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A Wide-Angle Seismic Experiment in the Skagerrak

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Odd Nilsen
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Cover page: Preparation of dynamite

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1 Introduction

From May 21-27, 1999, a wide-angle seismic experiment was carried out in the Skagerrak Graben (Fig. 1). The experiment was a combined effort of the department of Geology, University of Oslo and Geomar, Kiel (as partners in the EU-TMR project: PERMO-CARBONIFEROUS RIFTING IN EUROPE (PCR) - MAGMATISM, GEODYNAMICS AND THERMAL EVOLUTION OF THE LITHOSPHERE), the Geological Institute, University of Copenhagen (Denmark) and the Geophysical Institute, University of Hamburg (Germany).

Earlier cooperation between some of these groups has led to successful experiments like e.g. the MONA LISA project in 1997 (MONA-LISA Working Group, 1997). Cooperation with Christian Hübscher from the University of Hamburg was established by Ernst Flüh. The involvement of the University of Hamburg made it possible that the off-shore part of the experiment could be carried out from the R/V VALDIVIA, during cruise VAL-175, which was used for teaching purposes at that time. For a list of participants in the experiment, both on- and offshore, see Appendix A.

In 1987, the Mobil Search experiment acquired deep reflection seismic data in the Skagerrak (Husebye, et al., 1988)(Fig. 1). This survey gave us a good idea of the upper crustal geometries (e.g. Ro et al., 1990), but to understand the deeper part of the crust we needed velocity data as well. An earlier refraction seismic experiment was carried out in the period from 1962-1965 (Hirschleber et al., 1966; Weigel et al., 1970), but the data was too poor to build a proper crustal model. This is also the case for a refraction experiment carried out in the Oslo Graben in the 1970's (Tryti and Sellevoll, 1977).

The combined use of both reflection and refraction data allows to extract the maximum possible information and to "tie up" the structural interpretation. This study will allow a new tectonic interpretation of the Skagerrak and Oslo grabens and will shed new light on the role of underplating on the style and timing of lithospheric deformation. Moreover, these experiments will benefit considerably from deep seismic reflection and refraction data acquired in nearby areas (EUGENO-S and MONA LISA; see Fig. 1)

1.1 The PCR project

The PCR-project is a multi-disciplinary research project to further our understanding of the geodynamics of Permo-Carboniferous rifting and associated magmatism within the northern foreland of the Variscan orogenic belt, funded by the European Commission

The most important objectives of this project are to:

- determine the relationship between the onset of magmatism, regional uplift and extensional tectonics.
- date by high quality Ar-Ar and U-Pb zircon methods, the chronology of magmatic events
- evaluate the role of thermally anomalous mantle plumes in the petrogenesis of the magmas and the excess mantle temperature via geochemical, He-Ne-Ar and Sr-Nd-Pb isotopic studies of the most primitive mafic magmas erupted within the province.
- constrain the onset and magnitude of basement uplift and thermal subsidence across the area, in order to evaluate the magnitude of any thermal pulse.

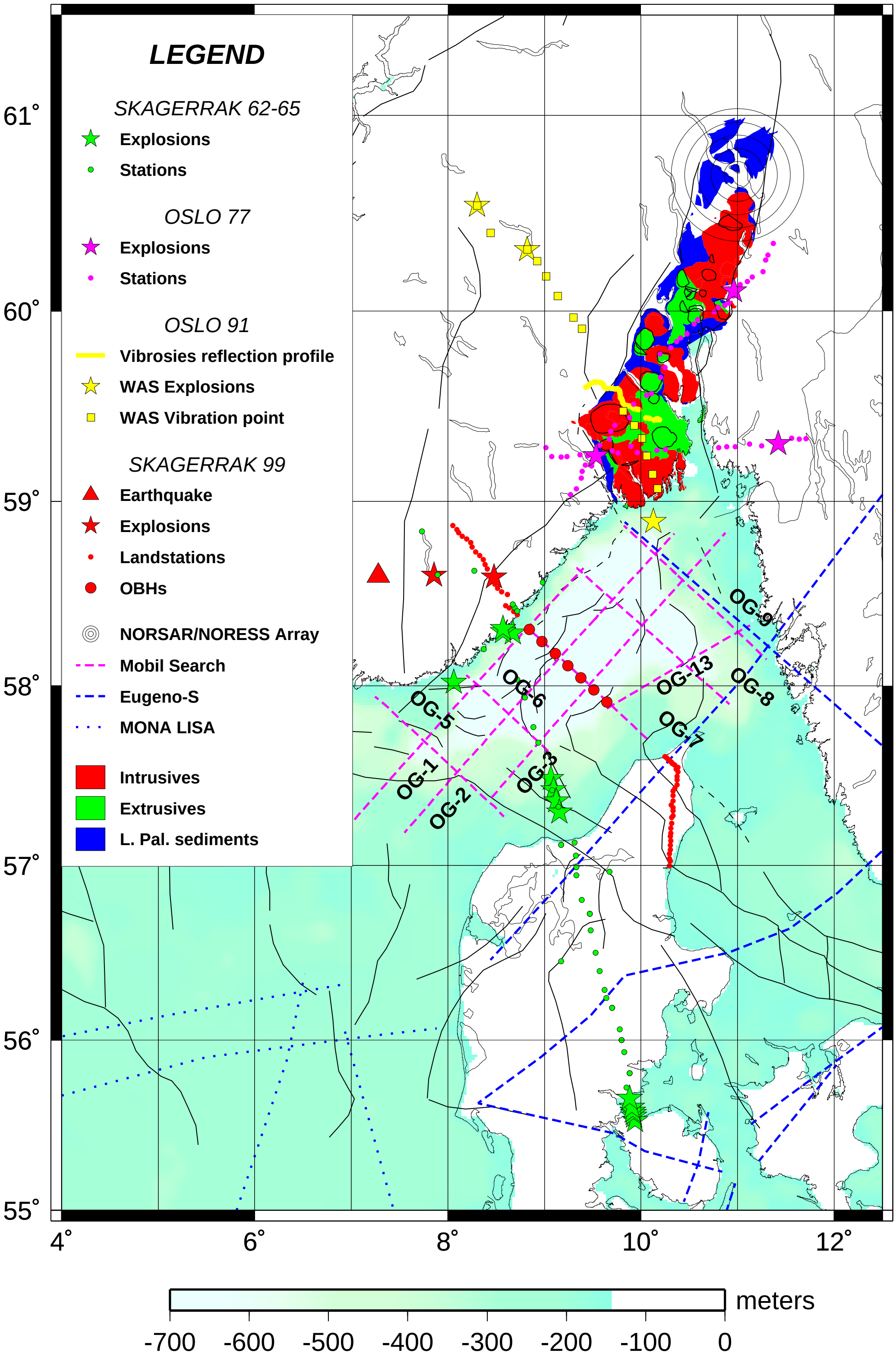

Figure 1. Overview of the Oslo Rift area with Oslo Graben geology and the main seismic surveys

- integrate petrological/geochemical data with both onshore and offshore geophysical (seismic, gravity, magnetic) and geological data to understand the geodynamics of the rifting process and its associated magmatism.
- model the thermal evolution of the lithosphere in the northern foreland of the Variscan orogen during Permo-Carboniferous times.

2 Geological and geophysical framework

The Skagerrak Graben is the offshore continuation of the Oslo Graben (Ro et al., 1990; Fig. 1). Both the Oslo Graben and the areas surrounding the Skagerrak Graben show evidence of Permo-Carboniferous magmatic activity. The Skagerrak Graben was until recently believed to be almost non-magmatic (Lie et al., 1993). Recent seismic interpretation, however, suggests the presence of late-Palaeozoic (Permian) volcanics in the graben. The same approach led to the inference of volcanic rocks within the Sorgenfrei-Tornquist Zone, which was confirmed by borehole data. A body of dense, mafic, rocks in the lower crust has been described in the Oslo Graben using wide-angle seismics and gravity anomalies (Ramberg, 1976; Neumann et al., 1992). The Bouguer gravity anomaly map over the central Skagerrak (Fig. 2) strongly suggests the presence of such a magmatic body at depth in this area as well (Ro and Faleide, 1992). The gravity anomaly also features a deviation from the graben axis while reaching the Sorgenfrei-Tornquist zone.

Modelling studies of the Oslo and Skagerrak Grabens have revealed substantial problems in determining the evolution of the deeper crust in the grabens. Crustal stretching factors differ considerably from model to model. Upper crustal stretching factors for the Oslo and Skagerrak Grabens are estimated to be lower than 1.3 (Ro and Faleide, 1992; Pallesen, 1993). However, stretching factors in the lower crust of the Oslo Graben can reach values as high as 2 when the thickness of the accreted material at the crust-mantle interface is taken into account (Ro and Faleide, 1992). Rheological models for that area (Ro and Faleide, 1992; Heeremans, 1997) suggest that during formation of the Oslo Graben, the lower crust had limited shear strength, making it capable to flow. These rheological models are based on simple assumptions and need therefore to be better constrained.

3 Scientific objectives

The first objective of this study is to collect wide-angle seismic data in this area, and, in conjunction with low aperture seismic data and gravity, to study the structure and formation of the Skagerrak graben and its surrounding basins.

Cross-rift profiles at the highest gravity anomalies, OG7 and OG8 lines (Fig. 1 & 3), may be the two key-profiles to understand the tectonic structure of the Oslo Rift in Skagerrak. These two deep reflection profiles have recently been reprocessed at GEOMAR with new techniques (pre-stack depth migration). The reprocessing attempts to enhance the resolution mostly in the first 8 seconds and to provide a good picture of the lithospheric deformation. Moreover, the downward extension of some of the faults in the lower crust will be possible.

The estimate of the stretching factor depends on the presence of additional crustal material. Because a magmatic body in the lower crust cannot be detected by normal incidence seismics only, no sensible estimation of the amount of stretching within the lower crust is possible without constraints from the wide-angle seismic data.

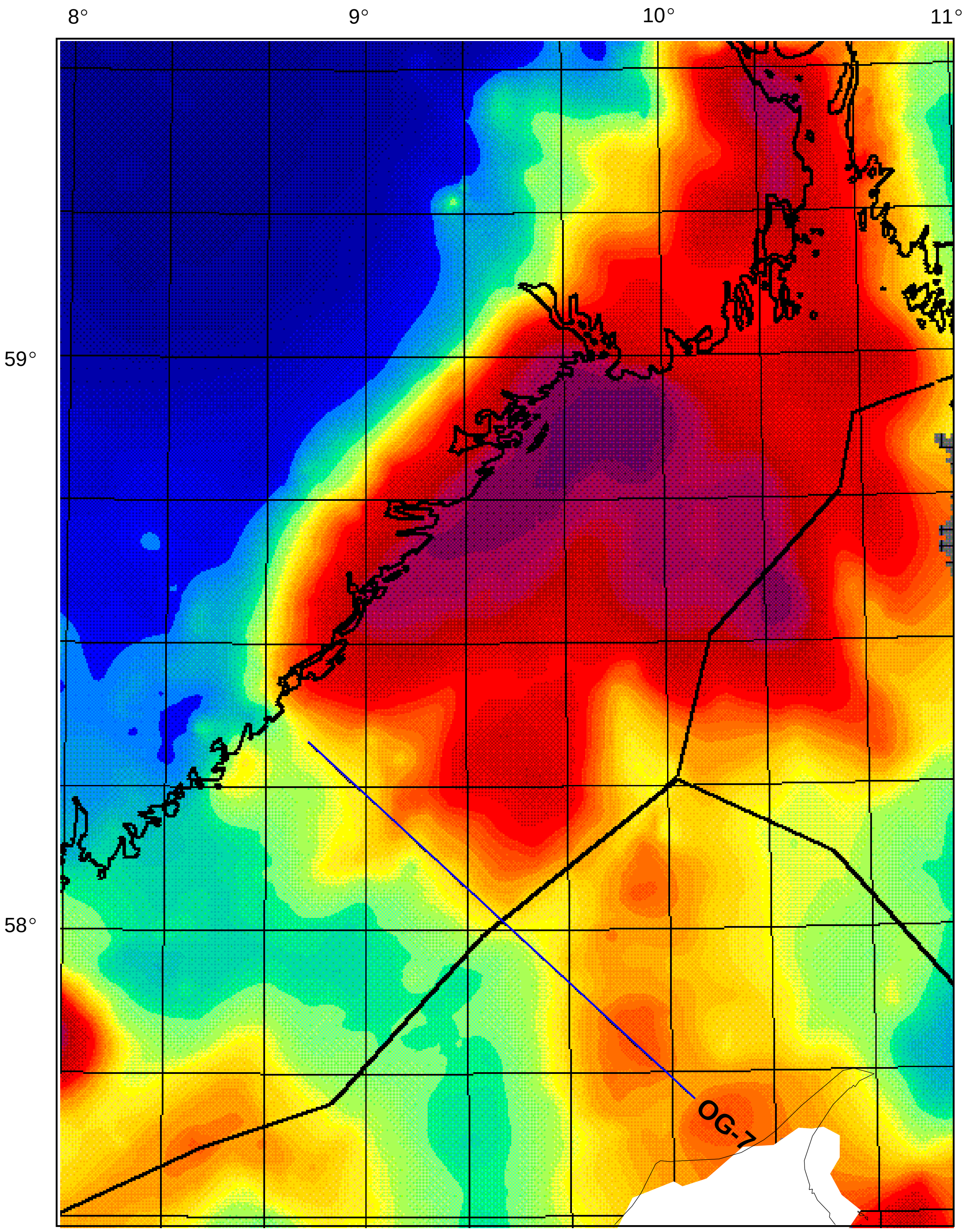

Figure 2. The total Bouguer gravity anomaly in the Skagerrak. Note the high positive anomaly below the southeastern part of OG7, which corresponds with the high reflectivity as visible in Figure 3. Courtesy of TGS-NOPEC ASA

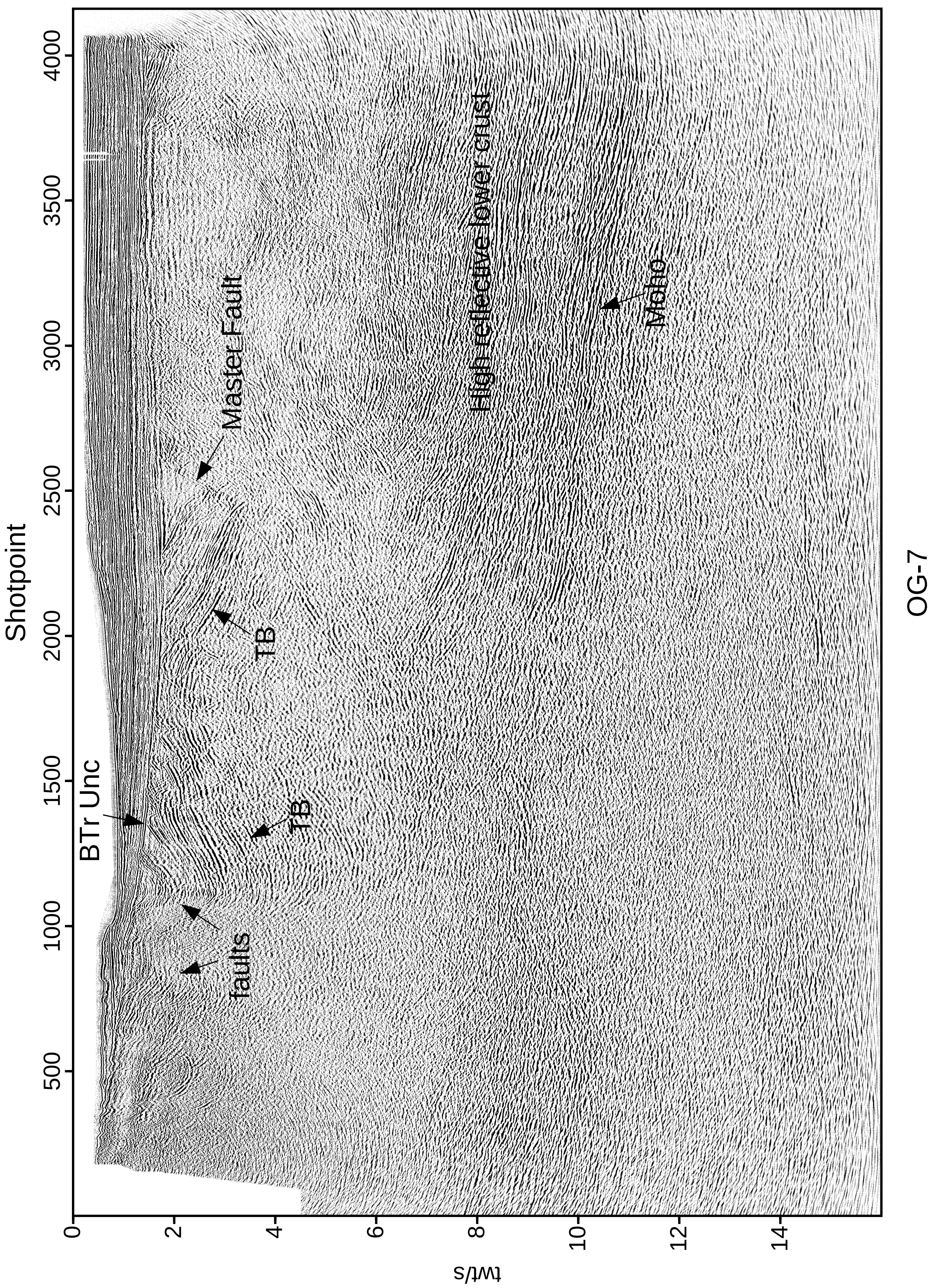

Figure 3. Seismic section OG-7 with mian structures pointed out. BTr-Unc: Base Triassic unconformity; TB: Top Basement

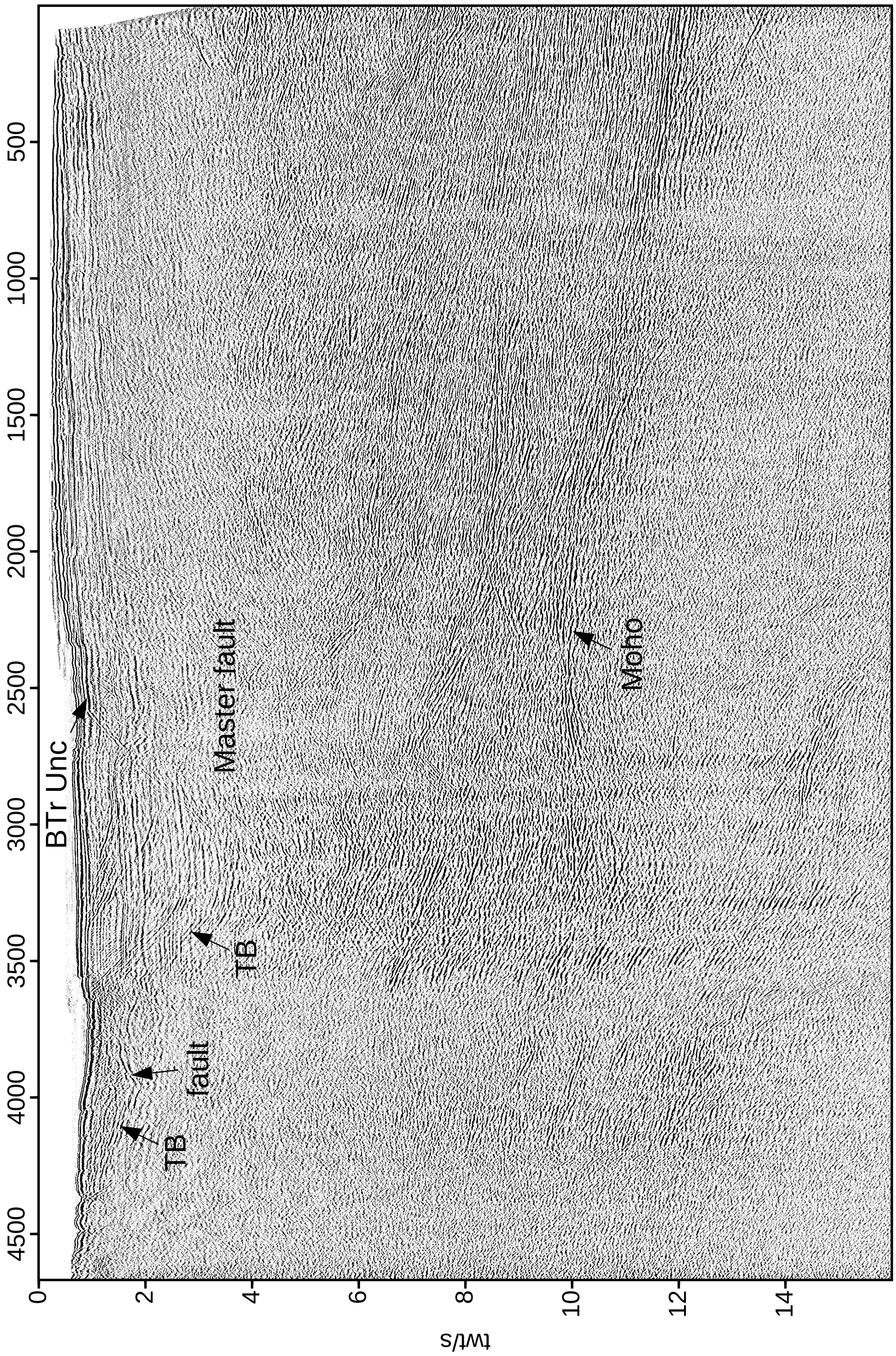

Figure 3 continued. Seismic section OG-8 with mian structures pointed out. BTr-Unc: Base Triassic unconformity, TB: Top Basement

The second objective focuses on the magmatic body itself. Because deformation processes are strongly dependent on temperature and chemistry, investigation of magmatic intrusion is of key importance to understand the evolution of the rift system.

The wide angle profiles alone will allow to study the intrusion in two ways:

- The depth and lateral extent of the magmatic body. This will provide structural constraints needed for gravity modelling.
- Mapping the variations of the volume of the magmatic body within the Skagerrak Graben, using the constraints of the gravity data. A new estimate of the overall volume of magmatic products along the Oslo rift will then be discussed. A new map of the Moho depth will result from the combined interpretation of gravity and wide-angle seismic data.

Furthermore, the deviation of the gravity anomaly from the graben axis may bear important constraints on the relation between the intrusion of magmatic bodies and the geometry of the rifted zone (e.g. relation between deep-seated magmatism and shallow deformation).

Finally, the integration of refraction and reflection seismic investigations will allow a study of the influence of underplating on rifting processes. A description of the faults and their distribution (reflection) and the magmatic body (refraction) opens the way to estimate the possible differential stretching between the upper, brittle crust and the ductile lower crust. It will be attempted to relate the faulting pattern and its extent to the presence of the magmatic intrusion. Special attention will be devoted to the low angle reflector that crosses the whole crust and offset the presumed crust-mantle boundary (see Fig. 3). Its existence as an initial weak plane resulting from a previous compressive stage (Sveconorwegian orogeny) will be discussed in a mechanical framework.

The heat release associated with the cooling and solidification of molten rocks is expected to substantially weaken the lithosphere. Based on the diffusion of heat, this process is strongly time-dependant. A 2D model of cooling of a magmatic body intruding the deep crust will be tested, following the 1D approach of Pedersen et al. (1998).

4 Wide-Angle experiment

The original proposal (Rouzo, 1998, http://www.uio.no/~heereman/proposal.html), aiming for industry partners, had in mind to acquire 5 wide-angle profiles in the Skagerrak Graben. With the economic situation at that time we did not succeed in an industry cooperation. Through contacts between Prof. Ernst Flüh (Geomar) and Dr. Christian Hübscher (Hamburg) we were made aware of that the University of Hamburg was going to use the R/V VALDIVIA for a training and teaching course in the Skagerrak in the month of May, 1999. The actual time at sea would not be sufficient to perform the whole proposed experiment, but since the experiment would run under the PCR project, terminating at the end of 2000, it was necessary to perform the experiment in 1999. We decided therefore to accept the offer of the University of Hamburg to join their cruise and perform a short version of the experiment. The program was even more reduced due to exercises of the Norwegian Navy at the time of the experiment.

We decided to shoot only wide-angle seismics along the same transect as the seismic reflection profile OG-7 (Fig. 3)(Mobil Search 1987, Husebye et al, 1988), since there would not be time to move the recorder devices.

4.1 Recording

Seismic recorders were provided by Geomar (Ocean Bottom Hydro phones) and the University of Copenhagen (REFTEK land recorders). The instruments were positioned along a fairly straight line with a far offset from the main graben segment in order to receive refracted waves from the Moho.

4.1.1 OBH

The OBH (Ocean Bottom Hydro phones) systems used are constructed at Geomar (for mechanical details see Flueh and Bialas, 1996, or http://www.geomar.de/sci_dpmt/geodyn/obh/geodyn-OBH.html). During the cruise, 7 OBH systems were available from and deployed by people from Geomar. They were equally distributed across the Skagerrak (Fig. 1 & 6; App. B). Due to possible fishery activities all positions were chosen to be at more than 50 m water depth.

Deployment of the OBH systems was started on May 23, 02:00 ships time and finished on May 23, 08:15 ships time. The OBH systems were active until recovery. Recovery started on May 27, 20:50 UTC and finished on May 28, 03:35 UTC.

Due to parallel support of three cruises no data playback device could be provided on board RV VALDIVIA. Therefore no detailed check of data quality was possible. Nevertheless, it could be stated that two stations (OBH-6 and OBH-7) reported a data buffer overflow indicating that not all data had been written to tape. All other recording devices returned with no error message.

Ship traffic noise is visible in the recordings of OBH systems which have been placed at the shallowest water depths.

4.1.2 REFTEK land stations

A total number of 57 REFTEK land stations were provided and deployed by the Geological Institute of the University of Copenhagen. Both on the Danish side as well as on the Norwegian side of the Skagerrak, instruments were set up (Fig. 1, App. C). For technical details on the REFTEK instruments see http://www.reftek.com.

4.2 Air-gun shooting

Air-gun shots were provided by the Institute for Geophysics of the University of Hamburg. Air-gun trigger was provided by the so called “Mutteruhr”, a high precision time system. In

No	SOL	EOL	SP-int
Profile 1	23.05.2000 12:44	24.05.2000 02:33	60
Profile 2	24.05.2000 02:48	24.05.2000 22:14	50
Profile 3	24.05.2000 22:31	25.05.2000 07.22	50
Profile 4	26.05.2000 13:27	27.05.2000 00:39	6
Profile 5	27.05.2000 12:00	27.05.2000 19:40	12

SOL: Star of Line in UTC; EOL: End of Line in UTC; SP-int: Shot point interval in seconds

Table 1: Profile details

order to provide shot times with respect to the GPS synchronization of the OBH recording devices a spare recorder was set up to record the trigger pulse.

Details of the air-gun shooting can be found in Table 2. Due to compressor capacity two 8 litre guns were shot at 60s interval for the first profile. For the second profile the shot interval was set to 50s. Due to gun failures and necessary repair time the line was not finished before May 24, 22:14 UTC. Profile 4 was shot with a 3 litre air-gun at 6 s interval towards the OBH and a 150 m long streamer. Prior to recovery of the OBH's a last run was done operating two guns. A 2.5 litre and a 3 litre gun were shot on the OBH and the streamer.

A capacity of 2x8 litres is on the low side for refraction seismic experiments and since the capacity of the air guns decreased over the duration of the experiment, the first run profile is therefore of best quality. Figure 4 shows the shot point locations and the OBH locations for the first run profile (Start of line May 23, 1999, 12:45:46 GMT, end of line May 24, 1999, 02:32:38, from UKOOA-file)

4.3 Land shots

While the research vessel had to be out of the area due to Navy exercises, two land shots were fired by the team of the University of Oslo. Together with the Head of the Department of Ecological Management of the Aust-Agder Fylkeskommune, Per M. Optun one suitable (meaning not damaging faunal and floral environments and proper seismic coupling with the basement) location was found. A second site was found by reconnaissance on the day of the second shot. Both sites were abandoned mine shafts filled with water. For details on the shots and their locations see table 2.

Each shot contained ~400 kg of TNT. The charges consisted of 32 PVC-pipes containing 12.17 kg of explosives each, tied up in bundles of three or four (Fig. 4). The charges were lowered in the water by hand (Fig. 5). The charges were detonated using a precise GPS clock for synchronization with the recorders. Both shots were successful; the second one was recorder by the NORSAR as well (as shown in Appendix D). The blow out of the second shot caused damage to the surrounding forest. In addition to both shots, a small earthquake occurred in the same area during the recording time (see Fig. 1 and Appendix E).

SP	Date	Time	Lon	Lat	X (m)	Y (m)	Z (m)
Askland	25/5	18.30	8˚ 28’ 32.2’’E	58˚ 35’ 37.7’’N	469519	6494940	270
Flatebygd	26/5	16.30	7˚ 51’ 26.4’’E	58˚ 36’ 7.7’’N	433597	6496320	300

Table 2: Wide-Angle land shot point information (May 1999, General Mean Time). Shot point located using 1:50.000 scale topographical maps (UTM 32, ED50). Both shots used 400 kg of TNT

4.4 Navigation

The navigation has caused some problems, since there was no computer dedicated to navigation recording and processing. Different PC's recorded the navigation which got stuck now and then. The raw navigation files had to be hand filtered by Stephane Rouzo to get proper navigation files for the seismic processing. Depth values were digitized from a map after the cruise. Figure 6. shows the filtered navigation for profile 1 together with the position of the OBH systems.

Figure 4. Each single PVC pipe contained 12.17 kg of dynamite. The pipes were tied together in bundles of 3-4 pipes each. To every bundle 1200 grams of extra dynamite and a detonator of 250 grams were attached. From left to right: Benny Bruun, Andy Ross and Michel Heeremans.Phot by Annik Myhre

Figure 5. In total 400 kg of TNT (10 bundles of either 3 or 4 PVC pipes) was lowered in the water filled quarry by hand. From left to right: Alf Kr. Nilsen and Michel Heeremans. Photo by Annik Myhre.

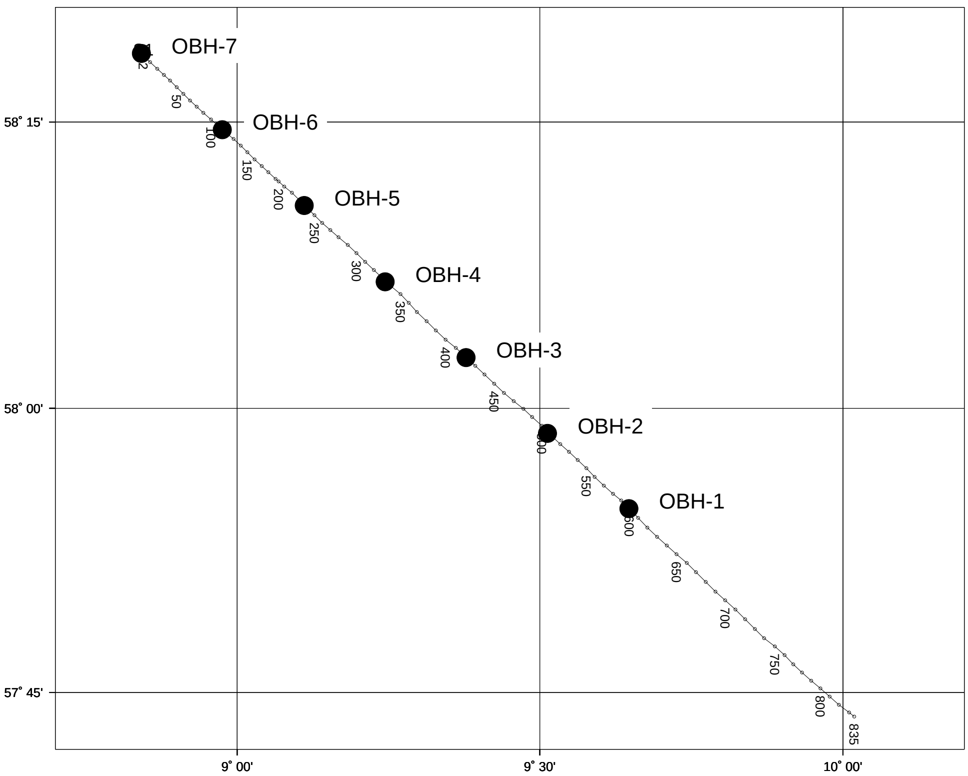

Figure 6. OBH positions and shotpoint positions for Profile 1 after filtering of the navigation data

5 Work in progress

Benny Bruun from the University of Copenhagen is currently doing a Master's on the processing and interpretation of the data recorded by the land stations. Results are not present yet. The OBH data will be send to Copenhagen were processing will start while Benny Bruun is still working on his Master thesis. The OBH data will hopefully constrain this work.

Reflection profiles OG-7 and OG-8 have currently been reprocessed and post-stack depth-migrated at Geomar by Stephane Rouzo and Dirk Klaeschen. The combination of the depth migrated reflection data and the refraction data will give us the opportunity to perform a well constrained gravity modelling study.

A combined reflection and refraction experiment was carried out in the Oslo Graben in August 1991 (Planke et al., 1992). The data, stored at the Institute of Solid Earth Physics of the University of Bergen, is still not processed. The present experiment will hopefully speed up the process of processing this data in order to get a better control on the deeper crustal structures of the total Oslo Rift.

6 Acknowledgements

Per M. Optun (head of the Department of Ecological Management of the Aust-Agder Fylkeskommune), Hans Fløystad of Froland Kommune and Hildur Håkås of Evje kommune helped us in finding the locations for the land shots. We thank Paul Askland and Åse

Gullsmedmoen for giving us permission to fire the land shots on their properties. The experiment was supported by the TMR Program: Access to Large Scale Facilities, GEOMAR OCEAN BOTTOM SEISMIC RECORDERS AND PROCESSING CENTER FOR MARINE GEOPHYSICAL DATA and the Institute of Geophysics, University of Hamburg.

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8 Appendices

Appendix A) List of participants

Name	Position	Institution
Marine crew		
Christian Hübscher	Crew leader	University of Hamburg
Ali Dehghani	Scientist	University of Hamburg
Max Krüger	Student	University of Hamburg
Mike Lüdde	Student	University of Hamburg
Christian Wenz	Student	University of Hamburg
Joerg Bialas	Scientist	Geomar
Stephane Rouzo	Scientist	Geomar
Dirk Bruns	Captain	R/V VALDIVIA
Land crew		
Annik Myhre	Scientist	University of Oslo
Michel Heeremans	Scientist/Logistics	University of Oslo
Jan Inge Faleide	Scientist/ship-to-shore contact	University of Oslo
Alf Kr. Nilsen	Explosive expert	University of Oslo
Benny Bruun	Student/REFTEK operator Norway	University of Copenhagen
Andy Ross	Scientist/REFTEK operator Norway	University of Copenhagen
Lars Nielsen	Scientist/REFTEK operator Denmark	University of Copenhagen
Peer Joergensen	Technician/REFTEK operator Denmark	University of Copenhagen

Appendix B) Position and elevation of the OBH systems

No	Latitude	Longitude	Depth (in m)
OBH-1	57˚ 54’ 43.8”	9˚ 38’ 47.4”	98
OBH-2	57˚ 58’ 42.0”	9˚ 30’ 44.4”	220
OBH-3	58˚ 02’ 40.8”	9˚ 22’ 41.4”	496
OBH-4	58˚ 06’ 39.6”	9˚ 14’ 38.4”	633
OBH-5	58˚ 10’ 37.8”	9˚ 06’ 37.8”	622
OBH-6	58˚ 14’ 36.6”	8˚ 58’ 33.0”	410
OBH-7	58˚ 18’ 34.8”	8˚ 50’ 30”	278

Appendix C) Positions of REFTEK land stations

Denmark				Norway			
Location	**Easting**	**Northing**	**Elev.**	**Location**	**Easting**	**Northing**	**Elev.**
Østerkilt	574706	6385891	10	Dale	445350	6526075	330
Ravkilt	575401	6385276	15	Vestenåknuten	447600	6523500	230
Skram	576149	6384590	16	Hasledalsbekken	448650	6521600	240
Tuen	577009	6383940	15	Tverråbekken	450900	6519450	220
Sørig Enge N	577702	6383294	12	Ytrehommen	453525	6517950	230
Sørig Enge Ø	578556	6382617	8	Svarvarodden	455875	6515800	200
Landkanalen	579200	6381874	7	Toftefjorden	456650	6513050	200
Nørre Sørig	579851	6381202	10	Åpål	458625	6510150	190
Lyngshede	580649	6380777	12	Båsmyr	461125	6507775	180
Råbjerg Mose	581550	6378258	12	Rønningen	463300	6505450	190
Napstjert Mose	582673	6379496	10	Skeidmo	464250	6502500	180
Klitten	582872	6376488	10	Flateland	465650	6499700	180
Vester Holmen	582422	6373866	13	Hynnekleiv	466450	6495800	190
Nørgård	582215	6371702	28	Rosæ	469650	6494050	240
Nederskov	582393	6368444	45	Stølemarka	470025	6490550	200
Østerhalden	580946	6366262	45	Mjåvatn	471850	6488050	140
Ørnhøj	580069	6364536	57	Uvann	474050	6485900	80
Øster Foldstad	580004	6361767	43	Åveland	477525	6484400	80
Pandbjerg	580156	6358362	50	Furre	476500	6477400	60
Risager	579144	6355874	45	Spikkelia	478750	6476175	65
Halden	580159	6354247	45	Nedenes	481300	6473875	30
Sønder Krogsdam	580206	6352253	35	Søm	483675	6472175	1
Skæveled	580356	6349350	20				
Åleng	579565	6348109	16				
Englund	579477	6344377	13				
Løgtholtsholt	579005	6341455	30				
Frederiksminde	579200	6338342	50				
Kyllingborg	579001	6336273	18				
Østerledgård	579231	6333496	11				
Hjemkær	579021	6330672	7				
Heden	579108	6327939	6				
Rimerne	578593	6325300	9				
Nørreskovgård	578620	6322283	6				
Stokbro	579201	6320918	5				
Landbolyst	578692	6317814	2				

Coordinates in UTM, Zone 32. Elev: Elevation in meters

Appendix D) NORSAR Detection of landshot #2 (Flatebygd, Evje) on May 26 1999 (see also http://www.norsar.no/bulletins/gbf/1999.htm

AGDER, NORWAY									
Origin time	Lat	Lon	Azres	Timres	Wres	Nphase	Ntot	Nsta	Netmag
1999-146:16.29.57.0	58.64	7.44	2.87	0.93	1.64	4	6	2	1.13

Sta	Dist	Az	Ph	Time	Tres	Azim	Ares	Vel	Snr	Amp	Freq	Fkq	Pol	Arid	Mag
NRS	328.1	226.5	Pn	16.30.45.2	0.4	222.2	-4.3	9.6	9.1	301.2	8.41	1	1	121784	0
NRS	328.1	226.5	p	16.30.50.2	0	224.0	-2.5	9.1	5.7	372.6	6.26	2	1	121788	0
NRS	328.1	226.5	s	16.31.27.1	0	213.7	-12.8	4.1	6.1	625.7	4.59	1	-2	121792	0.97
NRS	328.1	226.5	Lg	16.31.30.0	-0.7	230.0	3.5	4.2	4.2	539.2	3.96	3	0	121794	0.96
HFS	392.7	247.6	Pn	16.30.54.4	1.6	224.9	-22.7	7.9	3.9	53.8	8.05	4	0	121777	0
HFS	392.7	247.6	Sn	16.31.33.2	-0.3	250.9	3.3	3.5	6.5	186.7	4.11	1	-3	121795	1.43
HFS	392.7	247.6	Lg	16.31.49.6	0.5	245.8	-1.8	3.4	4.3	189.2	3.92	3	0	121797	1.46

Appendix E) NORSAR Detection ofearthquake (Vest Agder, Norway) on May 26 1999 (see also http://www.norsar.no/bulletins/gbf/1999.html

AGDER, NORWAY									
Origin time	Lat	Lon	Azres	Timres	Wres	Nphase	Ntot	Nsta	Netmag
1999-146:13.40.59.0	58.60	7.28	11.04	3.18	5.94	4	7	3	2.31

Sta	Dist	Az	Ph	Time	Tres	Azim	Ares	Vel	Snr	Amp	Freq	Fkq	Pol	Arid	Mag
NRS	338.5	227.1	Lg	13.42.39.4	3.8	237.9	10.8	4.0	4.2	998.3	1.93	2	0	121171	1.41
GER	1164.6	341.2	Sn	13.45.19.8	1.6	347.3	6.1	5.3	5.0	1201.1	7.23	4	0	121179	3.00
GER	1164.6	341.2	s	13.46.07.3	0	346.4	5.2	3.4	8.8	396.7	1.48	2	2	121180	0
GER	1164.6	341.2	s	13.46.10.0	0	342.7	1.5	3.8	4.7	557.4	2.35	2	3	121181	0
GER	1164.6	341.2	s	13.46.14.1	0	323.6	-17.6	3.8	4.0	443.4	1.69	3	0	121182	0
GER	1164.6	341.2	Lg	13.46.25.1	-6.6	326.1	-15.1	3.3	2.8	758.7	3.00	3	0	121185	3.19
ARC	1498.3	224.6	Sn	13.46.27.5	-0.7	236.8	12.2	4.8	8.4	249.6	4.92	3	0	121177	2.34