A review of major faults in Svalbard

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ABSTRACT

Eleven major fault zones, either observed or sometimes postulated, are selected for discussion. Some show a long history, possibly dating back to Precambrian time, certainly to mid-Palaeozoic time, with evidence of late Devonian sinistral transcurrence. The best observed parts of these and most other faults are seen where later Phanerozoic rocks are displaced and in Tournaisian through Palaeocene time there is no evidence of strike-slip. However, with the general evidence of dextral strike-slip throughout Cenozoic time in the Spitsbergen Transform there is a short period of Palaeogene transpression (the West Spitsbergen Orogeny) and at that time probably many faults to the east of the orogenic front were initiated or reactivated. Graben faulting followed in the line of that orogeny, and seismic and thermal activity today completes our knowledge of a long mobile sequence.

CONTENTS

1. INTRODUCTION

Svalbard is an archipelago, and Spitsbergen is the largest island with representatives of most geological ages and structures representing most tectonic events. Other islands each expose different features: Nordaustlandet - mainly Precambrian, some Early Palaeozoic and Permian through Triassic rocks; Edgeøya and Barentsdya - mainly Triassic strata; Kong Karls Land - mainly Jurassic and Cretaceous strata; Hopen - mainly Triassic and possibly Jurassic; Bjørnøya - Late Precambrian through Triassic; Prins Karls Forland - Late Precambrian, Early Palaeozoic and Palaeogene.

There is little for our purposes that cannot be seen in Spitsbergen but it is necessary to explore the rest of the archipelago (and indeed the full extent of the Barents Shelf) for continuity of the structures seen in Spitsbergen or for related structures.

Minor faults in Svalbard are ubiquitous, well exposed and generally easy to identify and interpret. Major faults on the other hand are generally inferred, being seldom observed directly. This is because they are drawn through zones of poor exposure or where cover of superficial deposits, of ice or water leave much to the imagination.

It is not unreasonable to assume that the course of major faults will be poorly exposed because extensive dislocation will produce a less resistant outcrop and that their displacement will also be difficult to determine for the reason that the dislocated rocks that might be identified as once continuous may have been removed some distance; morever if they are old faults the displaced rocks may have been subject to different environmental histories so as to make recognition still more difficult.

This paper concerns the major faults of Svalbard, which are in some parts more speculative than minor faults whether associated or not.

1.1 Historical note

Exploratory surveyors generally tended to plot fault lines in Svalbard so as to separate areas of distinctive rock type. Although exposures are generally clean the gaps between are often obscured, so the direct evidence is seldom available. Additionally the distinctive cliffs and coast lines of many fjords were initially interpreted (eg. de Geer 1909) as the effects of faulting. Subsequent research has modified these tendencies, but in two opposing ways so that a similar balance has been preserved. On the one hand investigations of the ancient orogenic structures (eg. of Ny Friesland) have reinterpreted the old concept of Archaean schists and gneisses faulted against younger rocks (as in Tyrrell 1922) by postulating a folded geosyncline in which the older rocks were metamorphosed at greater depth in contrast to less altered younger rocks. On the other hand Spitsbergen appears to have been a mobile region throughout much of its history, viewed either as a site on the margins of plates (eg. Harland 1965) or as a block faulted structure (eg. Sokolov, Krasil'shchikov & Livschits 1968).

The standard current geological maps have drawn greatly upon the early 1:1 M geological map by Orvin (1940).

A particular contribution that fault studies in Svalbard may make to fault studies in general derives from the relatively complete late Precambrian and Phanerozoic stratigraphic record. Thus the way faulting relates to the overall tectonic sequence should be relatively well understood. To put this in perspective an introduction to the tectonic sequence of Svalbard follows immediately.

1.2 Tectonic sequence

The tectonic history of Spitsbergen is punctuated by two main events that not only concern in the study-of faulting but which conveniently divide Svalbard history. These are labelled Svalbardian (late Devonian) and West Spitsbergen (mid-Cenozoic) phases of diastrophism.

If, as I suspect, the Svalbard transcurrent faulting resulted in the juxtaposition of units of lithosphere previously distant, then the earlier history would be a composite one. The later history is certainly unified.

The tectonic sequence in Svalbard is summarized in Table 1, in which (in an oversimplified arrangement) the rock sequences and events have been plotted against a rough vertical time-scale and separated horizontally in an E-W direction but not N-S. This is possible because of the dominant N-S trend of *many* of the structures.

The table shows how at least one fault zone (Billefjorden Fault Zone) and possibly others (Central Western Fault Zone and Greenland Spitsbergen Fault Zone) can be recognized as late Devonian events, each with earlier histories, separating (or developing in) the Holtedahl Geosyncline to the west, the Hecla Boek Geosyncline to the east, and with possibly a distinct Hornsund Geosyncline in the centre.

The eastern (Hecla Hoek) geosyncline, consisting of 18 km of relatively continuous strata, was tectonized very thoroughly in late Ordovician to Silurian time with late orogenic plutonism. It was begun with about 12 km of well stratified volcanic material, both acid and basic.

The western (Holtedahl) geosyncline, of slightly less exposed thickness. is of different facies and thickness distribution. Volcanic facies continue later in this sequence than in the east. Vendian and Early Palaeozoic strata are thicker and of highly mobile facies. Deformation produced large nappes but not with such high grade metamorphic facies as are exposed in the east. This orogeny was post part Silurian and possibly even Devonian. It has some analogy with the Ellesmerian Orogeny of the North American Arctic.

The central (Hornsund) geosyncline, with about 14 km thickness exposed, is more similar to the Eastern sequence in its Palaeozoic facies but compares better with the western sequence in its earlier rocks. Claims have been made by Birkenmajer for several diastrophic phases in the area; but Harland (in press) has suggested an alternative stratigraphy which throws doubt on some of these phases.

After these mid-Palaeozoic orogenies, which may or may not have been synchronous, the Central Province accumulated Old Red Sandstone. There is no evidence of such Devonian rocks to either the east or the west. The Old Red Sandstone was of Early and Middle Devonian age.

The Svalbardian phase of folding and faulting was a major phase of sinistral transcurrent movement along one, two or more faults.

There was then a period of relative stability throughout the whole of Svalbard from Tournaisian to Eocene with deposition of a platform sequence. Then followed the Cenozoic ocean-spreading in the Eurasian Basin and Greenland-Norwegian Sea from about 60 Ma, presumably along the Spitsbergen Fracture Zone (SFZ), Knipovich Ridge (KR) etc. In mid-Cenozoic (?late Eocene) time dextral transpression took place and caused the West Spitsbergen Orogen. Its eastern front followed the line of the postulated Central Western Fault Zone and to the west was mobile, while to the east there was minor reactivation along the old lines, especially along the Billefjorden Fault Zone (BFZ).

The various major fault zones indicated in Table 1 are also shown in Figure 1, which maximises the number of likely major faults.

1.3 Identification of lineaments

In this discussion only those lineaments that have been thought to represent major fault zones are discussed. It so happens that the faults that are more easily identified in the field and mapped with more confidence tend to be of relatively small displacement, at least so far as later motion is concerned. Large earlier displacement generally carries with it the difficulty of recognising and matching ruptured rocks and structures on either side of the faults possibly now far distant. Subsequent different environmental histories and the weakening in a fault zone that leads to poor exposure add to the problem.

Major lineaments are shown in Figure 1. They are treated in the following order in the next section, and the abbreviations are used freely

1. Lady Franklinfjorden Fault (LFF)
2. Hinlopenstretet Fault Zone (HFZ) - postulated
3. Lomfjorden Fault Zone (LFZ)

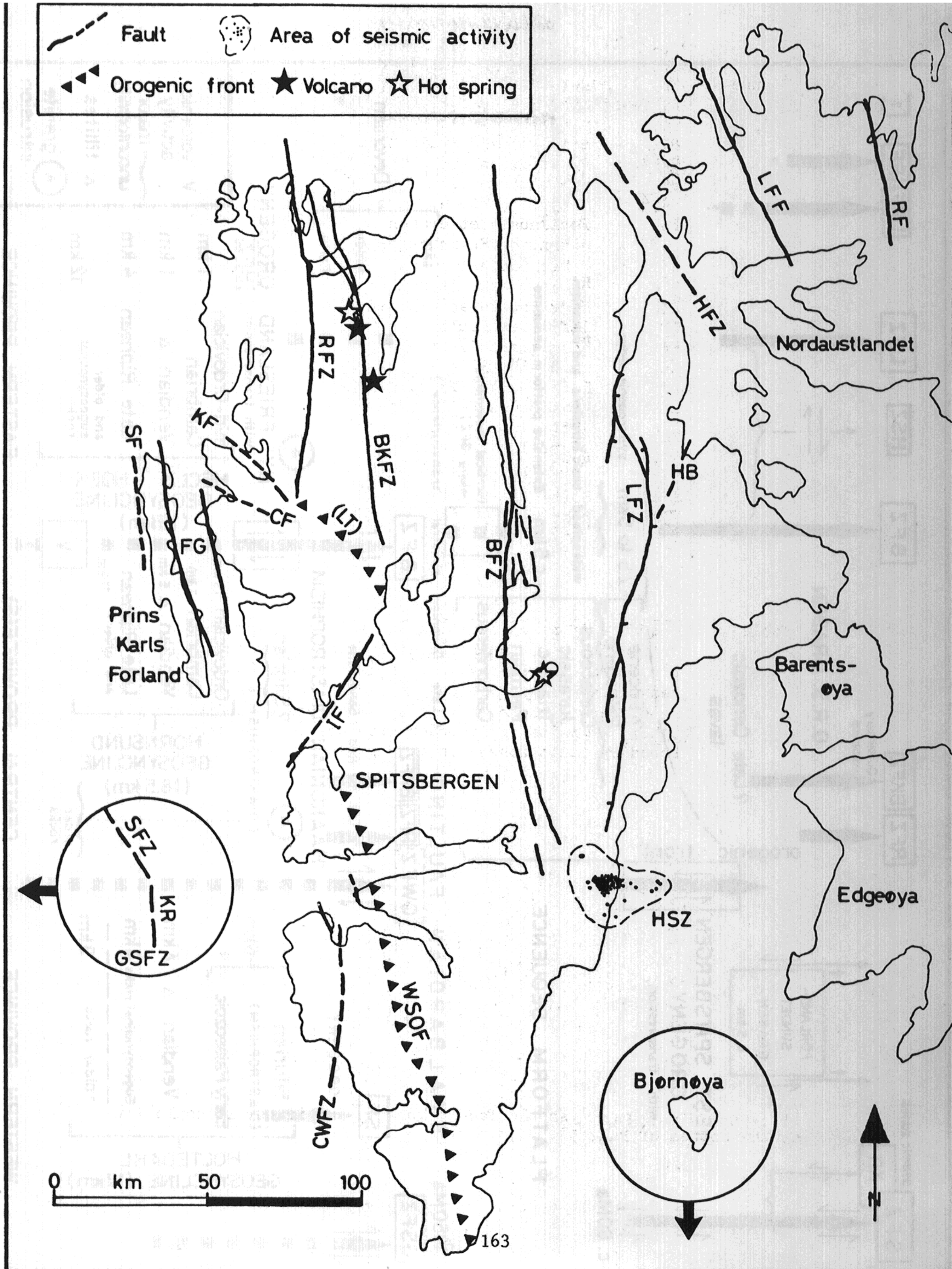
4. Billefjorden Fault Zone (BFZ)
5. Bockfjorden Fault Zone (BKFZ)
6. Raudfjorden Fault Zone (RFZ)
7. West Spitsbergen Orogenic Front (WSOF)
   and the
   Central Western Fault Zone (CWFZ) - postulated
8. Forlandsundet Graben (FG)
9. Sutorfjella Fault (SF) - postulated
10. Spitsbergen Fracture Zone (SFZ)
    and Knipovich Ridge (KR)
    Greenland Spitsbergen Fault Zone (GSFZ) - postulated
11. Heerland Seismic Zone (HSZ)

Figure 1: Map of major faults and indicators of fault activity. Abbreviations are as follows:

BFZ	Billefjorden Fault Zone
BKFZ	Bockfjorden Fault Zone
CF	Comfortlessbreen Fault
CWFZ	Central Western Fault Zone
FG	Forlandsundet Graben
GSFZ	Greenland Spitsbergen Fault Zone
HB	Hinlopenbreen
HFZ	Hinlopenstretet Fault Zone
HSZ	Heerland Seismic Zone
IF	Isfjorden Fault
KF	Kongsvegen Fault
KR	Knipovich Ridge
LFF	Lady Franklinfjorden Fault
LFZ	Lomfjorden Fault Zone
LT	Lappdalen Thrust
RF	Rijpdalen Fault
RFZ	Raudfjorden Fault Zone
SF	Sutorfjella Fault
SFZ	Spitsbergen Fracture Zone
WSOF	West Spitsbergen Orogenic Front

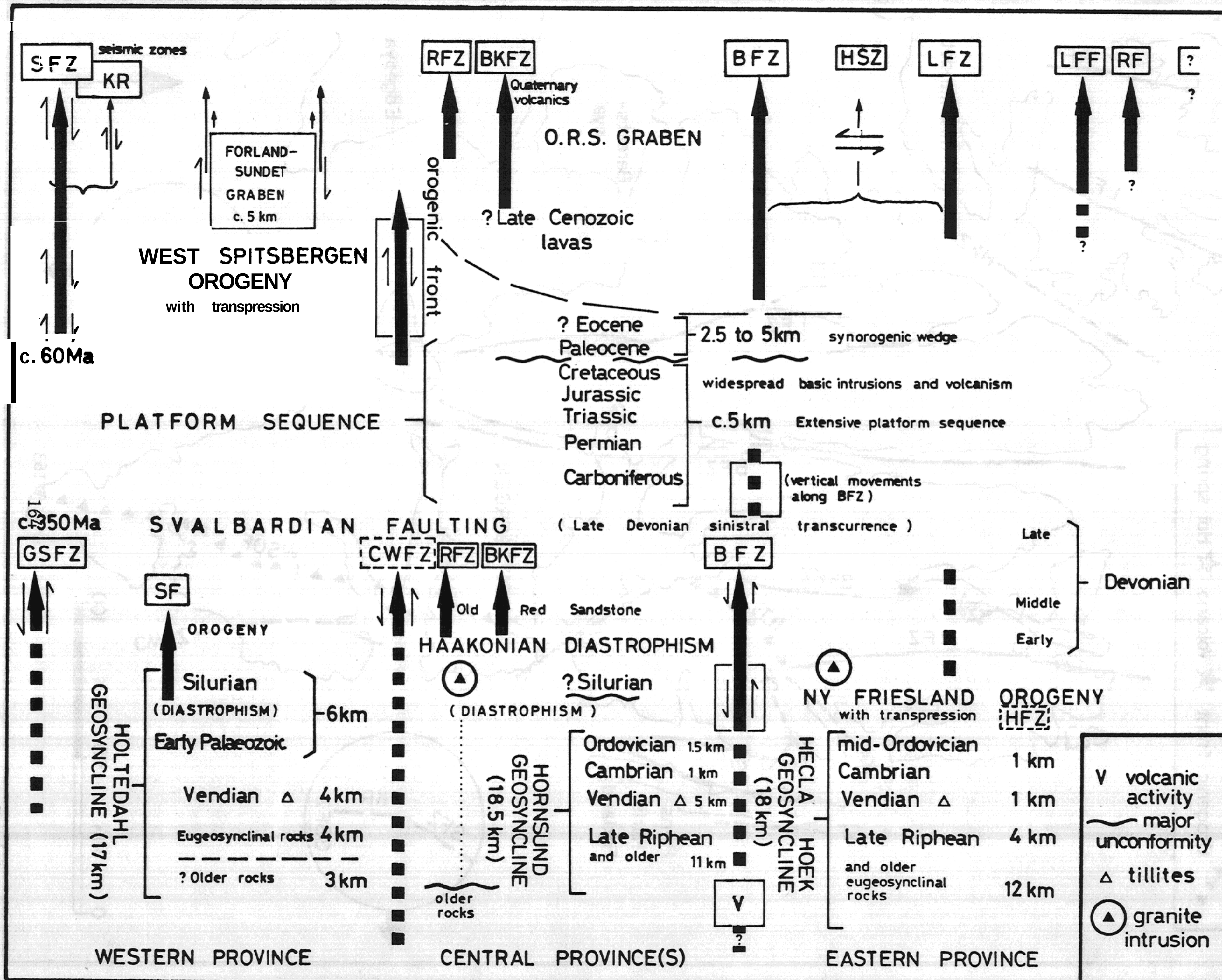
Table 1: Sequence of major faulting in Svalbard. Vertical axis represents time and horizontal axis represents the various provinces, traversing west to east across Spitsbergen. Heavy black lines indicate activity on a particular fault zone, dashed where uncertain. Sequence of sedimentary (and other) deposits within each province (as distinguished by boundary fault zones) is also given.

[Note to Editor: Page 6 should face Figure 1, but if not it could fit at the bottom of Page 5].



Fault
Area of seismic activity
Orogenic front
Volcano
Hot spring
LFF
RF
HFZ
Nordaustlandet
RFZ
BKFZ
KF
SF
CF
(LT)
FG
BFZ
LFZ
HB
Prins
Karls
Forland
Barents-
øya
TF
SPITSBERGEN
SFZ
KR
GSFZ
HSZ
Edgeøya
WSOF
CWFZ
Bjørnøya
0 km 50 100
N
163

Figure 1



SFZ
KR
seismic zones
RFZ
BKFZ
Quaternary volcanics
BFZ
HSZ
LFZ
LFF
RF
?
FORLAND-SUNDET GRABEN c. 5 km
O.R.S. GRABEN
orogenic front
? Late Cenozoic lavas
WEST SPITSBERGEN OROGENY
with transpression
c. 60Ma
? Eocene
Paleocene
2.5 to 5km
synorogenic wedge
Cretaceous
Jurassic
Triassic
Permian
Carboniferous
widespread basic intrusions and volcanism
PLATFORM SEQUENCE
c.5km
Extensive platform sequence
(vertical movements along BFZ)
c. 350Ma
SVALBARDIAN FAULTING
(Late Devonian sinistral transcurrence)
GSFZ
CWFZ
RFZ
BKFZ
BFZ
Late
Middle
Early
Devonian
SF
OROGENY
Old Red Sandstone
HAAKONIAN DIASTROPHISM
Silurian
(DIASTROPHISM)
6km
Early Palaeozoic
?Silurian
(DIASTROPHISM)
NY FRIESLAND OROGENY
with transpression
HFZ
HOLTEDAHL GEOSYNCLINE (17km)
Vendian 4km
Eugeosynclinal rocks 4km
? Older rocks 3km
older rocks
HORNSUND GEOSYNCLINE (18.5 km)
Ordovician 1.5 km
Cambrian 1 km
Vendian 5 km
Late Riphean and older 11 km
V
HECLA HOEK GEOSYNCLINE (18 km)
mid-Ordovician
Cambrian 1 km
Vendian 1 km
Late Riphean 4 km
and older eugeosynclinal rocks 12 km
V volcanic activity
major unconformity
tillites
granite intrusion
WESTERN PROVINCE
CENTRAL PROVINCE(S)
EASTERN PROVINCE

Table 1

2. DISCUSSION OF MAJOR LINEAMENTS

2.1 Lady Franklinfjorden Fault (LFF)

The latest map of north-western Nordaustlandet (Flood et al. 1969) shows many faults, but the only one that might qualify as a major fault is one that appears to turn from Wahlenbergfjorden in the south, north to and through Lady Franklinfjorden, where it separates the Kap Hansteen Formation with granites to the east from the Murchison Bay Supergroup to the west. There is no reason to suppose that the rocks on either side are not closely related in the sequence, so the evidence is for dip-slip with downthrow as well as downfold to the west but no evidence of strike-slip. Any extension to the south of Wahlenbergfjorden is obscured by ice as well as Permian and Triassic strata which have not been sufficiently investigated to provide evidence of continuity.

2.2 Hinlopenstretet Fault (HF)

The straits that separate Spitsbergen and Nordaustlandet will almost certainly contain some minor faults, but there is no evidence for a major fault. It is mentioned here as it is the site of the Proto-Atlantic suture as proposed by Wilson (1966). The similarity of late Precambrian and Early Palaeozoic rocks on both sides of this synclinal structure, however, make it probable that no major discontinuity intervenes.

2.3 Lomfjorden Fault Zone (LFZ)

A long and very well defined fault zone is named from Lomfjorden in the north, where one splay of the fault may reach the shore. The fault is easily mapped because the sub-Carboniferous unconformity runs sub-parallel to the topographic surface, so that on the downthrow side Carboniferous or Permian strata are generally juxtaposed against Hecla Hoek strata (Harland, 1969). The fault system branches, forming a small graben east of the Chydenius granite - the uplift of which appears to accentuate the upthrow on the west as well as being deflected by the granite so as to curve convex to the east. In the northern part of this fault system the structural and stratigraphic constraints preclude any major strike-slip, Palaeozoic or later.

The fault can be traced south nearly to Storfjorden. Orvin's map (1940) shows the fault coming out to sea at Agardhbukta, but Flood et al. (1971) show it turning inland. J.R. Parker (private communication) had independently mapped it there and shown a splay further north as indicated in Figure 1.

The southern extent of the fault almost certainly shows no strike-slip in Late Palaeozoic or Mesozoic rocks, and indeed there is no evidence that the fault existed in Palaeozoic time. However, if it did, strike-slip motion could not be accommodated to the north; but a possible route could be along Hinlopenbreen to Hinlopenstretet. I believe the chance of this to be small and the fault pattern is mostly the result of Tertiary movement as now seen with control (and possibly initiation) in late Caledonian structures and uplift.

2.4 Billefjorden Fault Zone (BFZ)

Tracing this lineament from north to south it first follows a course beneath the long fjord (Wijdefjorden) in the north. It then traverses the isthmus between Wijdefjorden and Billefjorden, where a complex array of 34 faults is observed with demonstrable motions at least in mid-Palaeozoic and mid-Cenozoic time (e.g. McWhae 1953, Harland ―. 1974, , Cutbill, Henderson & Wright 1976). It then continues south under Billefjorden and traverses south-west Bünsow Land where Tertiary faults are seen in Upper Palaeozoic rocks. They were also active in Late Palaeozoic time. The fault zone crosses Sassenfjorden and is observed there first in Upper Palaeozoic rocks but mostly in Mesozoic strata (Parker 1966) and with decreasing effect in younger rocks till it appears to cut the coast at Storfjorden.

Mesozoic and Cenozoic tilting has resulted in deeper exposure in the north, while in the south the fault line is much less evident in later Mesozoic strata. A consequence of this variation in depth exposure is that the structural nature of a fault zone at different levels may be seen - but more important perhaps is the unusually long history that is documented in the strata. Being the subject of a longish paper already (Harland et al. 1974) only a summary of the sequence (taken from that paper) is given here with some additional comments.

(1) Basic volcanism in early Recla Hoek times suggests an early phase of crustal extension and/or high mantle heat flow during late Precambrian time at, say, 1000 Ma ± 200. This might relate to an early oceanic phase (Proto-Iapetus).

(2) Basic rocks alternate with, and are then superseded by, acid strata with a volcanic and possibly an arkosic contribution. This indicates at least proximity to a continent or island arc.

Both (1) and (2) show the area to have been a mobile zone characteristic of a lithosphere plate margin. The later Hecla Hoek rocks, of miogeo-synclinal facies to Mid-Ordovician age suggesting long slow subsidence, are only preserved down dip, say 10-15 km to the east of the lineament.

(3) Around Silurian time the main Caledonian deformation (Ny Friesland Orogeny) took place and at first resulted in E-W compression and crustal thickening. This could correspond to the final closure of the Iapetus Ocean further south (Harland & Bayly 1958).

(4) Normal compression was succeeded by N-S extension as evidenced by boudinage. This could correspond to a change of motion from compression to sinistral transpression along the axial zone of the Billefjorden Lineament which served to localize it.

(5) A late stage in the Ny Friesland Orogeny showed local N-S basic dyke emplacement. This has been interpreted as local transtension in a dominantly transcurrent regime.

(6) During Early and Middle Devonian time no evidence of faulting is known but uplift to the south and west provided detritus for deposition with continued subsidence. Because there is no evident disturbance in the Old Red Sandstone or coarse deposits to indicate uplift near the fault line I assumed

that the fault was inactive through this time span. On the other hand purely stike-slip motion could have continued throughout this time without obvious effect if the fault were cutting deposits on a river flood plain. This became clear to me from the lack of topographical expression where the San Andreas Fault cuts the alluvial plain east of Palm Springs.

(7) Old Red Sandstone sedimentation was interrupted between mid-Devonian (Givetian) and earliest Carboniferous (Tournaisian) time and this corresponded to the Svalbardian movements. Folding and thrusting appear to be secondary transpression effects of dominantly sinistral transcurrence along the central and northern areas. This episode corresponded to substantial transcurrence of two major plates, with or without minor plate slivers between them (Harland 1972).

From internal evidence a movement of at least 200 km is probable. From external evidence 100 to 1000 km or more is possible. Such a large displacement might have been accommodated either all along the Billefjorden Lineament or have been distributed amongst more than one fault.

(8) No further strike-slip is recorded from strata ranging in age from Tournaisian to Palaeocene that cover the fault zone in the southern part of Spitsbergen. Nevertheless vertical movements are recorded in these strata, which by comparison with the preceding history were relatively minor. They do, however, indicate that the lineament continued to exercise some basement control.

(9) Carboniferous sedimentation was closely controlled by vertical movements as, for instance, the Pyramiden conglomerates. At the same time (? Late Moscovian or early Bashkirian) N-S lamprophyre dykes indicate localised E-W extension.

(10) Relative stability with only widespread, rather than localised, disconformities continued through Permian to the end of Jurassic time.

(11) Basic intrusive and volcanic activity began in post part-Volgian time and continued intermittently over a broad area of Svalbard into Barremian time. At the same time faulting and some folding took place along the lineament.

Intrusion was in no way limited to the lineament; nevertheless some considerable sills seem to have been controlled in their emplacement by the fault zone.

(12) Late Cretaceous upwarping was also general rather than localised, as was Palaeocene subsidence.

(13) In Mid-Cenozoic time the main E-W compression and transpression of the West Spitsbergen Orogeny, transmitted somewhat independently through cover and basement, appeared as minor folds and faults in the platform strata, especially localised along the lineament.

(14) Some extension or compensatory subsidence with renewed minor graben formation may have accompanied a general mantle expansion.

(15) Thereafter transcurrent motion transferred still further west to the Spitsbergen Fracture Zone and Spitsbergen itself behaved as a block with differential uplift, erosion, renewed uplift and dissection to the present.

2.5 Bockfjorden Fault Zone (BKFZ)

This is a well defined major fault zone that can be seen clearly throughout its northern extent, where older metamorphic rocks to the west form the margin of the Old Red Sandstone Graben that occupies the terrain between this BKFZ and the BFZ.

The age of faulting is not certain. Orvin's map (1940) shows the fault apparently unconformably overlain by Carboniferous and Permian strata at its southern limit. If this be the case then the fault, like the main Balliolbreen Fault of the BFZ, must be Svalbardian (late Devonian). However, exposures may not be good enough to determine this.

This fault zone would appear to have been active in Quaternary time with volcanoes at Sigurdfjellet and Sverrefjellet (Gjelsvik 1963). Hot springs are also present.

Its earlier history is also evident because the line coincides with a zone of thrusted Siktefjellet Group rocks. Their age is latest Silurian or early Devonian and the Haakonian compressive phase is earliest Devonian (pre- Red Bay Conglomerate which is basal Old Red Sandstone). This northerly development shows a westerly splay of the Graben fault (Gee 1972).

All evidence suggests a long and complex history analagous to the BFZ. That the fault is not traced south of Isfjorden is not surprising because that is the area of thickest basin development of later rocks, but these later rocks do show Tertiary compressive structures (e.g. east of Adventfjorden) which might be located by a deep extension of this fault. They are certainly in a plausible location for such basement control.

2.6 Raudfjorden Fault Zone (RFZ)

The northern part, which outcrops along the west shore of Raudfjorden, is well known at Konglomeratodden where there is downthrown basal Old Red Sandstone (Red Bay Conglomerate) on the shore side. It appears to run N-S as a straight line and was so mapped by Orvin (1940) for 100 km. However, Gee (1972) showed a sinistral oblique displacement west of Liefdefjorden.

The fault zone has a similar effect to the BKFZ, juxtaposing downthrown Old Red Sandstone to the east against Precambrian metamorphics to the west.

Thus the western edge of the Old Red Sandstone graben has two stepped fault zones (BKFZ and RFZ). Sedimentation in the Old Red Sandstone suggests contemporaneous uplift along these lines. On the other hand the eastern margin (BFZ) appears as a transcurrent fault.

The southern end of the fault appears to be truncated by the oblique West Spitsbergen Orogenic Front (see below) and it could well have continued as an earlier fault through some length of this orogen.

2.7 The West Spitsbergen Orogenic Front and the Central Western Fault Zone

The orogenic front is observed (e.g. Orvin 1940, Lowell 1972, Harland & Horsfield 1974); the Central Western Fault Zone has been inferred (Harland & Wright [1975] in press, cf. Harland 1978).

Kongsvegen Fault (KF)

The course of the front is shown on Figure 1 (WSOF). Its northern part has long been considered a major fault and was referred to by Harland (1972) as "fault f" (The Kongsfjorden discontinuity and Kongsvegen lineament):

> "A major fault system can be imagined running through Kongsfjorden and the glacier Kongsvegen. Opposing structures strike differently. Palaeogene orogeny has, apparently, radically affected only the areas south of Kongsfjorden. Kongsfjorden probably conceals a Tertiary dislocation or thrust front. To the south-east the line does not dislocate post-Devonian rocks-therefore any strike-slip would be earlier. Most Phanerozoic systems crop out south of the fjord; only Lower Hecla Hoek-type sediments and Caledonian granite and migmatite are north of the fjord. It has proved difficult to correlate the Pre-Carboniferous rocks on each side."

West Spitsbergen Orogenic Front (WSOF)

The main extent of the orogenic front is an abrupt transition from overfolds and overthrust sheets piled on each other to only slightly folded platform sediments. There are indeed many thrust faults, all clearly of Palaeozoic age and closely associated with the folding (Challinor 1967, Lowell 1972, Harland & Horsfield 1974, Challinor 1979). North of Isfjorden the West Spitsbergen Orogen is relatively wide (Harland & Horsfield 1974). The structures are concentrated in Brøggerhalvøya (between KF and CF) with nappe strucures illustrated by Challinor (1967 & 1979). Further to the south and east the orogen widens. Its front is marked by the Lappdalen Thrust; but to the south-west there are many other thrusts.

South of Isfjorden the West Spitsbergen Orogenic Front is offset to the west, possibly along the Isfjorden Fault. The orogen on land is narrow in Nordenskiöld Land, only occupying the western tip of Nathorst Land before widening again to the south of Bellsund.

The whole structure relates to non-oblique compressive or transpressive phases in mid-Palaeogene time, when dextral transform movements transported Spitsbergen past Greenland. The folds and thrusts (over to the north-east) show a dextral transpression. As exposed at the surface the thrusts comnly pass down into low angle faults and are probably rooted to the west. This root zone is probably located off the coast of Spitsbergen and may be imagined as a transpressive shear zone (Lowell 1972).

Interpretation of the structures is difficult in this orogen because most of the thick Cenozoic overfolding and overthrusting to the east is superimposed on mid-Palaeozoic overfolding and overthrusting to the west. In addition the latter was on a more massive scale with some metamorphism.

Central Western Fault Zone (CWFZ)

This is not seen, but has been inferred from the sequences of older rocks along the central west coast of Spitsbergen, which contrast with the sequences to the east (Harland & Wright in press, Harland 1978).

The argument runs that the sequences to west and east were formed in widely different regions and were juxtaposed by sinistral transcurrence, in Late Devonian time, analagous to the BFZ movements. This was postulated as a major fault zone that provided, from Carboniferous through Mesozoic time, a sedimentary axis and then the basement control that determined part of the WSOF. The CWFZ must come out to sea in the south through Torellbreen. It may pass out through Kongsvegen (KF) in the north or even in the extreme north in RFZ. If the CWFZ is an old transcurrent fault its trace may probably curve convexly to the east as a result of the Palaeogene transpression.

The strength of the argument, put forward by Harland & Wright in 1975 (in press), has been diminished somewhat by fieldwork in 1977 and 1978 which reduced the supposed contrast in Vendian rocks east and west of the CWFZ. Birkenmajer (1960) gave a Vendian sequence with no tillites - but it would now appear that Vendian tillites are well developed there (Harland in press). Other contrasts, however, persist - especially in Early Palaeozoic sequences.

2.8 Forlandsundet Graben (FG)

Within the West Spitsbergen Orogen is a graben running parallel to it and apparently post-dating the main fold and thrust structures. It is therefore a late orogenic structure.

The Western Forlandsundet Fault Zone, seen along the northern half of Prins Karls Forland, indicates a compressive phase because the Palaeogene strata dip steeply near the margin and are not always easily distinguished from the Palaeozoic strata. There is no doubt about this graben boundary structure. Further south on this western boundary and also on the Eastern Forlandsundet Fault there is step-faulting with only low stratal dips. It would thus appear that the graben has had a complex history, with opening and subsidence during an extensile episode (following the transpression of the main West Spitsbergen orogenic phase), and a short transpressive phase to compress the earlier sediments in the graben.

The sequence of (1) transpression, (2) transtension, (3) minor transpression and (4) transtension again, are all part of a major transcurrent zone. This is the transform between the spreading ocean basins of the Gakkel Ridge in the north and the North Atlantic to the south.

Similar graben structures appear along the west coast of Spitsbergen further south, e.g. both north and south of Bellsund, but the graben structure in these cases is not so obvious.

It is not clear to what extent the extension in these graben zones took place with a strike-slip component. It is however, reasonable to suppose that the graben vas the result of transtension. We know that throughout Cenozoic time a general dextral transcurrence took place along the transform between the Eurasian Arctic Ocean Basin with its spreading Gakkel Ridge, and the North Atlantic basins with their complex pattern of mobile zones. The West Spitsbergen Orogeny resulted from a compressive component producing transpression. The sequel with graben formation, was the result of an extensile component with transtension (Harland 1971, Lowell 1972, Harland & Horsfield 1974).

Another problem is the the question of where the West Spitsbergen Orogen thrust sheets may be rooted. They could be squeezed out of this zone before it was a graben or have been rooted still further to the west - west of Prins Karls Forland - or both.

2.9 Sutorfjella Fault (SF)

The only evidence for a fault along this margin is the occurrence of very coarse Sutorfjella Conglomerate, which could only have formed on a fault scarp and probably to the west of one. Such an ancient fault - active in Early Palaeozoic time - would (together with the Forlandsundet Graben) make Prins Karls Forland into a horst at the present time, and it may initially have been a distinct block. There is no evidence of horizontal motion but it must have uplifted to the west.

2.10 Fault Zones offshore to the west of Spitsbergen

Spitsbergen Fracture Zone (SFZ)

This has been well identified by seismic activity (e.g. Horsfield & Maton 1970). It is a seismically active lineament trending NNW-SSE and located 100 km west of Prins Karls Forland.

Knipovich Ridge (KR)

Opposite Spitsbergen the SFZ is joined to a lineament with a different direction (it runs more or less due south) and it is a more pronounced positive feature - the Knipovich Ridge.

It appears that much of the dextral transcurrence that has separated Svalbard from Greenland took place along these zones. The configuration would suggest that the KR is partly transtensile (the transform may be a bit leaky) due to change of direction.

Greenland Spitsbergen Fault Zone (GSFZ)

This is a speculative zone of mid-Palaeozoic age. It was first postulated by me in 1964 (Harland 1965) to account for the similarity of the older rocks in Spitsbergen with those in central East Greenland, while the younger rocks compared more clearly with those of North Greenland and the Canadian Arctic. So I suggested that a phase of late Devonian sinistral transcurrence would have translated Spitsbergen from a position opposite East Greenland to one north of Greenland.

At that time I had not worked in Western Spitsbergen. However, it later became evident that western Spitsbergen showed a similar contrast with eastern Spitsbergen so it was suggested (Harland 1969) that some of this Late Devonian sinistral. motion took place along the

Billefjorden Fault Zone; and later still (Harland & Wright, in press) that it occurred also along the Central Western Fault Zone.

Thus the need for similar motion offshore was reduced - but shear motion may still have taken place there and been distributed through a number of subparallel anastomosing faults. If so, then the Cenozoic dextral motion reversed the translation but possibly ran along similar lines. It would then follow that the GSFZ may have preceded and determined the locus of the SFZ.

2.11 Heerland Seismic Zone (HSZ)

Earlier plots of earthquake epicentres, in addition to showing a spread of points related to the SFZ etc, showed one or two points on the south-east coast of Spitsbergen. This has proved to be a persistently active zone, and further work is in progress. I am grateful to Professor Mitchell for allowing me to use a pre-print of one of his papers (Mitchell & Chan).

A network of instruments was set up in Svalbard. During 1977, with a nine-week field season, nearly 50 events were recorded well enough to be located with some accuracy (errors between 3 and 8 km within the network). They show an area of high activity in Heerland. The suggestion is of an E-W trend with sinistral motion. Although such an E-W line extends for 25 km well into Storfjorden, 85% of the earthquakes occur in the 12 km segment on land. It so happens that this segment is approximately where the extension of the BFZ and the LFZ would cut the E-W line but with only exceptional coincidence. The concentration of earthquakes in the E-W line here may be due to some release of energy at the intersection with the older lines running N-S.

These results (with an EW motion) are totally unexpected and suggest that a change in stress pattern has obtained sometime since the early mid-Cenozoic transpression of the West Spitsbergen Orogen. This new pattern might be related to a spreading component along the Knipovich Ridge to the south of the E-W line, in contrast to the present purely transcurrent motion along the Spitsbergen Fracture Zone where it continues to the north. It might also be noted that one of the two centres of thermal activity which possibly indicate contemporary faulting is well to the east of the BFZ. This is the patch of warm water in Tempelfjorden, above which clear water persists in winter even when the rest is frozen (Harland et al. 1974, p. 45). This could be a newly active splay of the BFZ, opened up by the E-W motion indicated by Mitchell and Chan.

3.1 Continuity of motion in same lineament

The latest fault motions are evident from seismic activity that lies mostly to the west in the Spitsbergen Fracture Zone and the Knipovich Ridge, plus the Heerland Seismic Zone and a few other minor earthquake foci and hot springs. At first sight this activity bears little relation to the known faults mapped on the mainland, but there is some coincidence.

The fault pattern of Svalbard as generally mapped would appear largely to be the effect of Tertiary activity, although in most cases the dating of the last major movement is largely circumstantial. The stress pattern generated by the Palaeogene transpression appears to have reactivated older faults. In many cases it is not evident whether there was earlier faulting along these lines.

There is however good evidence that the Billefjorden Fault Zone was active through most of Phanerozoic time and possibly earlier. Similarly the Bockfjorden Fault Zone, and by analogy the Raudfjorden Fault Zone, might have a similar history. The Central Western Fault Zone was postulated largely to account for pre-Devonian sequences being apparently juxtaposed in late Devonian time. If that happened it probably controlled the West Spitsbergen Orogeny to some extent.

3.2 Evidence of displacement by dissimilarity of juxtaposed sequences

As horizontal displacement increases the difficulty of matching the dislocated margins also increases, especially their structures which will differ if subject to different stress regimes. Stratigraphic and tectonic sequencestogether are often sufficiently complex for similarity of both to be fair evidence of original juxtaposition.

From this point of view I began to argue on stratigraphic grounds for sinistral late Devonian strike-slip between Spitsbergen and Greenland (Harland 1965). Later the Billefjorden Fault Zone provided structural and sedimentological evidence of sinistral strike-slip. So sedimentary - tectonic older sequences in Eastern contrasting with Western Spitsbergen suggested that part at least of the substantial displacement in late Devonian time was related to the evident Svalbardian structures (Harland 1969).

The problem arises as to how to interpret the stratigraphic sequences in each fault block, i.e. to what extent to lump or to split them. The initial temptation in stratigraphic exploration is to lump all into one sequence if possible. Alternatively differences of sufficient degree may be reason for separating the areas by major faults. I made attempts along these lines in 1972 with Gayer (1972), in 1975 with Wright (in press), and again in 1978.

For example the north west corner of Spitsbergen consists of Precambrian rocks certainly metamorphosed in mid-Palaeozoic and possibly also in Precambrian orogenies. This area could be an independent province separated both by the Raudfjorden Fault Zone from rocks to the east and by the Kongsvegen Fault from those to the south. It could just be the basement, ie. the older part of either sequence to east or south. I would argue for a closer connexion to the east and a major fault to the south (KF) so including it with the Central Province (Harland & Wright in press).

Ten to sixteen areas have been distinguished (especially by me in 1972 and 1978) as a basis for multiple hypotheses of different major fault patterns between them. In each paper the sequences in each area was outlined and tabulated (in Figure 1 in 1972 and Figure 2.2 in 1978), and it would double the length of this paper to discuss these sequences with respect to their similarities and differences.

The areas are all those defined between the major faults. Indeed changing Views of the degree of strike-slip on particular faults go hand in hand with the interpretation of the tectonic - stratigraphic sequences between them.

In summary an hypothesis of at least three provinces separated by two faults appears to be the simplest that is consistent with present evidence. These are

(1) The Eastern Province including the whole area east of the Billefjorden Fault Zone.

(2) The Central Province including all that is west of the BFZ and east of the postulated Central Western Fault Zone.

(3) The Western Province including all that is west of the CWFZ at least to the end of the land.

Any of the above might also be divided - for example in the Western Provinces.

Harland et al. (in press) combined the sequences on both sides of Forlandsundet. It is possible they were distant when formed as the only rocks certainly common to both sides are the ubiquitous tillite facies. In this case the Forlandsundet Graben would be both a major transcurrent Palaeozoic fault as well as an important Cenozoic fault zone, possibly transcurrent with transtension.

3.3 Transcurrence, transtension and transpression

Strike-slip motion on a fault, if of sufficient degree, implies that a shear of some kind must extend through the lithosphere to the asthenosphere. It is indeed a mobile zone at a plate margin. Such is a transcurrent fault and in general a trancurrent fault will be part of a transform fault which typically runs from zones of divergence and convergence; such zones being located at its termini and perpendicular to it (Harland 1978b).

Oblique strike-slip motion may be extensile or compressive. The two tectonic processes have been termed transtension and transpression (Harland 1971). In each case they may arise in alternative ways which might be referred to as primary and secondary.

Primary transtension and transpression arise from motion between plates that is oblique to their mutual boundary. Typically oblique ocean spreading zones result in a series of stepped transform faults. The oblique motion is thus resolved into transcurrent faults and spreading zones normal to each other. Oblique opening of a graben or dyke zone is not so common an alternative mode of transtension, or it may just be more difficult to identify. Primary transpression, on the other hand, appears to develop into a subduction zone with a combination of compressive orogenic expression at the surface and a transcurrent fault system.

Successive changes in poles of rotation between plates may lead to a progression from dominant convergence to dominant transcurrence. Transcurrent faults running parallel to and to one side or within major orogens would be expected from such processes. The opposite progression from transcurrence to transpression would produce an orogenic belt out of a strike-slip zone. Its origins might then' be obscured.

Secondary transtension and transpression arise from parallel transcurrent motion between plates along a fault zone which is not straight **or** the arc of a circle. Irregularities in such a fault would produce local zones of relative extension (graben formation or en echelon normal faults) or compression (with for example en echelon folds at a superficial level).

Structures in Spitsbergen illustrate all the above phenomena as will be outlined below.

A(i) Primary transtension is **only** easily recognisable in the late Phanerozoic record because ocean floor is **part** of the resultant oblique spreading pattern. The Spitsbergen Fracture Zone is part of the oblique zone extending between the Eurasian Arctic Basin (spreading along the Gakkel Ridge) and the complex of spreading ridges extending north from the North Atlantic Ocean basin through the Greenland and Norwegian Sea basins. This whole zone might be referred to as the Spitsbergen Transform. It may well have operated through fault zones other than the Spitsbergen Fracture Zone, either simultaneously or in sequence. Such might be nearer the coast of the Spitsbergen or even on the line of the Forlandsundet Graben. An example of pure primary transtension might be the Knipovich Ridge.

A(ii) Primary transpression was interpreted in the Ny Friesland Orogen where limited folding and nappe formation gave rise along the margin of Wijdefjorden (east of BFZ) to an elongation lineation with boudinage, elongated tilloid stones, and a penetrative linear fabric all homoaxial with the fold structures. Where oblique shear is evident it is sinistral (Harland 1959 & 1971).

The progression from compression to strike-slip is interpreted as the generation of the Billefjorden Fault Zone at a late stage following orogenic transpression.

The progression from strike-slip to compression is illustrated in the Cenozoic dextral shear zone (referred to above as the Spitsbergen Transform). At some point (not yet precisely defined) around mid-Palaeogene time the West Spitsbergen Orogeny developed from a dextral transpression when the Greenland and Eurasian plates moved obliquely towards each other for a relatively short time. This orogenic deformation would appear to be a relatively superficial phenomenon extending out to the West Spitsbergen Orogenic Front from a relatively narrow and deep rooted zone or zones (Lowell 1972).

B(i) Secondary transtension may be illustrated by two examples in Spitsbergen. The first is the speculative explanation of late dykes to the east of the northern part of the BFZ after transpression had ceased and when transcurrence was progressing. A local irregularity could cause sufficient relaxation for parallel dyke formation without the need to postulate a general extensile regime at that time, for which we do not know any other evidence.

Secondly the Forlandsundet Graben is interpreted as a late orogenic graben associated with the West Spitsbergen Orogen. Dextral strike-slip is known to have been active along the Spitsbergen Transform and mostly with purely transcurrent motion. The graben could be of limited extent and be the result of motion along an irregular plate boundary. To what extent strike-slip activity preceded or followed this graben along its length is not clear. An alternative possibility is that the same principle of a dextrally transcurrent pressure shadow could apply but along a neighbouring fault just to the west.

B(ii) Secondary transpression. The evidence for sinistral transpression on a small scale, to accompany the Svalbardian phase of strike-slip along the Billefjorden Fault Zone, is best seen west of the northern part of the BFZ where it bounds the Old Red Sandstone graben. Structures in the graben show both dip-slip thrusts (possibly rooted in the BFZ) and also en echelon folds (NE-SW) adjacent to the BFZ.

One problem in oblique tectonics relates to the tendency for transpressive motion to resolve into a major strike-slip fault zone with dip-slip thrust margins. Similarly also transtensile regimes may lead to deep strike-slip with superficial dip-slip. This leads to difficulty in recognition of strike-slip motion if some of the superficial phenomena are dip-slip. The difficulty is accentuated by the tradition of representing tectonic interpretation in cross-sections which give only the dip and not the strike components of structures.

3.4 Transcurrent slices

It appears that in a major transcurrent environment at the margin of two large plates, the shear motion may not be restricted to one fault zone. Parallel fault zones may take some of the motion either synchronously or sequentially.

I proposed such a model for Early and mid- Palaeozoic sinistral faulting in Spitsbergen and used the Californian analogy (Harland 1972). Developing this concept might lead to the idea of two or more lithosphere slices between the Greenland and Eurasian plates, bounded certainly by BFZ and possibly by one or more of BKFZ, RFZ, CWFZ and GSFZ.

Similarly with Cenozoic dextral faulting, while the dominant motion now appears to be concentrated in SFZ and KR, at earlier times the Forlandsundet Graben (or an adjacent) Zone (or wherever the West Spitsbergen Orogen was rooted) might have shared some of the transform motion.

Such transcurrent slices are a manifestation on a large scale of the response of an irregular plate margin to large transcurrent motion. It thus appears that in mid-Palaeozoic time sinistral shear, and throughout Cenozoic time dextral shear, obtained, and in each case the plate boundary could have been characterized by transcurrent slices. To what extent the Palaeozoic pattern determined Cenozoic faulting is not clear.

3.5 The nature of displacement at different depths in a fault zone

The Billefjorden Fault Zone affords a useful example for study because, as a result of Mesozoic and Cenozoic tilting, exposure is deeper in the north than in the south

The Mesozoic (and Palaeogene) cover in the south is folded over the presumed fault structure in the basement. This may be partly due to contemporaneous fault-control of sedimentary thicknesses in various areas, resulting in folding by differential subsidence. The structure appears as two parallel fault/fold zones.

Where Palaeogene strata are exposed three or more faults appear to distribute the movement. Many could be Tertiary faults but at least three were active in early Carboniferous time and one was the main fault between Caledonian (metamorphosed) Precambrian rocks and Old Red Sandstone.

It is a matter for speculation how much sinistral faulting took place in late Caledonian time. It is possible that at depth all the mid-Palaeozoic motion was concentrated in a shear zone at depth - analagous to, but more extreme than, the elongate linear fractures of the western margin of the Ny Friesland Orogen just east of BFZ.

Another problem relates to the rooting of the nappes and thrusts of the West Spitsbergen Orogen. It would appear that low angle thrusts to the east must root in a near vertical root zone to the west.

The downward transition of these superficial faults remains a problem.

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References

BIRKENMAJER, K. 1960.
Geological sketch of the Hornsund area. Int.geol. Cong. 21st Session (Norden 1960). Supplement to Guide for Excursion A.16: Aspects of the geology of Svalbard. 12pp.

CHALLINOR, A. 1967.
The structure of Brøggerhalvøya, Spitsbergen.
Geol.Mag., 104 (4), 322-336.

CHALLINOR, A. 1979
Spherical harmonic deformation.
J. Petrol.Geol., 1 (3), 75-102.

CUTBILL, J.L., HENDERSON, W.G. & WRIGHT, N.J.R. 1976.
The Billefjorden Group (Early Carboniferous) of Central Spitsbergen.
Norsk Polarinst. Skrifter, Nr. 164, 57-89.

DE GEER, G. 1909.
Some leading lines of dislocation in Spitsbergen.
Geol. Fören. Forh., 31 (4), 199-208.

FLOOD, B., GEE, D.G., HJELLE, A., SIGGERUD, T. & WINSNES, T.S. 1969.
The geology of Nordaustlandet, northern and central parts.
Norsk Polarinst. Skrifter, Nr. 146, 139p.

FLOOD, B., NAGY, J. & WINSNES, T.S. 1971.
Geological map of Svalbard 1:500,000. Sheet 1G, Spitsbergen Southern Part.
Norsk Polarinst. Skrifter, Nr. 154A.

GEE, D.G. 1972.
Late Caledonian (Haakonian) movements in northern Spitsbergen.
Norsk Polarinst. Årbok 1970, 92-101.

GJELSVIK, T. 1963.
Remarks on the structure and composition of the Sverrefjellet volcano, Bockfjorden, Vestspitsbergen.
Norsk Polarinst. Årbok 1962, 50-54.

HARLAND, W.B. 1959
The Caledonian sequence in Ny Friesland, Spitsbergen.
Quart.J.Geol.Soc.Lon., 114 (3), 307-342.

HARLAND, W.B. 1965.
The tectonic evolution of the Arctic-North Atlantic region.
Phil.Trans.R.Soc. Ser.A.No. 1088. 258, A Symposium on Continental Drift, 59-75.

HARLAND, W.B. 1969.
Contribution of Spitsbergen to understanding of tectonic evolution of North Atlantic Region.
Am.Ass.Petrol.Geol. Mem 12, 817-851.

HARLAND, W.B. 1971.
Tectonic transpression in Caledonian Spitsbergen.
Geol.Mag., 108 (1), 27-42.

HARLAND, W.B. 1972.
Early Palaeozoic faults as margins of Arctic plates in Svalbard.
In: Int.geol.Cong. 24th Session, Montreal 1972. Section 3, 230-237.

HARLAND, W.B. 1973.
Tectonic evolution of Barents Shelf and related plates.
In: Arctic Geology, Am.Ass.Petrol.Geol. Mem. 19, 599-608.

HARLAND, W.B. 1978.
The Caledonides of Svalbard.
Geol.Surv.Canada Pap., 78-13, 3-11.

HARLAND, W.B. (in press)
A reconsideration of late Precambrian stratigraphy in southern Spitsbergen.
Polarforschung.

HARLAND, W.B. & BAYLY, M.B. 1958.
Tectonic regimes.
Geol.Mag., 95 (2), 89-104.

HARLAND, W.B., CUTBILL, J.L., FRIEND, P.F., GOBBETT, D.J., HOLLIDAY, D.W., MATON, P.I., PARKER, J.R. & WALLIS, R.H. 1974.
The Billefjorden Fault Zone, Spitsbergen, the long history of a major tectonic lineament.
Norsk Polarinst. Skrifter, Nr. 161, 72p.

HARLAND, W.B. & GAYER, R.A. 1972
The Arctic Caledonides and earlier Oceans.
Geol.Mag., 109 (4), 289-384.

HARLAND, W.B. & HORSFIELD, W.T. 1974.
The West Spitsbergen Orogen.
In: Spencer, A.M. (Ed), Mesozoic-Cenozoic Oregenic belts, Data for orogenic studies, Geol.Soc.Lond. Special Pub. 4, 747-755.

HARLAND, W.B., , HORSFIELD, W.T., MANBY, G. & MORRIS, A.P. (in press)
An outline of pre-Carboniferous stratigraphy of Central Western Spitsbergen.
Norsk Polarinst. Skrifter, [1975 Oslo symposium].

HARLAND, W.B. & WRIGHT, N.J.R. (in press)
Alternative hypothesis for the pre-Carboniferous evolution of Svalbard.
Norsk Polarinst. Skrifter, [1975 Oslo symposium].

HORSFIELD, W.T. & MATON, P.I. 1970.
Transform faulting along the De Geer Line.
Nature, Lond.. 226, 256-257.

LOWELL, J.D. 1972.
Spitsbergen Tertiary Orogenic belt and Spitsbergen fracture zone.
Bull.Geol.Soc.Amer., 83 (10), 3091-3101.

McWHAE, J.R.H. 1953.
The major fault zone of central Vestspitsbergen.
Quart.J.Geol.Soc.Lond., 108. 209-232.

MITCHELL, B.J. & CHAN, W.W.W. (in press) Will be published in Polarforschung
Characteristics of earthquakes in the Heerland seismic zone of eastern Spitsbergen.

ORVIN, A.K. 1940.
Outline of the geological history of Spitsbergen.
Skr. Svalb. og Ishavet, Nr. 78, 1-57.

PARKER, J.R. 1966.
Folding, faulting and dolerite instrusions in Mesozoic rocks of the fault zone of central Vestspitsbergen.
Norsk Polarinst. Årbok 1964, 47-55.

SOKOLOV, V.N., KRASIL'SHCHIKOV, A.A. & LIVSHITS, Yu.Ya. 1968.
The main features of the tectonic structure of Spitsbergen.
Geol.Mag., 105 (2), 95-115.

TYRRELL, G.W. 1922.
The pre-Devonian basement complex of central Spitsbergen.
Trans.roy.Soc. Edinb., 53, 209-229.

WILSON, J.T. 1966.
Did the Atlantic close and then reopen?
Nature, Lond., 211, 676-681.