<u>First Annual Report</u> <u>January – December 2000</u>

SMSITES: Developing stress-monitoring sites and infrastructure for forecasting earthquakes

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- 5 USAV5 University of Savoie F WP5
- 6 UIB University of Bergen NO WP6
- 7 UPMC7 University of Pierre & M.Curie F WP7

PROJECT HOME PAGE: http://www.smsites.org/

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1. SUMMARY BY CO-ORDINATOR

The first year of the SMSITES Project has been highly successful. It has achieved all its deliverables and milestones, and all programmes of all partners are running on time, with two minor exceptions. One unqualified success has been the recruitment of Dr Sebastien Chastin as the Financial and Scientific Manager of the Project at UEDIN (and the compiler of this report). He has taken over the day-to-day management of SMSITES and his energy and expertise has successfully co-ordinated all the various activities.

Progress with the Workpackages is as follows: **WP1 Routine DOV/COV surveying** – **ON TIME:** No activity expected until SMS installation up and running.

WP2 Commissioning extra SIL Stations -

Installation of the four hydrological equipment (Stations S-8, S-9, S-10, and S-11) in wells has been completed and recording and transmission is expected to begin in February, 2001. The installation of three additional seismic stations FLA, BRE, and HED, has been delayed. FLA and BRE are very remote and although now successfully installed, technical difficulties (some 40km from the Arctic Circle) has meant that their data has not yet been incorporated into the SIL Network automatic analysis programme. This now has the highest priority.

WP3 Comissioning DOV/COV surveying -

The SMS-experiment in the deep ex-geothermal wells has had two field operations in October and December, 2000, and will resume in April, 2001, when weather conditions (c50km from Arctic Circle) are again amenable (the weather will not be a problem when the equipment is fully operational). There were several minor delays in installing the Stress-Monitoring Site (SMS) experiment in the three deep boreholes due to having to take cheapest options when requesting services from commercial companies (see Note on Timing, Section 1.2). The field trip included a series of repeated signals from the same source and receiver positions to determine short-term temporal stability of the signals. These signals are still being analysed (end January, 2001).

WP4 Developing processing techniques for multi-event processing - MINOR DELAYS:

is on time, but processing actual data depends on data from the FLA, BRE, and HED, seismic stations and this has been delayed (see WP2, above).

WP5, WP6, WP7 Gological and Geophysical mapping and modelling – ON TIME:

MINOR DELAYS:

MINOR DELAYS:



Field work in recording GPS data, measuring and modelling veins in outcrops, and measuring and modelling fractures in outcrops is on schedule. Please see technical reports in Section 3, below.

Note there have been two problems with the SMS-experiment in WP3, one technical, and one geological.

(1) The technical problem is that the recently available, recently commercialised, Downhole Orbital Vibrator (DOV) source transmits shear-wave signals over the 300m to 500m ray paths between the boreholes but with significantly less shear-wave signal-strength than expected theoretically or as P-wave radiation in a pond in a quarry, when tested by subcontractor UEDIN-S1. The DOV tool has not previously been used in this shear-wave mode. The poor response is believed to due to the fluid-to-borehole-wall coupling where the viscosity of the borehole fluid is crucial to the transmission of shear-waves. *This can certainly be improved* and extensive tests in concrete blocks, the quarry pond, and underground in a salt-mine are planned in February, 2001. This will be in time to put any improvements in place before the planned start of further SMS operations in April, 2001.

(2) The geological/geophysical problem is that the (pre-existing) wells at Husavik are through strongly layered, strongly fractured, basaltic rocks. There appears to a homogeneous c200m-thick from 500m to 700m. This means that records in HU04 of signals, from 500m to 700m in the source well HU05, are dominated by interface waves propagating along the top of the homogeneous layer. The behaviour along these (interface) ray paths, although carrying information, is very much more difficult to interpret in terms of increasing stress than the direct ray paths would be. We hope that the improved DOV signals following the investigations in (1), above, will help to resolve this problem.

In summary:

The SMSITES Project is on schedule, and the minor problems are believed to be resolvable. We confidently look forward to years two and three.

2. SECTION 1: YEARLY MANAGEMENT REPORT

2.1. Objectives of the reporting period

The principal objectives of the first year of the project were

- 1. To organise the project, including secretariat. This included
 - Recruiting staff
 - Assemble and test equipment
 - Survey wells at Húsavík
 - Analysing interpreting, and writing up previous data relevant to SMSITES
- 2. To set-up the infrastructure of the project:
 - SMS site
 - additional SIL station
 - hydrological monitoring stations
 - GPS stations
 - Website
 - Co-ordination system and protocol
- 3. Perform initial field studies and surveys.
- 4. Analyse and interpret these first results

All these various works have met their goals successfully and the SMSITES project is well within the planned time and budget schedules.

2.2. Scientific/Technical progress made in different work packages according to the planned time schedule:

IN ALL CASES THE PROGRESS IS GOING ACCORDING TO THE PLANNED SCHEDULE as specified in

- Table 1: Gantt update
- Table 2: Comparison of planned and used manpower.

However please see "Note on timing" immediately below.

Detailed scientific and technical progress per work package is given in Section 3, summary of progress is presented below.



Note on timing:

The SMSITES project is tightly funded. It requires borehole operations (mainly for the SMS) and Oil Industry standards and techniques, which are expensive. The SMSITES project cannot bid/compete equally with private companies for access and provision of equipment and services. This means that the SMSITES project has had to go for the cheapest, but adequate, option. In several circumstances (e.g. well logging, delivery of equipment such as winch etc.) SMSITES simply had to take the back of the queue and wait for the convenience of the service companies. Therefore delays occurred in the acquisition and delivery of equipment and some service, mostly for the SMS (WP3). These delay are usually cumulative which meant that the infrastructure of the project, especially the SMS at Húsavík has not progressed as fast as expected in the first six-month. Most of these delays have however been caught up with in the second semester. The installation of the SMS equipment was postponed from June to September 2000. This has meant that the installation had to be carried out in much less favourable weather condition and restricted daylight. However thanks to the efforts of UEDIN-S1 (P.Leary), IMCG (J.Gregson), UEDIN(S.Crampin, S.Chastin), and the very helpful support from Orkuveita Húsavíkur (H.Hjartarson) the Húsavík Water Company and of the local population, the SMS is set-up and operational as planned. Similarly all the other hardware parts of the infrastructure are in place and all targets have been.

Co-ordination:

Dr Sebastien Chastin was appointed (1st June, 2000) as Financial and Scientific Manager of the Project. The efficiency of the secretariat and the co-ordination is greatly improved and close to optimum. The SMSITES website is now in place and the key to the co-ordination of the project. A desktop PC was purchased to administrate the project, produce publications, and maintain the website.

Table 1 : Project planning and time table.



Note: Most task are continuous and therefore have no dated target

Table 2: Comparison of planned and used manpower and financial resources.

Workpackage	Deliverable	Title	Lead Contractor	Comparison	Financial
WP1	а	Process and interpret shear-wave splitting ay SMS	UEDIN	!	As planned
	b	Issue earthquake stress forecast	UEDIN	As planned	As planned
	с	Co-ordinate source monitoring	UEDIN	*	As planned
WP2	а	Expand SIL network	IMOR.DG	As planned	As planned
	b	Install hydrological equipment	IMOR.DG	As planned	As planned
	с	Determine earthquake parameters	IMOR.DG	As planned	As planned
	d	Monitor and interpret hydrologiccal data	IMOR.DG	As planned	As planned
WP3	а	Install SMS	UEDIN & IMCG	As planned, !	As planned
	b	Operate SMS	UEDIN & IMCG	As planned	As planned
WP4	а	Develop multi-event evaluation	UU	As planned	As planned
	b	Interpret multi-event	UU	As planned	As planned
WP5	а	Record GPS data	USAV5	As planned	As planned
	b	Interpret and model GPS data	USAV5	As planned	As planned
WP6	а	Measure veins in outcrop	UIB	As planned	As planned
	b	Model locking/unlocking mechanism	UIB	As planned	As planned
WP7	a	Measure interpret stress	UPMC	As planned	As planned
	b	Model fracture/stress regime	UPMC	\$	As planned

* Forecasting activity cannot be anticipated \$

Workpackage schedule to start in January 2001

See Note on timing section 1.2 !

2.2.1. WP-1 Stress monitoring site data analysis (UEDIN, UEDIN-S1)

The SMSITES data analysis falls in two categories

- System analysis and set-up
- Routine monitoring

The need for more effort to be put into the SMS set-up meant that there was some delay and less time could be dedicated to analysis. Therefore the core of the data analysis has been focused on establishing the performance of the SMS and less time was spent on shear-wave splitting analysis.

Taking advantage of the period until the next field season (planned in April 2001 for weather and daylight conditions) to fully focus on the shear wave analysis.

The shear wave analysis from SMSITES data has been delayed by the necessity to focus efforts on the SMS installation, but will soon be back on schedule.

2.2.2. WP-2 Installation of further SIL seismic stations and hydraulic monitoring equipment in wells near Húsavík (IMOR.DG)

Three additional SIL stations have been set up:

- Brettingsstaðir 66 07.403 17 54.580 hæð: 56 m. BRE
- Flatey 66 09.640 17 50.850 hæð: 25 m. FLA
- Héðinshöfði 66 04.847 17 18.586 hæð: 80 m. HED

Data and earthquake parameters have been integrated in the IMOR.DG earthquake website's database, which can also be accessed via the SMSITES website.

Hydrological station monitoring wells in the Húsavík-Flatey fault zone have also been set up. The stations are named:

- s8: In 500 m deep well in Flatey, only pressure at 50m depth
- s9: In Arnes, pressure at 70 m and temperature of artesian flow
- s10: At Storu-Tjarnir, pressure at 70 m and temperature of artesian flow plus wellhead pressure of another well.
- s11: In well 4 at Húsavík, pressure at 50 m only.

A web data server has been set-up (which can be accessed from the SMSITES website). It is in Icelandic for the moment.

This work program is on schedule



2.2.3. WP-3 Installation of the SMSITES (UEDIN, UEDIN-S1, IMCG)

The installation of the SMS infrastructure took two trips to Húsavík. A first trip in September 2000 to first instrument receiver and source well, put in place the winch and the data acquisition cables, and run first test. A second trip in November 2000 to do so house keeping. Reduce the noise in the system, consolidate and automate the data acquisition system, take data for orientation of the DOV and receiver geophones. From these data it appears that the heavy layering in the basalt at Húsavík prohibit the high angle ray path (near vertical ray path or deepest DOV location) to be use in the present context. Remedies have been though and during the winter interval between field trips, laboratory experiment will be conducted. These experiment aim at increasing the amount of energy delivered by the DOV by making the coupling more efficient. More energy means that the high angle ray path could be use

The installation is now finished. The SMSITES cannot at this stage be left in place continuously, but every effort have been made so that the set-up at the beginning of every survey does not take more than a day work.

The installation is on schedule

2.2.4. WP-4 Multievent analysis (UU)

For relative location of microearthquakes near Húsavík on the Tjörnes fracture zone it is vital to have the seismic stations at Flatey and Flateyjardal in operation. As these stations have only been put in operation recently, emphasis has been put on software developments related to later analysis of the microearthquake data.

The multi-event analysis will be underway as soon as the New Stations have acquired sufficient data

2.2.5. WP-5 GPS surveys (USAV-5)

A first GPS campaign has been performed from June 6 to June 12, 2000, USAV has re-measured a set of 10 points from the TGN. These points are striking perpendicular to the Húsavík fault (Fig 1). All points have been observed at least 24 hours. The measurements were made with Ashtech dual-frequency receivers and choke-ring antennas. Collected data are of good quality and have been processed.

The work package is on schedule



2.2.6. WP-6 – WP-7 faults and fractures (UIB, UPMC) 2.2.6.1. WP6

A conceptual and a generic numerical models of fluid pressure locking the Húsavík-Flatey Fault (1) have been developed whereby dyke injection (and normal faulting) in the nearby volcanic systems can lock or unlock the central parts of the Húsavík-Flatey Fault.

To put constraints on the fluid overpressure and transport inside the Húsavík-Flatey Fault during seismogenic faulting, field measurements were made of more than 17 hundred mineral-filled veins in its damage zone *WP6 is on schedule*

2.2.6.2. WP7

The first field work of the SMSITES programme has been carried out during last summer (30th of June to 15th of September), essentially in the Tröllaskagi, Flateyjarskagi and Tjörnes peninsula. At each site structural observations were made and tectonic features, such as faults and dykes, were measured when available. The analysis process of these tectonic features is now in progress A mechanical modelling has been developed to study how the northward migrations of the Icelandic rift, as well as the development of fractures zones, contribute to this instability of the stress field.

WP7 is on schedule

2.3. Milestones and deliverables achieved

The SMSITES project deliverables come under three forms: Reports, Data and equipment installation.

2.3.1. Reports

2.3.1.1. Monthly Report (D0)

Deliverable D0 has been in use since February 2000 and has been issued every month since then, at the exception of December 2000 since this report and the end of year report replace it. All issues are available on the SMSITES website.

2.3.1.2. Technical Reports (Internal not deliverables)

- DOV Processing and Far-field Amplitude analysis
- SMSITES Depth Section Anisotropic Shear Wavelet Processing
- DOV Orientation by Clockwise & Couterclockwise-sweep Shear-wavelet Analysis
- DOV Performance at Stoney Cove Quarry
- Validating DOV point force radiation model in acoustic medium
- Validating DOV orientation via far field acoustic wavelet phase
- DOV wire line operation development notes
- Logging and fishing in Húsavík wells 1-,4 and 5
- Winsford II
- Deep Quarry Survey
- Initial Húsavík Cross-well Survey
- Húsavík2 Summary



- Húsavík2
- S-Wave Analysis

2.3.1.3. Field work reports

Fieldwork reports are included in the first year report section 3 as part of the Partners annual progress reports. These will be posted on the SMSITES website.

2.3.1.4. Other publications

All the partners publication pertaining to the SMSITES project are listed in Appendix A

2.3.2. Data

2.3.2.1. Earthquake Parameters (D2c)

The earthquake parameters from earthquake recorded at the new SIL stations BRE, FLA and HED will soon be routinely determined and posted on the IMOR.DG website, for use by the partners.

2.3.2.2. SMS data (D3b)

Two full sets of data have been recorded during the two surveys at the SMS.

- The first set recorded in September 2000, was for installation purposes and testing only.
- The second set of data contains house keeping data, signal stability survey and a 3 day continuous monitoring

2.3.2.3. Routine Multi-event evaluation (D4a)

UU Brief progress report on multi-event evaluation and interpretation is included in the first year report.

2.3.2.4. Fracture and Stress (D7a)

Two maps of the Tjörnes peninsula have been drawn, based both on remote sensing imagery (SPOT and ERS1) and field observations.

- ERS1 interpretation map.
- SPOT interpretation map.

They are available on the SMSITES websites (Too large to reproduce here)

2.3.3. Equipment

2.3.3.1. SIL and Hydrological monitoring stations (D2a, D2b)

New SIL and Hydrological station are now installed and fully functional (see section 1.2.2)

2.3.3.2. SMS installation (D3a)

The infrastructure of the SMS at Húsavík is now in place. The signal has been improved and noise level reduced to amplifier noise. The SMS is ready to be used again during the next field season.



2.4. Deviations from the work plan or /and time schedule and their impact to the project

There are no deviations from the work plan and time schedule. The note on timing in section 1.2, above, merely indicates that the SMSITES stress-monitoring program is not going as fast as was hoped. The project is now speeding up and catching up. There has been no impact on the overall project. SMSITES is still well within the time schedule as set out in the original Description of Work.

2.5. Co-ordination of the information between partners and communication activities

2.5.1. Co-ordination

The main Co-ordination tool is the Monthly Reports (Deliverable D0) compiled by the Co-ordinator and distributed to the Scientific Officer, the Partners and various associated people.

The Monthly Reports are also posted on the SMSITES website now in place at <u>http://www.smsites.org</u>. The website play a major role in the co-ordination of the project. It links all the partners' webpages. It contains all reports* for reference and archiving, the partners publications. It also serves as data* repository and forum for discussion between the partners.

Aside this important role the website is also a promotional tool for the project. Therefore the site also includes Introduction pages and news pages. The SMSITES website recorded 161 hits last month.

(Note * these pages are confidential and protected by password)

2.5.2. Meetings

2.5.2.1. SMSITES meeting

The first SMSITES meeting took place on the 16th September 2000. Then meeting was moved from June to September to allow for the summer field season. During meeting progress was discussed and first results of the field season were presented.

The second SMSITES meeting will take place in June 2001, before the next field season.

2.5.2.2. Conferences

All conferences attended by SMSITES Partners are listed in appendix B with a list of the abstract, presentation given. The list also includes dates of the conference.

(Note: Many of the conference have not been attended with SMSITES fund. Nevertheless, they are all used to promote and publicise the SMSITES Project)



2.5.3. Co-operation with other projects

This project is heavily dependent on the various procedure set-up by previous European Commission Projects PRENLAB 1 and 2.

2.6. Difficulties encountered at management and co-ordination level and proposed/applied solutions

The SMSITES project consists of three distinct groups of Partners with different commitments and different interactions with other Partners. These are:

- The Partners directly involved with the stress-monitoring in boreholes near Húsavík. Principally Edinburgh (UEDIN) employing Sub-Contractor (UEDIN-S1), IMC Geophysics Limited (IMCG) and various well-logging and maintenance Sub-Contractor in Iceland.
- Seismic Station and Hydraulogical monitoring equipment installation, monitoring and interpretation spearheaded by IMOR.DG.
- Partners involved in field observation and theoretical, numerical and laboratory studies. USAV5, UIB, UPMC

2.6.1. Stress Monitoring Sites

Partners UEDIN and IMC, and Subcontractor UEDIN-S1 are all based in the UK. They work very closely together, daily e-mails, phone calls are exchanged and frequent meetings are held. There is excellent and fruitful contact, and work.

In the field the relationship with the local population and Orkuveita Húsavíkur (Proprietor of the wells, who we wish to thank) is also excellent. *There are no management difficulties*

2.6.2. Installation equipment near Húsavík

The Installation of both SIL stations and hydrological borehole equipment has been performed by IMOR.DG. IMOR.DG continues to determine earthquake parameters within Iceland as it has been done during the EC project PRENLAB 1 & 2. This work is essential to monitoring stress-changes in Iceland and by UEDIN and the multi-event analysis by UU.

IMOR.DG, UEDIN and UU have had a good working relationship since the PRENLAB Projects and this continues

There are no particular management problems

2.6.3. Other Studies

The activities of Partners IMOR.DG, UIB, USAV5, UPMC involved field observation. These are largely independent. The work of UIB and UPMC are related and they work very closely (as they did during the PRENLAB project) and have co-authored publications.

There are no management difficulties



3. <u>SECTION 3 TECHNICAL REPORTS AND</u> <u>DELIVERABLES</u>

3.1. WP1 — Partner 1 UEDIN

There has been little activity in workpackage 1 for two reasons. First the installation of the SMS has been delayed therefore also delaying data to analyse, this delay has meant that more attention had to be focused on WP3 the set-up and commissioning of the SMS.

However numerous software routine have been written and they will be inlined in the near future for an integrated analysis package of the SMS data. The DOV is a new instrument and data and expertise are scarce, we are therefore breaking ground. We have developed a shear-wave analysis technique based on correlation. We are going to test this technique against the only other technique based on deconvolution.

Once the technique refined and the routine bundled in a package data analysis should become a fully integrated and routine task.

SMSITES

3.2. WP2 — Partner 2 IMOR.DG

EXTENDING THE SIL SEISMOLOGICAL NETWORK CLOSE TO THE HÚSAVÍK-FLATEY FAULT ZONE, AND BUILD-UP OF A HYDROLOGICAL BOREHOLE MONITORING SYSTEM



Figure 1. The microearthquake network (stations bre, fla and hed). The SIL station gra was installed in 1993.

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1 INTRODUCTION

The two main tasks of the first year workprogramme were in first hand to build a microearthquake network of 3 stations close to the Húsavík-Flatey fault zone and secondly to build a hydrological network for monitoring water pressure/water height in 5 boreholes in an extended area around the fault zone. Both these tasks have successfully been carried out.



The microearthquake network started operation as soon after the necessary equipment was obtained, i.e. in the first days of September 2000. The network was in the following weeks integrated with the comprehensive Icelandic SIL network of 40 stations and its semi-real-time acquisition and evaluation. The results of evaluations of the data are available as other SIL seismic data through the IMOR.DG website and waveform data through the IMOR.DG staff. One of the stations has been operating well through the entire period. The remaining two stations are situated at remote sites along the fault zone, close to persisting seismic microearthquake activity, but in areas which is very difficult to get to, especially during wintertime. There have been some unexpected problems in acquiring data from these two remote stations, so very few satisfactory observations have been collected so far. Much effort is put into solving these problems and as we are coming close to a solution an effective data collection from the remote stations can be expected in January 2001.

The hydrological network, built by the subcontractor Orkustofnun, started operation in November 2000 and semi-real-time data of water pressure/water height in the boreholes are available at the Orkustofnun website.

As the data could not be acquired until in the autumn scientific evaluation has only just started. Evaluation of the seismic data has mostly been limited to the daily manual evaluation and merging of the data to other parts of the SIL network and the all over evaluation of the system. The same is valid for the hydrological data. These have also been prepared for using for further comparison with other data from the area.

2 BUILD-UP OF THE MICROEARTHQUAKE NETWORK, ITS INTEGRATION TO THE SIL NETWORK AND ITS EVALUATION PROCESSES

2.1 Location

Work on determining station locations for the project began in the fall of 1999. The following sites for three seismological stations of SIL type were chosen:

1. **bre** in Flateyjardalur valley, which is in the vicinity of the farm Brettingsstadir. Coordinates: 66°07.403'N and 17°54.580'W'. Elevation: 56 meters.

2. **fla** on the island Flatey in Skjalfandi bay, by the church. Coordinates: 66°09.640'N and 17°50.850'W'. Elevation: 25 meters.

3. **hed** at Hedinshofdi farm, north of the town Húsavík. Coordinates: 66°04.847'N and 18°18.586'W'. Elevation: 80 meters.

As soon as the sites had been chosen work began on digging pits for underground vaults to house instruments. At the stations **hed** and **fla** this was completed in early winter 1999. The following spring digging at the station **bre** was completed. The installation of instruments and windmills at the stations **fla** and **bre** began at the end of August 2000.



2.2 A SIL seismological station

Figure 2 shows how a SIL seismological station can be divided into two parts. On the one hand there is an underground vault containing the geophone and digitizer. On the other hand is the site computer which communicates with the digitizer and a central processing station situated at the IMOR.DG in Reykjavik. A vault is buried in soil 1-2 m thick atop bedrock in order to minimize wind disturbances. The site computer is situated where there is access to electricity and a telephone line. Communication with the central computer at the IMOR.DG is through an X.25 link provided by the Iceland Telecom. Communication between the two parts of the seismic station depends on the distance between them. If the vault is within 2 km of the site computer they are connected by a cable. Most SIL stations have this arrangement, including **hed** (Figure 2). But for stations where there is no access to neither electricity nor a telephone line, as is the case at **fla** and **bre**, power for the vault instruments is obtained by installing windmills and solar cells. Communication with the site computer is then via radio signals. For stations **fla** and **bre** the computers are housed at a Iceland Telecom relay station on Húsavík mountain, where there is access to electricity and a telephone line (Figure 3).



Figure 2. A SIL seismological station.

2.3 Hardware

The seismometers used are Lennartz geophones Le-3D/5s from Lennartz Electronics. The geophones are 3-component and very reliable. They are in use at most of the SIL stations and have never needed repair. The movement of the earth which the geophone detects is digitized using a digitizer with a synchronized clock. The data is then sent to the site computer. Two types of digitizers are in use. At the station **hed** a 16-bit RD3 digitizer from Nanometrics is in use and a Trimble SveeSix GPS receiver for synchronization of the data. This type of digitizer is becoming old. At the stations **fla** and **bre** 24-bit DM-24 digitizers from Guralp Systems are in use, which are a newer design, and an internal Barmin GPS receiver.

The radio modems used for data transmission from the geophones at the stations **fla** and **bre** are of the type DGR 115 HWW from FreeWave. The modems use a so-called spread spectrum method for communication. The communication is full duplex and has the frequency range 915-928 MHz. These modems are of extremely high quality and are widely used abroad for this type of data transmission.



Figure 3. The stations bre and fla.



Figure 4. Brettingsstadir. The yellow dot shows the position of the vault housing the instruments.

The windmill power stations at **fla** and **bre** are of the type AIR400 from Southwest Windpower. Unfortunately these power stations have not proven well in Iceland and it is necessary to exchange them at the first opportunity. Four batteries, totalling 400 amper hours, are situated at each site and should be sufficient for 10-12 days of monitoring without a power supply. At the time of installation the solar batteries that were ordered had not arrived.

The site computers are regular PCs running UNIX which is a multitasking control system and practical in a research environment. The Linux edition is used, which is the most common UNIX control system today. An X.25 card has been installed in the site computers and software from the Software Group. The data goes through the computers' serial port. The site computer at the station **hed** is connected to the digitizer by a long cable and therefore a serial port was installed which uses the standard RS-422 instead of the RS-232, in addition to an X.25 card.

2.4 Installation

Instrument installation began at the end of August 2000. Two employees from the Meteorological Office performed the task, i.e. Bergur H. Bergsson, technical engineer, and Hjorleifur Sveinbjornsson, geologist. The station **bre** in Flateyjardalur was first installed (see Figure 4). The installation of the windmill and other



Figure 5. Hedinshofdi. The yellow dot shows the position of the vault.

instruments went well.

Two days later installation began at the station **hed** (Figure 5). But before the work was completed it was decided to sail to the island of Flatey due to an unfavorable weather forecast. A ship-owner from Húsavík transported the work crew and equipment to the island. He had taken care of the digging at the stations **bre** and **fla**. He owns a house on the island of Flatey and supplied accommodation and the use of a tractor. Arrival at the island was in the evening and installation of the station **fla** was completed the next day (see Figure 6). Installation at **hed** was then completed and data acquisition there commenced. At the same time Helgi Gunnarsson, electricical engineer, was working on two Linux computers for use on Húsavík mountain for receiving data signals from **bre** and **fla**. To save on X.25 costs it was decided to have the computers on a different network and only connect one of them to an X.25 link provided by the Iceland Telecom. In September the computers were installed on Húsavík mountain and data acquisition commenced from the stations **bre** and **fla**.

2.5 Operation



Since the installation of the stations the operation of **hed** has gone well but there have been computer problems at the stations **bre** and **fla**. There are difficulties in holding the X.25 connection, but the cause has not been determined and therefore a solution has not been found. The windmills still seem to be intact, but they are what makes most concern about of the instruments.



Figure 6. Flatey. The yellow dot shows the position of the vault. The windmill power station mast can been seen to the left.

2.6 The future of the stations

To ensure the future operation of the stations it is believed to be necessary to exchange the windmills at the stations **bre** and **fla**. It would then be convenient to install the solar cells. When the computer problems on Húsavík mountain have been solved it is our opinion that the type of SIL stations as are at **bre** and **fla** can become as operationally reliable as the SIL stations of the type that are at **hed**.

3 HYDROLOGICAL MONITORING STATIONS IN BOREHOLES NEAR THE HÚSAVÍK-FLATEY FAULT ZONE. INSTALLMENT AND NOVEMBER TO DECEMBER 2000 PERFORMANCE

3.1 Introduction

An automated data logging system is described, which monitors hydrological parameters in wells near the Húsavík-Flatey fault zone. In February 2000, the IMOR.DG subcontracted Orkustofnun-GeoSciences, to install and operate this system for three years time. Five wells in total are to be monitored by 4 logging stations. All the necessary equipment was purchased and ready for assembly in Orkustofnun



electrical lab in May to June 2000, to be installed and field-tested while still summer in Iceland. But due to the two large seismic events, which struck the South Iceland seismic zone in June 2000, this plan changed and was delayed until November 2000. Meanwhile, valuable experience was achieved by installing and operating similar logging stations in the earthquake hazard zone.

The report is structured as follows. First comes a description and location information for the wells selected for monitoring. Secondly the design of the automated logging system is described. Finally the two months of field operation are discussed and the collected data presented in graphs.

3.2 Well selection strategy and locations

Table 1 shows the wells selected for the hydrological monitoring and Figure 7 shows their locations. In general the monitoring wells should have the following properties:

- 1. To be either non-artesian or fully closed and with pressure on the wellhead.
- 2. Water temperature must be lower than 30-40°C at the depth of a submerged pressure sensor.
- 3. Wells must be cased through free-surface groundwater systems, in order to minimize meteorological disturbance.
- 4. Located on both sides of the Húsavík-Flatey fault zone.

Two of the logging stations comply with all the above (Flatey and Húsavík), whereas in the case of Arnes and Storu-Tjarnir a compromise had to be made. At Storu-Tjarnir we choose to log two artesian wells. One is periphery to the local, fracture hosted geothermal system and flows 0.1 l/s, while the other is drilled directly into it. That one remains fully closed most of the year. In Arnes, a mild artesian flow of a few litres/minute resides. Instead of measuring directly the flowrates of the free flow wells, we simply monitor the temperature of the discharged fluid. This way the logging stations show indirectly if the flowrate increases, due to the sensitivity of the discharge temperature to the flowrate.

Well	Well	Logger	Site name	Depth	Location	Well status
name	ID	Name		(m)	Hjörsey datum	
FE-01	56811	S-8	Flatey	555	66.163476 N	Non-artesian
					17.841316 W	Waterlevel at 16.5 m
AA-01	59701	S-9	Arnes	1250	65.875338 N	Artesian flow of a few
					17.405956 W	litres/minute
ST-06	57226	S-10	Storu-Tjarnir	595	65.709058 N	Artesian flow of a few
					17.738454 W	litres/minute
ST-07	57227	S-10	Storu-Tjarnir	452	50 m to the	Closed most of the time
					south of ST-06	and with pressure
HU-04	51031	S-11	Húsavík	504	66.055088 N	Non-artesian
					17.347046 W	Waterlevel at 15.75 m

Table 1. Wells near the Húsavík-Flatey fault zone selected for hydrological monitoring.





Figure 7. Location of the hydrological monitoring stations.

3.3 Configuration of the data loggers

The data logging system now operating in the Húsavík-Flatey fault zone is using, in our view, the most modern way of logging, retrieving, storing and presenting remote field data. In the field we stack: A Campbell CR-10-X logger, a GSM cell phone, power supply, internal battery and the necessary connecting cables into the same watertight box. On the outside are cables to well sensors and external power (220 V from national grid or a combination of 12 V batteries and solar cells). The loggers are programmed to record all connected sensors every minute to store in their own memories, plus the loggers internal temperatures and battery voltages. Every 24 hours the loggers are called upon by an in-house, PC-Windows computer at Orkustofnun. It retrieves the newly collected data and stores as files on a UNIX operated and frequently backed-up computer system. About 1 hour after new information is downloaded, a special shell script will automatically update GIF images, showing status of each hydrological station for the last 2 days, last week, last month and finally last year. At the time of writing this report, in January 2001, this part is also near completed and should be visible on the web in late February. The webpage www.os.is/ros/eftirlit/forbodiskjalfta/s8/ is showing the basic structure of the upcoming webpages. Note that this way the system generates and updates its own hydrological report near automatically.

3.4 Field data collected in November to December 2000



The following figures present the field data collected since commissioning of the logging stations in early November 2000. The graphics are made in two parts. The upper half shows the status of well sensors, whereas the lower half is showing logger voltage and temperature. These data are important in order to judge the data quality.

Figure 8 shows the pressure at 50 m depth in well FE-01 in Flatey. No abnormal pressure signals are recorded during these two months. Tidal fluctuations are, on the other hand, dominating the pressure signal. The higher frequency signal is simply the daily tides, whereas the lower frequency correlates with the 28 days lunar circle. In total the tidal amplitude is in the order of 0.15 bars, and much lower if only the daily tides are considered. This logger should therefore clearly show stress related pressure changes, if similar to those now observed in the South Iceland seismic zone. Despite a 100% uptime, some loss of data appears to happen between December 17 and 24. The loss is due to lack of sunlight and, therefore, to low datalogger voltage for providing reliable pressure data.



Figure 8. Pressure at 50 m depth (upper half), and logger temperature and voltage (lower half) for station S-8, monitoring well FE-01 in Flatey. Prystingur is Icelandic for pressure (bars-g) and hiti is temperature (°C).

Figure 9 shows data collected in the Arnes (S-9) monitoring station. The well is artesian with a pressure sensor at 80 m depth. A pressure rise equivalent to 30 cm of water is measured during these first two months of logging. The rise is most likely only due to the pressure sensor installment, i.e. when removing the leaking wellhead we temporarily disturbed the well. A constant state is then achieved in a week. We also monitor the discharge temperature of the well (not plotted yet). The average temperature is 7.75°C and its standard deviation is 0.14°C. Overall this means that the

well is mostly stable during the logging period. This logger is supplied with 220 V grid power and has 100% uptime.



Figure 9. Pressure at 70 m depth (upper half), and logger temperature and voltage (lower half) for station S-9, monitoring well AA-01 in Arnes. Prystingur is Icelandic for pressure and hiti is temperature (°C).

Figure 10 shows discharge temperature and pressure of well ST-06 at Storu-Tjarnir, and wellhead pressure of well ST-07 also at Storu-Tjarnir. Both are connected to logging station S-10. Like in the case of well AA-01, this field remains practically stead-state during November and December 2000. But some problems are, however, encountered. Firstly that the logger is not responding after December 25 due to low voltage on its single, 12 V external battery. The station is located in deep valley and enjoys therefore practically no sunshine at this time of the year. Secondly it is clear that the pressure sensor of well 6 is defective. This is concluded from the very stable discharge temperature of the well and from the unrealistically high-pressure value recorded. Thirdly it appears that the GSM conditions in the area are weak, leading to some data losses between November 13 and 17. Finally, it should be mentioned that the second well, number 7, is not fully closed all year round. The well must produce if pressure of the local heating pipe network falls below a certain minimum. The spikes in its pressure history are, therefore, coherent with temporary discharge from this well.



Figure 10. Well data (upper half), and logger temperature and voltage (lower half) for station S-10, monitoring wells ST-06 and 07 in Storu-Tjarnir. In the upper graph, the top curve is the defective pressure sensor of well 6. The sagged centre curve is its discharge temperature. The lowest curve in the upper portion shows the wellhead pressure of well 7.

Figure 11 finally shows pressure data collected in well HU-4 in Húsavík, monitored by logging station S-11. Due to its location inside town, a concern arose for the safety of the logger. Therefore a subsurface cable was specifically plowed from well 4 to well 1, near 400 m distance. In this location the logger is comfortably stored inside a cottage at near tropical temperature, due to inside pipe and pumps used for hot water production out of well 1. The pressure sensor in well 4 is placed at 80 m depth. Waterlevel at the time of installation was found at 15.75 m depth. Like in Storu-Tjarnir it appears that the pressure sensor failed after 1 month of operation. During this period a daily tidal fluctuation is observed and also the 28 days lunar circle. The logger performs therefore almost identically to the one in Flatey. But in early December some type of a sensor problem arises, resulting in substantial fluctuation of the pressure signal.

SMSITES



Figure 11. Pressure at 80 m depth (upper half), and logger temperature and voltage (lower half) for station S-11, monitoring well HU-04 in Húsavík.

3.5 Conclusions

The main conclusions drawn from the installment and two-month operation of automated hydrological logging stations near the Húsavík-Flatey fault zone are as follows:

- 1. Five wells are presently connected to 4 automated logging stations near the fault zone.
- 2. The data loggers themselves are performing very well and with only minor losses of data.
- 3. Some battery voltage problems are; however, faced by solar powered stations in December to January, due to the limited sunlight available this close to the Arctic Circle.
- 4. High quality pressure sensors are performing poorly in two wells. Possibly they are too sensitive for gases and other chemicals, which are observed at low concentrations in these wells.
- 5. Automated shell scripts, which daily update web pages showing well status in the monitored wells, are nearly completed.

4 PRESS MEETING

A very good co-operation has been with the local authorities of Húsavík in carrying out the project. A common press conference was scheduled at Húsavík on December 6. 2000, for informing the Iceland public about the project. Unfortunately, this press meeting had to be postponed because of very bad weather conditions in the area during that day. It will be held early 2001.

3.3. WP3 — Partners 3 IMCG & 1 UEDIN

3.3.1. UEDIN Reports

INSTALLATION OF THE STRESS MONITORING SITE PROGRESS REPORT 1st January to 31 December 2000

Authors: Stuart Crampin, Sebastien Chastin University of Edinburgh Dept. of Geology and Geophysics

The commissioning of the Stress Monitoring Site (SMS) at Húsavík was done in two stages. Due to delay in the: acquisition and delivery of equipment and services,



Figure 1. Well Location

place.

Despite these restrictions, the SMS is now operational at Húsavík and is on schedule. Some improvements are possible. These will be investigated during the winter and implemented during the first field trip, expected to be in April 2001.

1 INITIAL SET-UP

detailed in Section 1, the actual set-up on the ground in Húsavík did not start until September 2000 rather than June. Various housekeeping details were attended to in November 2000.

The late start meant that working condition were far from optimum, with weather rapidly deteriorating and decreasing hours of daylight.

The SMS uses wholly new source-receiver geometry and a new source tool, the Downhole Orbital Vibrator (DOV), for which there is little pre existing experience in a deep uncased bore-hole, new recording geometry, and demanding data acquisition requirements.

Therefore the SMS commissioning had to progress with caution. It is essential that the parameters of the experiment are well understood and that safe operating procedures are put in



The aim of this first trip was to instrument the wells and record calibration data. This was achieved successfully. It was a crucial stage in the project, since many obstacles stood in the way, and an early failure to transmit seismic energy between two wells would have been very damaging to the project.

Stuart Crampin (UEDIN), Sebastien Chastin (UEDIN), Peter Leary (UEDIN S-1), John Gregson (IMCG), and Larry Walters (GERI) worked on the site in order to establish field procedures and collect the first seismic data.

The initial field activity included:

(i) Installing an Oyo-Geospace cable with 4 levels of 3-component geophones at 1m intervals to depth of ~535m in HU05, one of two Húsavík sensor wells;

(ii) Installing the Oyo-Geospace wireline winch at the 1500m deep source well, HU01, 300m from the geophone-installation sensor well;

(iii) Recording noise and signal data.

1-1 Sensor- and source-well installation

The DOV source and the 4-level string of 3-component geophones were installed at the two wells, HU01 and HU05, hereafter referred to as 1 and 5, respectively. Their geometry is sketched in Figure 2.

At Well 5, the geophone string was weighted by a rope with embedded lead pellets to compensate the geophone-cable buoyancy and lowered into the well to the logged depth. The Oyo-Geospace DAS (Data Acquisition System) detected when the geophone string reached well bottom. The string was then withdrawn ~3m, to allow the coarser grains of basaltic sand to travel past the geophones, and the remaining well interval filled, as shown on Figure 3. The DAS continued to monitor the geophone



Figure 2. Schematic layout of the wells





Figure 3. Sanding the geophone in well 5

activity as more sand was shovelled into the well. When free-suspension geophone activity ceased, the remainder of the sand supply was emptied into the well, and the weighted rope and geophone cable tied off at the wellhead.

Note that Well 1 is a centre of health bathing facilities used by the local population, who graciously allowed us

to use the facilities. The winch was set up over Well 1. Initially the onboard mast was used, as in figure 4. This severely disrupted the bathing facility. The winch was later moved away from the well, and a removable tripod erected over the well, in an effort to minimise the impact of the experiment.

The Winch odometer was calibrated and the DOV attached to the wire line ready for lowering (Figure 5).

The data acquisition system was set-up and data cables laid out before recording could take place.

Over the rest of the trip the installation continued addressing issues such as impact, security, and a relentless quest for minimising 50Hz pick-up.



Figure 4. The winch initial installation

1.1 First records

The DOV was tested at the surface and lowered into the well to a succession of 100m intervals from 500m to 1100m depth. Groups of clockwise (cw) and counterclockwise (ccw) sweeps were recorded by the DAS located at Well 5. The source sweep and DAS records were synched verbally by mobile phone. The first data recorded (shown on figure 6) for a horizontal ray path demonstrated that we could transmit seismic energy between the wells, and created a great sense of excitement specially since the experiment is set in basalt.

Similarly it was possible to observe DOV sweep energy arrive at the sensor geophones for DOV depths 500m, 600m and 700m. At 800m and below, it was difficult to detect a signal based on the small sweep stack. The signal strength vanishes into noise level with DOV depth faster than expected.

At this stage there was three sources of noise in the Húsavík data:

- 1. Instrument (amplifier) noise of Oyo-Geospace DAS (Data Acquisition System);
- 2. Ambient seismic motion at the sensor; and



Figure 5. DOV on wireline



3. Capacitive pickup of 50Hz ground currents and overtones.

2 SECOND SURVEY

Data collected during the first trip revealed that signal had to be improved and raised other questions, which needed to be answered. P.Leary (UEDIN-S1), S.Chastin (UEDIN) and J.Gregson (IMC) return to Húsavík in November in order to do some house keeping, improve and automate the data acquisition system, and finally record the first set of monitoring data.

There were six aims for this second trip:

- (i) Confirm optimally quiet sensors;
- (ii) Eliminate spurious instrument noise from the signal wavelet;
- (iii) Automate signal stacking;
- (iv) Orient geophone and DOV;
- (v) Relate the signal wavelet quality to rock quality through the layered basalt sequence; and
- (vi) Acquire prolonged signal stacking data for a preliminary assessment of shortterm travel-time and amplitude monitoring stability.

2.1 Noise reduction

A new data acquisition system was laid out with a low impedance digital line using a string of repeater stations replacing the high impedance seismic cable prone to 50 Hz pick up. This procedure significantly reduced the 50 Hz noise giving a RMS noise of 10^{-3} mV $\equiv \mu$ V.



This noise survey also revealed that noise levels vary over the 5 minutes recording interval. This is believed to be due to the wide variety of response to the acoustic noise induced by the wind and the ocean waves beating on a shoreline between 50m and 100m away.

Covering the wellhead of well 5 to prevent wind generated acoustic noise in the well drastically reduced the RMS noise level to $0.12 \,\mu$ V, when the ocean was quiet.

Higher noise levels appear to be of surface origin and associated with rough sea state, which is difficult to reduce. Consequently, the noise level in the Húsavík system is only 20-30% higher than irreducible electronic noise of the recording equipment $(0.1 \,\mu\text{V})$. In rough sea condition, the seismic noise level can reach to 0.2 to 0.3 μ V).

2.2 Data acquisition system

The data acquisition system was improved on two levels. Firstly, the recording is now fully automated. A timing device build by J.Gregson records a series of pulses for a given time interval, so that the duty cycle remains 50%. The device triggers the DOV pulse, the recording DAS, and sequentially switches the DOV controller between clockwise (CW) and counter-clockwise (CCW) directions of rotation. (Note this revealed failures in the DOV Control system, when the synchronicity was lost.)

Acquired data are transferred from the DAS to the recording laptop via a D-Line, to be automatically processed and stacked.

2.3 Data set

Once noise issues where resolved and the new recording system was in place, new data could be acquired. Over 4000 pulses were acquired using a single DOV as source without significant deterioration.

Three distinct data set were acquired during the exercise:

1) A 20m step over a depth of 400m between 350m and 750m in source well. Designed to establish the DOV radiation pattern, try to relate the result of the first field trip to rock quality, and orient the receiver geophone.

2) A 1m step survey over a depth of 40m from 500m in the source well, designed to study the orientation of the DOV and rotation with depth.

3) Monitoring over three days at deepest possible location (700 metre) not requiring lengthy stacking sequences. This was design to study the stability of the DOV pulse with time and study the short-term sensitivity of the data.

3 RESULTS, IMPROVEMENTS, AND INDICATIONS OF FURTHER WORK

The large volume of data recorded during the two trips to Húsavík have enabled us to optimise the set-up, and attain a better understanding of the experimental parameters of the location and of the DOV.

The SMS is functioning and the conditions are good for DOV depth < 700m. This



Figure 7. Amplitude versus DOV depth

can be seen in the crude data of the first trip in Figure 7, and the data of the second trip in Figure 8, where the amplitude of the signal appears to fall off with increasing radiation angle from vertical rather than expected from a point force.



As there is plenty of visual evidence for severe horizontal layering in Húsavík. It is possible that this layering is responsible for the loss of signal. We acquired new well logs, in particular N-N scattering logs which is a very good proxy for porosity. It appears that the DOV signal amplitude behaves remarkably like the inverse of the porosity figure 9. Indeed maximum amplitude is observed for ~530m which is also a minimum in porosity and the DOV signal is negligible at DOV depth above and below the low porosity layer . It is clear that the heavy layering below 700 meters renders data acquisition for steep angle ray path very difficult. Signal is close to noise level and very long stacking sequence will be required.

However solutions are being sough, mainly boosting the energy send by the DOV, which might be able to resolve this problem. The DOV cannot be re-engineer therefore we must minimise losses of energy, in other word we need to strengthen the coupling between the DOV and the bore-hole

During the winter, when conditions are unfavorable in Húsavík, tests will be undertaken to clarify and resolve the coupling problem.



Figure 8 Peak amplitudes of 8 P-wavelets (4 levels, CW and CCW sweeps) for DOV depths between 315m and 755m compared with (i) point-force radiation as function of DOV depth (black lines), and with (ii) instrumental amplifier noise limit (green asterisks).





Figure 9. P-wave maximum amplitudes (asterisks) plotted as a function of source depth against (left) the source well caliper log and (right) the "anti-porosity" log (negative of the porosity log). The logs are reduced to zero-mean unit-variance form. Note (I) that the P-wave peak amplitude corresponds to a zone of maximun well diameter and minimum formation porosity (maximum "anti-porosity"); and (ii) that the maximum P-wave amplitudes occur for source locations immediately above the strong porosity high (plotted as "anti-porosity" low) between 450 and 500m.

3.3.2. IMCG Reports

<u>Technical Report for Year 1; 1st January – 31st December 2000</u>

Author: Peter James Jackson Technical Director IMC Geophysics Ltd

I Introduction

The role of IMC Geophysics Ltd within this project has been to assist in the practical aspects of fieldwork necessary to collect the required seismic data. The hazards of running expensive instruments within deep uncased boreholes are well known, and must be addressed by the development of operating procedures, which minimise risk. The data acquisition requirements within the project call for repetitive operations over



long periods, ideally 24 hours a day and 7 days per week, and techniques have been devised to facilitate this.

The ultimate aim of the project is to develop, and demonstrate the efficacy of, a routine stress monitoring service that can be implemented at short notice anywhere in the world and operated by staff without a detailed understanding of the principles involved. It is hoped that the IMC Geophysics input has focussed on the development of practical solutions to problems encountered, which will result in the development of a robust and widely applicable service.

Details of the project components completed by IMC are contained within the periodic progress reports supplied during the year 2000. Below we simply list the major tasks. Since nearly all the input has been in parallel with staff from the project co-ordinator, the University of Edinburgh, or Dr Peter Leary there will inevitably be some duplication with the technical reports from these contributors.

II Tasks Completed

II.1 Borehole Logging

The initial action necessary to start the project was to ascertain the status of the three pre-existing wells at Húsavík. The wells were known (on the basis of previous logging activity) to contain some 'squeeze' points where the hole diameter had apparently been reduced either by physical deformation of the rock itself or by the accumulation of debris. Similarly, it was known that one or more of the wells contained lengths of wireline lost during previous attempts to run geophysical logs. This fact was strongly indicative of the potential risks of running the Downhole Orbital Vibrator (DOV) which is central to the SMSITES project.

IMC Geophysics remotely co-ordinated the relogging of the Húsavík wells which proved that they were suitable for running the source and receiver tools, and during which some abandoned wireline obstructions were removed.

II.2 DOV Commissioning

On arrival into the UK of the DOV and DAS-1 seismic recorder IMC in collaboration with UEDIN-S1 carried out underwater tests within a Leicestershire flooded quarry to assess the operational characteristics of the source and to start to develop procedures for its use within boreholes.

At this stage some technical malfunctions of the source were identified and ultimately associated with an internal wiring fault. Shortcomings within the internal reference geophones were also identified and ultimately corrected with the assistance of the manufacturer.

II.3 DOV Trials in a Salt Mine



As part of a continuing effort to assess the DOV in field conditions it was used during a seismic survey within a UK salt mine. Although some operational problems were encountered relating to the coupling of the tool to the rock salt, this component of work did bring about additional understanding of the operating envelope of the DOV. The output voltage of the tool reference geophones (too high for accurate registration on some seismic recording instruments) was also corrected by addition of a signal divider.

Data collected during these commissioning activities also allowed UEDIN-S1 to start to compile a library of software tools necessary for the later phases of the project.

II.4 Initial Icelandic Visit

IMC participated in the first operational visit to the project site in northern Iceland. The logistics of delivering the project winch (ex OYO, Houston) were in part handled by IMC. John Gregson (project engineer for IMC) attended the site in collaboration with Peter Leary, Professor Stuart Crampin, Sebastien Chastin and Larry Walters (of OYO Geospace) to establish field procedures and collect the first seismic data. This was a crucial stage in the project, since a failure to run the DOV, to install geophones within the receiver well or to successfully transmit seismic energy between two wells would all have been potentially damaging to the project aims.

In fact, all project goals for this set-up visit were achieved. Two DOV's were used, and further faults in tool construction were identified and subsequently corrected. Winch operating procedures were established as was the safe maximum operating depth for the DOV. A need was identified for a means of automatically acquiring multiple sweeps across particular shot-detector paths to facilitate stacking and/or monitoring of any earth tide effects, which may subsequently be sought in the data.

II.5 Automatic Sweep Initiation

On return to the UK IMC built a system for automatically initiating multiple sweep recording with specified parameters. This is a hardware device, which may ultimately be overtaken by a software solution.

II.6 Second Iceland Visit

John Gregson took part in the second data acquisition campaign in Húsavík. Again, fieldwork was successful. Large volumes of data were collected which have since enabled Peter Leary to reach a much better understanding of the performance of the DOV. The automatic sweep initiator worked well and reliably and allowed the field crew to work much more effectively than had previously been possible.

III Future Activity

As at January 2001, the following activities involving IMC Geophysics are either underway or in prospect.



III.1 Viscosity Trials

A full understanding of the operational characteristics of the DOV requires investigation of the influence of borehole fluid viscosity on the radiated wavefield. Trials within various fluids are currently being designed to achieve this investigation.

III.2 Further Fieldwork

As soon as weather in Iceland permits, further fieldwork will proceed in Húsavík. This work will hopefully be carried out in the light of the information gained from viscosity and other source trials in terms of the optimal conditions for shear wave propagation.

III.3 Additional Project Sites

Although outside of the scope for eligibility within this project, further efforts are underway to develop additional sites for the development stress monitoring installations using the SMSITES principles. Such sites will, if successfully developed, add to the research results gained from Húsavík.

3.4. WP4 — Partner 4 UU

Multi-event Analysis

Author: Reynir Bödvarsson University of Uppsalla

For relative location of microearthquakes near Húsavík on the Tjörnes fracture zone it is vital to have the seismic stations at Flatey and Flateyjardal in operation. As these stations are not yet in operation we put our emphasis on software developments related to later analysis of the microearthquake data. Therefore we can not report on any results from data analysis in the area.

We have been working on a modification of the multievent analysis for more automatic operation. This includes handling of error exceptions during the automatic operation due to some possible errors in the waveform or parameter data base. When initiating a batch job that will run on a large amount (tens of GBytes) and will run for tens of hours it is important to handle all exceptions in a stable manner.

We have also collected all waveform data in the Tjornes area since 1994 and are creating databases for fast access to this data for automatic multi-event analysis.

We have been looking into the problem that is related to possible different population of earthquakes within the data set. When analysing the b-value we see differences both in time and space. We also see indication of that the microearthquakes in an area at a specific time can belong to at least two different groups.

The three component analysis for identifying S-waves of different polarisation and for automatic timing of such phases has been designed and is under evaluation and testing.

Some work on analysing the seismicity and dynamic source parameters of the microearthquakes has been initiated. The microearthquake seismicity analysis based on not only location and origin time but also on dynamic parameters especially the fault radius, and aiming to earthquake warnings has been further developed. As these earthquake warning algorithms are based on the microearthquake source parameters (and not the on the wave propagation) they serve as a complement to the shear splitting method. As pointed out by several scientists' different approaches (warning parameters) may strongly improve the total performance, especially by reducing false alarms.

Analysing the variation of the spectral amplitudes observed from earthquakes



in specific areas has indicated variations on which fractures take up the ongoing deformations. This seems to be a sensitive measure of variations in the stress orientation in the rock mass. Methods are being developed for differential measure of the stress orientation using Spectral Amplitude Grouping. This means analysis of patterns of the radiation from earthquake sources in small epicentre areas.

3.5. WP5 — Partner 5 UVAV5

author T.Villemin

3.5.1. Report on GPS data recording (Deliverable D5a) author T.Villemin

GPS Measurements have been performed to measure crustal deformation in Iceland since 1986. In North Iceland different groups have done several Network campaigns. In a first step a network using some of the most accessible old geodetic points and new benchmarks has been set-up in order to follow the post rifting episode at Krafla (Foulger et al. 1992; Hofton and Foulger, 1996; Pollitz and Selwyn Sachs, 1996; Árnadóttir, et al., 1998). This network of about fifty points, measured in 1987, 1990, 1992 and 1995, cover an area of 300x250 km and has not been designed to follow the surface deformation due to the Húsavík-Flatey Fault. For that reason the University of Savoie started new measurements in 1995 with a network specially drawn to follow the surface displacements (1) on each side of the Húsavík fault and (2) at the rift-transform junction. 32 points were initially measured in 1995 (Fig. 1). All these points have been re-occupied in 1997 and 1999 with 13 new points added to the network in 1997. This network (Fig. 1) has been named Tjörnes GPS Network (TGN).

In the frame of SMSITES, we selected 10 points from the TGN (Fig. 1) to be followed during the 3 years of the program. A first measurement of these 10 points has been done in June 2000 (See Deliverable 5b). These points are striking perpendicular to the Húsavík fault, e.g. N20°E in average. The distance from point to the Húsavík fault trace varies from 0 for two points close to the city to 20 km both North and South.

On the basis of our previous GPS campaign (1995, 1997, 1999) GPS measurements in that area allow to detect with a very good confidence displacements of at least 0.5 cm (Jouanne et al., 1999) for the horizontal components. Vertical accuracy is largely poorer. All this fix the instrumental limitation on our strain measurements.

It is known that between repeated earthquakes, elastic strain build-up in the upper part of the crust increases the load of stress on faults. This interseismic strain accumulation occurs until an earthquake release elastic strain and stress by fault slip. In order to schedule at best the repeated GPS campaigns, the question is to know how the strain accumulation varies through time during the interseismic period. Observation made on Continuous GPS network (e.g. in California) show linear rates in most cases. Unfortunately no continuous GPS data are available in North Iceland and the preliminary results from the ISGPS network (Arnadottir et al, 2000) concern too short time series on a limited number of points to be able to address this question at this time.



The first displacements we measured on TGN concern the period 1995-1997 (Jouanne et al. 1999). On Figure 2 the velocity field has been drawn by reference to point 7440 which is located in the southern part of the network (Fig. 1). Point 7440 is now part of the 10 SMSITES points. Two tendencies have been distinguished on the Tjörnes peninsula: eastward velocities reaching 13 mm.y-1 for the most northern points of the peninsula and NNE velocities up to 15 mmy-1 for the points located on both sides of the HFF. Displacements to the east have been computed for the points located in the fissure swarms. Points on Flateyjardalur move to the North. The point on the Flatey Island reveals a large displacement to the NE that could be due to a local instability. This is probably also the case for point 9509, which is placed a few meters near a fault outcrop.

The assumption of an interseismic strain has been tested by using a simple dislocation model (Feigl and Dupré, 1999). This model assumes that a set of buried planar fault surfaces are locked above a given depth and are affected by uniform aseismic creep below this depth. In order to determine this brittle/ductile transition we assume that most earthquakes are localised in the brittle crust (e.g. 10 km in our case according to SIL data)

The model (Fig. 3) minimising differences between simulated and observed velocities assumes (1) a dyke opening of 20 mm.y-1 affecting all the brittle crust along the Kobleinsey ridge (2) two dyke openings of 30 mm.y-1 and 20 mm.y-1 respectively along the Krafla and Theystareykir fissure swarms; (3) a dextral strike slip fault striking N100°E between the two previous rift segments with a velocity of 50 mm.y-1 below a depth of 10 km and completely locked above the brittle/ductile transition; (4) a 15 mm.y-1 opening zone striking N140°E south of the HFF; (5) a fault along the Grimsey lineament with both a 15 mm.y-1 opening and 20 mm.y-1 dextral strike slip movements. In addition small wavelength tendencies has been adjusted by superficial faults.

This model based on our 1995-1997 TGN comparison revealed extension and strike slip movements 3 to 4 times larger than the average velocity. The transform motion seems to be locked on a large (150x10 km) fault surface and this represents the main risk for destructive earthquakes in the near future. From a mechanical point of view, the lockage could be due to the increase of normal stress on this surface following the double opening north and south of the fault zone.

In comparison with to the first period and using the same reference (point 7440 located in the southern part of the network), the 1997-1999 or the 1997-2000 velocity field have the following main characteristics (Fig. 2): (1) The eastward tendencies north of Tjörnes is always present but the average velocity has been divided by 2 and is now less than 1 cm.y-1 north of Tjörnes. (2) The NNE displacements observed in 1995-1997 on both side of the Húsavík fault are always observed but their component are in the opposite direction of those observed during the first period. These points are now moving to the south also with smaller velocities for the two second periods compared to the first one.



From this comparison we can conclude that the displacements on Tjörnes have varied significantly in sense and size in less than 2 years. This probably reveals a very instable displacement regime. Consequently it is not possible to deduce from these previous measurements when it should be the most appropriate to acquire new data. Continuous observations appears as the best strategy to follow strain accumulation in such areas. In our case this requires at least 3 stations, one in the vicinity of the fault and the two others at a distance of about 15 km on each side. IMO is planning to set up these stations in the near future. However a better temporal coverage on 3 points will not be sufficient to analyse the complex strain field of the area. We also need a good spatial coverage to test mechanical models of the interseismic regime because unquestionable interactions between different active crustal discontinuities. 3 set of measurements are planed in 2001 on the 10 points we decided to follow. This will be done in early spring, summer and late fall 2001. In addition, we will take advantage of the CGPS which is going to be installed next spring in Akureyri by Landmaelingar.

3.5.2. Observation and Modelling of temporal Changes(Deliverable D5b) author T.Villemin

In the framework of SMSITES a first GPS campaign has been performed from June 6 to June 12, 2000, USAV has re-measured a set of 10 points from the TGN. These points are striking perpendicular to the Húsavík fault (Fig 1). All points have been observed at least 24 hours. The measurements were made with Ashtech dual-frequency receivers and choke-ring antennas. Collected data are of good quality and have been processed.

The data were analysed with the Bernese V4.0 software in the ITRF94 reference frame using IGS precise orbits, IGS Earth Orientation Parameters, and data from IGS stations. The data have been analysed as follow : (1) L3 free solution with all the data, (2) residual analysis (residuals > 0.03 m have been marked), (3) estimate of the ambiguities with two different strategies according to the baseline length. The ambiguities have been revolved using the QIF strategy of resolution (Beutler et al., 1996) for baselines longer than 50 km. For the short baselines, the Melbourne - Wuebbena ambiguities have been solved using a time-dependent ionosphere model and the L3 ambiguities have been fixed using these solved ambiguities. More than 80% of the carrier phase ambiguities have been fixed. The mean repeatatibilities of North, East and vertical components of the baselines are respectively 2.8, 2.3 and 16 mm.

A special attention was paid to the evolution of the displacements on these points between August 1997 and June 2000. In the light of the previous studied periods (1995-1997), the relative velocities are indeed decreasing (See 5a for more details).

In addition to that work a continuous GPS station has been installed by University of Savoie and Halldor Geirsson (IMO) at Skrokkalda, in the central



part of Iceland. This station is located near a SIL station and benefits of the computer already installed there for downloading and control the seismic station. This is the first CGPS installed in the Highlands. The operation has been supported by the French polar Institute (IFRTP) and could be extended to the North next year. The idea is to monitor displacements near the hotspot centre and compare them with data from both north and south seismic zones.

Antoine BERGER (PhD) is now working at University of Savoie for 3 years since fall 2000. His research will be devoted to modelling the propagation of crustal failure from the hot spot centre to the oceanic ridge in northern Iceland. This work includes the understanding of transfer mechanisms in the Tjörnes fracture zone. He will be working 50 % of his time on SMSITES.

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3.6. WP6 — Partner 6 UIB

Fluid overpressure and locking of the Húsavík-Flatey Fault

Author: Agust Gudmundsson

There was considerable seismic activity associated with the Húsavík Fault up to the 1975-1984 rifting episode in the Krafla Volcanic System (1,2). Following the early part of this rifting episode, the Húsavík-Flatey Fault in general, and the Húsavík Fault in particular, have been seismically very quiet. It is proposed that this lack of seismicity on the Húsavík-Flatey Fault for nearly two decades is attributable to its being locked by fluid pressure and associated faulting at the junction between the north end of the Krafla Volcanic System and the Grimsey lineament. The locking is attributed to fluid (magma) pressure and associated faulting at the junction between the north end of the Krafla Volcanic System and the Grimsey lineament resulting in a temporary stress field encouraging sinistral slip on an otherwise dextral fault.

During the past several years, there has been renewed seismicity on the Húsavík-Flatey Fault. Following a M5.5 earthquake in 1994, at the junction between the Húsavík-Flatey Fault and the Kolbeinsey Ridge, the seismicity has increased and also expanded to the southeast along the fault. Thus, it is proposed, the Húsavík-Flatey Fault is currently being unlocked. This unlocking is likely to be partly related to changes in the controlling stress field, partly to fluid-pressure changes along the fault plane. It is proposed that this unlocking started in the westernmost part of the fault because that part is at the greatest distance from the Krafla Volcanic System, and that the stress condition for faulting (unlocking) will gradually migrate southeast along the fault. Thus, in the not-too-distant future, condition for seismogenic faulting will reach the town of Húsavík, with obvious consequences for seismic hazard and risk in the area.

Seismicity in the Húsavík-Flatey Fault, like in other terrestrial faults, is related to fluid pressure. This pressure can either encourage faulting, particularly by reducing the stress difference needed for failure and the friction on the potential slip plane, or suppress faulting via locking of the potential slip plane. In order to understand the build up of fluid pressure on a fault plane, one must know the groundwater conditions and permeability in a large area surrounding the fault and how these conditions change as the fault is loaded to failure.

This workpackage considers the effects of fluids (groundwater and magma), transported through the crust as hydrofractures, in triggering or, alternatively, suppressing earthquakes on the Húsavík-Flatey Fault using field observations and analytical and numerical models. It is convenient to discuss these the processes leading to suppressing and triggering of earthquakes in separate sections.

1 Fluid pressure locking the Húsavík-Flatey Fault

A conceptual and a generic numerical models (1) have been developed whereby dyke injection (and normal faulting) in the nearby volcanic systems can lock or unlock the central parts of the Húsavík-Flatey Fault. The model attributes the locking effects to the fluid overpressure of injected dykes in the nearby volcanic zones. It applies also to the South Iceland Seismic Zone (3). In this model, dyke injection in the those parts of the North Volcanic Zone and the East Volcanic Zone that are between the Húsavík-Flatey Fault and the South Iceland Seismic Zone tends to open (unlock) these zones and trigger seismogenic faulting. For example, there are indications of a positive correlation between volcanic activity in parts of the East Volcanic Zone and seismic activity in the South Iceland Seismic Zone. By contrast, dyke injection north of the Húsavík-Flatey Fault and south of the South Iceland Seismic Zone tends to lock these faults and suppress seismogenic faulting. Locking by dyke injection, however, is always temporary because plate pull gradually relaxes the compressive stresses generated by the fluid overpressure of the dykes.

In terms of this model, the largest historical eruption in Iceland, Laki 1783, may have triggered the largest known earthquake sequence in South Iceland, that of 1784. The largest shock in this earthquake sequence is estimated at magnitude 7.1. The feeder-dyke of the Laki eruption is at least 27 km long at the surface, and perhaps longer at depth. Field observations indicate a near-surface dyke thickness of at least 6-10 m. Such a dyke, coming from a depth of 10-20 km, can develop a static magmatic overpressures of 10-50 MPa (4-7). Displacements and compressive stresses of this magnitude, generated over a period of only 8 months (the length of the Laki eruption), certainly increased the shear-stress intensity in the South Iceland Seismic Zone. This shear-stress increase may have caused small earthquakes already at the end of the eruption, in early 1784 and, it is suggested, triggered the main earthquake sequence in the summer of 1784.

By contrast, the Húsavík-Flatey Fault has recently experienced locking by dyke injection (1). There was considerable seismicity associated with the Húsavík-Flatey Fault until early 1976, when dyke injection and normal faulting of the 1975-1984 rifting episode of the Krafla Volcanic Systems occurred in its northernmost part. The dyke injection in this part generated horizontal compressive stresses encouraging sinistral movement on the otherwise dextral Húsavík-Flatey Fault, thereby locking the fault.

The models discussed in (1) have been extended (4-6) by considering the stress fields associated with hydrofracture (dyke) propagation. For a dyke to have maximum suppressing (locking) or triggering (unlocking) effects on a nearby seismic zone, the dyke should have a high internal fluid overpressure (driving pressure) and, preferably, propagate to the surface as a feeder dyke (5). Thus the conditions for dyke arrest and propagation in volcanic zones (4,5) have been investigated using numerical and analytical models, as well as the condition for dykes opening up joints and discontinuities in the host rock to form their pathways (6). The results indicate that dyke propagation and arrest depend much on mechanical anisotropy in the host rock, in particular on sharp discontinuities and changes in Young's modulus. The models also indicate that Young's modulus commonly contributes to changes in local stresses along the potential pathway of the dyke, and thus to the dyke's overpressure distribution

which, in turn, affects the probability of the dyke suppressing or triggering earthquakes.

2 Fluid pressure triggering earthquakes

To put constraints on the fluid overpressure and transport inside the Húsavík-Flatey Fault during seismogenic faulting, field measurements were made of more than 1700 mineral-filled veins in its damage zone (7,8). Most veins are of quartz, chalcedony and zeolites, strike roughly parallel or perpendicular to the fault zone, and are members of dense palaeo-fluid transporting networks, commonly with 10 veins per metre. Around 79% of the veins are extension (mode I) cracks; 12% are sinistral, and 9% dextral, strike-slip faults. The thicknesses (apertures) of most veins are from 0.1 mm to 85 mm, and the thickness size distribution is a power law.

The average length/thickness ratio of veins is 400, indicating fluid overpressure (with reference to the minimum principal compressive stress) at the time of vein emplacement of 20 MPa. Such a high fluid pressure on a potential fault plane makes the effective normal stress on that plane negative and reduces the friction, thereby triggering earthquakes. Simple analytical models indicate that volumetric flow rates for a horizontal fracture and a vertical fracture in a rigid (non-deforming) host rock would be around 1.5 $\cdot 10^{-4} m^3 s^{-1}$ and 5.8 $\cdot 10^{-4} m^3 s^{-1}$, respectively. The volumetric flow rate in a vertical fracture of equal size but in a deforming host rock, with buoyancy added to the driving pressure, is around 9.7 $\cdot 10^{-4} m^3 s^{-1}$. Thus, vertical propagation of hydrofractures is favoured under these conditions, in agreement with the observation that most of the measured veins are subvertical.

Analytical models (7-9) indicate that the inferred fluid overpressure in veins in the damage zone of the Húsavík-Flatey Fault can be generated by groundwater originating at shallow depths in the fault zone. This water is most likely transported to the fault zone from the surrounding areas. Numerical and analytical studies (10) indicate that groundwater transport to an active fault zone depends much on the trend of the fault zone in relation to the hydraulic gradient in a large region surrounding it. The effects of the fault zone on the groundwater flow is normally small if the flow is at high angle to the fault zone, but gradually increases as the angle between the flow and the fault zone decreases.

Boundary-element studies of an active strike-slip fault zone, such as the Húsavík-Flatey Fault, subject to fault-parallel loading of 6 MPa show tensile stress concentration in large areas around the fault-zone tips. In these areas, tensile stress exceeds typical in situ tensile strengths of rocks, resulting in the formation or reactivation of tensile fractures (2,3). These fractures curve toward the tips of the fault zone, and if interconnected they increase the rock permeability. Fault slip also increases the temporary permeability of the fault zone, by as much as many orders of a magnitude. When the trend of the fault zone and the groundwater flow coincide, the upstream part collects groundwater whereas the downstream part expels it. It follows that the yield of springs decreases in the upstream part, but increases in the downstream part. The results



obtained during the June 2000 earthquakes in the South Iceland Seismic Zone support the conclusions of this model.

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3.7. WP7 — Partner 7 UPMC

Annual Report – Partner 7

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1 Field study of fracture

A preliminary field study has been carried out in the framework of the Prenlab2 programme and the first results have been already reported in the previous monthly reports and in some communications of international meetings (Bergerat *et al.*, 2000; Garcia *et al.*, 2000).

The first field work of the SMSITES programme has been carried out during last summer (30th of June to 15th of September), essentially in the Tröllaskagi, Flateyjarskagi and Tjörnes peninsula. The studied outcrops (with their reference number) are located on Figure 1. At each site structural observations were made and tectonic features, such as faults and dykes, were measured when available. The analysis process of these tectonic features is now in progress (statistical analysis, stress-tensor computation).



Figure 1. Location of the sites of measurements (structural and microtectonic analysis)

In addition to this field study, we drawn maps of the Tjörnes peninsula based on high-resolution imagery, including Synthetic Aperture Radar (SAR) images of the European Remote Sensing (ERS) satellite, SPOT images and aerial photographs (Garcia *et al.*, 2001). These maps have been checked and completed by field observations (see previous monthly reports).



On the other hand, a detailed study of the geometrical pattern of dykes of the Flateyjarsakagi peninsula has been undertaken in the field for a better understanding of the behaviour of the Húsavík-Flatey Fault. We collected some samples in the different sets of dykes in order to date the successive volcano-tectonic events (Fig. 2). The dating process is now in progress (Ar^{39} - Ar^{40} method).



Figure 2. Location of the collected samples of dykes (trends indicated as red lines)

2 Inversion of double couple focal mechanisms.

The field data will be used joined with focal mechanisms of earthquakes in order to reconstruct the seismo-tectonic pattern of the Tjörnes Transform Zone (Garcia *et al.*, in prep.). We considered the data provided by the SIL network during the period 1995-1997 in a rectangular area surrounding the HFF (between 66°N and 66.25°N and between 17°W and 18.5°W). Only the earthquakes with M>1 have been selected, therefore we used 669 double couple focal mechanisms.

In order to estimate the relative importance of each type of focal mechanisms, we first carried out a simple geometrical separation: the strike-slip mechanisms



represent 70.3% of the total set, the normal mechanisms, 18.4% and the reverse mechanisms, 11.3%.

Considering the orientation of the nodal planes included in each of these three main types, we obtained a further separation into nine classes as shown in Figure 3. There are four strike-slip regimes (called arbitrarily SSR2, SSR3, SSR4 and SSR5), three extensive regimes (NR2, NR3 and NR4) and two compressive regimes (RR3 and RR4).



3.7.1.1. Figure 3. The nine stress regimes determined from the analysis of focal mechanisms of earthquakes

Based on these nine groups determination, we applied a new inversion method (Angelier, 1998) in order to calculate the corresponding tensors. The stress tensors corresponding to the nine groups separated above have been determined. For the strike-slip regimes (SSR2, SSR3, SSR4 and SSR5), the trends of extension (σ_3 axis) are, respectively, N76°E, N56°E, N141°E and N02°E. For the normal regimes (NR2, NR3 and NR4), they are N92°E, N58°E and N122°E. The other regimes (RR3 and RR4) are reverse and the trends of compression (σ_1 axis) are N49°E and N138°E. As for the field data, strike-slip and normal regimes that have a similar trend of extension can be grouped pairwise (σ_1/σ_2 permutation). So, we can associate SSR2 with NR2, SSR3 with NR3 and SSR4 with NR4, as compatible regimes. The occurrence of σ_1/σ_3 permutation can also be supposed. Then, RR3 and RR4 are associated with SSR3-NR3 and with SSR4-NR4, respectively. Finally, we obtained three main tectonic regimes: an ENE-WSW (N79°E) extension (SSR2 and NR3 coupled with the opposite regime SSR5), a NE-SW (N55°E) extension (SSR3 and NR3 coupled with the



opposite regime RR3) and a NW-SE (N134°E) extension or compression (SSR4 and NR4 coupled with the opposite regime RR4).

The NE-SW and the ENE-WSW extensions are the two most important regimes (respectively 43.2% and 39.5% of the used data, whereas the NW-SE extension or compression corresponds only to 17.3% of the data. Moreover, the large magnitude earthquakes are linked to the regional stress field in close relationship with the transform motion, whereas the low magnitude earthquakes depend on local stress field.

<u>3 Numerical modelling of stresses and displacements associated with</u> <u>the Tjörnes Fracture zone development</u>

The present-day structural fabric of the Tjörnes Fracture Zone (TFZ) exhibits faults of various strikes (including strike-slip and normal faults) and dykes trending both parallel and oblique to the Icelandic rift system (Gudmundsson *et al.*, 1993). Reconstruction of paleostress through analysis of secondary faults (Bergerat *et al.* 2000) indicates that the stress field near TFZ changed with time. Similarly, the present-day stress regime inferred from focal mechanism inversion (Garcia *et al.*, in prep.) is largely heterogeneous. These data suggest that the accommodation of the transform motion between the Kolbeinsey oceanic ridge and the Icelandic rift and the related tectonic activity of the TFZ is governed by temporal and spatial changes of the stress field (Angelier *et al.*, in-press). We have investigated through a mechanical modelling how the northward migration of the Icelandic rift, as well as the development of fractures zones, contribute to this instability of the stress field.

3.1 Evolutive mechanical models of the Tjörnes Fracture Zone

Using the 2D distinct element code UDEC (Cundall, 1980), we computed the stress and displacement distribution in the horizontal plane near the TFZ for various key periods since accretion began in the Icelandic rift (Fig 4). The oldest periods (Fig. 1a) hence corresponds to the original structural pattern before development of the TFZ.



Figure. 4 Mechanical models of the Tjörnes Fracture Zone (TFZ). Models in a, b, c, and d characterise four key periods of the TFZ development. Kolbeinsey oceanic ridge (KR) and Icelandic rift (IR) in grey. Thick line: zone of reduced friction due to faulting and following a. Mohr-Coulomb behaviour. Location of the Dalvik fault (DF), Húsavík-Flatey fault (H-FF) and Grimsey fault (GF) indicated with dashed lines. See in text for explanation.

At that time, no faults or fractures exist between the Kolbeinsey ridge and the Icelandic rift. The later stages correspond to the successive development of the Dalvik fault (Fig. 4b), the Húsavík-Flatey fault (Fig. 4c), and the Grimsey fault (Fig. 4d), related to the northward migration of the Icelandic rift. The rifting zones are simulated as weak elastic elongated bodies (i. e., with a small Young modulus) imbedded in a resistant elastic medium. Faults obey a Mohr-Coulomb behaviour. Slip on the faults is defined by a linear normal and shear behaviour. The presented models are situated at 0.6 km depth. An *in situ* stress of 5MPa was thus imposed to account for the horizontal part of the lithostatic stress tensor. The eastern and western boundaries are displaced outward to simulate the divergence induced by the plate tectonics.

3.2 Stresses and displacements

Two key periods are presented in Figures 5 and 6. The first period illustrated in Figure 5 began since faulting and fracturing have developed along the Húsavík-Flatey fault (i. e., since 7-9 Ma) due to the shear stress concentration between the Kolbeinsey ridge and the Icelandic rift. It predates propagation of the Icelandic rift north of the Grimsey fault. The second period presented in Figure 6 follows the propagation of the Icelandic rift north of the Grimsey fault. It corresponds the future structural pattern of the TFZ after a significant structural fabric has



developed along the Grimsey fault due to faulting. For this late model, we suppose that the Kolbeinsey ridge will not propagate to the south.



Figure 5. Computed past stress field (a) and past displacement field (c) in the TFZ. The period considered here follows the decrease of the crustal strength along the Dalvik and Húsavík-Flatey faults (thick lines) due to faulting. (model in Fig. 4c). Kolbeinsey oceanic ridge and Icelandic rift in grey.

For the two periods illustrated in Figures 5 and 6, the stress field near the TZF zone is heterogeneous. The computed stress states exhibit a maximum horizontal stress either perpendicular or at small angle to the TFZ zone as indicated by analysis of secondary faults and focal mechanism inversion (see section 2). Furthermore, the stress pattern varies with time (compare Figures 5a and 6a). The northward propagation of the Icelandic rift and the development of faulting along the three structural lineaments of the TFZ are thus crucial for the stress distribution (and associated activity) along the TFZ.

Particularly striking is that the deflection of the maximum horizontal stress between the Dalvik and Húsavík-Flatey faults (Figures 5a and 6a) is similar to that of dykes in the area (e.g. Bergerat *et al.*, 2000). This similarity suggests the heterogeneous stress field related to faulting on the TFZ is responsible of the change in the dyke trends



Figure 6. Computed future stress field (a) and future displacement field (c) in the TFZ. The period considered here follows the decrease of the crustal strength along the Dalvik and Húsavík-Flatey and the Grimsey faults (thick lines) due to faulting. (model in Fig. 4d). Kolbeinsey oceanic ridge and Icelandic rift in grey.

Young et al. (1985) and Jancin et al. (1995) suggested that this change corresponds to block rotation due to the shearing along a wide zone containing the Húsavík-Flatey fault. According to them, the present-day orientation of dykes and faults do not reflect the past stress field near the TFZ. Our modelling does not support large block rotation. In contrary, it indicates that the present day fault orientations reliably reflect the past activity of the TFZ.

Our mechanical models suggest that the northward propagation of the Icelandic rift is followed by a jump to the north of the transform motion and related seismicity. For the model illustrated in Figure 5b, although slip is encouraged along the Dalvik and Húsavík-Flatey faults due to their low friction, displacement occurs for a large part along the Húsavík-Flatey fault. This displacement field is in agreement with the frequent seismicity along the Húsavík-Flatey. According to our modelling, the seismicity should increase along the Grimsey fault as the right lateral displacement jumps to the north (Figure 6b).

3.3 Further work

The presented models account for several aspects of the TFZ, like the deflection of dykes near the Húsavík-Flatey fault, and the present-day frequent seismicity along the Húsavík-Flatey and Grimsey faults relative to the less active Dalvik fault. In our models, the internal structure of three main faults constituting the TFZ has not been included. As an example, the Grimsey fault and the Dalvik fault include N-S faults, probably inherited from the rifting tectonics. Because such weak zones are favourite areas of faulting, they are very likely crucial in the tectonic activity of the TFZ. Further models will take into account this strength anisotropy. Particular attention will be given to the stress orientation and shear stress concentration (the necessary condition for earthquake occurrence) in order to



determine possible locations and sizes of future earthquakes. Another unresolved aspect of the TFZ is that this transform zone is not only subjected to strike-slip faulting, but also to normal faulting and tension fractures, either oblique or parallel to the TFZ. Understanding this mixed mode of deformation that commonly characterises oceanic transform fault will require a 3D mechanical analysis.

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4. <u>APPENDIX A - SMSITES PARTNERS</u> <u>PUBLICATIONS</u>

The SMSITES project has generated a wealth of scientific publications and reports to local authorities. The SMSITES partners have published a total of 27 scientific publications in a wide range of journals, and a further 4 are in preparation.

- Terra Nova (1)
- Tectonics (1)
- Journal of Structural Geology (4)
- Annual Review of Earth and Planetary Science (1)
- Journal of Geophysical Research (2)
- Journal of Volcanology and Geothermal Research (1)
- Geophysical Research Letters (4)
- Tectonophysics (2)
- Computational Seismology (1)
- SEG online (1)
- Geophysical Journal International (2)
- Other (7)

A number of these publication are available for downloading on the SMSITES website: <u>http://www.smsites.org</u>.

4.1. Partner 1-UEDIN

Crampin, S.

Stress-Forecasting earthquake in a critical crust. *Computational Seismology.* Issue commemorating the 80th birthday of Professor V. I. Keilis-Borok , In Press

Crampin, S. Chastin, S.

Shear-wave splitting in a critical crust: II - compliant, calculable, controllable, fluid-rock interactions Proceeding of 9IWSA conference, Proceeding of 9IWSA conference, *SEG online*

Volti, T. Crampin, S.

Shear-wave splitting in Iceland: four years monitoring stress changes before earthquakes and volcanic eruptions *Geophysical Journal International*, submitted

Crampin, S.

Developing Stress-Monitoring Sites (SMSs) using cross-hole seismology to stress-forecast the times and magnitudes of future earthquakes

Tectonophysics, In Press



Crampin, S. Volti, T. Stefansson, R. A successfully stress-forecast earthquake *Geophy. J. Int.*, **138**, F1-F5

Crampin, S. Volti, T. Jackson, P.

Developing a stress-Monitoring Site (SMS) near Húsavík forstress forecasting the times and magnitudes of future large earthquakes Destructive Earthquakes: Understanding Crustal Processes Leading to Destructive Earthquakes. Proc. 2nd EU-Japan Workshop on Seismic Risk., (eds) B.Thorkelsson, B.Yeroyanni, M., June 23-27, 1999. Europ. Comm., Res. Dir. Gen., 136-149.

4.2. Partner 2-IMOR.DG

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4.3. Partner 5-USAV5

Henriot, O. Villemin, T. & Jouanne F. (2000) Long period interferograms reveal 1992-1998 steady rate of deformation at Krafla volcano (North Iceland). Geophys. Res. Lett., in press Dauteuil O., Angelier J., Bergerat F., Verrier S., Villemin T., (2001) Deformation partitionning of a fissure swarm in the Northern Icelandic Rift. Journal of Structural Geology, in press Villemin T., Ouillon G. & Ferber V., (2001) Processes of fractures pattern evolution deduced from field data : the Krafla fissure swarm and the last rifting episode in North Iceland. Journal of Geophysical Reasearch, submitted. Villemin, T. & Jouanne F. Active deformation in Northen Iceland at the rift transform junction : a dynamic system in rapid evolution. in preparation Henriot, O. Villemin, T. The Krafla fissure swarm, Northern Iceland : the end of the subsidence due to the postrifting cooling of magma?



in preparation

Villemin, T, Henriot, O.

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4.4. Partner 6-UIB

Gudmundsson, A., 2000.
Dynamics of volcanic systems in Iceland: Example of tectonism and
volcanism at juxtaposed hotspot and mid-ocean ridge systems
Annual Review of Earth and Planetary Science, 28: 107-140.
Acocella, V., Gudmundsson, A. and Funiciello, R., 2000.
Interaction and linkage of extensional fractures: Examples from the rift zone of Iceland.
Journal of Structural Geology, 22: 1233-1246.
Belardinelli, M.E., Bonafede, M. and Gudmundsson, A., 2000.
Secondary earthquake fractures generated by a strike-slip fault in the
South Iceland Seismic Zone.
Journal of Geophysical Research, 105: 13,613-13,629.
Gudmundsson, A., 2000.
Displacements, stresses, and arrest of hydrofractures.
Tectonophysics (submitted).
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Journal of Structural Geology, 22: 1221-1231.
Gudmundsson, A., 2000.
Active fault zones and groundwater flow.
Geophysical Research Letters, 27: 2993-2996.

4.5. Partner 7-UPMC

Angelier J., Bergerat F. And Homberg C. (2000) Variable coupling explains complex tectonic regimes near oceanic transform fault: Flateyjarskagi, Iceland.



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Bergerat F., Angelier J. And Homberg C. (2000).

Tectonic analysis of the Húsavík-Flatey Fault (northern Iceland) and mechanisms of an oceanic transform zone, the Tjörnes Fracture Zone, *Tectonics*, **19**, p. 1161-1177.

Dauteuil O., Angelier J., Bergerat F., Verrier S. And Villemin T. (2000). Deformation partitioning inside a fissure swarm of the Northern Icelandic Rift.

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Garcia S., Angelier J., Bergerat F. And Homberg G. (....).

Tectonic behaviour of an oceanic transform fault zone from fault-slip data and focal mechanism of earthquakes analyses: the Tjörnes Fracture Zone, Iceland,

in preparation.

5. <u>APPENDIX B – SMSITES AT CONFERENCES</u>

The SMISTES project has been presented at many conferences

2000

- The Nordic Geological Wintermeeting, Trondheim (*P6*)
- Seismic signatures of fluid flow, Berlin 27-29 February 2000 (P1)
- GeoMaths 2000: the behaviour of rocks undergoing changes, Innsbruck 1-3 March 2000 (**P1**)
- 9th International Workshop on Seismic Anisotropy, Houston 26-31 March 2000 (P1)
- Meeting on hydrogeology and environmental geochemistry, the Geological Survey of Norway, Trondheim, Norway (*P6*)
- 18^{ème} *RST*, Paris, April 2000 (*P7*)
- XXV EGS General Assembly, Nice, France, April 25-29, 2000 (P4)
- European Association of Geoscientists and Engineers, Glasgow 29 June 2000 (**P1**)
- Natural and Anthropologically Induced Hazards, Maratea 25-29 June 2000 (P1)
- SEG/Calgary 2000 The Society of Exploration Geophysicists 6-11 August 2000 * Stampede Park (**P1**)
- 4th International Conference of LACDE Local Authorities Confronting Disasters and Emergencies, Reykjavik, Iceland, August 27-30, 2000.(P2)
- Conference on Research Infrastructures (18-20 September 2000), Palais de la musique et des congres, strasbourgh. (P1)
- XXXVII ESC Lisbon 10-15 September 2000 (**P2,P4**)
- Meeting « Drilling the Seismogenic Zone », Birmingham, 15 September 2000, (P7)

• AGU fall meeting in San Francisco, California, December 15-19, 2000, (**P2**) The 31st Nordic Seminar on Detection Seismology 27-29 September 2000 (P4)

The following sections list the abstracts and presentation given by the partners at these conferences.

5.1. Partner 2-IMOR.DG

Stefansson, R. 2000.

Warnings about seismic and volcanic hazards in Iceland.

Abstracts

4th International Conference of LACDE – Local Authorities Confronting Disasters and Emergencies, Reykjavik, Iceland, August 27-30, 2000.

Stefansson, R., K. Agustsson, G.B. Gudmundsson, B. Thorbjarnardottir & P. Einarsson 2000.

A successful prediction and warning of an eruption in the Hekla volcano, Iceland. In:

Abstracts

AGU spring meeting, Washington D.C., USA, May 30 - June 3, 2000.

5.2. Partner 4-UU

- R. Bodvarsson, R. Slunga, B. Lund and R. Stefansson utilization of micro-earthquakes down to ml 0. partial results from three multinational earthquake prediction projects. XXXVII ESC Lisbon 10-15 September 2000
 B. Lund and R. Bodvarsson
- B. Lund and R. Bodvarsson

spectral amplitude grouping of microearthquake focal mechanisms **XXXVII ESC Lisbon 10-15 September 2000**

R. Slunga

A simple earthquake warning algorithm based on microearthquakes **XXXVII ESC Lisbon 10-15 September 2000**

R. Stefansson and R. Bodvarsson

Advances in earthquake prediction research. some results of the Prenlab projects.

XXXVII ESC Lisbon 10-15 September 2000

S. Jakobsdottir, R. Bodvarsson and R. Stefansson

The capability and usage of the sil system during 10 years of operation **XXXVII ESC Lisbon 10-15 September 2000**

5.3. Partner 6-UIB

Lyslo, K.B. and Gudmundsson, A., 2000.
Abstruct unu tutk. Crustal strasses fault reactivation and groundwater flow in
the Bergen area, western Norway
The Nordia Coological Wintermosting Trondhoim
Lucle K.D. Cudmundson A. Darg S.S. and Shurtucit E. 2000
Lysio, K.B., Guullullusson, A., Derg, S.S. and Skurtven, E., 2000.
Abstract and talk.
Geometrical properties, reactivation and hydraulic conductivity of
fracture systems in west Norway.
The Nordic Geological Wintermeeting, Trondheim.
Gudmundsson, A., 2000.
Abstract and talk.
Fault slip and groundwater transport.
The Nordic Geological Wintermeeting, Trondheim.
Lie, H. and Gudmundsson, A., 2000.
Abstract and poster (in Norwegian).
Hydrogeological model of the Abeddissen area, Askøy, West Norway.
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the Geological Survey of Norway, Trondheim, Norway.
Lyslo, K.B. and Gudmundsson, A., 2000.
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Permeability and stress concentration around active faults.
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Skurtveit, E., Gjesdal, O. and Gudmundsson, A., 2000.
Abstract and poster
Hydrogeological model of Øygarden, West Norway.
Meeting on hydrogeology and environmental geochemistry,
the Geological Survey of Norway, Trondheim, Norway.
Waage, H., Amaral, H., Stueland, E. and Gudmundsson, A., 2000.
Abstract, poster
Fault zones and permeability in the Vaksdal area.
Meeting on hydrogeology and environmental geochemistry,
the Geological Survey of Norway, Trondheim, Norway.
Gudmundsson, A., 2000.
Abstract and talk.
Propagation of hydrofractures in a layered rock mass.
Meeting on hydrogeology and environmental geochemistry,
the Geological Survey of Norway, Trondheim, Norway.
Bergerat, F., Angelier, J. and Gudmundsson, A., 2000.
Abstract and talk.
The Leirubakki fault, a large earthquake rupture of the South Iceland
Seismic Zone.
European Geophysical Society. General Assembly. Nice. France.
Gudmundsson, A., 2000.

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Abstract and talk.Fracture networks, fluid overpressure and transport in theHúsavík-Flatey Fault.Meeting of the Prenlab2 group, Nice, France.Gudmundsson, A., 2000.Abstract and talk.Effect of fault slip on the flow of crustal fluids.European Geophysical Society, General Assembly, Nice, France.Gudmundsson, A., 2000.Abstract and talk.Magma flow beneath the volcanic zones of Iceland.European Geophysical Society, General Assembly, Nice, France.

5.4. Partner 7-UPMC

Bergerat F., Garcia S., Angelier J. And Homberg C. (2000).

abstract

Sismotectonics of an oceanic transform zone : the Tjörnes Fracture Zone (Iceland).

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Garcia S., Angelier J., Bergerat F And Homberg C. (2000).
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 18^{ème} RST, Paris, April 2000.

6. <u>APPENDIX C - SMSITES RELATION TO THE</u> <u>PUBLIC & MEDIA</u>

A very good co-operation has been with the local authorities of Húsavík in carrying out the project. A common press conference was scheduled at Húsavík on December 6. 2000, for informing the Iceland public about the project. Unfortunately, this press meeting had to be postponed because of very bad weather conditions in the area during that day. It will be held early 2001.

6.1. Partner 1 – UEDIN

UEDIN has been approach by the Newscientist and by Cable TV channels for interviews about the SMSITES project.

6.2. Partner 7-UPMC

Interview by Cécile OLIVIER (journalist, Eureka, popular monthly magazine): "Vers la prévision des tremblements de terre ?", Eurêka, December 1999, n° 50, small item.

