the granodiorite fabric and have long-axes plunging shallowly W. The asymmetry of these xenoliths indicates ductile deformation occurred during transtensional magma-emplacement on an active, E–W, dextral-normal shear. Ductile shear on the Auriga Nunataks shear zone overlapped with the peak of metamorphism dated by Sm–Nd in garnet at 188 ± 4 Ma (Millar, unpublished data). As the Auriga Nunataks shear zone was a large-scale and long-lived, arc-orthogonal,
Fig. 3. Correlation chart illustrating duration of main periods of magmatism (mag.), sedimentation (sed.) and deformation (def.) in the Antarctic Peninsula together with main tectonic events in the South Atlantic and Weddell Sea region. The volume of Pacific crust production is taken from Larson (1991). The periods of crustal block rotation are taken from Grunow et al. (1991) and Grunow (1993a, b). EA, East Antarctica; FI, Falkland Islands; KP, Kenyon Peninsula; LaB, Latady basin; LB, Larsen Basin; NF, Nordenskjöld Formation. (Time scale, Harland et al. 1990).
transfer fault (Vaughan et al. in press), the structures preserved are likely to represent arc-wide processes, so it seems reasonable, in this case, to link transtension in the arc to probable extension in the back-arc region.

The Latady basin (Fig. 2a) formed along the SE margin of the Antarctic Peninsula, behind the active continental arc system, after a period of Early Jurassic crustal reworking and bimodal magmatism (Wever & Storey 1992; Wever et al. 1994, 1995). The basin was infilled by several kilometres of arc-derived sedimentary rocks (Latady Formation) containing locally abundant, marine invertebrate fossils of Mid- and Late Jurassic (up to latest Tithonian) age (Quilty 1982; Thomson 1983; Rowley et al. 1983). Undated bimodal volcanic and hypabyssal rocks are mainly exposed along the W and NW margin of the basin, where they intruded the magmatic arc rocks as a series of dykes, and formed flows and sills within the sedimentary rocks.

Contemporaneous and slightly younger sedimentation also occurred along the NE margin of Graham Land (Fig. 2a). Interbedded tuffs and mudstones of the Nordenskjöld Formation (Farquharson 1982, 1983; Whitham & Doyle 1989) were deposited in anoxic marine basins on the eastern side of the magmatic arc during Late Jurassic to Early Cretaceous times (Kimmeridgian–Berriasian). The sedimentary rocks are part of a much more widespread anoxic event in the South Atlantic region (Farquharson 1982).

The data from the magmatic arc, together with evidence of subsidence and probable extension in the Latady and Nordenskjöld basins, lead us to conclude that extension, in a probable E–W orientation (Fig. 2a), prevailed from Late Triassic to Late Jurassic times coeval with Late Triassic–Early Jurassic and Mid-Jurassic (Pankhurst 1982; Storey et al. 1992; Scarrow et al. in press) magmatic episodes.

Late Jurassic/Early Cretaceous dextral transpression

The Latady Formation, the sedimentary infill of the Latady basin, and associated volcanic rocks were folded and overthrust in the Late Jurassic or Early Cretaceous (Fig. 2b) during an event generally referred to as the Palmer Land deformation event (Kellogg & Rowley 1989). Folding is on a decametric to kilometre scale. Folds are symmetric to asymmetric, and angular to chevron in profile. They are open to isoclinal, and upright to recumbent, with sub-horizontal plunges. Shortening is of the order of 30–60%. A penetrative, axial planar cleavage is well-developed in finer grained rocks. Thrusts have small offsets. Overthrust-sense and fold vergence is to the E and SE. Fold axes and thrust faults strike parallel to the curvilinear long axis of the Antarctic Peninsula. The age of deformation has not been directly determined. Folding deforms the youngest sedimentary infill, which is latest Tithonian in age (Thomson 1983). The onset of folding could be earlier, and pencontemporaneous with sedimentation, although syn-sedimentary deformation features with bedding disruption would be expected in this case, particularly in thrust zones (Knipe et al. 1988). Without exception, structures described are ductile, or brittle-ductile (Williams 1970; Williams & Rowley 1971, 1972; Rowley 1973, 1978; Plummer 1974; Kellogg & Rowley 1974; Rowley & Williams 1974), and sedimentary sequences are described as repetitive and monotonous in sections up to 830 m thick (Thomson et al. 1978). The scale and geometry of folding is consistent with a thin-skinned, foreland fold-and-thrust belt, as suggested by Kellogg & Rowley (1989). These observations make it more likely that the onset of deformation post-dated the end of sedimentation. A minimum age limit on deformation comes from the age of post-tectonic granitoids (122–96 Ma: Pankhurst & Rowley 1991) that intruded folded Latady Formation (Kellogg & Rowley 1989). Deformation is therefore considered to be post-Tithonian and pre-Early Cretaceous (pre–122 Ma) in age.

Kellogg & Rowley (1989) noted that rocks from deeper structural levels were exposed from S to N along the SE coast of Palmer Land. This trend is continued in NE Palmer Land, where, in contrast to the thin-skinned nature of the deformation that affected the sedimentary rocks (Latady basin), magmatic and gneissic rocks were deformed in large heterogeneous ductile shear zones (Meneilly et al. 1987) (Fig. 2b). The rocks are characterized by a moderately W-dipping foliation. Stretching lineations pitch at high angles on the foliation planes. In zones of intense shear, foliated granitic gneisses are retrogressed to porphyroclastic gneisses and mylonites. Shear-sense indicators, including S–C fabrics and asymmetric pressure shadows, indicate that ductile thrusting was dominantly towards the E. At Mount Jackson (Fig. 2a), locally developed mylonite in ductile thrust zones deformed leucogranite dated by Rb–Sr whole rock at 199 ± 7 Ma (Wever et al. 1995).

In the Welch Mountains, the syn-magmatic foliation described above was deformed by steep W-dipping ductile thrusts and about major,
E-verging, tight to isoclinal, asymmetric folds that plunge steeply NW. The asymmetry of these folds suggests sinistral shear, but long fold limbs are dextrally sheared. A mineral stretching-lineation plunges steeply NW in fold hinges, but moderately NW in dextrally-sheared fold limbs. These structures can be explained by superimposed N-trending dextral shear on the W-dipping syn-magmatic foliation. The steep western dip of the fold envelope suggests that the superimposed shear was mainly strike-slip. Minor, WNW-trending sinistral shears bands cut dextrally-sheared fold limbs and may represent shears conjugate to the main shear direction (Harris & Cobbold 1984). The relationship of this strike-slip deformation to ductile thrusting, described above, is not clear. It is possible that strain partitioning (Jones & Tanner 1995) was active. N–S dextral strike-slip and E–W thrust deformation may represent the simple shear and pure shear components of NE–SW shortening (Fig. 2b), respectively, and be coeval. Although these shear zones have not been directly dated, the fact that they deformed Early Jurassic plutonic rocks and are post-dated by unfoliated plutonic rocks with Rb–Sr whole-rock ages ranging from 123 ± 1.7 Ma to 104.9 ± 1.1 Ma (Wever et al. 1994) lead us to conclude that they are part of the Palmer Land deformation event.

At Auriga Nunatak, NW Palmer Land (Figs. 2b), gneiss, marble and granodiorite, dated at 205 ± 3 Ma by U–Pb zircon (Millar, unpublished data), were deformed in a 2.4 km wide sinistral-reverse shear zone (sinistral transpression). We interpret this reactivation of the Auriga Nunatak shear zone as transfer faulting conjugate to the main NE–SW compression direction (Fig. 2b). A sinistral shear fabric is cut by early Cretaceous intrusives (see below). This shear zone may be a large-scale example of minor conjugate sinistral shears described above from the Welch Mountains.

At Campbell Ridges, in NW Palmer Land (Fig. 2b), K-feldspar megacrystic gneiss, with a Rb–Sr whole rock age of 153 ± 10 Ma (Piercy & Harrison 1991), is deformed by steep, NW-dipping ductile shear zones (Vaughan unpublished data). K-feldspar megacrysts have asymmetric, o-porphyroclast geometries (Passchier & Simpson 1986) indicating reverse shear with overthrusting to the SE. These shear zones are overprinted by extensional shear fabrics associated with the emplacement of syn-magmatically deformed granodiorite dykes. A minimum age for sinistral movement on the Auriga Nunataks shear zone comes from a hornblende gabbro body, dated by conventional K–Ar at 133 ± 4 Ma, and a garnetiferous aplite dyke, with a Sm–Nd garnet age of 130 ± 11 Ma, that cut the ductile fabric (Vaughan & Millar, unpublished data). The gabbro is part of an Early Cretaceous period of magmatism that commenced c. 140 Ma (Vaughan & Millar 1996). We conclude, based on the above evidence from Auriga Nunataks and Campbell Ridges, that the Palmer Land deformation event in NW Palmer Land took place between 150 and 140 Ma. Geochronological data (Pankhurst 1982, 1990; Hole et al. 1991; Storey et al. 1992) suggest that deformation occurred during a break in the magmatic record, although a switch to volcanic emplacement during compression is possible (Glazner 1991).

In E. Graham Land, in the northern part of the Antarctic Peninsula, Whitham & Storey (1989) reported marine sedimentary rocks of the Nordenskjöld Formation (Fig. 2a) deformed from Tithonian times (152 Ma). Deformation spanned dewatering and lithification, producing a wide range of structural features. These include, layer-parallel extensional and compressional structures, large-scale asymmetric folds, in some case plunging up to 60°, fold-associated cleavage, and brittle faults. The kinematic history is difficult to unravel with apparently coeval NW-directed thrusting, extensional faulting and strike-slip deformation. Whitham & Storey (1989) concluded that deformation most likely took place in a NE–SW strike-slip regime. NNW-trending fault plane lineations and clockwise cleavage transection of fold axial planes (BAS unpublished data) is consistent with NE–SW sinistral transpression and strain partitioning (Jones & Tanner 1995), with NNW–SSE compression coeval with, or shortly after, deposition. A Late Berriasian–Valanginian (145–140 Ma) break in sedimentation along this margin (Macdonald & Butterworth 1990) suggests that deformation peaked at that time.

Cretaceous magmatism and extension

The Early Cretaceous represents a significant period of magmatism, sedimentation and crustal growth in the Antarctic Peninsula. In NW Palmer Land, plutonic rocks were emplaced from 141 to 80 Ma (Vaughan & Millar in press) whereas in NE Palmer Land plutonic rocks are 128–83 Ma (Pankhurst & Rowley 1991; Wever et al. 1994). The difference in timing may be significant and suggests that the locus of magmatism broadened eastward during Early Cretaceous times.

In NW Palmer Land, from the Traverse Mountains in the N (Vaughan & Millar unpub-
lished data) to the Batterbee Mountains (Fig. 2c) in the S (C. D. Wareham pers. comm. 1995), plutonic rocks preserve evidence of syn-magmatic crustal extension and deformation during a rapid phase in crustal growth (e.g., Creswick Peaks, 141 ± 2 Ma, Vaughan & Millar in press). The main shear zones dip moderately NE and SE, with antithetic shear zones dipping steeply SW (Vaughan unpublished data). Deformation textures range from sub-magmatic phenocryst alignment to ultramylonite, with formation textures range from sub-magmatic to post-magmatic. Deeply deformed rocks preserve evidence of syn-magmatic extension across the peninsula in Early Cretaceous times. Kinematic information from syn-magmatically deformed plutons suggest that this had a probable E-W orientation (Fig. 2c).

**Mid-Cretaceous compression**

The Early Cretaceous extensional shears in NW Palmer Land were reactivated by reverse ductile shear (Vaughan & Millar in press). New E-directed thrusts also formed in NE Palmer Land (Meneilly 1988). This deformation occurred during a period of Pacific-wide compression (Vaughan 1995) in the mid-Cretaceous (Gallic & Harland et al. 1990, from 132 to 89 Ma, including Barremian to Turonian). In NE Palmer Land, at Engel Peaks (Fig. 2d), a 1 km thick reverse ductile fault affected 113 Ma granophyre (Meneilly 1988), placing a maximum age on this deformation. The ductile fault has an unusual footwall geometry defining a staircase trajectory, within which cataclasite, layered and folded fault breccias and foliated granitoid are developed. In the shear zone at Auriga Nunataks, distributed ductile to brittle–ductile, sinistral-reverse movement with large-scale modification of early structures, offset and folded earlier gneissic foliations and Early Cretaceous garnetiferous aplite described above. The large-scale geometry of the fault zone resembles a positive flower structure. Layering in marble and amphibolite enclaves is tightly folded; folds plunge gently to E and W, and have wavelengths of up to 200 m. Mafic dykes are folded and boudinaged providing further evidence for sinistral reverse displacement with strongly oblique overthrusting to the SW or W. In W Graham Land (Fig. 2d), W-directed thrusts deform 117 Ma (no error given) lavas, and are cut by 96 Ma (no error given) granodiorite plutons, dated by K–Ar whole rock (Birkenmajer et al. 1994).

Although we have no precise age for this mid-Cretaceous deformation in NW Palmer Land, a minimum age of 80 ± 3 Ma is provided by Rb–Sr dating of a microgranite sheet which intruded thrust-deformed volcanic rocks at Mount Lepus (Vaughan & Millar, unpublished data). A maximum age of 113 Ma is provided by the age of the deformed granophyre at Engel Peaks (Meneilly 1988). Within these age constraints it is possible that a K–Ar biotite cooling age of 108 ± 3 Ma from a thrust deformed gabbro at Auriga Nunataks dates this event (Vaughan & Millar, unpublished data).

The sedimentary rocks of Kenyon Peninsula were folded and thrust (Fraser & Grimley 1972), perhaps during this deformation episode. Folds are upright to inclined; vergence and overthrust sense is to the NE. In contrast, there was no penetrative deformation of the sedimentary rocks in the Larsen Basin. However, major pulses of coarse sediment were deposited in the basin during Aptian–Albian times. These may reflect periodic uplift and rejuvenation of the arc (Ineson 1989) during this mid-Cretaceous deformation event. The break in the sedimentation record and major facies change in Turonian-Coniacian times (see above) may represent the final effects of this deformation in NE Graham Land. This mid-Cretaceous episode was also coeval with, and may correspond to, deformation and basin inversion of the fore-arc basin.
sequence on Alexander Island (Storey & Nell 1988). Mid-Cretaceous thrusting was followed by large-scale E–W extension and block faulting in NW Palmer Land (Vaughan unpublished data), suggesting increased intra-arc extension. This may be related to increased rates of subduction and related arc-tensional forces (Hamilton 1994) associated with a superplume event (Larson 1991). Sedimentation and subsidence resumed in the Larsen Basin, and continued to Tertiary times.

**Weddell Sea history**

Oceanic crust underlies the northern part of the Weddell Sea region (Bell et al. 1990). Free-air gravity maps, derived from high-resolution Geosat altimetry data, reveal a herring-bone pattern of closely spaced NW–SE and NE–SW ridges and troughs (Fig. 1). These are interpreted as short offset fracture zones (flow lines) resulting from the separation of South America and Antarctica (Bell et al. 1990; Livermore & Woollett 1993). Magnetic anomaly C34 (83 Ma) (LaBrecque & Barker 1981) is clearly identified throughout the Weddell Sea during the NW–SE spreading phase. The age of the transition between the two spreading directions was considered to be at c. 80 Ma by Bell et al. (1990). However, the calculations of Livermore & Woollett (1993) show that it occurred as a gradual change during the Cretaceous Normal Polarity Superchron (83–118 Ma). There is much less certainty in interpreting the M-series anomalies formed during NE–SW spreading. The herring-bone pattern of gravity anomalies is terminated by a distinct E–W gravity anomaly, referred to informally as the 'Anomaly-T' (Fig. 1) (Livermore & Hunter this volume). Its age and significance are uncertain. Livermore & Woollett (1993) suggested that an associated magnetic anomaly may represent M11 (135 Ma), the time of South Atlantic opening, whereas Livermore & Hunter (this volume) suggest that it may be younger in age (M4–M0 time). LaBrecque & Barker (1981), in an initial interpretation of marine magnetic data, suggested that the Weddell Sea contained oceanic crust of Mid-Jurassic age (M29, 165 Ma), which would be some of the first ocean floor to form during the break-up of Gondwana, but this has not subsequently been substantiated. Anomalies M4 (127 Ma; Bell et al. 1990), M10 (132 Ma; Martin & Hartnady 1986), and M13 (139 Ma; Bell et al. 1990) have been tentatively identified, although interpretations are conflicting, probably reflecting poorly formed anomalies and a slow spreading rate.

The crustal structure of the southern part of the Weddell Sea, an area which we refer to as the Weddell Sea embayment (WSE) (Fig. 1), is even less certain. Interpretations of refraction seismic data suggested that extended continental crust underlies the WSE (Kadim et al. 1983; Kamenev & Ivanov 1983) with up to 14 km of sedimentary infill. An escarpment, the Andenes Escarpment, and an aeromagnetic anomaly, the Orion Anomaly (Fig. 1) have been interpreted as a possible ocean–continent boundary between the Weddell Sea and continental embayment region (Kristoffersen & Haugland 1986; LaBrecque et al. 1986; Hinz & Kristoffersen 1987; Bell et al. 1990). The age and origin of these features is of crucial importance to models of Weddell Sea evolution and is by no means clear (for discussion of the age and origin of the Andenes Escarpment see Lawver et al. 1991). However, tectonic models, based primarily on palaeomagnetic data, indicate translation of the Ellsworth–Whitmore mountains (EWM) microplate from an original position off southern Africa, following 90° counterclockwise rotation pre-Mid-Jurassic (Grunow et al. 1987a, b), to its present position in West Antarctica (Grunow et al. 1991; Grunow 1993a, b). In the most recent palaeomagnetism-based model for this region, Grunow (1993a, b) proposed that a southwestern Weddell Sea basin, up to 1000 km wide, formed between the EWM and the Antarctic Peninsula, from 175–155 Ma, during clockwise rotation of the Antarctic Peninsula. This was followed by subduction of relatively young southern Weddell Sea lithosphere beneath the southeastern margin of the Antarctic Peninsula between 155–130 Ma during anti-clockwise rotation of the peninsula. A consequence of this model is that remnants of Jurassic oceanic crust may underlie the southwestern Weddell Sea.

**Correlation between Antarctic Peninsula events and Weddell Sea history (Fig. 3)**

**Early and Mid-Jurassic arc extension: the initial rifting phase, pre–157 Ma**

Early and Mid-Jurassic extension, magmatism and sedimentation in the Antarctic Peninsula corresponded with the initial rifting phase of Gondwana breakup (Cox 1992; Storey et al. 1992) prior to formation of the oldest known seafloor (estimated to be pre–157 Ma based on the location of identified anomaly, M22 in the Somali and Mozambique basins; Simpson et al. 1979; Ségoufin & Patriat 1980; Lawver et al. 1992
for discussion). According to Kristoffersen & Hinz (1991), Cox (1992) and Lawver et al. (1992), this period involved sinistral motion of Africa and South America (West Gondwana) relative to Antarctica (East Gondwana) (Fig. 4b; Stage 1 rifting of Cox 1992). Stage 1 rifting would have resulted in extension in the Weddell Sea region (Fig. 4b; failed Weddell Rift, Hinz & Kristoffersen, 1987). Cox (1992) suggested that the first stage corresponded with the initial phase of Karoo magmatism (193 ± 15 Ma, Fitch & Miller 1984), an event that is associated with a mantle plume beneath the Karoo province, formation of volcanic margins (imagined as dipping reflector sequences in the Explora wedge) on the Dronning Maud Land margin of Antarctica (Kristoffersen & Hinz 1991) and the major pulse of Early Jurassic magmatism along the active Pacific margin (Storey et al. 1992). However, new Ar–Ar dating from the Karoo province (Hooper et al. 1993) failed to substantiate this early magmatic phase and indicated instead a short-lived magmatic episode, 182 ± 2 Ma. This is slightly older than the age of a basalt province along the Transantarctic Mountains (Ferrar province, 176 ± 2 Ma, Ar–Ar dating of Heimann et al. 1994) and corresponded with emplacement of the second, Mid-Jurassic magmatic phase in the Antarctic Peninsula (180–160 Ma, Pankhurst 1990; Storey et al. 1992).

Palaeomagnetic data suggest clockwise rotation of the Antarctic Peninsula (Grunow 1993a) during our initial rifting period, with formation of the postulated southwestern Weddell Sea (up to 1000 km wide) between c. 175 and 155 Ma, separating the SE Antarctic Peninsula from the EWM. The geological evidence for this is inconclusive. Sedimentation in the Latady basin is consistent with both extension at a passive margin, and extension behind a magmatic arc. However, evidence in NE Palmer Land for Early and Mid-Jurassic arc granitoids hosted in extensional fault zones is perhaps more consistent with subduction-driven arc extension (Hamilton 1994).

This initial rifting phase also marks a significant and potentially unique period during the history of Gondwana breakup that was characterized by formation and translation of separate microplates in the West Antarctic-South Atlantic region (Dalziel & Elliot 1982). According to palaeomagnetic data, the Falkland Islands rotated 120° from a position off SE Africa to their present position close to South America between Early Jurassic times (c. 190 Ma) and South Atlantic opening (Mitchell et al. 1986; Taylor & Shaw 1989), and the EWM rotated 90° counterclockwise from a position off southern Africa (based on Cambrian palaeomagnetic data of Watts & Bramall 1981, Jurassic palaeomagnetic data of Grunow et al. 1987a, b, and geological observations of Schopf 1969; for discussion see Curtis & Storey this volume) prior to 178 Ma (Grunow et al. 1991).

At present, there appears to us to be no totally adequate mechanism to explain the rotation and translation of the Falkland Islands microplate and rotation of the EWM during the initial rifting period in the Early Jurassic, and there is still some uncertainty in their original pre-break-up positions. Some plausible palaeomagnetism-based models involved rotation, with translation of the Falkland Islands microplate, by generation of moderate volumes of oceanic lithosphere (Marshall 1994). However, similar to Grunow (1993a, b), we prefer a model involving crustal extension, limited generation of oceanic lithosphere pre-178 Ma, but with transcurrent motion along large-scale strike-slip faults (see below). It is perhaps no coincidence that these crustal microplates originated in the vicinity of the Karoo plume (Fig. 4a), and their rotation and translation may have been initiated by doming of the lithosphere above the plume and involved strike-slip faulting and extension. Marshall (1994) suggested that the Gastre fault system, an Early Jurassic E–W-trending dextral fault system in southern South America (Rapela & Pankhurst 1992), may have played an important role in the westward translation of Patagonia and rotation of the Falklands microplate. Further major strike-slip faults may be hidden beneath the WSE region. If this is the case, then the original movement between East and West Gondwana must have been more complex than previously envisaged (Cox 1992). Early Jurassic dextral movements on the Auriga Nunataks shear zone provide the only evidence of this in the Antarctic Peninsula region but this is likely to be a transfer fault similar to the Gastre fault system in southern South America. It is also possible and perhaps more likely given the lack of evidence for rotations during the initial rifting period, that the rotations occurred during the Permo-Triassic Gondwanian dextral transpression event recognized by Curtis (1994) in the Ellsworth Mountains.

Taking all these factors into account, we conclude with a two part (stage 1a and 1b) model. Stage 1a involved significant strike-slip motion in the Weddell Sea region at some time during this initial rifting or end-Gondwanian period to account for the rotation of the Ellsworth–Whitmore mountains block (EWM) prior to 178 Ma (in keeping with palaeomagnetic
results of Grunow et al. (1987b) and other microplates in this region. The movement history may be represented only by the Gastre fault system and Auriga Nunataks shear zones, although these are not considered to be the main shear zones involved. The rotations may correspond with either the Late Triassic to Early Jurassic pulse of magmatism along the Pacific margin (Storey et al. 1992) or the break in the currently known magmatic record, 199–180 Ma. We suggest that stage 1a was followed by stage 1b, involving sinistral motion of Africa and South America relative to Antarctica (stage 1 model of Cox 1982), resulting in extension or transtension in the WSE, formation of the Explora wedge, and extension (Fig. 2a) along the eastern margin of the Antarctic Peninsula with formation of the Latady basin and anoxic basins in the South Atlantic region (Fig. 4b). We do not rule out the possibility of seafloor spreading in the WSE at this time but see no geological reasons to invoke a southwestern Weddell Sea between the EWM and the Antarctic Peninsula. The initial extensional episode was contemporaneous with emplacement of the main phase of Karoo magmatism (182 ± 2 Ma), the Ferrar province (176 ± 2 Ma), and Mid-Jurassic Pacific-margin magmatism (180–160 Ma Pankhurst 1982) on the Antarctic Peninsula. It also corresponded with a period of high (c. 8 cm a⁻¹) to moderate (c. 4 cm a⁻¹) half spreading rate in the Pacific Ocean, and early growth of the Pacific Plate after a major plate reorganization at about 190 Ma (Nakanishi et al. 1992).

Late Jurassic/Early Cretaceous deformation; ?change in plate motions

The peninsula-wide deformation (?Tithonian–Berriasian age; c. 150–140 Ma), that has locally been referred to as the Palmer Land deformation event (Kellogg & Rowley 1989) corresponded with an apparent break in the magmatic record (Pankhurst 1982, 1990; Hole et al. 1991; Storey et al. 1992) and represented a significant and important change in the stress regime along the Pacific margin. It also approximately coincided with reduced Pacific spreading rates and the M21–M20 (c. 150 Ma) global changes in spreading rate described by Nakanishi et al. (1992). In the following section we will explore some potential reasons for this deformation and pursue possible links with Weddell Sea history.

The Palmer Land deformation event has previously been related to (1) collision of the EWM with the southeastern margin of the Antarctic Peninsula during its passage through the proto-Weddell Sea region (Grunow et al. 1991), and (2) westward subduction of relatively young southern Weddell Sea lithosphere beneath the eastern margin of the peninsula (155–130 Ma, Grunow 1993a, b). Collision of the EWM with the Antarctic Peninsula is consistent with geological evidence for E-directed ductile thrusting and dextral transpression in NE Palmer Land, and a foreland fold-and-thrust belt in the Latady Formation. However, the geological evidence for westward subduction of relatively young southwestern Weddell Sea lithosphere is poor. (1) The onset of subduction is likely to place the arc in tension, rather than compression, producing structures indicating extension (Hamilton 1994) rather than shortening as is seen. This will be the case even for young or shallowly-dipping oceanic lithosphere (Hamilton 1994), for example, in Peru, where shortening of the arc would be expected above the anomalously gently dipping Nazca plate, Miocene sediments are almost undeformed across the Altiplano between the Eastern and Western Cordillera (Kono et al. 1989). (2) West-directed Weddell Sea subduction, combined with ongoing-(10,5),(989,989)
ated syn-sedimentary deformation, bedding disruption and bedding-parallel extension (Knipe et al. 1988). (4) There is little one can deduce about the polarity of subduction beneath the peninsula from the magmatic record as roughly half of the proposed period of subduction (155–130) corresponded, from our present knowledge of the magmatic history, to a break in the record (160–141 Ma, Pankhurst 1982). Early Cretaceous (140–80 Ma) arc plutons in NW Palmer Land were hosted in syn-magmatic extensional shear zones consistent with intra-arc extension during either E- or W-directed subduction.

Other possible mechanisms for the Palmer Land deformation event include the following two. (1) It may have resulted from terrane or seamount accretion on the W side of the peninsula. A large Hawaiian-type ocean-island has been recognized in the LeMay Group peninsula. A large Hawaiian-type ocean-island accretionary complex in Alexander Island (Tranter 1986; Doubleday et al. 1994) although its precise time of accretion is currently unknown. (2) It may represent eastward gravitational spreading of a magmatically overthickened arc pile, as has been proposed for eastward thrusting in the Eastern Cordillera of the Peruvian Andes (Hamilton 1994). Continental crust beneath the WSE region would be necessary as a backstop in compressional models, as the arc would be likely to override oceanic lithosphere, causing it to subduct, incurring similar objections to compressional deformation as those outlined above.

Although no clear mechanism can be identified for the Palmer Land deformation event, we suggest that the change from an extensional to a compressional margin may be related to the major change, from E–W to N–S, in the direction of plate motion between East and West Gondwana prior to South Atlantic opening (Fig. 4c; Lawver et al. 1991) particularly if subduction had temporally ceased along the Pacific margin. If this was the case, the change in the stress regime would broadly correlate with formation of the continent-ocean boundary (Bell et al. 1990) at the shelf break on the northern margin of the Weddell Sea embayment region (Jokat et al. this volume), and with initial oblique seafloor spreading in the Weddell Sea. The boundary would truncate earlier rift structures formed during the initial, Stage 1, rifting period and represent a change to N–S motion of East and West Gondwana (Lawver et al. 1991; stage 2, Cox 1992; Fig. 4c). Stage 2 plate motions would have resulted in a strike-slip component along the margin of the East Antarctic craton and transformation of the Dronning Maud Land margin from a rifted to a strike-slip margin with formation of the Explora Escarpment (Hinz & Krause 1982; Lawver et al. 1992), and depending on the orientation of the Antarctic Peninsula, a dextral transpressive component during the Palmer Land deformation event. Initial seafloor spreading in the Weddell Sea would also produce a sinistral shear couple along the NE margin of the Antarctic Peninsula accounting for deformation and inversion of the Nordenskjöld Formation.

If the correlation of deformation and changes in the plate configuration in the Weddell Sea that we suggest is correct, then the initiation of seafloor spreading in the Weddell Sea must have been c. 150 Ma and could conceivably correlate with formation of anomaly M22 in the Somali and Mozambique basins. If seafloor spreading in the Weddell Sea was older than M22, as has been suggested for the Somali and Mozambique basins (Lawver et al. 1991), then our correlations are invalid and the Palmer Land deformation event may be related to Pacific margin arc or forearc processes mentioned above. The presence of a potential continent-ocean boundary along the northern margin of the WSE does not preclude southwestward translation of the EWM between 155 and 130 Ma (Grunow 1993a, b), but it implies that the block was very large, incorporating the WSE. Palaeomagnetic data for the Antarctic Peninsula and EWM are consistent with these blocks being adjacent at 175 Ma (Grunow et al. 1987; DiVenere 1995). If they moved relative to East Antarctica as part of a single block in the rigid Weddellia (Antarctic Peninsula + EWM + Thurston Island blocks) suggested by Grunow et al. (1987b), then the EWM could have been close to its current position relative to the Antarctic Peninsula by 175 Ma (Fig. 4b). This would preclude the need for a large southwestern proto-Weddell Sea if no subsequent relative movement is assumed. Palaeomagnetic data (Grunow 1993a, b), however, do not rule out independent motion of the Antarctic Peninsula and EWM blocks, although interpretations of Mid-Jurassic to Early Cretaceous Antarctic Peninsula motion are questioned by DiVenere et al. (1995).

**Early Cretaceous arc extension; early drift phase**

Early Cretaceous arc extension is consistent with continuing E-directed Pacific subduction, seafloor spreading in the Weddell Sea and resumed crustal extension in the Weddell Sea embayment region. Pacific spreading rates increased through
the Early Cretaceous, peaking at about 120 Ma (Larson 1991). A resulting potential increase in subduction rates, or changes in the subduction regime (e.g. subducting young crust, Alabaster & Storey 1990) could have resulted in shallowing of the slab and eastward broadening of the magmatic focus as documented from W to E Palmer Land. On the E of the peninsula, probable back-arc sedimentation resumed after the Palmer Land deformation event. The Early Cretaceous peak in extension and magmatism overlapped with opening of the South Atlantic at about Anomaly M11 time (135 Ma) and has been correlated with formation of 'Anomaly T' (M11, 135 Ma), the distinctive E–W-trending gravity feature in the Weddell Sea (Fig. 1; Livermore & Woollett 1993).

Mid-Cretaceous arc compression; change in spreading direction

The mid-Cretaceous event had a remarkably similar effect to the Late Jurassic/Early Cretaceous compressional event, producing diverging structures in Palmer Land and a significant change in the sedimentation pattern in the basins on the eastern margin of Graham Land. We suggest that it was broadly contemporaneous with a further change in plate configuration in the Weddell Sea region as indicated by the gradual change from NE–SW to NW–SE spreading that occurred during the long Cretaceous interval of normal polarity (Livermore & Woollett 1993). In global models, these events corresponded to and may have been triggered by the 50–75% increase in ocean crust production (Fig. 3) in the Pacific Ocean basin between 120 and 80 Ma, the mid-Cretaceous superplume event of Larson (1991). Thermal effects of the mid-Cretaceous superplume are global (Larson 1991) and may have affected the spreading regime in the Weddell Sea. Changes in Pacific spreading associated with the superplume event may also have temporarily increased the component of ridge-push in plate-marginal forces affecting the Antarctic Peninsula (Vaughan 1995). This may have caused compression seen within the arc at probably 110 Ma. Subsequent block-faulting and extension may be due to superplume-related, increased subduction rates and subduction-related extension (Hamilton 1994). In the Weddell Sea, the change to NW–SE spreading is consistent with an increased influence of forces related to Pacific-plate processes, particularly, more E–W, subduction-related tension on the Antarctic Peninsula, with possible westward migration.

Conclusions

Reasonable correlations can be drawn between the four main tectonic regimes recognized in the Antarctic Peninsula and some known events within the Weddell Sea region, and these can be used to constrain geodynamic models. (1) Late Triassic to Late Jurassic arc extension correlates with initial rifting in the Weddell Sea region during sinistral motion between East and West Gondwana. There is currently no record of large-scale pre-Mid-Jurassic transcurrent deformation in the Antarctic Peninsula to account for rotation of crustal blocks in the initial rifting period; these may be hidden beneath the WSE by thick Jurassic and Cretaceous sedimentary rocks. (2) A peninsula-wide Late Jurassic/Early Cretaceous compressional event may correlate with the major change in plate motions from E–W to N–S separation of East and West Gondwana. This change could have resulted in formation of an ocean–continent boundary along the northern margin of the Weddell Sea embayment and initial seafloor spreading. In our view, geological data do not support subduction of young, southwestern proto-Weddell Sea oceanic lithosphere beneath the eastern margin of the peninsula at this time. (3) Cretaceous arc extension corresponds with continuing seafloor spreading in the Weddell Sea. (4) Mid-Cretaceous arc compression, linked to a global increase in ocean floor spreading rates and a superplume event, correlates with a change from NE–SW to NW–SE spreading in the Weddell Sea.

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