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THE TECTONO-MAGNETIC SIGNATURE OF THE OLD RED SANDSTONE AND PRE-DEVONIAN STRATA IN THE HÅSTEINEN AREA, WESTERN NORWAY, AND IMPLICATIONS FOR THE LATER STAGES OF THE CALEDONIAN OROGENY

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Abstract. The structural fabrics recorded from Devonian rocks and substrate in the Håsteinen area, Western Norway, show near E-W trends. In the Devonian rocks these fabrics are a consequence of post-depositional regional folding at a considerable depth, presumably attended by the aquisition of an thermoviscous (TVRM) or thermochemical (TCRM) remanence (group A). Post or possibly late syntectonic group A remanences (declination=210, inclination=+18, α_{95}=9) constitute the principal remanence in both Devonian rocks and their substrate, whereas a younger group B magnetization (declination=047, inclination=+59, α_{95}=7) relates to early Mesozoic shearing. The palaeomagnetic (group A) and structural data from the Håsteinen and Kvamshesten Old Red Sandstone Massifs favor a regional compressive N-S shortening event (Svalbardian-Solundian), which probably occurred during latest Devonian times. Some recent extensional-basin models, appealing to listric-normal faulting to account for both the sedimentation and the subsequent deformation of the Western Norwegian Devonian rocks, are rejected on the basis of inadequate structural information.

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INTRODUCTION

The Devonian massifs of Hornelen, Håsteinen, Kvamshesten, and Solund constitute the main areas of Old Red Sandstone (ORS) sedimentation in Western Norway (Figure 1a). Hypotheses based on tectonic controls on sedimentation have gained considerable attention [Bryhni, 1964, 1978, 1982; Nilsen, 1968; Steel and Gloppen, 1980; Hossack, 1984; Steel et al., 1985; Norton, 1986], from which three principal geodynamic models have emerged: (1) Sedimentation occurred in migrating basins related to hinge faulting [Bryhni, 1964], (2) basins formed through the action of oblique-slip faulting, i.e., the pull-apart model [Steel and Gloppen, 1980], and (3) basin infill in response to listric normal faulting, i.e., extensional basin model [Hossack, 1984; Norton, 1986]. A common feature of these models is the invocation of existent faults at or close to the present margins of the Devonian

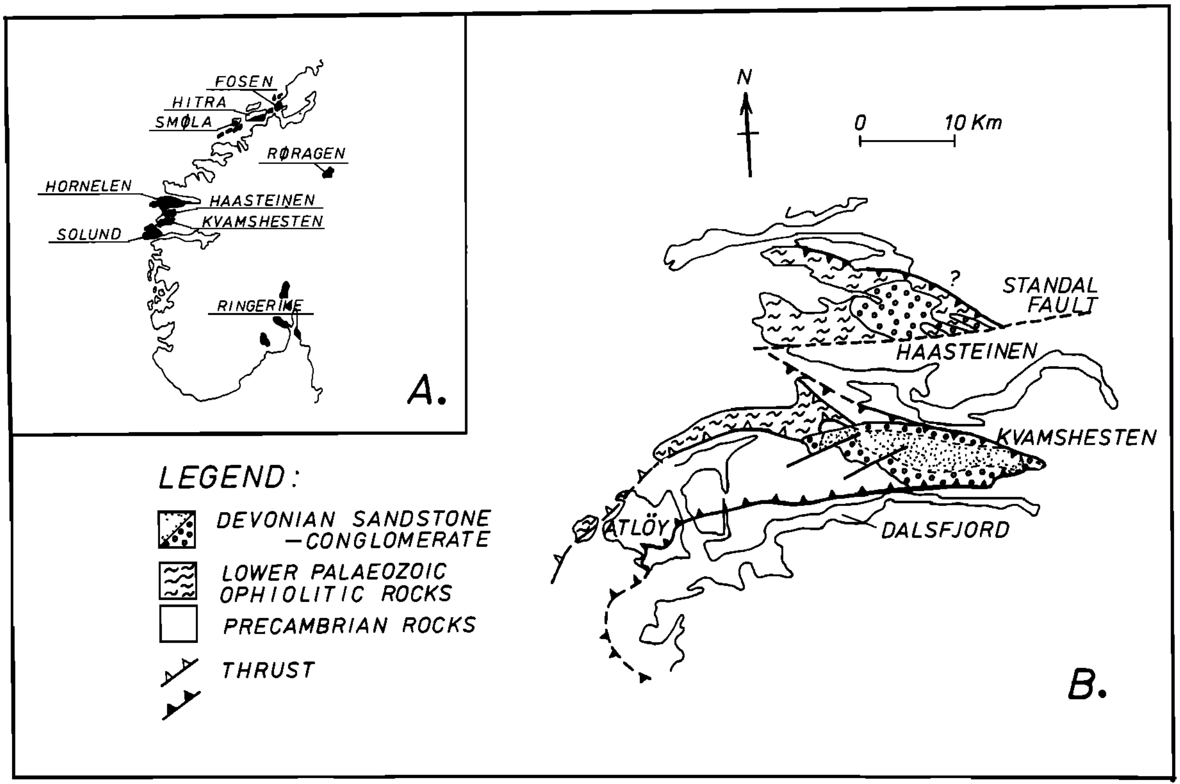

Fig. 1. Distribution of Old Red Sandstone deposits (a) in Southern Norway (simplified from Roberts [1983]), and (b) a simplified geological sketch map of the Kvamshesten and Håsteinen area. The low-angle fault or thrust denoted with solid triangles has recently been reinterpreted as a listric normal fault (cf. text), and termed the Nordfjord-Sogn detachment by Norton [1986].

"basins" as representing controlling elements in the sedimentary evolution.

Folding on approximately E-W axes together with later faulting is a characteristic feature of all the Devonian areas of Western Norway [Roberts, 1983], and in the Solund and Kvamshesten massifs pebble lineations and axial plane cleavage have been described [Nilsen, 1968; Torsvik et al., 1986]. It is generally held that the eastern margins of all four massifs are bounded by low-angle faults or thrusts [Roberts, 1983]. In recent extensional basin models, these "Devonian" thrusts have been re-interpreted as listric normal faults, and a basal shear detachment (including the Solund and Dalsfjord Faults) has been termed the Måløy Fault by Hossack [1984] and the Nordfjord-Sogn detachment by Norton [1986]. Remapping by the authors, however, has revealed that the eastern margin of both the Håsteinen and Hornelen Devonian Massifs is a surface of unconformity rather than a fault.

The nature and timing of the deformation in the ORS Massifs is a controversial subject. In the various extensional basin models it is contended that the observed deformation features can be readily explained in terms of a tensional syndepositional tectonic framework [Hossack, 1984; J. Mikkelsen, personal communication, 1986]. Others, developing the views of Vogt [1928], advocate that folding, thrusting, and metamorphism of the Devonian rocks was the result of postdepositional and compressive N-S shortening [Nilsen, 1968; Sturt, 1983; Roberts, 1983; Torsvik et al., 1986], probably in late Devonian times. This tectonic event has been termed the Svalbardian [Vogt, 1928] or Solundian Orogeny [Sturt, 1983]. The Håsteinen ORS (Figure 1) is located between the Hornelen and Kvamshesten massifs. Accounts of the regional geology have been given by Kolderup [1925], Bryhni [1962, 1964], Bryhni and Grimstad [1970], Bryhni and Sturt [1985] and Norton [1986]. The

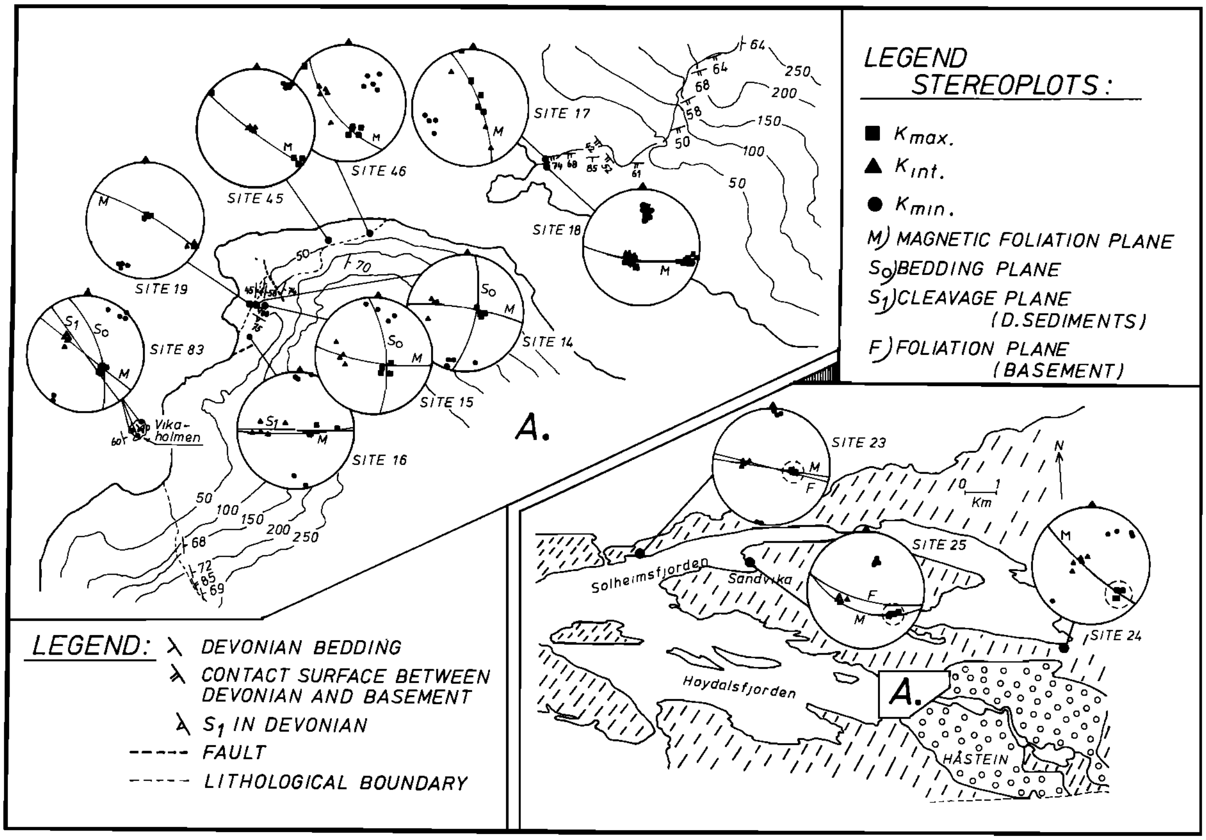

Fig. 2. Magnetic fabric and structural data from Precambrian (23-25), Lower Palaeozoic (17, 19, and 45-46) and Devonian (14-16, 18 and 83) sampling sites. Structural data included in stereograms (downward dipping planes) refer to those recorded at the specific sampling site. From site 19 (profile crossing the unconformity), only the magnetic fabric data from position e (site 19e) are shown (see Figure. 4 and 12 for details concerning this site).

Devonian rocks of Håsteinen together with the immediate substrate are folded into several large and high-amplitude folds with noncylindrical axes plunging up to 70°. Over the whole Massif these folds integrate into a large-scale synclinorium. Despite the paucity of planar markers in the poorly bedded coarse conglomerates of the Devonian the form of the folds and the outcrop pattern is defined by the prominent surface of unconformity (compare western margin in Figure 2). In the cores of the larger folds and close to the unconformity, the compressive orogenic strains were sufficiently penetrative to be marked by some degree of preferred orientation of pebble axes parallel to an axial plane cleavage observed in small siltstone lenses.

For palaeomagnetic and magnetic fabric investigations 12 sites were selected (Figure 2), of which three sites (sites 23-25) sampled from the oldest unit of the pre-Devonian substrate and included Precambrian anorthosites and amphibolites. The upper part of the tectonostratigraphy comprises Lower Palaeozoic rocks of the Stavfjord Ophiolite [Skjerlie, 1974] and Devonian clastic sediments. The Lower Palaeozoic rocks (sites 17, 19 and 45-46), chiefly greenstones and greywackes, have been sampled along the western border of the Håsteinen Massif (Figure 2). The Devonian of Håsteinen consists primarily of conglomerates, and apart from some minor sandstone-siltstone lenses, no significant development of a fine-grained facies has been recognized. The southern margin of the Devonian is marked by a high-angle fault contact, the Standal Fault (Figure 1b), while the other margins are a primary unconformity. Sampling in the Håsteinen

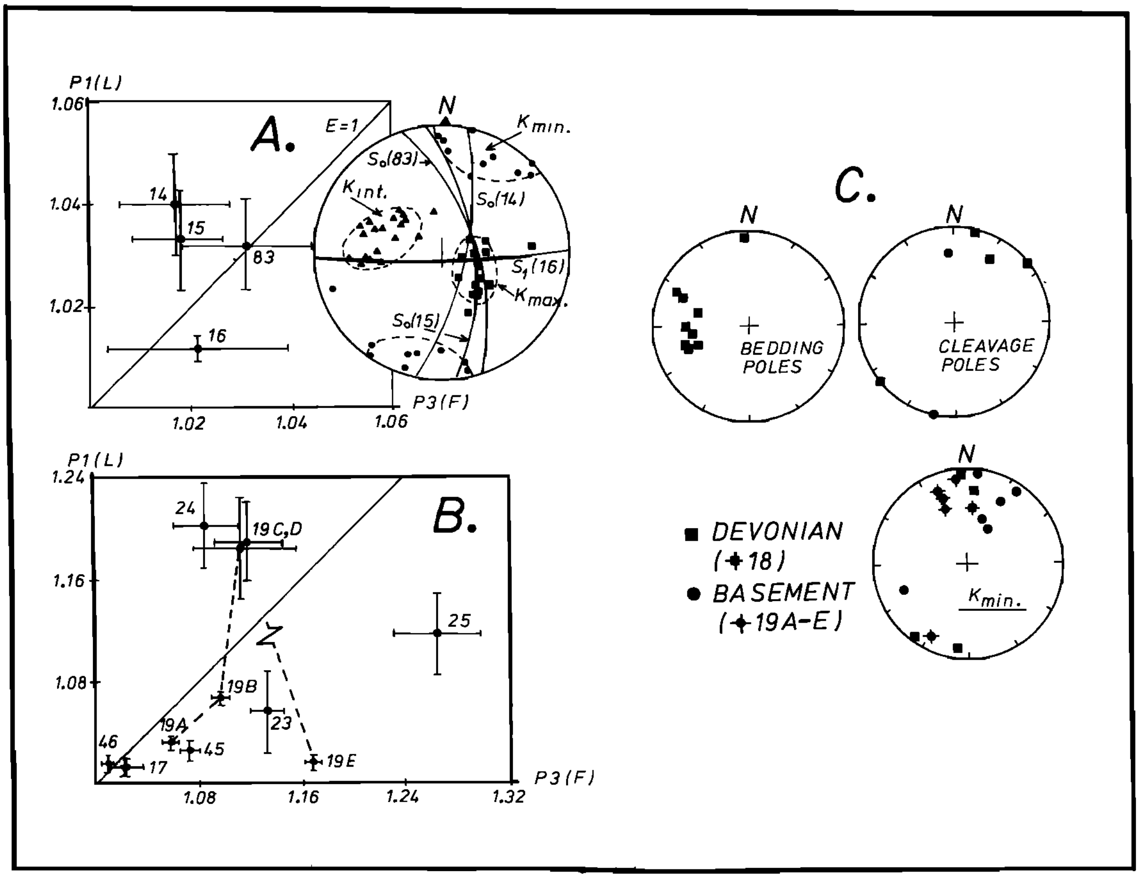

Fig. 3. Compilation of petrofabric data from (a) Devonian sandstones; (b) Flinn diagram for pre-Devonian (basement) samples (stippled line shows the progressive change recorded from site 19); (c) shows the distribution of observed poles to bedding (western margin of the Håsteinen Massif) and cleavage (S_1) and site-mean directions of K_{min}. Note the close correspondence of observed cleavage and K_{min} from both the Devonian and basement samples (Flinn diagrams, site means, are given with error confidences).

Massif was essentially from grey to reddish sandstone-siltstone lenses (sites 14-16 and 83) and some greenstone boulders in the conglomerate (site 18). This account forms part of an ongoing study of the Solund, Kvamshesten, and Hornelen area, and therefore site numbers are not listed sequentially.

THE MAGNETIC FABRIC

The anisotropy of magnetic susceptibility (AMS) was measured on a low-field induction bridge (KLY-I). The orientation and shape of the magnetic susceptibility ellipsoids are described by the principal axes $K_{max}>=K_{int}>=K_{min}$, and the axial ratios $P1=K_{max}/K_{int}$ (lineation), $P3=K_{int}/K_{min}$ (foliation), and E=P1/P2 (ellipticity). $P2=K_{max}/K_{min}$ (anisotropy) is expressed in the form of %An.=(P2-1)*100.

Pre-Devonian Rocks

From sites 23-25 (mylonitic rocks), steeply dipping and approximately ESE-WNW magnetic foliation planes (K_{max}-K_{int}) can be recognized (Figure 2). Poles to cleavage fits K_{min} and is almost subhorizontal with a near NNE-SSW trend (Figure 2 and 3c). Easterly plunging magnetic lineations (K_{max}) correspond well with regional mineral lineation data described by, e.g., Bryhni and Grimstad [1970]. The degree of total anisotropy is relatively high, varying from 20 to 40%. Compatible planar and linear fabrics are

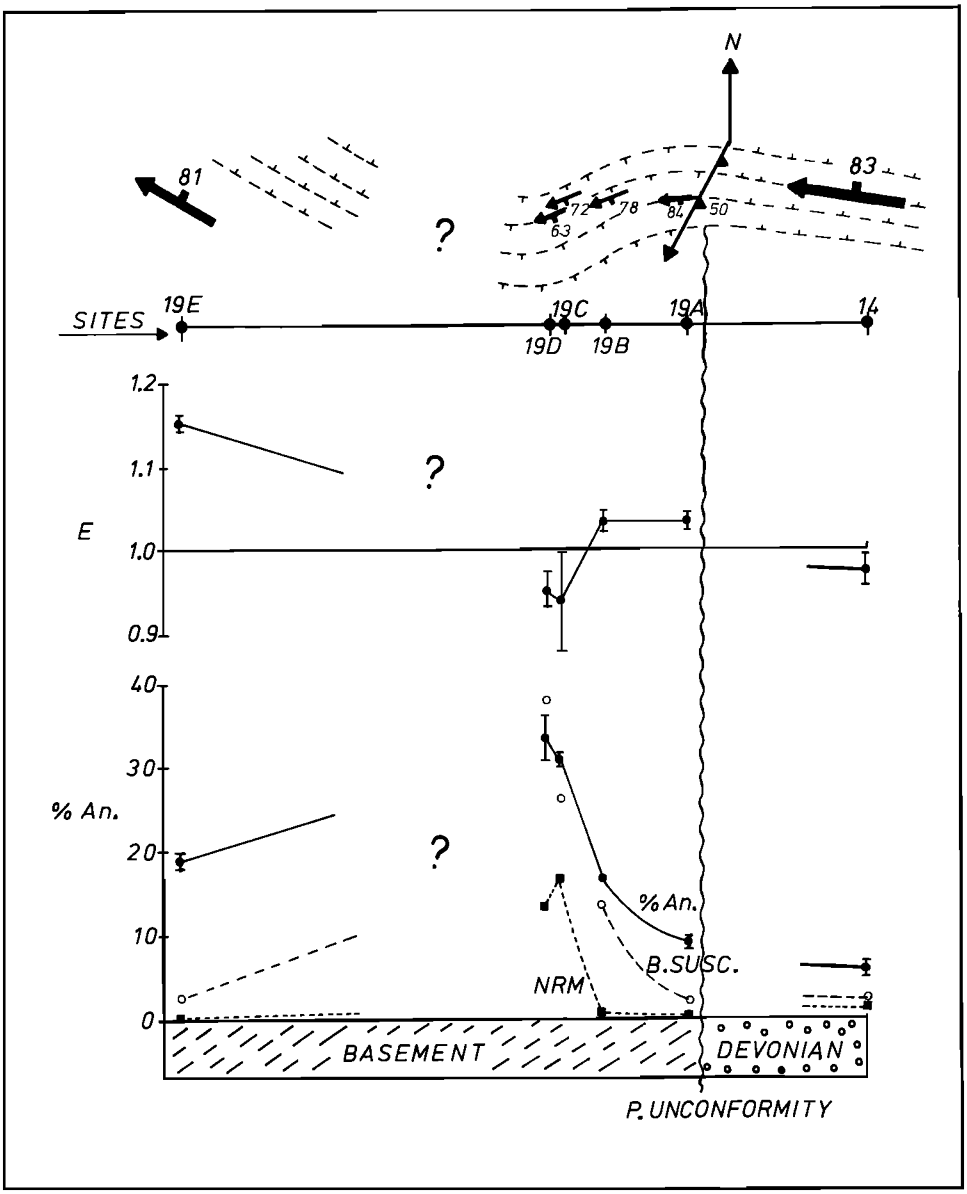

Fig. 4. The orientation and dip of the magnetic foliation planes (top figure) from site 19 (and 14), together with recorded variations in the shape of the magnetic ellipsoids (E; see also Figure 3b) and degree of anisotropy (%An.). E and %An. are plotted with error confidences (if exceeding the size of the plotting symbols). Bottom figure also includes NRM intensity and bulk-susceptibility. Horizontal distance between site 14 and site 19e is 4 m.

recorded from the Lower Palaeozoic rocks (Figure 2) along the western margin of the Håsteinen Massif (Sites 17, 45 and 46). However, a substantial reduction of total anisotropy is recognized, with typical values of 8-10%.

Devonian Rocks

Poles to bedding along the western margin of the Håsteinen Massif (Figure 3c) indicate E-W folding, including the primary unconformity, with a steep easterly plunge

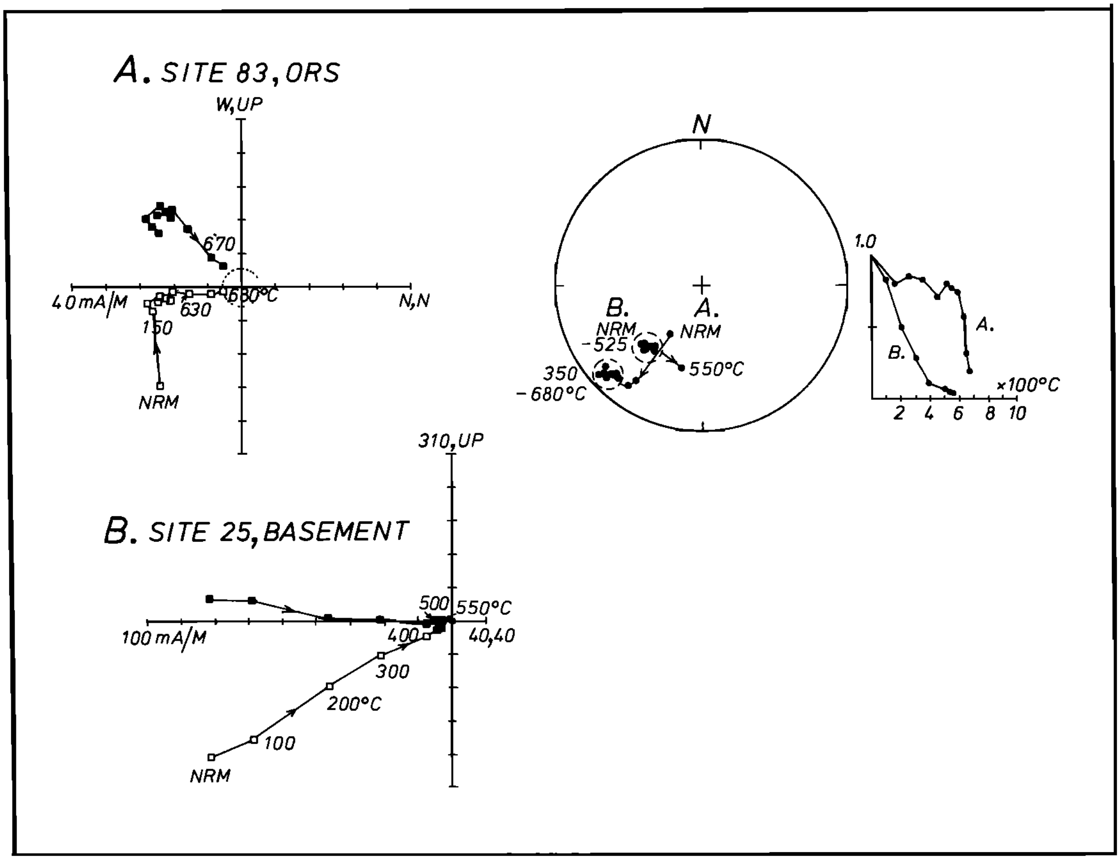

Fig. 5. Examples of thermal demagnetization of (a) a Devonian (displaying a group B remanence superimposed on the shallow inclined group A remanence) and (b) a basement (Precambrian anorthosite) sample. In the stereograms, open (closed) symbols represent upward (downward) pointing inclinations (all plots in insitu co-ordinates). In vector diagrams, open (closed) symbols represent points in the vertical (horizontal) plane. Note that some vector diagrams are optimally projected, and in (b) the projection plane (40, 40) are selected as declination for the characteristic remanence component. Note that denotations A and B in stereoplot and decay curves correspond to vector diagram Figures 5a and 5b.

of circa 70°. The orientation of planar fabrics in the Devonian rocks (Figure 2) corresponds closely with those recorded from the pre-Devonian rocks, and the magnetic foliation planes correspond to cleavage (S_1). The apparent shapes of the magnetic ellipsoids are mainly prolate, and the easterly plunging, fold-hinge parallel lineations (K_{max}) match the intersection of S_o and S_1 (Figure 3a). The degree of anisotropy in the Devonian sediments is typically around 5-6%. Four greenstone boulders (site 18; Figure 2) gave anisotropies around 4%, which is substantially lower than the greenstones in the basement. The magnetic foliation was steeply inclined with lineations approximately E-W and subhorizontal.

The Primary Unconformity

Sites 19 and 14 are located from a profile which crosses the primary unconformity (Figure 2 and 4). There is a noticeable anticlockwise rotation in the trend of the magnetic foliation planes (Figure 4), associated with a change from northerly dips of around 80° (site 14) to southerly ones of circa 65° (site 19d). At site 19e, 3 m from the contact, the magnetic foliations coincide with the regional foliation, i.e., E-W (ESE-WNW).

It is evident from the magnetic fabrics that a secondary shear zone cuts the primary unconformity at this locality (Figure 4). Sites 17 and 45-46 and the marginal parts of site 19 display

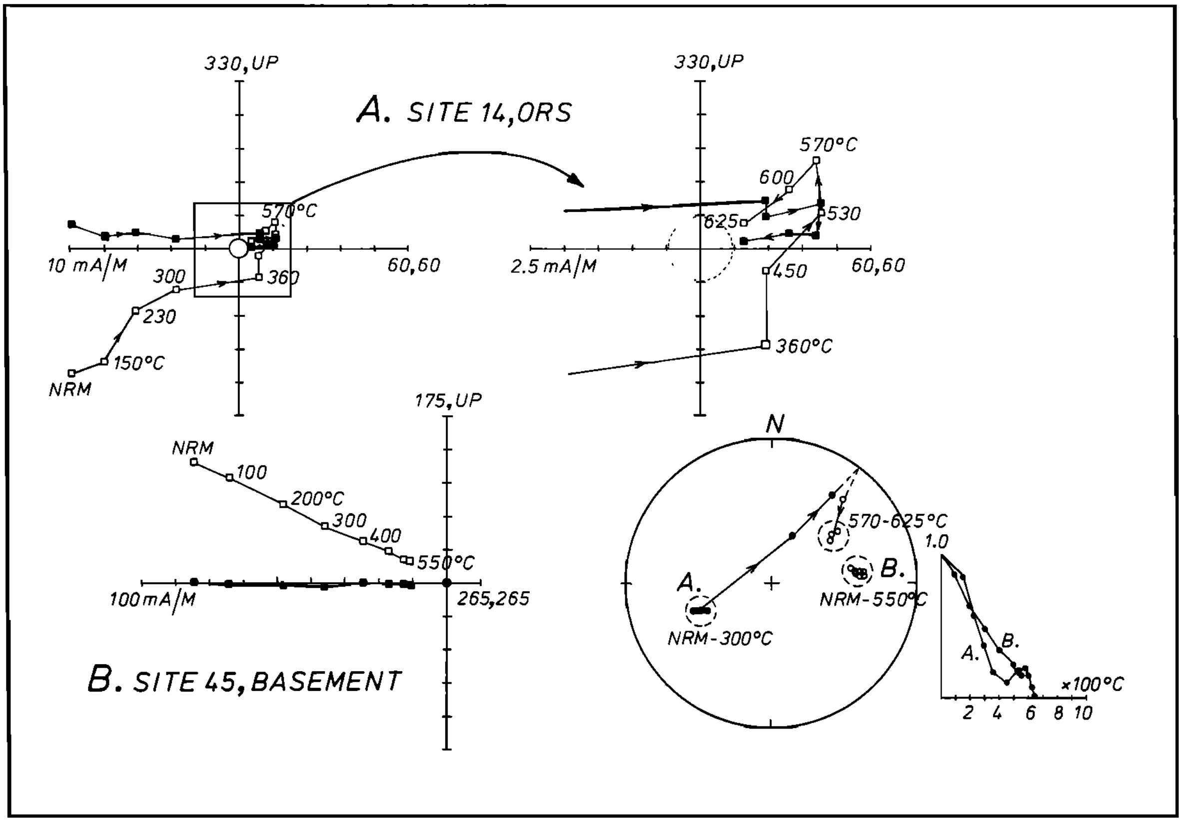

Fig. 6. Further examples of thermal demagnetization of (a) a Devonian and (b) a basement sample (Lower Palaeozoic greenstone). Stippled circle in vector plot defines a typical instrumental noise level (0.5mA/m).

apparently oblate magnetic ellipsoids, but strongly prolate magnetic ellipsoids are developed at sites 19c and d, i.e. within the central part of the shear zone (Figure 3b and 4). Changes in the shape and the orientation of the magnetic ellipsoids are also attended by abrupt changes (peaks) in fabric parameters (and remanence/magneto-mineralogical properties). Inadequate sampling in the area between sites 19d and e (Figure 4), relates to the fractured nature of the rocks in this section, suggesting that although the shear zone is characterized by ductile strain, it has also been the site of later brittle reactivation.

DEMAGNETIZATION AND SOME ROCK-MAGNETIC EXPERIMENTS

The stability of the natural remanent magnetization (NRM) in 135 samples was tested by means of stepwise thermal and alternating field (AF) demagnetizations. Characteristic remanence components were obtained by visual and numerical interactive computer line fitting in orthogonal vector projections [Torsvik, 1986] and/or estimates of linear segments using the Linefind Program [Kent et al., 1983].

From successfully tested samples, two major remanence components, both of dual polarity, can be recognized (denoted groups A and B). Group A constitutes the principal and intermediate to high-blocking remanence in both pre-Devonian and Devonian rocks and is characterized by shallow to intermediate dipping magnetizations with NE-SW declinations (Figures 5 and 6). Precambrian and Lower Palaeozoic samples exhibit blocking temperatures and directional stability up to 680°C, but a number of samples are characterized by distributed and almost total unblocking below 580°C and define essentially single component group A remanences (Figure 5b and 6b). Dual-polarity interplay (group A remanences) is notably, particularly in the Devonian samples, and may in addition be masked by group B remanences (see below), thus complicating the isolation of characteristic remanence components. In Figure 6a the

TABLE 1. Overall Palaeomagnetic Data From the Håsteinen Old Red Sandstone and Basement Rocks

Site	Group	Dec	Inc	N	α95	Polarity
14-ORS	A	209	24	5	16	M
	B	039	64	3	16	N
15-ORS	A	204	22	4	14	M
16-ORS	A	211	13	5	17	M
17-Basement	A	214	- 5	6	10	R
18-ORS Cgl.	A	187	21	5	8	R
19-Sheared Unc.F.						
a	B	059	62	4	16	N
b	A	042	-21	7	16	N
	B	034	49	8	11	N
c	B	073	61	4	11	N
d	B	097	56	5	5	N
e	NRM intensity below instrumental noise level					
23-Basement	B	245	-55	6	5	R
24-Basement	A	015	-10	4	19	N
25-Basement	A	225	14	6	17	M
45-Basement	A	232	39	7	18	M
46-Basement	NRM intensity below instrumental noise level					
83-ORS	A	208	16	11	13	M
	B	039	61	9	10	N

Site Mean Statistics:
Group A:
(I) Devonian Sandstone: Dec,208; Inc,19; N,4; α_{95},5; k,193.
(II)Basement : Dec,216; Inc,15; N,4; α_{95},20; k,12.
All sites combined (I+II,site 18, 19b):
Dec,210; Inc,18; N,10; α_{95},9; k,23.
VGP: S16, E335 d_p,5; d_m,10.
Group B:
(All sites except 19c and 19d):
Dec,047; Inc,59; N,5; α_{95},7; k,71.
VGP: N54, E111 d_p,8; d_m,11.

Dec, declination; Inc, inclination; N, number of specimens/sites; α_{95}, 95% confidence circle [Fisher, 1953]; k, precision parameter; Polarity: N, Normal, R, Reverse, M, Mixed polarity.

early-intermediate stage of thermal treatment indicates the removal of a reverse, group A remanence, which is probably partly overlapping with a high-temperature component of normal polarity. This latter component is well defined in the vector diagram (T>570°C; see expanded area of Figure 6a).

Unfortunately, the NRM intensity in the conglomerate boulders is generally low (mostly <0.5 mA/m), only two boulders were subjected to stability tests, and samples define reasonably consistent magnetizations both between and within boulders, i.e., near south or SSW (group A; Table 1).

Thermal decay curves associated with blocking temperatures up to 670°-680°C indicate that haematite is a major remanence carrier in the Devonian sediments. This is also indicated from isothermal remanent magnetization (IRM) acquisition curves, almost dominated by high coercivity phases (not saturated in fields of 0.9T) and having minimum remanence coercive forces (RCF) above 250 mT (Figure 7a and d). Thermomagnetic

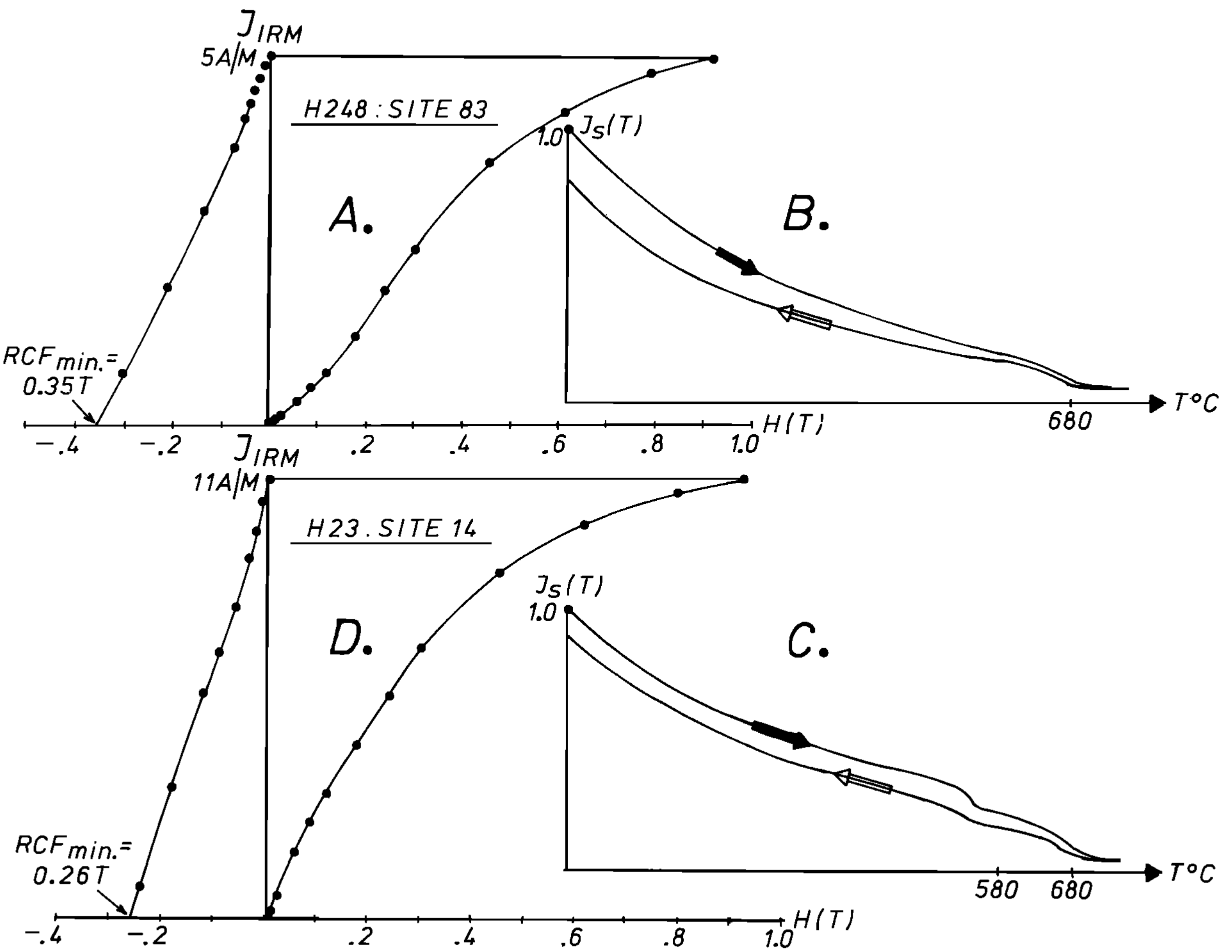

Fig. 7. (a, d) Typical IRM aquisition and (b, e) thermomagnetic curves obtained from Devonian sandstones.

analysis gave Curie temperatures around 680°C, i.e., haematite (Figure 7b), but in some instances a minor contribution of magnetite (Curie temperatures around 580°C) can be recognized (Figure 7c). Petrographic studies show that haematite is the most abundant opaque phase and occurs as (1) interstitial cementing material, (2) pseudomorphs of probably iron-bearing silicates, and (3) as small needles (banded; circa 2x20μ). Magnetite/Titanomagnetite (TM) is also present as grains generally below 20μ, which may show granulated rims (?FEOOH), while some less abundant TM grains (circa 100-150μ) exhibit exsolution features (ilmenite lamellae-oxidation class >III; Ade Hall et al. [1971]). Magnetite/TM may represent primary detrital grains, whilst the haematite is considered to be of secondary origin.

Group B is essentially a low-blocking magnetization randomized at temperatures below 300°C and characterized by north-easterly and steeply, downward dipping magnetizations (Figure 5a and 8b). Apart from some low blocking components (T<300°C) of reverse polarity (probably group B) noted from site 23 (Table 1), group B remanences are identified in samples close to the primary unconformity. Haematite-bearing group A remanences dominate in Devonian sandstones but may be sporadically contaminated by group B remanences randomized below 150°-300°C (Figure 5a). In samples from the marginal sites of the shear zone (sites 19a and b) group B remanences dominate the total NRM, but assumed group A remanences were readily obtained from site 19b at temperatures exceeding 300° to 500°C (Figure 8b). The central parts of the shear zone (sites 19c

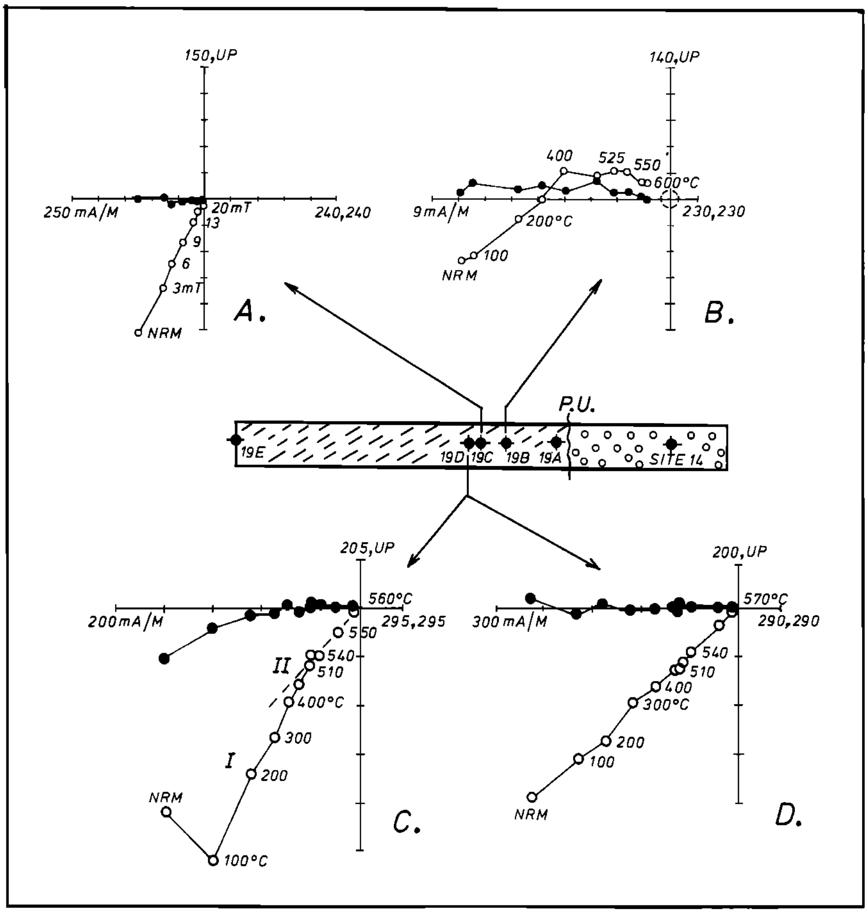

Fig. 8. Examples of (a) Af and (b-d) thermal demagnetization from site 19. The remanence buildup of samples from site 19b (Figure 8b) shows typical multicomponent features, i.e., group B remanence superimposed on group A remanences. Thermal treatment at temperatures above 600°-630°C proved impossible due to severe magneto-mineralogical changes (cf. text). Sites 19c and d may show essentially single-component group B remanences (Figures 8a and d), but often two steeply inclined "group B" remanences are observed (Figure 8c). The low-temperature component (I) is generally steeper and more northeasterly directed than the high temperature component (II). Horizontal sampling scale as Figure 4.

and d) coincide with substantial changes in NRM intensity (Figure 4), bulk susceptibility, and magnetomineralogy. Group A remanences are apparently obliterated, whereas the group B magnetizations may define an almost single component magnetization covering the entire blocking temperature spectra below 550°-580°C (Figure 8d). An almost single-component group B magnetization is shown in Figure 8a, in this case being an AF demagnetized sample which is totally demagnetized in fields of 20 mT. A number of tested samples can show clear evidence for the presence of at least two steeply inclined "group B" remanences (Figure 8c), mostly attended with substantial overlapping blocking-temperature spectra. The significance of these observations will be discussed in the next section.

Marginal shear zone samples (sites 19a, b and e) are dominated by high coercivity mineral phases associated with Curie temperatures around 680°C, which are indicative of haematite (Figure 9). Some indications of an accessory magnetite phase (Curie temperatures around 580°C) were sporadically detected. Laboratory heating

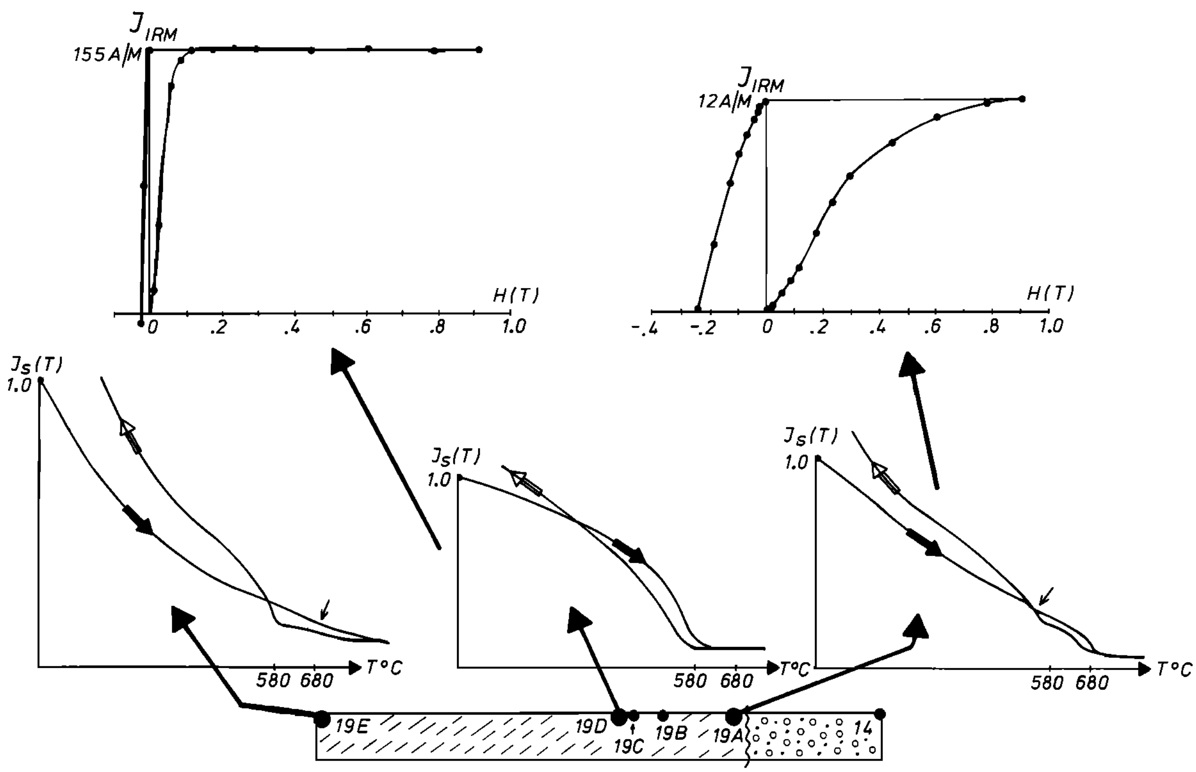

Fig. 9. Thermomagnetic analysis and IRM aquisition curves from marginal (sites 19a and d) and central parts of the shear zone. Note that secondary production of magnetite is readily observed on the cooling curves, attended by increase in saturation magnetization.

to temperatures around 550°-600°C readily produced secondary magnetite in all tested samples, resulting in irregular and viscous behavior during thermal demagnetization. Polished thin sections of samples from these marginal sites are characterized by a reddish stained matrix and needle shaped, anisotropic and translucent opaques (haematite), occurring in three typical grain-size ranges ,<5μ, 10-30μ and >100μ. Secondary magnetite production may also be detected from samples in the central parts of the shear zone, but they have essentially reversible cooling and heating curves compared with those of site 19a,b and e. Curie temperatures around 580°C, IRM acquisition curves saturated in fields of 0.1-0.2 T, RCFs below 30 mT (Figure 9) and petrographic studies indicate substantial magnetomineralogical differences in samples from the central (magnetite) and marginal parts (mainly haematite) of the shear zone. The matrix of strongly sheared samples is less red, opaques are less abundant and there are notably fewer large grains (i.e., >50-100μ). Magnetite occurs as inclusions in quartz, or as cubic- to needle shaped isotropic grains (<40μ), the latter clearly of synshear origin and preferentially developed in ductile shear bands.

Secondary magnetite production causes an increase in bulk susceptibility (Figure 10a), total anisotropy and apparent "flattening strain", while leaving the orientation of the principal axes unchanged (Figure 10b). These processes are initiated around 550°-600°C (1 hour heating time - zero ambient field) but are readily activated at lower temperatures (e.g., at 500°C as shown in Figure 10c) with increase in heating time. It should be emphasized that the laboratory induced alterations decrease with degree of increasing (natural) shear. Marginal samples show the strongest alterations, and, e.g., anisotropies around 100 to 150% can be observed at temperatures around 700°C (Figure 10a). The most sheared samples, however, show alterations of a magnitude 5-20 times less than marginal samples. This suggests that the bulk magnetic properties

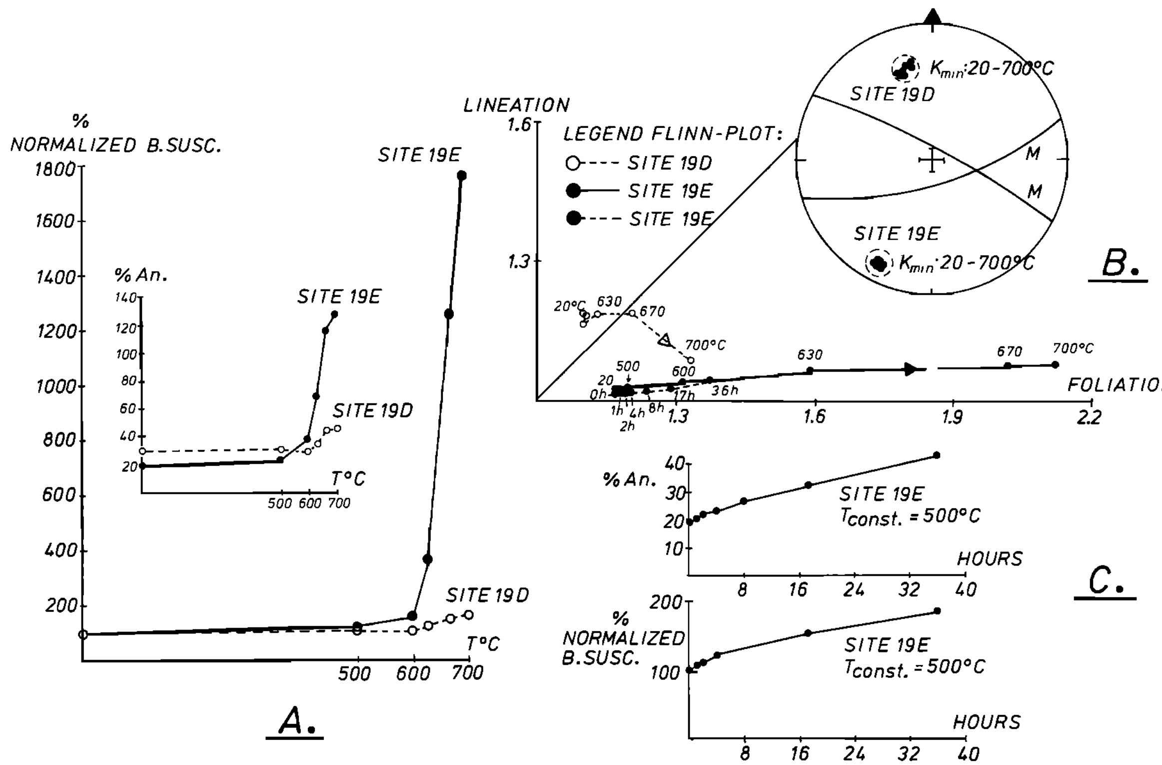

Fig. 10. Laboratory induced changes (a) in the bulk susceptibility and %An. from a marginal (site 19e) and a central (site 19d) shear-zone sample. (b) The apparent flattening trend in a Flinn diagram as a function of pure heating or time with constant temperature (500°C). Note that no directional movements are observed for the principal axes (K_{min} and the mean magnetic foliation plane in the NRM-700°C range are shown). (c) Variation of bulk susceptibility and %An. with increasing time and constant temperature (T=500°C).

of sites 19c and d (at least partly), represent "saturated" alteration phases resulting from secondary production of magnetite from some mineral phases still present in the marginal parts of the shear zone ("original phases") and/or reduction of haematite.

REMANENCE ANALYSIS

Characteristic remanence directions have been compiled in Figure 11 and Table 1. The two principal magnetization groups, A and B, define two statistically different directional populations, and exhibit strong blocking-temperature contrasts at sample level. Group B remanences are typically randomized (apart from site 19c and d) at temperatures around 150°-300°C, while those of group A retain the intermediate- to high blocking temperature spectra. It must be emphasized that it has not proved possible to discriminate between remanences preserved in Devonian and pre-Devonian samples.

Group A Remanences

Considerable within-site dispersion which may relate to possible effects of strain (if syntectonic) or unresolved multicomponent remanences are noted (Table 1), but the overall directional grouping and dual polarity structure of group A is reasonable well established (Figures 11a, 11b and 11d), and define a magnetization axis trending approximately NE-SW. Fold tests can only be applied to the Devonian sediments, and a combination of sites 14-16 and 83 (sediments) and site 18 (conglomerate which in itself represents a negative field stability test) indicates a negative fold test owing to the systematic increase in the radius of the confidence circle

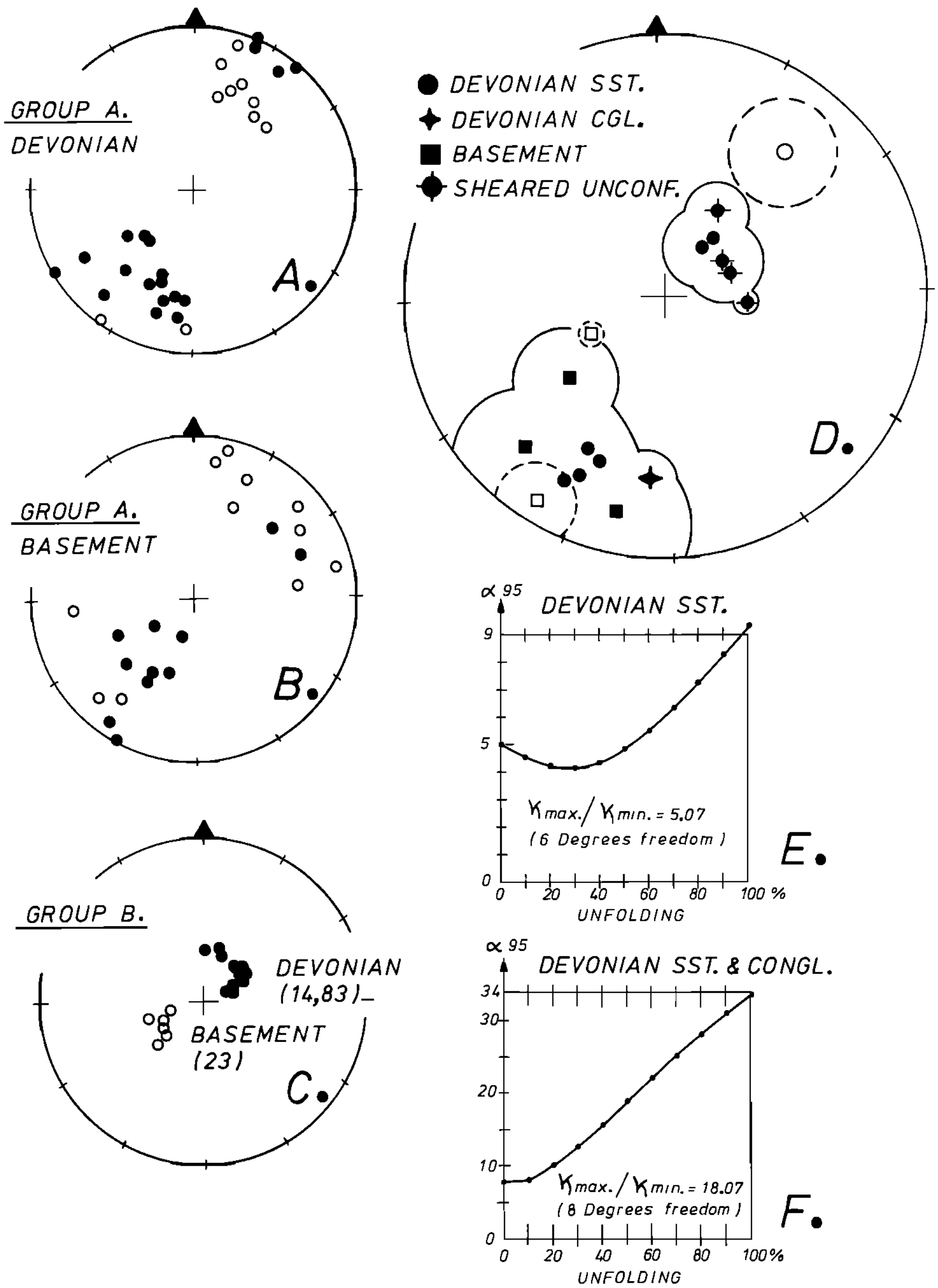

Fig. 11. Compilation of characteristic remanence directions:(a) and (b) show group A remanences obtained from Devonian and basement rocks (sample-level). (c) show Group B remanences from Devonian and basement (sample-level), and (d) show site-mean values of Group A and B from all sites along with the radius of confidence (α_{95}). Fold-tests applied to Devonian sediments or combined with conglomerate data of site 18 are shown in (e) and (f). Note that all group A site means are plotted as reverse field directions, apart from site 19b.

(α_{95}) during progressive unfolding (Figure 11f), and passing at high statistical confidence. A similar test for the Devonian sediments (sites 14,16 and 83), however, may indicate an origin of magnetization that is synfold, but not statistically significant compared with the noncorrected data (Figure 11e). Thus, group A remanences, recorded in both basement and Devonian cover sequences, points toward a posttectonic (or possibly late syntectonic) magnetization, most likely acquired via thermoviscous (TVRM) or thermochemical processes TCRM). Preliminary work by Sturt and Vetti has indicated that phengite is developed in the cleavage and in ductile shear zones within the Devonian rocks, pointing to a low Greenschist facies metamorphism.

Group B Remanences

Group B obtained from relatively "unstrained" Devonian samples (sites 14 and 83;Figure 11c) can be shown to have been superimposed on group A remanences, and have a close correspondence to group B remanences isolated from sites 19a and b (and reverse polarity data of site 23; compare Table 1). In addition, the assumed group A remanence recognized from site 19b corresponds reasonably well with directional results from the Devonian sediments (site mean values; compare Table 1), but substantial within-site scatter and directional smearing are noted (Figure 12b).

From sites 19c and d, group A remanences are apparently missing, and group B remanences approach more easterly declinations, compared to the marginal sites (Figure 12b and c). From site 19e, the NRM intensities were below 0.2mA/m, and thus not suitable for demagnetization experiments. The overall directional path of remanence vectors in the shear zone shows a similar trend pattern as the principal axes of susceptibility (Figure 12a), indicating that the bulk remanence and susceptibility may be carried by the same grain and/or mineral fraction. As the regional planar fabrics near ESE-WNW (site 14 and 19e) can be matched across the shear-zone, it is possible to demonstrate how the magnetic foliation planes show a systematic rotation toward the contact surface plane (Figure 12a). With the exception of site 19b, the remanences show a deflection toward the intersection of the contact surface and the magnetic foliation plane (approximately the maximum susceptibility axis K_{max}). An improvement in within-site dispersion is recognized, with an increasing angle difference between K_{min} and the remanence vectors. This can be seen when approaching sites 19c and d (Figure 12b; Table 1).

Application of passive marker theory in deformed sediments to correct for both bedding and remanence distortional strains on an original assemblage of assumed pretectonic remanence vectors, has been attempted in a number of examples [Kliegfield et al., 1983; Cogne and Perroud, 1985]. Lowrie et al. [1986], however, argue that remanence destraining by means of passive marker theory is inconclusive. No independent strain markers were available from site 19. A simple rigid correction, ignoring internal distortional strain by rotating "local" magnetic foliation planes back to the regional foliation plane (using site 14), clearly improves the between-site dispersion (Figure 12c and d), and the tectonic corrected site means matches fairly well the directional data from sites 14 and 83 (Devonian sediments). Before tectonic correction, α_{95}=13.4 (k=26.3), whereas α_{95}=9.9 (k=50.1) after tectonic correction (site-mean statistic parameters; N=4). There must be, however, a certain amount of reservation concerning this tectonic unfolding. Group B remanences most probably originated in response to shear strain (syn-crystallization), facilitated by magnetite formation (CRM/TCRM) in different local stress fields within the shear zone. Thus, treating group B remanence vectors in the shear zone purely as passively deflected vectors is unlikely to be correct, although it is possible that thermochemical alterations and remanence blocking occurred during an early stages of ductile shearing, and the vectors were later passively rotated in response to increased shear. Some samples, however, from sites 19c and d, indicate the presence of at least two remanences, and most likely also of two steeply inclined "group B" magnetizations (Figure 8c). Low-temperature components (when reasonably isolated) show more northeasterly declinations (i.e. better correspondance with "unstrained" samples) with steeper inclinations, which may relate to:(1) multicomponent group B remanences, attributed to grain-size effects, with the coarser grain fractions being preferentially controlled by the fabric, (2) low

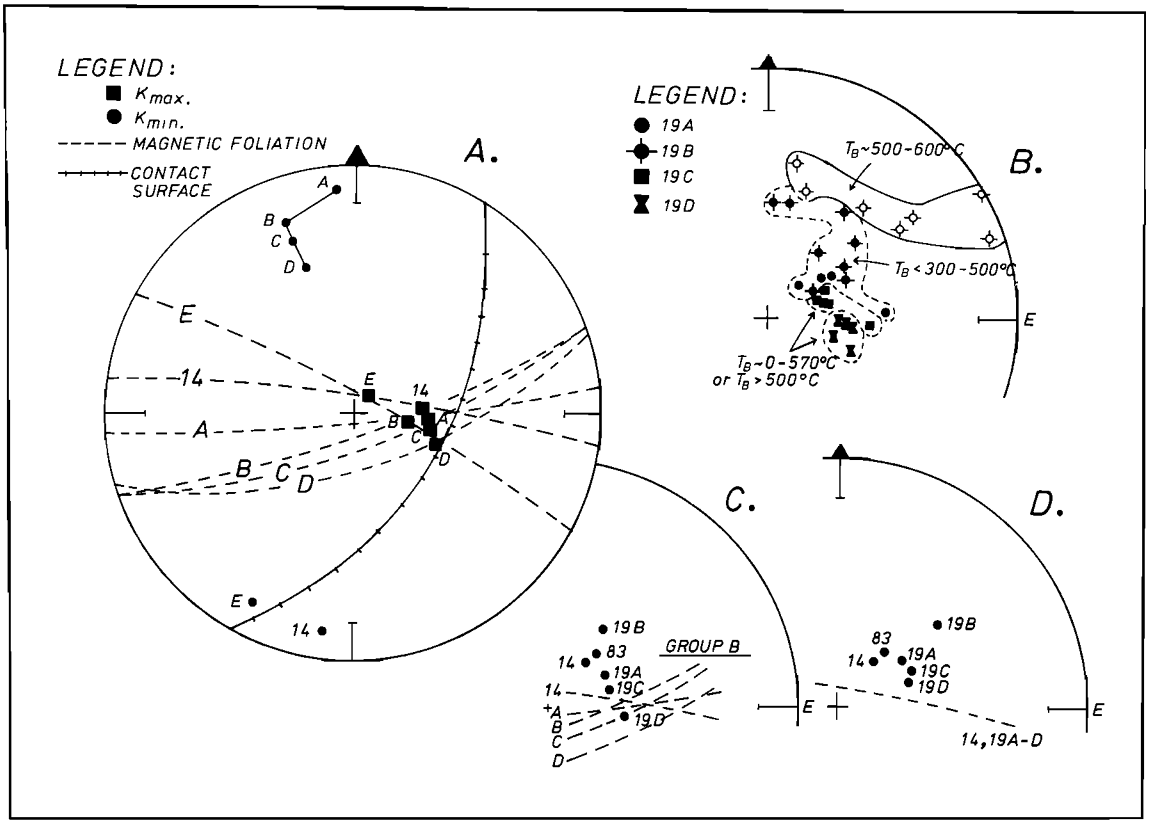

Fig. 12. Details concerning the magnetic fabrics (a:site mean values) and distribution of characteristic sample directions (b) from site 19. (c) Site-mean values of group B remanences from site 19 compared with group B remanences observed in the Devonian rocks (sites 14 and 83). (d) Group B remanences from site 19a-d have been tectonically corrected so that the local magnetic foliations (Figure 12a) fits the regional foliation (using site 14;cf. text). From sites 19c and 19d multicomponent features (two group B remanences) are observed (see Figure 8), but only the high-temperature component is included in figure 12 and Table 1 (cf. text).

temperature post-shear-zone magnetizations, e.g., precipitation from late fluid circulation, superimposed on syn-shear-zone magnetizations, and (3) grain-size dependent stress relaxation of syn-shear-zone induced remanences.

Results of laboratory heating experiments indicate substantial production of secondary magnetite in marginal samples. One may speculate, whether natural thermal effects can explain the high (natural) anisotropy values recorded for sites 19c and d. Most annealing experiments of sediments, however, and to some extent basaltic rocks, have shown that planar fabrics are preferentially developed during heat treatment [Kropacek, 1976, Nocharov et al., 1980, Torsvik and Løvlie, 1983; Perarnau and Tarling, 1985; Krutisch and Heller, 1985], and normally reproduce the "original" rock-fabric (as shown in Figure 10b). Such observations are incompatible with directional changes of the principal axes attendant on the development of prolate magnetic ellipsoids. Thus pure heating effects are unlikely to explain the observed features of site 19, and shear heat must necessarily have taken place.

DISCUSSION AND CONCLUSIONS

Devonian sediments from the Håsteinen Massif exhibit secondary, postdepositional magnetic fabrics. The magnetic foliation is controlled by an axial plane cleavage (S_1), whose orientation, together with fold axes and lineations display near E-W trends. In sandstone and siltstones the lineations are intersection structures (S_0/S_1) and/or stretching lineations. The eastward trending magnetic lineations in boulders from the conglomerate, however, can only relate to a stretching lineation.

Broadly similar E-W magnetic petrofabrics (i.e., cleavage-lineations) are recorded in the Devonian substrate, suggesting an exclusively "Devonian" magnetic fabric in the Håsteinen area or, alternatively the superposition of a "Devonian" fabric on an older but nearly E-W structural grain ("two phases of N-S shortening"). The contrast in degree of anisotropy between substrate and the Devonian cover sequence may relate to such features as differences in composition, competence and, original internal layering.

Group A remanences display no systematic differences between the Devonian rocks and the substrate. This, together with the negative field stability tests for the Devonian rocks, indicates a complete magnetic resetting in the investigated area. The Devonian rocks of Håsteinen and Kvamshesten [Torsvik et al., 1986] show structural similarities, i.e. E-W folding with axial plane cleavages developed in the fine-grained lithologies. Overall palaeomagnetic results from the Kvamshesten Massif were interpreted as being of synfolding to postfolding development, and the age of magnetic resetting was assigned to late Devonian times. Compatible pole positions for the two areas concerned may indicate a synchronous magnetic overprint, but there are some possible indications of age diachronism. Palaeomagnetic results from the Kvamshesten ORS, with the exception of two possibly retrograded mylonitic sites, gave only reverse polarity [Torsvik et al., 1986], while the deformation and subsequent magnetic resetting in the Håsteinen area apparently spans at least one polarity change of the geomagnetic field. This observation, however, could be explained in terms of differences in the late Devonian uplift history of the two areas.

The majority of group B remanences are attributed to post-Devonian shearing and faulting. In intensively sheared samples, remanence aquisition was probably facilitated by secondary formation of magnetite (synshearing) attended by substantial remanence "deflection."

Zones of high strain inevitably involve problems of differentiating between "true" and time-averaged palaeofield reordings and "artificial" remanences governed by the structural grain, as noted in the present account. In the attempts at using palaeomagnetism for dating of structural events in Western Norway, isotropic fault-breccias have attracted considerable attention [Sturt and Torsvik, 1986]. With age relevance to the observed shears in Håsteinen (group B remanences), such an approach has been applied to the Dalsfjord Fault (Figure 1b). Mylonites and pseudotachylites from the basal detachment beneath the Devonian rocks of Kvamshesten gave no firm identification of post-Devonian reactivation. In the west, however, on the island of Atløy (Figure 1b), two generations of fault breccias gave well-defined Permian and assumed late Jurassic/early Cretacous palaeomagnetic ages and was interpreted as dating (minimum ages) extensional fault movements and reactivation of the Dalsfjord Fault [Sturt and Torsvik, 1986]. In the context of European palaeomagnetic data, group B remanences obtained from Håsteinen fall between these two age estimates, and the relative pole position (Table 1; excluding sites 19c and d) may indicate a Triassic/early Jurrasic age. Although the precise ages are not well calibrated at the present stage, it is evident that extensional faulting, notably reactivation of "Caledonian" and in particular "Devonian" structures in Western Norway was widespread during the Mesozoic.

Magnetic fabric data from the Hornelen Massif may indicate the preservation of primary magnetic fabrics from the central parts of the Massif, whereas strong cleavage is observed close to the margins of the Devonian. Palaeomagnetic studies [Torsvik et al., in prep; M. Smethurst, personal communication, 1986], indicate a complication which may be related to possible primary magnetizations contaminated by posttectonic (syntectonic) remanences. It appears, however, that in the Kvamshesten and Håsteinen ORS and their substrates, at least, the principal magnetic signature postdates or witnesses the final stage of a major tectonothermal event. We consider that the obvious structural fabric is related to post-depositional regional folding of the Devonian rocks at a not inconsiderable depth.

Recently, the regional deformation and low-grade metamorphism of the Devonian rocks have been either included or ignored in theories appealing to syndepositional listric normal faulting as the modus operandi for the formation of the Devonian "basins" [Hossack, 1984; Norton, 1986]. It is felt that a degree of unwarranted confusion has been introduced into the literature by such all-embracing theoretical arguments which attempt to explain both sedimentation and the subsequent deformation of the Devonian rocks. The authors consider that the origin of the "basins" and their deformation should be viewed separately: Let us consider parts of the assumed controlling Nordfjord-Sogn detachment of Norton [1986], e.g., the basal detachment surface in the Kvamshesten area, the Dalsfjord Fault (Figure 1). This fault has been shown to cut already folded Devonian rocks [Høisæther, 1971], then is itself folded during subsequent tightening of the folds [Torsvik et al., 1986]. The fault, therefore, is not only subsequent to sedimentation but is an integral component of its progressive deformation. In addition, indications of synfold remanence aquisition in the Devonian sediments of Kvamshesten, if correct, obviously favor deformation attended by regional uplift. Thus the authors consider that the orogenic deformation of the Devonian rocks is related to a postdepositional N-S compressional event, and is possibly part of a final phase of easterly nappe translation.

The regional extent and importance of this late Devonian Svalbardian or Solundian event (Vogt [1928], Sturt [1983], Roberts [1983] and review by Steel et al. [1985]) is as yet unknown, but at least parts of the Bergen area, Western Norway, are dominated by group A compatible magnetizations [Rother et al., 1986], and the Lower-Middle Devonian rocks of the Trondheimsfjord region are strongly folded, cleaved, and faulted. On the other hand, recent palaeomagnetic data from the Upper Silurian-Lower Devonian Ringerike Sandstone [Douglass and Kent, 1986] can be interpreted in terms of only minor, if any, late Devonian contamination in this eastern part of the Norwegian Caledonides. Hence the available evidence indicates that both the Upper Silurian, Scandian (cf. review by Bryhni and Sturt [1985]), and the late Devonian (Svalbardian-Solundian) orogenic pulses tend to be most prominent in the western part of the Norwegian Caledonides.

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