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Transpressional deformation along the margin of Larsen Basin: new data from Pedersen Nunatak, Antarctic Peninsula

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Abstract: New structural data from the northern Antarctic Peninsula suggest that reverse faults and folds affecting the Pedersen Nunatak beds of the upper Mesozoic–Lower Cenozoic Larsen Basin succession were produced by transpressional forces acting parallel to the Weddell Sea coast of the Antarctic Peninsula during mid-Cretaceous compression of the Larsen Basin. At Pedersen Nunatak, Larsen Basin rocks are deformed into a series of synclines and anticlines that are cut by reverse faults.

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Key words: Antarctic Peninsula, Larsen Basin, structural geology, transpressional tectonics, Weddell Sea coast

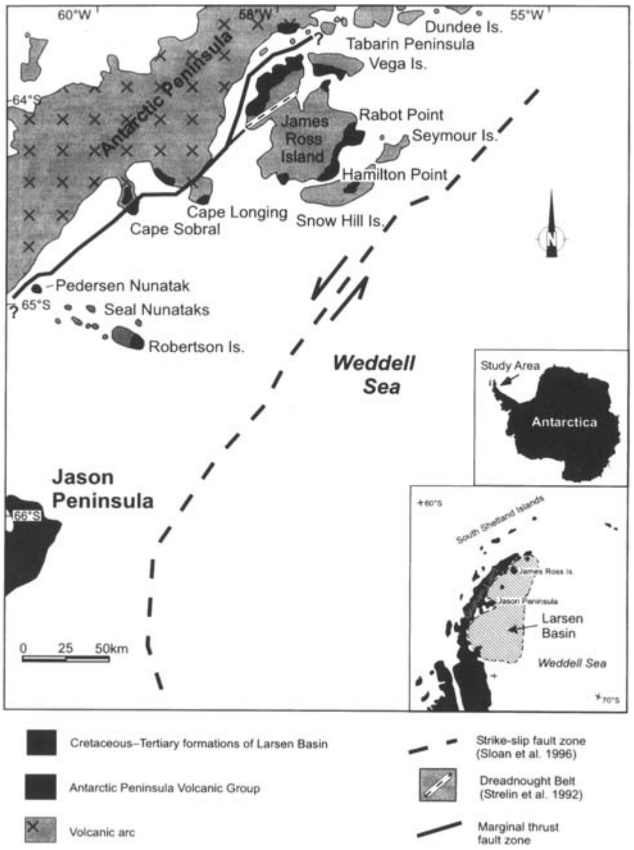

Fig. 1. Location map including Larsen Basin location (see inset after del Valle *et al.* 1992, modified from Sloan *et al.* 1995), simplified geology after Elliot (1988), modified from Sloan *et al.* (1995).

Introduction

The upper Mesozoic–lower Cenozoic Larsen Basin is situated on the continental shelf to the east of the northern sector of the Antarctic Peninsula (Macdonald *et al.* 1988) (Fig. 1). This depositional site formed as a result of Jurassic lithospheric extension during early stages of Gondwana break-up, and subsequently developed in a back-arc setting relative to the Antarctic Peninsula magmatic arc (Hathway 2000). Hathway (2000) proposed a division of the basin fill into four megasequences (Table I), which represent major phases of basin evolution.

According to numerous authors (Storey *et al.* 1996, Leat *et al.* 1995, 1997, Vaughan & Millar 1996, Vaughan & Storey 1997) most of the Mesozoic–Cenozoic tectonic evolution of the Antarctic Peninsula was dominated by across-arc extension. For most of this period, the regime was of dextral transtension style (Storey & Nell 1988, Storey *et al.* 1996), and across-arc compressive episodes were short-lived (Vaughan & Storey 1997): one occurred during latest Jurassic to earliest Cretaceous times, and another during the middle of the Cretaceous as part of circum-Pacific deformation and uplift (Vaughan 1995).

Deformations recorded in rocks of the four megasequences proposed by Hathway (2000, fig. 3) (Table I) reflect most of the Antarctic Peninsula Mesozoic tectonic evolution, which can be divided in four main events (Vaughan & Storey 1997):

1) Late Triassic to Late Jurassic extension,
2) Late Jurassic to Early Cretaceous dextral transpression,
3) Early Cretaceous extension, and
4) mid-Cretaceous compression.

East–west extension occurred in the northern Larsen Basin during the Late Triassic–Late Jurassic Event 1 (Vaughan &

Table I. Stratigraphical record of the Larsen Basin area (after Pirrie *et al.* 1997, Hathway 2000).

Groups	Formations	Age	Observations
James Ross Island Volcanic Group		Miocene–Recent	alkaline basaltic volcanics
	La Meseta Formation	Eocene	
Seymour Island Group	Sobral Formation	?Palaeocene	
	Cross Valley Formation	Palaeocene	
	Lopez de Bertodano Formation	Maastrichtian–Danian	
Marambio Group	Snow Hill Formation	Campanian–Maastrichtian	
	Santa Marta Formation	Santonian–Campanian	
	Hidden Lake Formation	Coniacian–Santonian	
	Whisky bay Formation	Albian–Coniacian	partial basin inversion
Gustav Group	Kotick Point Formation	Aptian–Albian	
	Lagrelius Point Formation and Pedersen Formation (Sobral Peninsula)	Barremian–Aptian	
	?		
	?Pedersen Formation (Pedersen Nunatak beds)	?Hauterivian	?regressive megasequence
	?		
	Nordenskjöld Formation		
	Larsen Member	Berriasian	
	Ameghino Member	Tithonian–Berriasian	transgressive post-rift megasequence
	Longing Member	Kimmeridgian–Tithonian	
	Cape Framnes beds(Jason Peninsula)	Kimmeridgian	
	?		
	silicic volcanics	?Upper Jurassic	
	mainly silicic ignimbrites	Middle Jurassic	syn-rift megasequence
Botany Bay Group		Lower Jurassic	deformation, low to high-grade metamorphism
		?latest Triassic–Lower Jurassic	continental breakup unconformably ?accretionary
Trinity Peninsula Group		?uppermost Carboniferous–Triassic	complex, mechanical basement of the basin

Storey 1997). It controlled the deposition of the non-marine Botany Bay Group and silicic volcanics as well as the early stages of Nordenskjöld Formation marine deposition. The sinistral transpression which occurred along north-east–south-west shear zones during the later stages of deposition of the Nordenskjöld Formation, was included in the Event 2 (Vaughan & Storey 1997). Strike-slip movements during Late Jurassic to Early Cretaceous times were also inferred by Millar *et al.* (1990) from the south-east coast of northern Graham Land. Doyle & Whitham (1991, fig. 14) postulated a dextral strike-slip fault, terminating the anoxic facies conditions of the Late Jurassic–Early Cretaceous Nordenskjöld Formation in the Albian.

Pedersen Nunatak is situated 7 km from the Nordenskjöld Coast, close to a tectonic lineament that separates James Ross Island and parts of some minor peninsulas from the main Antarctic Peninsula. The composition and structures of Sobral Peninsula to the north-east of Pedersen Nunatak (Fig. 2) are well known (Hathway 2000). However, the structures of Pedersen Nunatak have not been investigated in detail until now. The description of the Pedersen Nunatak structures, involving north-west directed thrusting (towards the arc-terranes) with associated folding and minor north-west striking normal extensional faults (Fig. 4), as well as a discussion of their regional significance are the main objects of this paper.

Structures at Pedersen Nunatak

Pedersen Nunatak (64°55'50.646"S, 60°44'59.734"W) is an isolated small (< 0.5 km^2) and low (210 m high) rocky hill located some 7 km south-east of the Antarctic Peninsula (Figs 1 & 2). At Seal Nunataks, about 15 km east of Pedersen Nunatak, Late Cenozoic alkali basalts form east–west trending isolated eruptive centres.

The *c.* 530 m thick succession of marine sedimentary rocks exposed at Pedersen Nunatak consists mainly of conglomerates formed of rounded, arc-derived clasts (e.g. Jurassic silicic volcanics and Trinity Peninsula Group) and angular clasts of Nordenskjöld Formation, sandstones and mudstones (e.g. Elliot 1966, J.M. Lirio unpublished reports 1991). These lithologies were included in the Pedersen Formation by del Valle & Fourcade (1986). They are very similar to lithologies that form much of the Kotick Point and Whisky Bay formations, which are part of the lower Gustav Group of northern James Ross Island (Ineson *et al.* 1986, Ineson 1989).

Pedersen Nunatak beds show significant post-depositional deformation, consisting of north-west directed thrusting and related folding. They are affected by high- and low-angle

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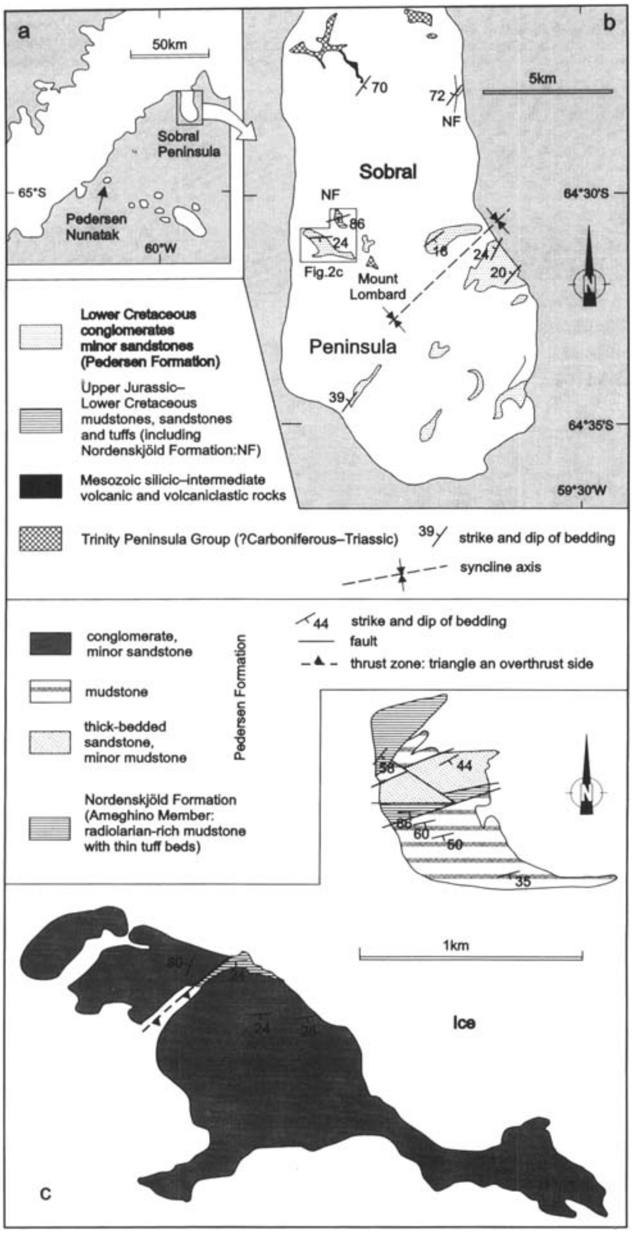

Fig. 2. Sobral Peninsula (taken from Hathway 2000, fig. 8). **a.** Location map, **b.** geological map of Sobral Peninsula (based on Elliot 1966 and Farquharson 1983a, 1983b), and **c.** sketch map of the area north-west of Mount Lombard (see (b) for location).

faulting, with associated gently plunging (up to 9°) asymmetric folds (Fig. 4). Two major north-west verging, high-angle thrust fault systems, named "North-Central Fault" (N-CF) and "Central-South Fault" (C-SF) divide the nunatak into three main tectonic blocks: North, Central and South blocks (Figs 3 & 4). The rocks in these blocks are folded, forming three open synclines and one anticline (Figs 3 & 4: North Syncline, Central Syncline, South Syncline and South Anticline).

The major structures (e.g. the axes of folds and N-CF) strike almost parallel to the south-east coast of Antarctic Peninsula,

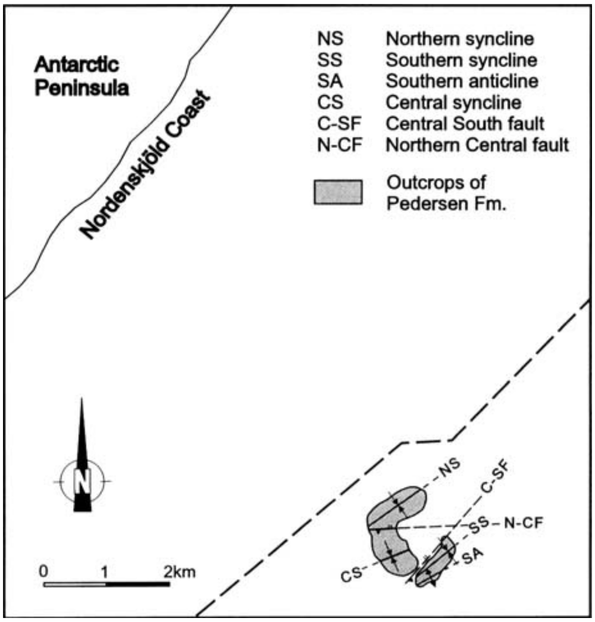

Fig. 3. Sketch map of Pedersen Nunatak showing the most important north-east striking structures almost parallel and locally oblique (North-Central Fault) to the Antarctic Peninsula east coast. The east coast of the Antarctic Peninsula is located *c.* 7 km west of Pedersen Nunatak.

except the N-CF which strikes approximately east–west, forming an angle of *c.* 45° with the C-SF (Figs 3 & 4).

Two sets of minor faults with strike directions either oblique (transverse set), or parallel (longitudinal set), to the fold axes cut the folds in each block (Fig. 4). Most faults of the transverse set are sub-vertical normal faults in all blocks, whereas the longitudinal set is composed of reverse faults dipping in opposite directions (north-north-west or south-south-east); they may represent conjugate shears ("Riedel shears", Jarrard 1986).

A thick succession of graded conglomerate–sandstone beds is exposed in the northern block, where the sediments form a syncline (Figs 3 & 4, NS: North Syncline) which plunges gently (5°) south-west. The northern limb of this syncline dips more gently (4–5° to the south-south-east) than the steeply dipping southern one (50–60° to the north-west), which is cut by a reverse fault (Fig. 4, North-Central Fault) that strikes approximately east–west (N85°) and dips *c.* 70° to the south-south-east. This high angle reverse fault separates the northern and central blocks, producing gentle drag-folding on the conglomeratic beds in the hanging wall (Fig. 4, Central Block), suggesting considerable northward displacement.

An open and shallow syncline plunging *c.* 5° towards the west-south-west is present in the conglomeratic beds that form the Central Block, where common normal minor faults of the transverse set dip towards the west (Fig. 4). The southern limb of this syncline is cut by a north-west directed, thrust-fault system that dips towards the south-east (Fig. 4, Central-South Fault).

The beds in the southern block show a complex structure

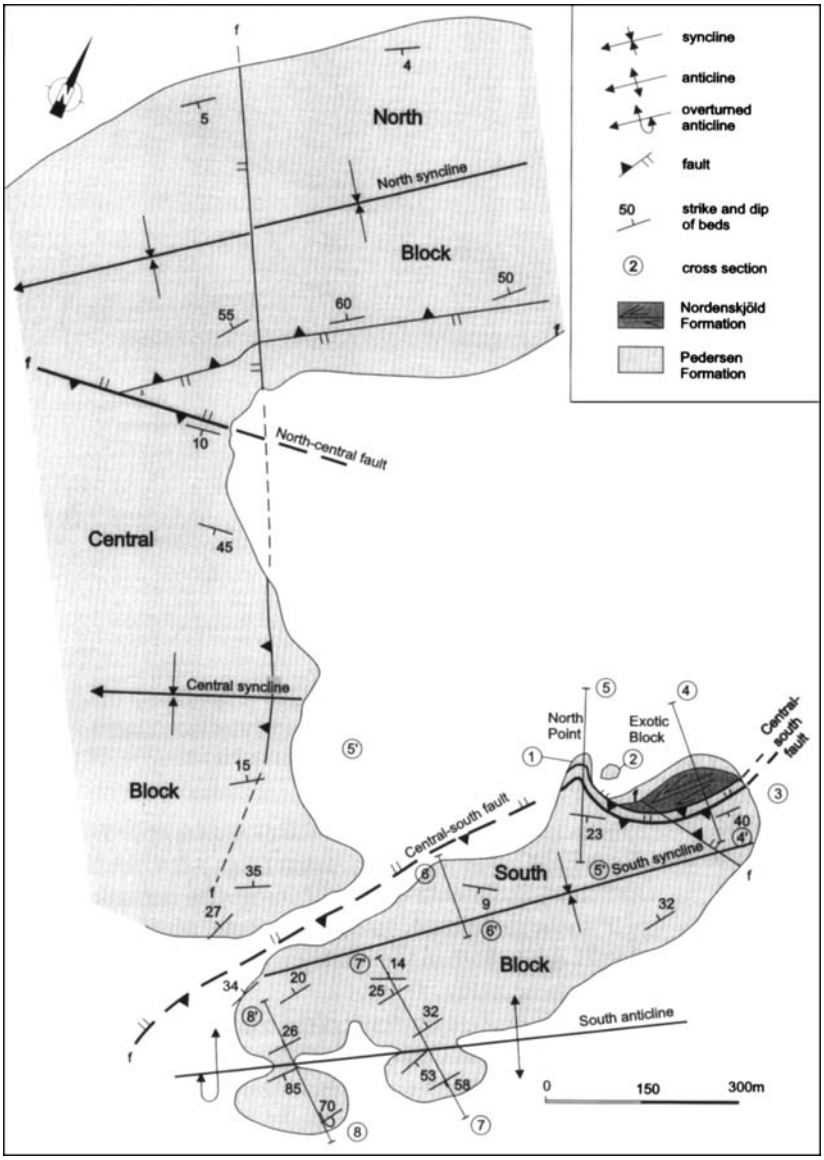

Fig. 4. Sketch map of Pedersen Nunatak showing the main structures affecting the Lower Cretaceous conglomeratic sequence (Pedersen Formation) and the three main tectonic blocks (North, Central and South blocks) described in the text. A tightly deformed exotic block of the Late Jurassic Nordenskjöld Formation is shown at the south-east part of the nunatak. Cross sections indicated by numbers enclosed in small circles are shown in Figs 5, 6 & 7.

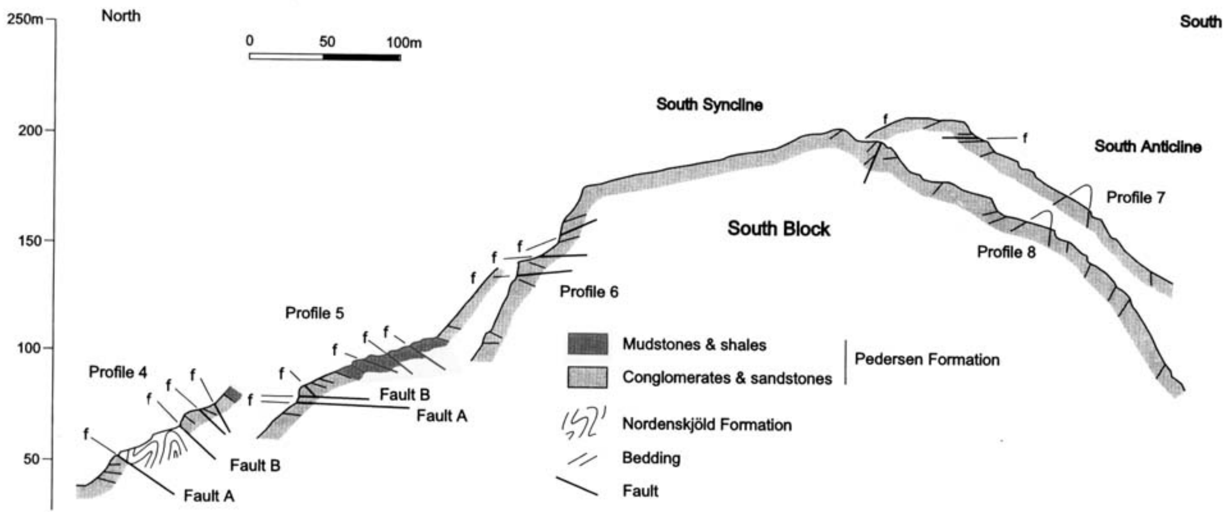

Fig. 5. Cross sections of the South Block of Pedersen Nunatak showing the structure of the beds (Figs 3 & 4). A and B: NW-directed thrust-faults of the Central-South Fault system. For location of profiles 4–8 see Fig. 4.

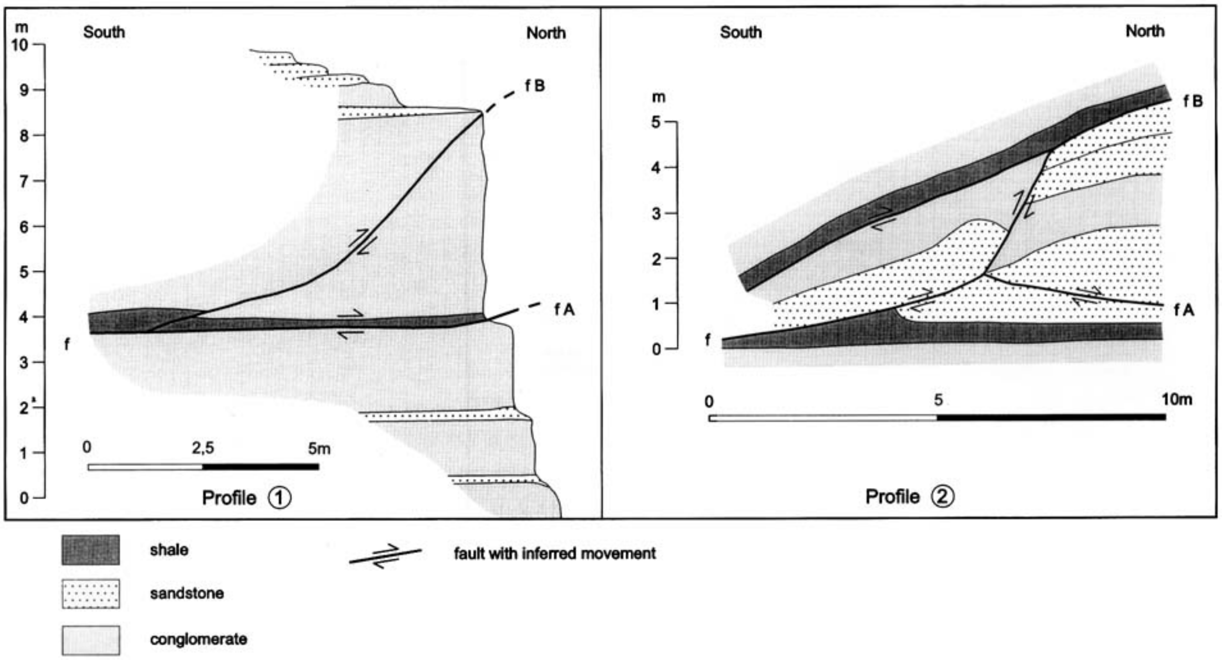

Fig. 6. Imbricated thrust-faults of the Central-South Fault system at the North Point area (Fig. 4). Faults A and B form small flats and ramps in laminated shale and conglomerate beds, respectively. Profile 1 shows a sub-horizontal north-west thrust fault (Fault A) and the low- to high-angle, north-west directed reverse Fault B. Profile 2: duplex-like faulting. Location of profiles in Fig. 4.

composed of a syncline (South Syncline) and an adjacent anticline (South Anticline), (Figs 4 & 5). In the north-eastern part of the block, the beds form a gentle syncline plunging *c.* 7° north-east, with the northern limb dipping 20–40° south-east (Fig. 4, South Syncline). This is associated with a suite of imbricate thrust faults gently dipping to the south-east. These

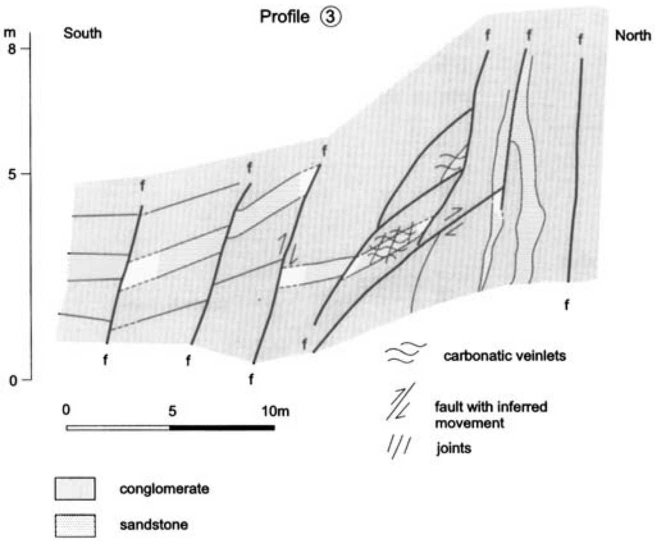

Fig. 7. Imbricated thrust-faults of the Central-South Fault system at the eastern extreme of the South Block (Profile 3, location in Fig. 4). Noteworthy is the absence of low-angle thrust-faults, which is attributed mainly to the lack of laminated shale beds. These acted as lubricating beds in other areas of the South Block (e.g. North Point, Fig. 6).

faults belong to the complex thrust fault system named "Central-South Fault" (Fig. 4). The anticline (Figs 3 & 4, SA: Southern Anticline), at the south-eastern extreme of the nunatak, plunges 5–9° to the south-west. Its southern limb, which usually dips steeply (up to 85°) to the south-east, is locally overturned to the north-west (Fig. 5).

At the north-western flank of the southern block, low-angle fault planes of the Central-South Fault system coincide with shale beds, which acted as lubricating layers forming small flats (Fig. 6a & b). These faults form minor thrusts in laminated shale beds, and ramps in alternated sandstone and conglomerate layers (Figs 6a, 6b & 7). High- and low-angle thrust faults form a north-west directed, imbricate thrust system (Fig. 5, e.g. faults A & B). This is characteristic at this locality, where abrupt variations in position of fault planes are common, and medium-scale duplex-like complex structures were observed (Fig. 6b).

At the north-eastern extreme of the South Block, 150 m thick beds of graded conglomerates alternate with sandstone grading to shale. Towards the base of this succession, conglomeratic beds are in tectonic contact with a large tabular, exotic block of ?Jurassic strata (150 x 25 m in cross section) (Figs 4 & 5, Profile 4). The exotic block lies parallel to bedding and is strongly internally deformed, with tightly folded beds of radiolarian-rich mudstones and finely laminated tuffs of the late Jurassic–early Cretaceous Nordenskjöld Formation (Farquharson 1983a). Folding is isoclinal with most fold-axes plunging steeply towards south-west, and a suite of closely spaced faults striking east-north-east. Exotic blocks of similar composition and much greater size (up to

800 m) than the above, were interpreted as olistholiths ("glide blocks") transported by submarine gravity sliding in the lower Gustav Group at James Ross Island (Ineson 1985).

Although fault-striations are poorly preserved, orientations of 33 fault-planes and fault lineations were recorded from the South Block. Two main fault-sets are shown in the Höppener (1955) diagram (Fig. 8):

a) north-east striking faults, most of which display dip-slip striation directions, indicating that the last displacements recorded along the fault-planes were mainly north-west directed dip-slip movements with a minimum dextral strike-slip component, and

b) north-west striking faults, which are interpreted as a set of oblique, mainly normal-slip faults with a minimum strike-slip component.

Age of deformation

The conglomeratic sequence at Pedersen Nunatak is poor in diagnostic palaeontological materials. Numerous unidentifiable stems and pinnae were found at the top of a conglomeratic sequence on the north-west side of the nunatak, but Elliot (1966) reported them of no value for stratigraphical purposes. Isolated ammonite fragments were found at the northern side of the nunatak and reported by Thomson & Farquharson (1984) as late Hauterivian–Barremian in age. Nannofossils from fine grained sediments indicate a late Maastrichtian age for the upper part of the conglomeratic sequence (Farquharson 1983b).

Based mainly on lithological and structural similarities exhibited by the conglomerates from Cape Sobral (Figs 1 & 2) and Pedersen Nunatak, Elliot (1966) proposed that both successions are of the same age (probably Upper Cretaceous by correlation with coarse conglomeratic sediments from the north-west side of James Ross Island). Clearly the structures at both localities could have been produced in a similar stress field. Regarding subsequent age determinations of the conglomeratic sequences (Farquharson 1983b, Thomson & Farquharson 1984), Elliot (1988) suggested that the deformation was more likely to have been mid-Cretaceous or late-Palaeocene.

The sparse palaeontological evidence and the almost certain lateral variations in lithology make direct correlation of the Pedersen Formation with the Gustav Group (Table I) difficult. However Hathway (2000, fig. 3) correlates the Pedersen Formation with the Gustav Group lowermost unit (Lagrelius Point Formation), and proposed that the early part of the Aptian–Eocene record of the Larsen Basin depositional and structural history is represented by the Pedersen Formation and the lower Gustav Group.

According to Hathway (2000), the Pedersen Nunatak beds (?Hauterivian) may be older than the southern Sobral Peninsula beds (Fig. 2) which are considered to be earliest Aptian in age, and on this basis the post-depositional deformation (north-west thrusting and related folding) of the Pedersen Formation can only be dated as younger than earliest Aptian.

The presence of a megaclast of Nordenskjöld Formation strata in the Pedersen Nunatak beds (del Valle *et al.* 1993, and this paper) extends the area with sedimentary evidence of large-scale Lower Cretaceous uplift from northern James Ross Island to Pedersen Nunatak (Fig. 1). Additionally confirmation of a Hauterivian age for the Pedersen Nunatak strata would extend the age range of the Pedersen Formation downward (Hathway 2000), verifying that the Larsen Basin margin in the James Ross Island–Pedersen Nunatak area was actively fault-controlled from at least Aptian to early Coniacian times (Farquharson *et al.* 1984, Ineson 1989, Hathway 2000), and probably from Hauterivian times.

Vaughan & Storey (1997) proposed that the deformation (north-west directed thrusting, extensional folding and strike-slip) of Nordenskjöld Formation strata in the north-eastern Antarctic Peninsula (Whitham & Storey 1989) was produced mainly by north-east–south-west trending sinistral transpression during the Event 2 (Late Jurassic to Early Cretaceous compression), and the late Berriasian–Valanginian break in sedimentation recorded along the Larsen Basin margin (Macdonald & Butterworth 1990) may suggest that this deformation peaked at that time.

Following the ideas of Vaughan & Storey (1997), during Event 4 (mid-Cretaceous compression) coarse sediments were deposited in the Larsen Basin during Aptian–Albian times (Table I, Pedersen Formation strata at southern Sobral Peninsula and lower Gustav Group). These may reflect

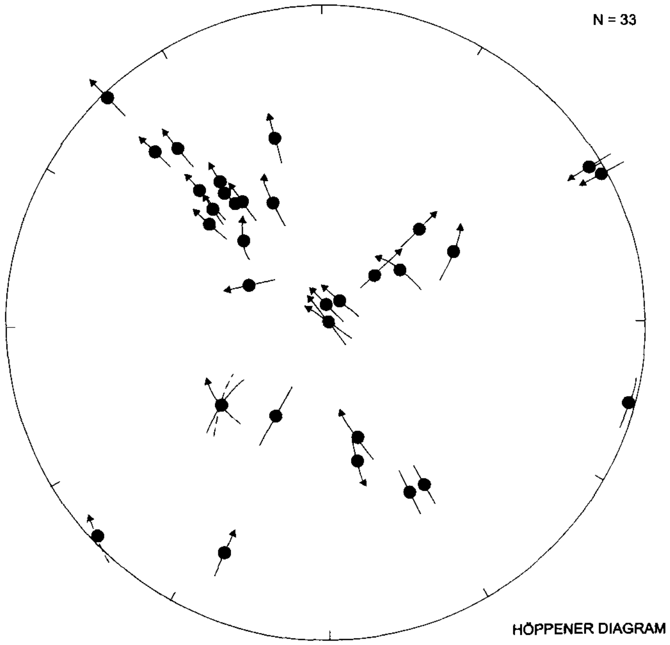

Fig. 8. Höppener (1955) diagram showing fault lineations (arrows and lines) plotted on fault plane poles (dots) from the Southern Block of Pedersen Nunatak. Arrows indicate direction of movement of hanging-wall, and lines indicate lineations of unknown direction of movement.

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periodic uplift and rejuvenation of the arc (Ineson 1989) during this mid-Cretaceous deformation event.

The progressive syn-depositional south-eastward tilting shown in the lower Gustav Group formations (Whitham & Marshall 1988) and the post-depositional deformation of Pedersen Formation were related to phases of the Coniacian partial basin inversion (Hathway 2000) of the northern Larsen Basin, which would fall within the latter part of the Early Cretaceous arc extension–mid-Cretaceous compression event suggested by Storey *et al.* (1996) and Hathway (2000), and may be included within Event 4 (mid-Cretaceous compression) of Vaughan & Storey (1997).

Discussion

Across-arc extension dominated the tectonic evolution of the Antarctic Peninsula for most of the Mesozoic and Cenozoic (Leat *et al.* 1997). During the Late Jurassic–Early Cretaceous sinistral transpression (Vaughan & Storey 1997), important north-west directed thrusting, extensional faulting and strike-slip movements along this fault system occurred from Tithonian times onwards (Whitham & Storey 1989). This mainly compressive deformation affected the Upper Jurassic Nordenskjöld Formation and the Lower Cretaceous Pedersen Formation strata at Sobral Peninsula (Whitham & Storey 1989, Whitham & Doyle 1989), (Fig. 2) and Pedersen Nunatak. Deformation was related by Hathway (2000) to Late Cretaceous partial basin inversion of the Larsen Basin documented in the northern James Ross Island. In all cases, deformation (e.g. north-west verging thrusts and/or north-east trending folds and monoclinal syncline) is concentrated in localized settings, forming a narrow (*c.* 10 km wide) belt parallel to the east edge of the Antarctic Peninsula (Fig. 1). Normal and reverse dip-slip faults and open, gently plunging folds are the most common type of associated structures. This suggests that the deformation may be related to a persistent, long and narrow thrust fault zone (Fig. 1).

Structures at Pedersen Nunatak are rather complex, but the north-east trending thrust faults and almost parallel open folds suggest that they were produced in the same stress field. The maximum compressive stress may have been directed north-west–south-east, locally oblique to the east coast of the Antarctic Peninsula (Fig. 3). Well preserved fault-lineations were recorded only in fault-planes from Pedersen Nunatak southern block. A Höppener (1955) diagram, showing fault-lineations plotted on poles to fault-planes from this part of the nunatak (Fig. 8), suggests that a north-west directed thrust system with minimum oblique displacements was dominant in this area. These thrust-faults are cut by north-west striking faults, which are thought to be a younger subordinate set of oblique, normal and reverse-slip faults with minimum strike-slip components (Fig. 8).

This suggests that north-east striking structures at Pedersen Nunataks were produced by compression oblique or almost perpendicular to the north-east axis of the Antarctic Peninsula (Fig. 3), forming part of a faulted and folded belt on the western border of the Larsen Basin in mid-Cretaceous times (Fig. 1).

According to Hathway (2000), it is not known whether the thrust and reverse faults represent reactivated extensional basement structures or if they formed entirely during a post-earlier Albian phase of Larsen Basin inversion. This appears to have been transpressive (e.g. Vaughan & Storey 1997, Event 4: Mid-Cretaceous compression), but it is uncertain whether inversion was caused by strike-slip dominated tectonics or oblique compression against the basin margin. This deformation is probably related to ?Coniacian deceleration and/or cessation of differential subsidence during deposition of the Hidden Lake Formation (uppermost Gustav Group), which Macdonald *et al.* (1988) and Pirrie *et al.* (1991) attributed to inversion-related tectonic uplift (Hathway 2000). Stratigraphical anomalies (gaps) in the Upper Cretaceous sedimentary record of the Larsen Basin noted by Strelin *et al.* (1992) in the west of James Ross Island may be related to this basin inversion.

Latest movements occurred along a north-east–south-west sinistral strike-slip fault zone proposed in the off-shore Seymour Island–Jason Peninsula area (Fig. 1, *c.* 150 km off-shore of the east coast of the Antarctic Peninsula), assigned a maximum Oligocene age (Sloan *et al.* 1995). The inverted flower architecture reported by Sloan *et al.* (1995) in this wrench fault zone may represent either structures produced by wrench tectonics or post-inversion structures such as reactivated graben faults and hangingwall vergent thrust faults produced by simple north-west–south-east compression. Nevertheless this deformation records the effects of a mid or late Tertiary transpressive deformational event in the Larsen Basin area, post-dating late Cretaceous to early Tertiary across-arc extension (Leat *et al.* 1997). From seismic data, sinistral shear affecting Larsen Basin equivalent rocks has also been identified from the southern Antarctic Peninsula by King & Bell (1996).

Due to the scarce and isolated nature of exposures on the south-east coast of the northern Antarctic Peninsula, recognition of the structures of Pedersen Nunatak and their correlation with structures at Sobral Peninsula and northern James Ross Island (Hathway 2000) is critical for identification of a faulted and folded zone close to the margin of Larsen Basin. This proposed Upper Mesozoic, north-west directed thrust fault zone is almost parallel to the upper Palaeogene wrench faulting zone reported by Sloan *et al.* (1995) (Fig. 1). No critical differences are envisaged in the regional pattern of the two deformation zones bounding the outcrops of the Larsen Basin. Both fault zones may be of similar origin, both being the superficial expression of important displacements at depth, which may have changed direction with time.

Conspicuous gaps in the Upper Cretaceous sedimentary sequence exposed on James Ross Island were linked to faulting mainly along the "Dreadnought Belt" (Strelin *et al.* 1992), (Fig. 1). This runs nearly parallel to the zone further north of deformation that affects the lower Gustav Group, and may be a branch of an anastomosing major fault zone (Fig. 1).

Other stratigraphical anomalies in this sequence at Rabot Point and Hamilton Point (Fig. 1) were also attributed to faulting (Strelin *et al.* 1992). Deformation probably post-dates the Upper Cretaceous fill of the basin and seems to be consistent with the stratigraphical evidence, which supports proposed up-throws of 180–600 m along the above mentioned deformation zones. These movements pre-date the Miocene–Recent James Ross Island Volcanic Group basaltic eruptions (Strelin *et al.* 1992).

Additionally there is an obvious spatial relation between the north-east directed fault zones proposed at Larsen Basin and the late Cenozoic eruptive centres at Seal Nunataks (Fig. 1), where the eruptions of alkali basalts are thought to be controlled by recently active faulting (Veit *et al.* 1997).

Conclusions

?Hauterivian conglomeratic beds exposed at Pedersen Nunatak were deposited during Early Cretaceous extension of Larsen Basin. They show significant post-depositional compressive deformation with north-west directed thrusting and related folding during the mid Cretaceous. These compressive structures are almost parallel to the Weddell Sea edge of the Antarctic Peninsula (Fig. 3), where Hathway (2000, fig. 5) inferred the existence of an important fault system developing since the Early Cretaceous.

The structural evidence presented above suggests that the tectonic regime switched from extension to compression such that the extensional basin was locally shortened and its marginal region at least became an area of positive structural relief. The latter suggests that south-east dipping thrusts at Pedersen Nunatak may represent part of a thrust fault system developed in an inverted extensional basin. This process may have involved the reactivation of pre-existing extensional faults as thrust faults, deforming the Pedersen Nunatak beds during mid-Cretaceous compression of the Larsen Basin.

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