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The July – September 1986 Skövde aftershock sequence

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August 1987

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THE JULY - SEPTEMBER 1986 SKÖVDE AFTERSHOCK SEQUENCE

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Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20) and 1986 (TR 86-31) is available through SKB.

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ABSTRACT

On July 14, 1986, one of the strongest earthquakes in Sweden during this century, M_L = 4.5, occurred near Skövde. A mobile network with analog and digital stations was rapidly deployed in the epicentral area. A comprehensive sequence of earthquakes was recorded, with three different temporal patterns of successively decreasing energy release. Besides a large shock, M_L = 3.4, less than one hour after the main shock, 20 aftershocks took place during nearly two months of field operation, 12 of them in the first 10 days. Four aftershocks could be independently located: the focal depth was approximately 30 km and the location of each epicentre was less than 10 km from that of the main shock. The magnitudes vary from -0.7 to 2.8. The main shock and aftershocks seem to be distributed along a plane trending N30^{o}W. The location of the foci in the lower crust is unusual for Baltic Shield earthquakes.

INTRODUCTION

On July 14, 1986, at 15:50 local time, an earthquake with magnitude 4.5 on the local Richter scale took place near Skövde in Västergötland (Fig. 1). This shock is one of the strongest in Sweden during this century.

The mobile field equipment available at the Seismological Department, Uppsala, was rapidly installed in the epicentral area with the purpose to record expected aftershock activity. The results from this investigation are reported below.

FIELD INSTRUMENTS AND STATIONS

The first station started operating in Kvighult (KVI) on July 16, at 13:09, i.e., about 45 hours after the earthquake. On July 17 another two stations were installed, in Simsjön (SIM) and Mariestad (MAR). In total, during the whole period of recording, July 16 - September 9, eight station sites were used, at the most six simultaneously. Station locations are shown in Fig. 1 and Table 1, and respective time periods of operation in Fig. 2.

Both analog and digital recording were used. The analog system consists of Teledyne-Geotech Portacorder RV-3208 and seismometer S-500. The filter setting was 5 - 50 Hz and the magnification 84 - 90 dB. The recording was made with ink at a speed of 120 mm/minute.

The digital system consists of Mark seismometers L4A-3D (three components), Lennartz Electronics Encoder 5000, and record player.

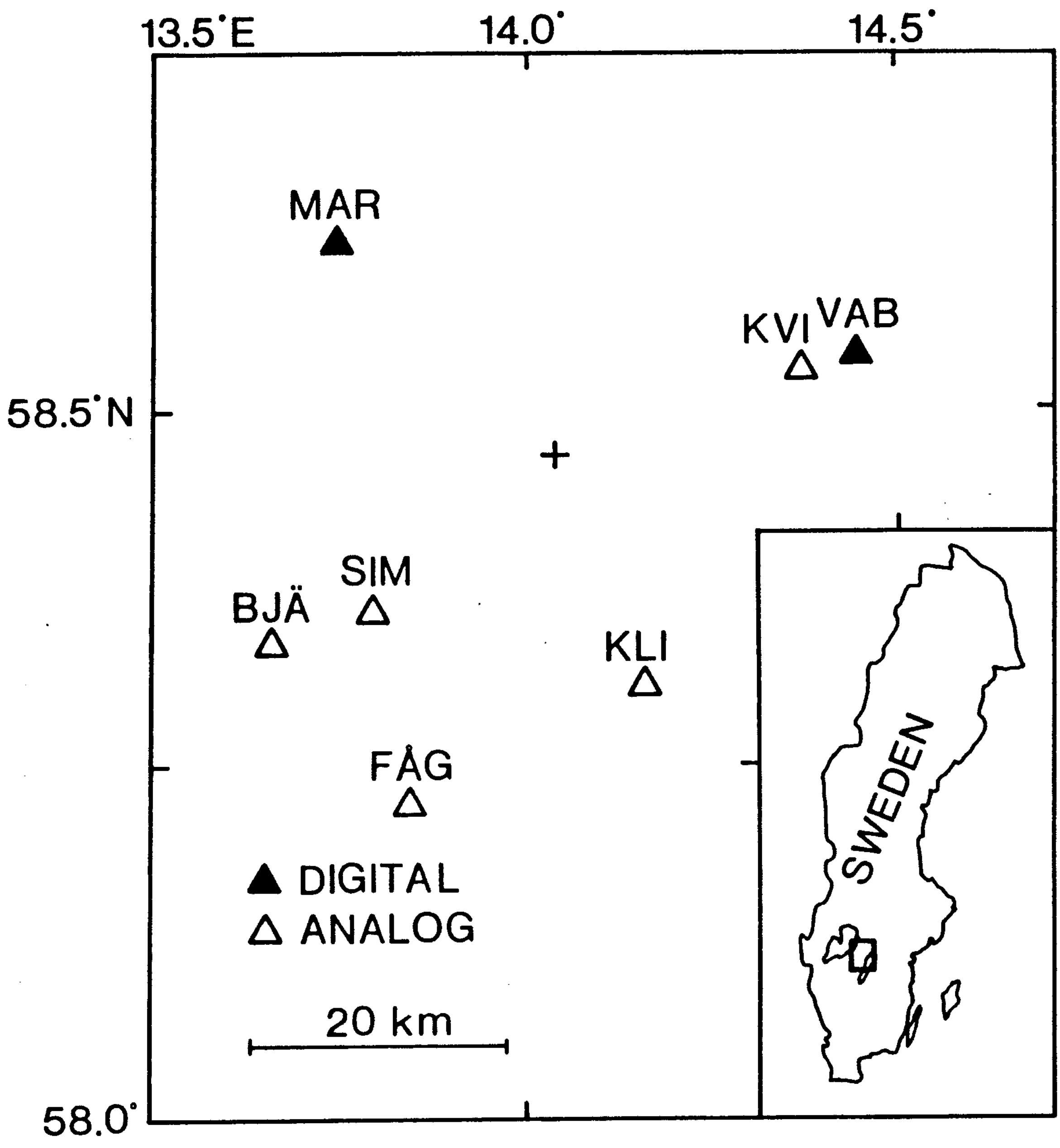

Fig. 1. Station sites, and location of the Skövde main shock on July 14, 1986 (cross). VAC is located in the vicinity of VAB.

An 80 Hz antialiasing filter was used in the encoders, the magnification was 60 - 66 dB and the sampling frequency 333 sps. A trigger algorithm was applied and the trigger unit used a 3 Hz HP filter.

DATA ANALYSIS AND EVENT DETECTION

Compiled data from various stations have been compared, and after teleseisms, explosions, and regional events outside the area of

Table 1. Locations of field stations.

Station		Type	Location lat. °N	lon. °E
Bjärsjön	(BJÄ)	analog	58.334	13.660
Fågelsången	(FÅG)	analog	58.221	13.846
Klinten	(KLI)	analog	58.306	14.162
Kvighult	(KVI)	analog	58.528	14.374
Mariestad	(MAR)	digital	58.617	13.746
Simsjön	(SIM)	analog	58.357	13.794
Vaberget I	(VAB)	digital	58.539	14.446
Vaberget II	(VAC)	digital	58.537	14.446

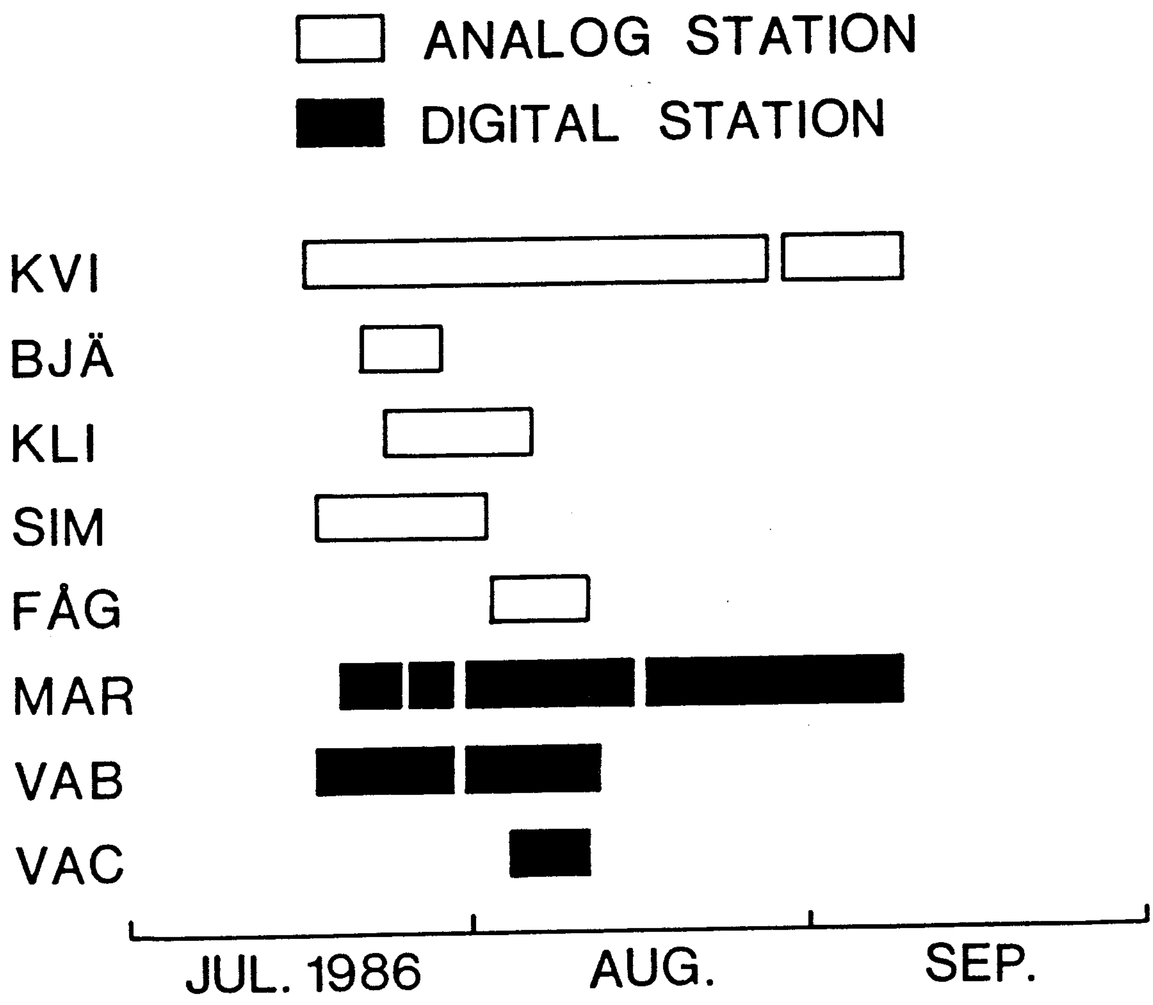

Fig. 2. Time periods of operation of the field stations.

interest have been sorted out, some 50 suspected minor earthquakes in the near region remain. Since three aftershocks were recorded already during the first 24 hours of field operation, we had good reference for identification of future events. All but 20 of the "interesting" events have been recorded only with one phase at one station. Of the remaining events 12 are almost identical as to partly the travel-time difference S-P, partly the seismogram appearance, except for relative size. Four have a slightly different appearance than these 12 events and four have a different S-P interval. Two of the 20 events were also recorded by four and one stations, respectively, of the permanent Swedish network (SSSN) run by the Seismological Department. The main shock and a large aftershock, M_L(UPP) = 3.4, occurring less than one hour after the main shock, were both recorded by all stations of the SSSN. The series of main shock - aftershocks is reported in Table 2. All field-station arrival times for the 20 identified aftershocks are given in APPENDIX.

LOCATIONS

Four of the field-recorded aftershocks (5, 6, 7 and 13) have been recorded by a sufficient number of stations to be individually located. Arrival times have been measured with a precision of 0.05 s from analog and 0.01 s from digital station records.

Locations have been performed with HYPOINV1, version 1 (Klein, 1978). Input parameters for the 1-velocity model are VP = 6.22 km/s and VS = 3.59 km/s (Båth, 1979). Different focal depths have been tried and the results are shown in Fig. 3. To account for possible uncertainty in absolute recording times, the epicentral distance for each station KVI, SIM and VAB (Vaberget I) has been computed from the respective S-P interval and has been plotted in Fig. 3. Apparently, these relative-time locations show good agreement with the absolute-time locations.

The optimum solution (least RMS) for the main shock is achieved for a focal detph of 30 km. This is also the depth obtained from macroseismic data. If we assume this depth for the four located aftershocks, the epicentres are separated by about 5 km, and no aftershock is more than 10 km distant from the main shock (see Fig. 3).

Table 2. Earthquake data.

No	Date y m d	Time h m s	Epicentre lat.°N	 lon.°E	Comments
	860714	155037	58.468	14.039	main shock
1	860714	164533	58.465	13.992	
2	860716	2025			
3	860717	0520			
4	860717	0734			
5	860718	023031	58.384	14.071	
6	860718	052451	58.418	14.049	
7	860720	042213	58.377	14.097	
8	860721	0917			**
9	860721	1721			
10	860721	2327			
11	860724	0202			
12	860725	0749			**
13	860726	105011	58.416	14.051	
14	860812	1406			*
15	860814	0800			**
16	860815	1155			
17	860815	1327			
18	860817	2007			**
19	860819	1603			*
20	860902	1037			*
21	860902	1535			*

Locations are for assumed focal depth = 30 km.
*: different appearance of recorded waves.
**: S-P = 2 s.

A depth of 20 km, or even 25 km, would decrease the separation of the four aftershocks to less than 2 km, which is the dimension of the rupture area for an earthquake the order of the Skövde main shock, according to scaling relations for Baltic Shield earthquakes established by Kim et al., 1985. However, the spatial separation between the main shock and the aftershocks is significant (up to 25 km) for these depths. Therefore, a focal depth of about 30 km also for the aftershocks is plausible. The epicentral coordinates obtained for this depth are listed in Table 2.

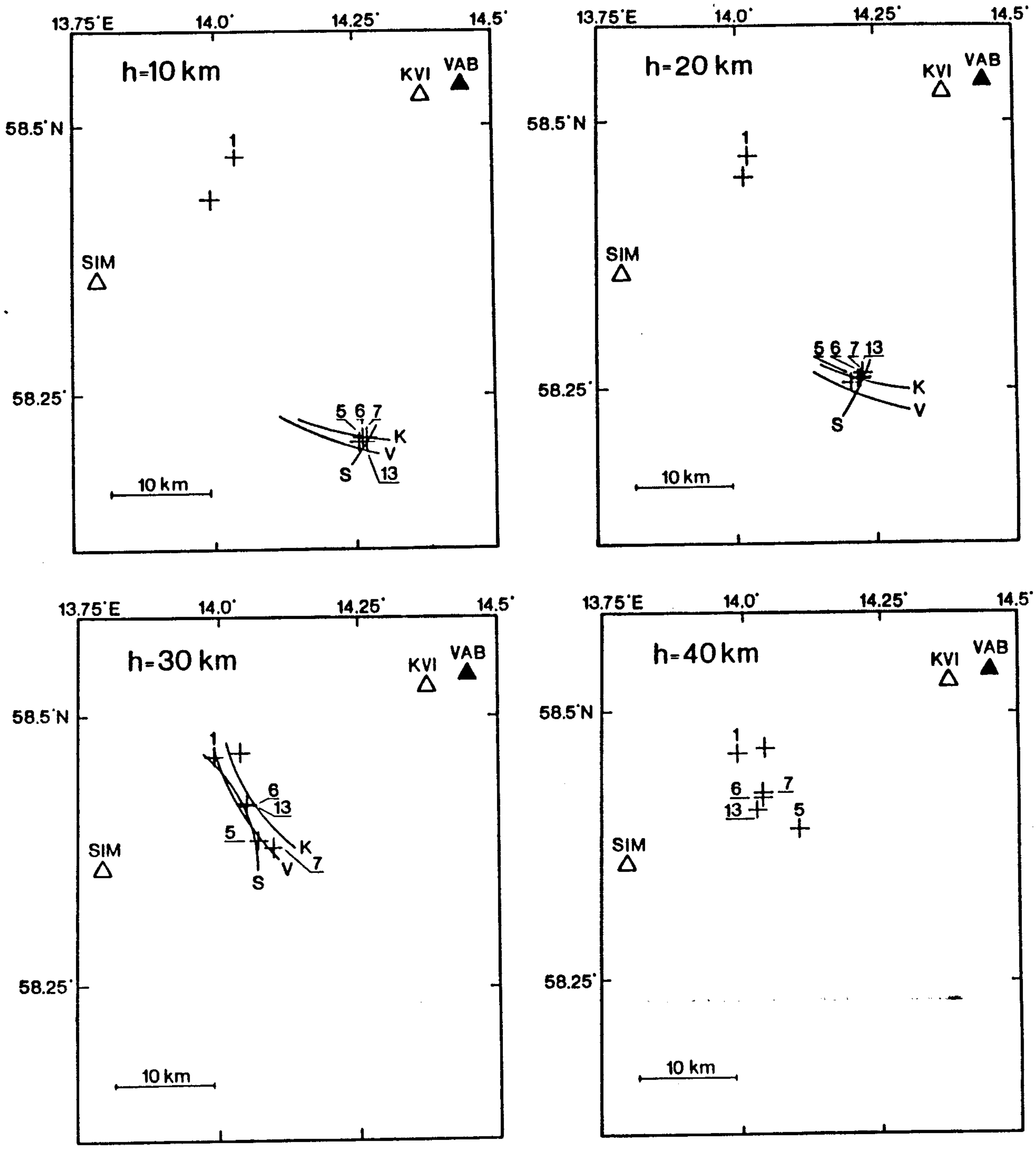

Fig. 3. Locations of the main shock and five aftershocks (1, 5, 6, 7 and 13) for different assumed focal depths. Crosses mark locations based on absolute arrival times: Pg and Pn from SSSN stations for the main shock (no number) and aftershock 1; Pg and Sg from field stations for the other four aftershocks. For depths of 10, 20 and 30 km solutions based on relative arrival times are indicated by intersections of curved lines marking epicentral distances for stations Kvighult (K), Simsjön (S) and Vaberget I (V) computed from S-P intervals for event 7. Similar good agreement between absolute-time and relative-time solutions is obtained for the other field-record located events.

MAGNITUDES

The regional magnitude scale in current use for Fennoscandian earthquakes reads:

$$ML(UPP) = \log(a) + \log[V_{WA}(T)] + 1.61\log(\Delta) + c_s \quad (1)$$

were a is Sg maximum ground amplitude (μm), $V_{WA}(T)$ magnification of the Wood-Anderson standard seismometer at corresponding period T, Δ distance (km), and c_s station correction. Assuming both the location (and thus Δ) and T are fairly constant for the studied aftershocks, (1) be approximately written:

$$ML(UPP) = \log(A) + C_s \quad (1a)$$

where A is trace amplitude at a specified instrument magnification, the latter included in C_s. The four events with different S-P interval are small and have been excluded from magnitude assignment.

The main shock and three aftershocks can be given values from (1) based on permanent-station readings (Table 3). Kvighult (KVI) recorded two of these aftershocks, 3 and 5, with oversaturated amplitudes, whereas Simsjön (SIM) recorded event 5 with measurable amplitude (Simsjön was not yet installed at the occurrence of event 3). Applying (1a) for the SIM reading, $C_{SIM} = -0.33$ is obtained. ML(UPP) is then computed for three additional events for which SIM has recorded amplitudes. These three events were recorded also by KVI, and so from KVI amplitudes and ML(UPP) computed from SIM, we obtain $C_{KVI} = -0.97(\pm 0.23)$. ML(UPP) can then be determined from KVI amplitudes for another 11 aftershocks. The various sets of computed magnitudes are shown in Table 3.

To compute magnitudes of regional events from the signal duration, τ, has become increasingly frequent in the past twenty years. Such magnitude formulae have also been developed for Swedish (Wahlström, 1980) and Finnish (Wahlström and Ahjos, 1984) stations. For small-size events a simple relation of the structure:

$$M = K_1\log(\tau) + K_2\Delta + K_3 \quad (2)$$

has often proved sufficient. For each station and a given epicentre location, (2) reduces to:

$$ML(UPP) = K_1\log(\tau) + K_2 \quad (2a)$$

where the calibration to ML(UPP) is made by inserting values derived from (1) or (1a).

Table 3. Magnitudes, ML(UPP).

No	SSSN	Amp.,K	Amp.,S	Dur.,K	Dur.,S	Preferred
	4.5					4.5
1	3.4					3.4
2		-0.7		-0.8		-0.7
3	2.8					2.8
4		0.2		-0.1		0.2
5	1.3		1.3	0.6	1.2	1.3
6		0.6	0.9	0.4	0.8	0.7
7		-0.3		0.0	0.2	-0.3
9		0.0	0.0	-0.2	-0.1	0.0
10		-0.5		-0.6		-0.5
11		-0.6		-0.6		-0.6
13		0.0	-0.3	-0.1	-0.2	-0.1
14		-0.1		0.1		-0.1
16		-0.1		0.1		-0.1
17		-0.7		-0.7		-0.7
19		0.1		0.6		0.1
20		-0.1		-0.1		-0.1
21		0.1		0.3		0.1

SSSN based on permanent stations.
Amp based on field-record amplitudes.
Dur based on field-record durations.
K Kvighult; S Simsjön

Signal durations have been measured on KVI and SIM records independently by the two authors. The average value is used in the regression to obtain K_1 and K_2. This is done separately for KVI and SIM. The duration for the large event 2 (at KVI) does not fit the simple model (2a) and has not been used. Computed constants are $K_{1,KVI} = 1.93(\pm 0.35)$, $K_{2,KVI} = -4.13(\pm 0.74)$, $K_{1,SIM} = 2.82(\pm 0.46)$ and $K_{2,SIM} = -5.92(\pm 0.46)$. Magnitudes determined from this set of values are listed in Table 3.

Since duration magnitudes are derived from amplitude-based magnitudes, priority is given to the latter. Preferred magnitudes are presented in the last column of Table 3. The average of KVI and SIM is taken where both have been computed.

Diagrams of the magnitude-frequency relation and the cumulative strain energy release are presented in Figures 4 and 5 (still with the "anomalous" events 8, 12, 15, and 18 excluded). To keep the detection threshold constant (at approximately -0.7), aftershock 1 has been excluded from both diagrams.

DISCUSSION

The Skövde aftershock sequence is the most comprehensive Swedish earthquake series that has ever been investigated in great detail with deployed field seismometers. It contributes with additional proof that the rupture process initiated by the main shock took place at an unusually large depth of about 30 km, whereas most Swedish earthquakes occur in the upper part of the crust. It may be noted, though, that a depth of about 40 km was obtained for the Solberg earthquake in 1983, ML(UPP)=4.1, then the largest event in Sweden in several decades (Kim et al., 1985).

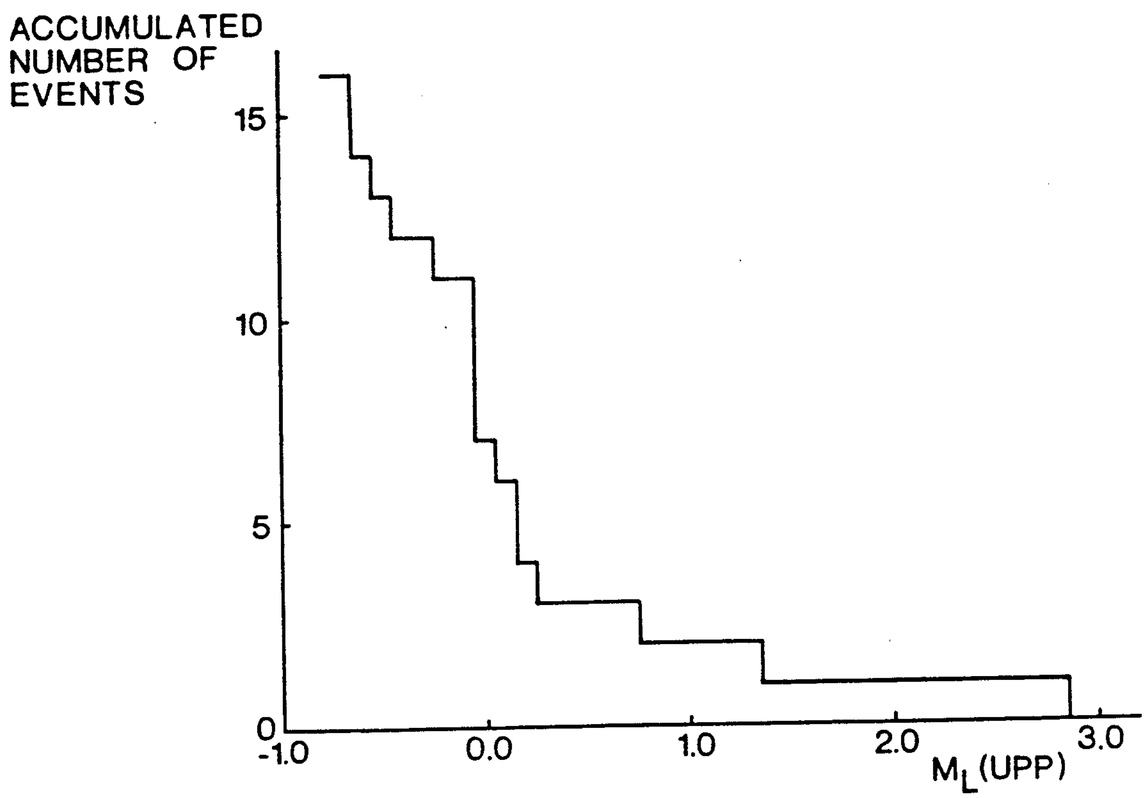

Fig. 4. Magnitude - frequency relation for the aftershocks, starting with no. 2.

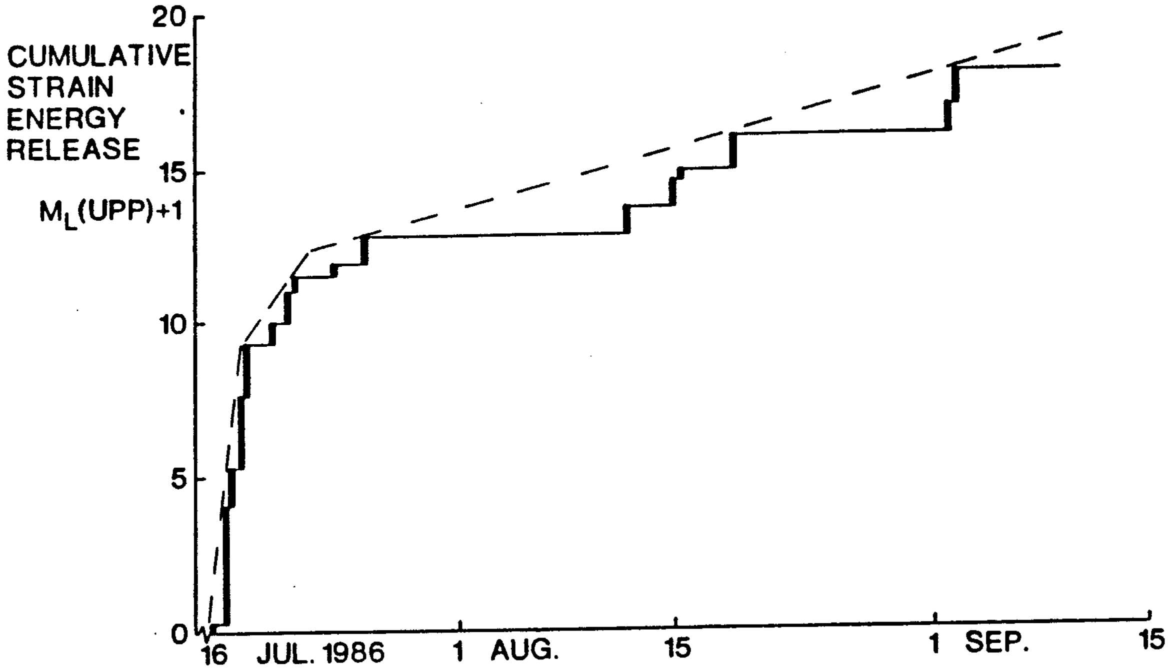

Fig. 5. Cumulative strain energy release for the aftershocks, starting with no. 2. The energy is represented by magnitude, ML(UPP). Three different phases of activity are indicated.

If the aftershocks are interpreted as strain readjustment after the main shock, the locations indicate an active source area of the order 10 km, i.e., significantly larger than suggested by spectral-scaling relations. However, the uncertainty of both the main shock and aftershock epicentres - the former determined from "distant" stations, the latter very sensitive to the assumed focal depth - may explain a major part of the spatial discrepancy.

The strain energy release pattern of the aftershock sequence contains three phases with successively decreasing activity (Fig. 5): the first lasts 2-3 days, the second 4-7 days and the third at least 40 days. The last phase may have been continued after the termination of the instrumental field operation, and it does perhaps represent the normal state of seismic activity in the region, since magnitudes are far below detection of our permanent stations.

Assuming 30 km is a good estimate of the focal depth, the main shock and the located aftershocks are distributed approximately along a plane trending N30°E. However, the main shock has to be analysed separately before the faulting mechanism can be determined with some confidence. It would be of utmost interest to follow up this study with an investigation of the focal mechanism and dynamic source parameters of the principal shock (of unique size), and of the first and largest aftershock (of unique size for a Swedish aftershock). To correlate the outcome from such a study with the spatial distribution of aftershocks obtained in the present study, and with the structural geology, could provide invaluable information for the understanding of the seismotectonics of the most seismically active zone in Sweden.

Acknowledgements.

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Arrival times for field-station recorded earthquakes.

No	Phase	Station and recorded time BJÄ h m s	KVI h m s	MAR h m s	SIM h m s	VAB h m s	Recording permanent stations of the SSSN
2	P		202515.85				
	S		202520.20				
3	P		052000.35 D				DEL,UDD,UME,UPP
4	P		073410.55 D				
	S		073414.85				
5	P		023036.80 D		023036.15	023037.22	UDD
	S					023041.98	
6	P		052457.30		052456.70	052457.74	
	S		052501.65		052500.85	052502.48	
7	P		042219.30		042218.60	042219.26	
	S		042223.65		042222.60	042224.04	
8	P		091729.50				
	S		091731.30				
9	P		172133.00				
	S		172137.40		172137.05		
10	P		232716.05				
	S		232720.35				
11	P		020249.60				
	S		020254.00				
12	P		074927.40				
	S		074928.75				
13	P	105016.95	105017.20			105017.37	
	S		105021.65		105020.65	105022.17	

/cont./

14	P	140633.25	140631.04
	S	140637.95	140633.74
15	P	080046.35	
	S	080048.40	
16	P	115556.70	
	S	115601.50	
17	P	132752.80 C	
	S	132757.30	
18	P	200755.35	
	S	200757.75	
19	P	160353.55	160351.40
	S	160357.80	160354.18
20	P	103745.65 C	103743.90
	S	103750.05	103747.42
21	P	153544.65	153542.96
	S	153549.40	153545.92

Analog station (BJÄ, KVI, SIM) time precision = 0.05 s.

Digital station (VAB, MAR) time precision = 0.01 s.

C = compression, D = dilatation.

List of SKB reports

Annual Reports

1977–78
TR 121
KBS Technical Reports 1 – 120.
Summaries. Stockholm, May 1979.

1979
TR 79–28
The KBS Annual Report 1979.
KBS Technical Reports 79-01 – 79-27.
Summaries. Stockholm, March 1980.

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The KBS Annual Report 1980.
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Summaries. Stockholm, March 1981.

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The KBS Annual Report 1981.
KBS Technical Reports 81-01 – 81-16.
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The KBS Annual Report 1982.
KBS Technical Reports 82-01 – 82-27.
Summaries. Stockholm, July 1983.

1983
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The KBS Annual Report 1983.
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Summaries. Stockholm, June 1984.

1984
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Including Summaries of Technical Reports Issued during 1984. (Technical Reports 84-01– 84-19)
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1985
TR 85-20
Annual Research and Development Report 1985
Including Summaries of Technical Reports Issued during 1985. (Technical Reports 85-01-85-19)
Stockholm May 1986.

1986
TR86-31
SKB Annual Report 1986
Including Summaries of Technical Reports Issued during 1986
Stockholm, May 1987

Technical Reports

1987

TR 87-01
Radar measurements performed at the Klipperås study site
Seje Carlsten, Olle Olsson, Stefan Sehlstedt, Leif Stenberg
Swedish Geological Co, Uppsala/Luleå
February 1987

TR 87-02
Fuel rod D07/B15 from Ringhals 2 PWR: Source material for corrosion/leach tests in groundwater
Fuel rod/pellet characterization program part one
Roy Forsyth, Editor
Studsvik Energiteknik AB, Nyköping
March 1987

TR 87-03
Calculations on HYDROCOIN level 1 using the GWHRT flow model
Case 1 Transient flow of water from a borehole penetrating a confined aquifer
Case 3 Saturated-unsaturated flow through a layered sequence of sedimentary rocks
Case 4 Transient thermal convection in a saturated medium
Roger Thunvik, Royal Institute of Technology, Stockholm
March 1987

TR 87-04
Calculations on HYDROCOIN level 2, case 1 using the GWHRT flow model
Thermal convection and conduction around a field heat transfer experiment
Roger Thunvik
Royal Institute of Technology, Stockholm
March 1987

TR 87-05
Applications of stochastic models to solute transport in fractured rocks
Lynn W Gelhar
Massachusetts Institute of Technology
January 1987

TR 87-06
Some properties of a channeling model of fracture flow
Y W Tsang, C F Tsang, I Neretnieks
Royal Institute of Technology, Stockholm
December 1986

TR 87-07
Deep groundwater chemistry
Peter Wikberg, Karin Axelsen, Folke Fredlund
Royal Institute of Technology, Stockholm
June 1987

TR 87-08
An approach for evaluating the general and localized corrosion of carbon steel containers for nuclear waste disposal
GP March, KJ Taylor, SM Sharland, PW Tasker
Harwell Laboratory, Oxfordshire
June 1987

TR 87-09
Piping and erosion phenomena in soft clay gels
Roland Pusch, Mikael Erlström, Lennart Börgesson
Swedish Geological Co, Lund
May 1987

TR 87-10
Outline of models of water and gas flow through smectite clay buffers
Roland Pusch, Harald Hökmark, Lennart Börgesson
Swedish Geological Co, Lund
June 1987

TR 87-11
Modelling of crustal rock mechanics fo radioactive waste storage in Fennoscandia—Problem definition
Ove Stephansson
University of Luleå
May 1987

TR 87-12
Study of groundwater colloids and the ability to transport radionuclides
Kåre Tjus* and Peter Wikberg**
*Institute for Surface Chemistry, Stockholm
**Royal Institute of Technology, Inorganic Chemistry Stockholm
March 1987

TR 87-13
Shallow reflection seismic investigation of fracture zones in the Finnsjö area method evaluation
Trine Dahl-Jensen
Jonas Lindgren
University of Uppsala, Department of Geophysics
June 1987

TR 87-14
Combined interpretation of geophysical, geological, hydrological and radar investigations in the boreholes ST1 and ST2 at the Saltsjötunnel
Jan-Erik Andersson
Per Andersson
Seje Carlsten
Lars Falk
Olle Olsson
Allan Stråhle
Swedish Geological Co, Uppsala
1987-06-30

TR 87-15
Geochemical interpretation of groundwaters from Finnsjön, Sweden
Ignasi Puigdomènech[1]
Kirk Nordstrom[2]
[1]Royal Institute of Technology, Stockholm
[2]U S Geological Survey, Menlo Park, California
August 23, 1987

TR 87-16
Corrosion tests on spent PWR fuel in synthetic groundwater
R S Forsyth[1] and L O Werme[2]
[1]Studsvik Energiteknik AB, Nyköping, Sweden
[2]The Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, Sweden
Stockholm, September 1987