# SEISMISKT DATASAMLINGSSYSTEM
# FÖR
# SÖDRA ISLANDS LÅGLAND

## NORDISKT SAMARBETE SOM SYFTAR TILL ATT REDUCERA SKADOR I JORDBÄVNINGAR OCH ATT KUNNA FÖRUTSÄGA DEM

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Oktober 1986

VEÐURSTOFA ÍSLANDS

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DENNA RAPPORT ÄR I STORA DRAG RESULTATET AV NÅGRA NORDISKA SEISMOLOGERS OCH FORSKNINGSINGENJÖRES MÖTE I OSLO I APRIL 1986. MÖTET HÖLLS MED STÖD FRÅN NOS-N OCH FRÅN DEN NORDISKA KULTURFONDEN.

AV PRAKTISKA SKÄL ÄR DOKUMENTET PÅ ENGELSKA, DOCK MED INLEDNING PÅ SVENSKA OCH ISLÄNDSKA.

Oktober 1986

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# 1.a INLEDNING

I detta dokument beskriver vi ett samnordiskt forskningsprojekt vars målsättning är att minska skadeverkningar av jordbävningar och om förhoppningsvis att skapa grundval för att kunna förutsäga dem.

Projektet beräknas vara 6 år och dess huvudmoment är utbyggnad av ett bassystem för kontinuerlig insamling av data från ett jordbävningsområde på Island, samt utveckling av metoder för att snabbt kunna beräkna olika fysiska parametrar, som är knutna till jordbävningars mekanismer och uppkomst och därför relevanta för jordbävningsprognoser. Ett lyckat genomförande av projektet är av mycket stor betydelse för Island. Men det är också målsättningen att denna nya erfarenhet och kunskap gagnar andra nordiska länder i deras strävan att minska faror från jordskalv, liksom för liknande strävanden i hela världen.

Jordbävningar orsakar mycket stora ekonomiska förluster och mänskligt lidande i stora delar av världen. Vidare visar det sig, att det moderna tekniska samhället blir allt känsligare för jordbävningars verkningar. Detta och utvecklingen inom geovetenskapen och tekniken inspirerar forskare och andra berörda till att utveckla metoder för jordbävningsprognoser.

Södra Islands lågland är den del av Island, som i det förflutna har varit mest utsatt för stora jordbävningar och stor skada och ödeläggelse som följd därav. Man vet definitivt, att sådana jordbävningar kommer att äga rum i framtiden.

På det internationella planet har man redan vidtagit åtgärder för ökat samarbete inom området. I en resolution från Europarådet har man föreslagit, att man skall koncentrera sina ansträngningar på 5 särskilda "test-områden". Ett av dessa områden är södra Islands lågland (SIL). Denna resolution från Europarådet är grunden för detta förslag om ett nordiskt samarbete inom jordbävningsforskning.

Den högt utvecklade tekniken och kunnandet i de nordiska länderna och den erfarenhet man har av att observera ofta förekommande naturkatastrofer på Island kommer att förenas i detta samarbete. På detta sätt syftar man mot en gemensam aktion för att minska jordbävningsfaran i SIL och mot utveckling av jordbävningsprognoser.

I kapitel 3 beskriver vi de geologiska förhållandena inom SIL, områdets seismiska karaktär och förstörelsezonen, utifrån historiska källor och nya observationer. Vidare finns också en kortfattad beskrivning av pågående och planerade undersökningar inom området. Dessa undersökningar har ökat de sista 10 åren och är av största värde för det projekt vi föreslår här. De är en naturlig fortsättning och utökning av dessa äldre observationer och målsättningen är, att lägga en ny dimension till dem.

I kapitel 4 diskuterar vi den metodiska målsättningen. I få ord kan man säga, att den är att samla och bearbeta geofysiska data så att man bättre förstår de fysiska förhållanden och processer som leder till jordbävningar, förstår bättre var och när stora jordbävningar förekommer. Detta anser vi vara nyckeln till framsteg vad beträffar att reducera förluster i jordbävningar och förutsäga dem.

Intresset för Island i detta sammanhang beror inte uteslutande på det faktum, att förödande jordbävningar förekomma. Skorpans fysiska tillstånd och de processer, som orsakar dess deformation och utlösning av jordskalv är av särskilt varierande slag på Island. Erfarenhet från detta område kan således vara av stor nytta i strävanden att modellera jordskalv överallt på jorden.

Vi bedömer studier av de små jordbävningar som ofta förekommer vara särskilt viktiga i samband med detta projekt. Därför föreslår vi att för området skall utformas och byggas upp ett datasamlingssystem av hög kvalitet, för att registrera och kontinuerligt bearbeta denna småskalvsaktivitet. Samtidigt måste nätet vara smidigt så att man lätt skall kunna observera och bearbeta andra geofysiska parametrar, som är av värde för projektets huvudsyfte.

Datasystemet beskrivs i kapitel 5 i den mån det redan är utformat. I projektets första fas har datasystemets slutliga design en högsta prioritet.

Systemet har kapacitet till att registrera och bearbeta ett stort antal jordbävningar från den seismiska zonen i södra Islands lågland i realtid. Data som är av värde för jordbävningsprognoser samlas kontinuerligt i systemets databank, som återspeglar områdets dynamiska tillstånd. Metoder som rutinmässigt jämför inströmmande data med bakgrundsmaterialet skall utvecklas.

På detta sätt kommer man att utveckla rutin för jordbävningsprognoser, samtidigt med nödvandig insamling och bearbetning av data.

Systemet kan lätt utvidgas för att registrera andra geofysiska parametrar, som är relevanta för undersökning av jordskalv.

Vidare är systemet utformat så, att det lätt kan utökas för att behandla liknande data från hela landet. Detta är av stor betydelse för Island i synnerhet men också för projektet i allmänhet.

Det är också av stor vikt i systemets utformning att data är lätt tillgängliga för forskare och andra berörda. Det gäller både bakgrundsmaterial, som belyser områdets dynamiska tillstånd och enstaka händelser.

I sektion 5.6 diskuterar vi datasystemets dynamik, d. v. s. vilken storlek av rörelser man skall kunna registrera med systemet. I sektion 5.7 försöker vi sedan estimera det antal jordbävningar systemet måste kunna behandla. Antalet jordbävningar per år är ca. 2.000. Dock är den seismiska aktiviteten mycket varierande, varför systemet måste kunna behandla flera hundra jordbävningar per dygn.

Datateknikens snabba utveckling de sista åren gör det möjligt, att utforma ett billigt och effektivt system, som klarar dessa arbetsuppgifter.

Enligt 5.8 skall en persondator PC vara i centrum på varje observationsplats där kontinuerlig registrering äger rum. Systemet skall kunna detektera enstaka jordbävningar och överföra data till en central enhet. Detta utförs i första hand av PCen på observationsplatsen, och sedan genom samspel med den centrala dataenheten. Överföring av data till Reykjavík sker via lokal telefon och Teletjänstens datanät.

Tidsplan för projektet presenteras i kapitel 6. Det beräknas starta 1986 och sluta 1991.

Nordiska seismologer har diskuterat detta projekt i flera år. I början av 1985 presenterade den isländska kommittén för seismologisk forskning ett allmänt förslag i denna riktning för de isländska medlemmarna av nordiska rådet. Liknande förslag var presenterat vid nordiska rådets möte i Köpenhamn 1986 av några representanter.

Med hjälp av ekonomiskt stöd från NOS-N och den Nordiska kulturfonden höll vi ett möte i Oslo i april 1986. Där startade planering och utformning av det seismiska nätet och forskningsprogrammet. Faktum är, att detta sexåriga projekt började redan tidigare i år. Fast man redan nu således har hunnit göra vissa förberedande planer, beror ett lyckat genomförande av projektet före 1991 på att man i tid lyckas finansera projektet.

I tabell 6.1 presenteras projektets tidsplan. De första 3 åren går åt utformning och konstruktion av systemet, medan aktiviteten under de senare tre åren består i att utveckla vetenskapliga metoder som kan vara användbara i kampen mot förluster i jordbävningar och för att underbygga jordbävningsprognoser.

Detaljerad budgetplan finns i kapitel 7. Den totala kostnaden för genomförande av detta sexåriga projekt beräknas bli 6.893.100 S.kr.

Denna summa uppdelas efter år:

| | |
|---|---|
| Kostnad 1987 och delvis 1986 | 677.000 S.kr. |
| 1988 | 3.568.300 S.kr. |
| 1989 | 1.082.600 S.kr. |
| 1990 | 782.600 S.kr. |
| 1991 | 782.600 S.kr. |

Budgeten kan också framställas med följande uppdelning:

Utformning och konstruktion av systemet, materialkostnad och löner för ingenjörer under uppbygnadsperioden, 3.911.500 S.kr.
Driftskostnad under uppbygnadstiden, 633.800 S.kr.
Driftskostnad frå 1989-1991 som inkluderar bl.a. nordisk forskartjänst. Per år, 782.600 S.kr.

Det anses nödvändigt att denna nordiska forskare kommer från något annat land en Island. Samma gäller om de ingenjörer som arbetar vid konstruktion,utformning och uppsättning av systemet. Tanken bakom detta är att importera tekniskt kunnande från de andra nordiska länder men också för att få bättre kontakter med parallella aktiviteter i de andra nordiska länderna.

I detta dokument finns inga planer om nordiskt samarbete inom detta område efter 1991. Men vi hoppas innerligen på, att detta projekt bara är en början på en epok med intimt och produktivt samarbete mellan nordiska seismologer, och en framgång för det nordiska samarbete.

# 1.b INNGANGUR

Í þessari skýrslu kynnum við áætlun um norrænt samstarf, sem miðar að því að minnka jarðskjálftahættu og leggja grunn að jarðskjálftaspám. Grundvöllur þessa átaks, sem standa mun um sex ára skeið, er að koma á laggirnar gagnasöfnunarkerfi fyrir jarðhræringar á jarðskjálftasvæði á Íslandi. Sömuleiðis að móta aðferðir, til að meta á fljótvirkan hátt eðlisfræðilega þætti, sem tengjast útlausn jarðskjálfta og hafa mikla þýðingu varðandi jarðskjálftaspár. Takist að hrinda þessari áætlun í framkvæmd, munu íslendingar njóta mjög góðs af. Markmið átaksins er einnig það að vera uppspretta nýrrar reynslu og þekkingar, til hagsbóta fyrir hin Norðurlöndin í viðleitni þeirra til að draga úr jarðskjálftahættu og raunar til gagns fyrir slíka viðleitni um allan heim.

Víða á jörðinni valda jarðskjálftar þjáningum og dauða manna og geysimiklu tjóni á verðmætum. Með örri tækniþróun nútímans vex jarðskjálftahætta og hefur sívaxandi áhrif á athafnir manna. Þessar staðreyndir, auk eflingar jarðvísinda og tækni á síðustu árum, gera jarðskjálftaspár að mikilvægu markmiði allra, sem láta sig varða þessi mál, ekki síst vísindamanna.

Nú að undanförnu hefur samstarf á alþjóðavettvangi aukist verulega á þessu sviði. Í ályktun frá Evrópuráðinu er hvatt til sameiginlegs átaks á þessu sviði í álfunni. Þar er einnig mælt með því að leggja sérstaka áherslu á samstilltar aðgerðir á fimm svokölluðum tilraunasvæðum. Eitt þessara svæða er Suðurlandsundirlendið. Þetta er meginástæða fyrirliggjandi tillögu um samvinnu Norðurlanda um jarðskjálftarannsóknir.

Jarðskjálftar hafa valdið meiri skaða og eyðileggingu á Suðurlandsundirlendinu en annars staðar á Íslandi. Ljóst er að slíkir jarðskjálftar munu enn eiga sér stað í framtíðinni.

Sú samvinna, sem hér er gerð tillaga um, gerir ráð fyrir að færa í einn farveg háþróaðar úrvinnsluaðferðir og tækni á Norðurlöndunum og þá reynslu, sem aflað hefur verið við að fylgjast með náttúruhamförum á Íslandi. Þetta er samstillt átak, sem miðar að því að draga úr jarðskjálftahættu á Suðurlandsundirlendinu og einnig að því að geta spáð um jarðskjálfta.

Í þriðja kafla þessarar skýrslu er lýst jarðfræðilegri gerð Suðurlandsundirlendisins, eðli skjálftavirkninnar og því svæði þar sem mest eyðilegging hefur orðið í jarðskjálftum. Þar er bæði byggt á sögulegum heimildum og nýlegum athugunum. Einnig er í kaflanum stutt lýsing á þeim rannsóknum á svæðinu, sem nú standa yfir, svo og þeim sem eru á döfinni. Rannsóknir þessar hafa verið auknar síðasta áratuginn og eru raunar forsenda þeirrar áætlunar, sem hér er kynnt. Markmiðið er að efla þessar rannsóknir og láta þær taka til fleiri þátta.

Fjórði kafli fjallar allnáið um vísindaleg markmið tillagnanna. Þau eru, í fáum orðum sagt, að safna jarðeðlisfræðilegum gögnum og vinna úr þeim, í því augnamiði að skilja betur eðlisfræðilega eiginleika jarðskjálfta, svo og hvar og hvenær stórir jarðskjálftar geta átt sér stað. Við álítum þetta vera grundvöll þess að geta dregið úr tjóni í jarðskjálftum, svo og þess að geta spáð.

Ísland er mjög freistandi vettvangur fyrir slíkar rannsóknir.

Stafar það ekki aðeins af því, hversu harðir jarðskjálftar geta orðið hér, heldur einnig vegna hinna margbreytilegu eðlisþátta, sem spenna og skæla jarðskorpuna á Íslandi og leiða til jarðskjálfta. Þess vegna eru slíkar rannsóknir á Íslandi gagnlegar til að skýra útlausn jarðskjálfta hvar sem er í heiminum.

Athuganir á smáskjálftavirkni, þ.e. á tíðum litlum jarðskjálftum, eru að okkar mati allramikilvægasti þáttur þessa átaks á Íslandi. Þess vegna leggjum við til að hannað verði og komið á fót mjög fullkomnu gagnasöfnunarkerfi fyrir jarðhræringar á svæðinu. Kerfið á að skrá og vinna hratt úr slíkri smáskjálftavirkni. Kerfið er þó þannig hannað, að vandalítið er að bæta við það söfnun á öðrum jarðeðlisfræðilegum mælingum, sem mikilsverðar eru fyrir markmið þessa rannsóknarverkefnis.

Í fimmta kafla er sagt frá gerð og hönnun gagnasöfnunarkerfisins. Lokahönnunin er aðalverkefni fyrsta hluta áætlunarinnar.

Kerfið verður að geta skráð og unnið nánast samstundis úr miklu magni jarðskjálftagagna af skjálftasvæði Suðurlandsundirlendisins. Gögnum, sem varða jarðskjálftaspár, mun í sífellu verða safnað í gagnasafn kerfisins, sem sýnir í hnotskurn ástand jarðskjálftasvæðisins. Aðferðir verða mótaðar til að geta borið samtímaathuganir saman við þau gögn, sem fyrir eru.

Þannig verður unnið að aðferðum til notkunar við jarðskjálftaspár um leið og nauðsynleg gagnasöfnun og gagnaúrvinnsla fer fram.

Annar eiginleiki kerfisins er sá, að það má auðveldlega færa út og nota til skráningar á öðrum mælingum af jarðeðlisfræðilegum toga. Má þá kanna og skrá aðra þætti, sem mikilvægir eru fyrir jarðskjálftarannsóknir.

Hönnun kerfisins er þannig, að færa má það út og vinna úr gögnum alls staðar að af landinu. Vissulega er þetta mikilvægt fyrir íslendinga, en einnig fyrir heildarárangur þessa átaks.

Til viðbótar frumvinnslu gagna, verður gagnamiðstöðin þannig búin, að hún geymi gögn á því formi, að auðvelt sé fyrir aðra vísindamenn að fá aðgang að þeim. Á það bæði við um samtímaathuganir sem og grundvallargögn, sem varða ástand svæðisins.

Undir töluliðnum 5.6 er rætt um hvað skjálftanetið skuli ná yfir stórt svið jarðskjálftahreyfinga. Undir tölulið 5.7 er áætlað, hversu mörgum skjálftum búast megi við að kerfið þurfi að vinna úr, en þeir eru um 2.000 árlega að jafnaði. Kerfið verður auk þess að geta varðveitt gögn frá hundruðum jarðskjálfta á dag, vegna þess hve jarðskjálftar hér á landi koma mjög í hrinum.

Stórstígar framfarir í tölvutækni á undanförnum árum gera kleift að setja upp athugunarkerfi, sem uppfyllir þær kröfur sem lýst er að framan, á mun ódýrari og skilvirkari hátt en fyrr.

Eins og lýst er undir töluliðnum 5.8, mun einmenningstölva (PC), verða þungamiðja hvers athugunarstaðar, þar sem sískráning gagna fer fram. Kerfið getur fundið og greint jarðskjálfta frá öðrum hræringum og truflunum og sent þá til miðstöðvarinnar. Þetta gerist í tölvunum á athugunarstöðunum, sem og í samspili þeirra og tölvumiðstöðvarinnar.

Sendingin til miðstöðvarinnar í Reykjavík mun fara fram um símakerfið á hverjum stað, svo og um gagnanet Pósts og síma.

Í sjötta kafla er kynnt tímaáætlun sú, sem unnið er eftir. Hafist er handa á þessu ári og viðfangsefninu lokið árið 1991.

Norrænir jarðskjálftafræðingar hafa rætt þetta verkefni um nokkurra ára skeið og kynnti íslenska nefndin um jarðskjálftavarnir fulltrúum Íslands í Norðurlandaráði tillögu í þessa átt í ársbyrjun 1985. Á þingi Norðurlandaráðs í Kaupmannahöfn í mars síðastliðnum, fluttu nokkrir fulltrúar svipaða tillögu.

Haldinn var fundur í Oslo í apríl síðastliðnum með fjárhagslegum stuðningi NOS-N og Nordisk kulturfond. Þar hófst vinna við hönnun á áætlaðu skjálftaneti og við rannsóknaráætlunina.

Þetta 6 ára átak, sem við leggjum til, hófst því í raun snemma á þessu ári. Þótt nú þegar hafi reynst mögulegt að byrja mjög þýðingarmikinn undirbúning, veltur það á hversu fljótt tekst að fá nauðsynlegt fé, hvort verkið muni til lykta leitt fyrir árslok 1991.

Tímaáætlun verkefnisins er sýnd í töflu 6.1. Þremur fyrstu árunum verður varið til hönnunar og uppsetningar kerfisins. Seinni þrjú árin eru til að móta vísindalegar aðferðir, sem nota má til að draga úr jarðskjálftahættu og til að spá fyrir um jarðskjálfta.

Í sjöunda kafla er nákvæm kostnaðaráætlun. Heildarkostnaður við þetta sex ára átak er áætlaður 6.893.100 sænskra króna.

Þetta skiptist eftir árum sem hér segir:

| | |
|---|---|
| Kostnaðurinn 1987 að meðtöldum hluta af 1986 | 677.000 S.kr. |
| 1988 | 3.568.300 S.kr. |
| 1989 | 1.082.600 S.kr. |
| 1990 | 782.600 S.kr. |
| 1991 | 782.600 S.kr. |

Fjárhagsáætluninni má einnig skipta efnislega sem hér segir:

Hönnun, efniskostnaður og uppbygging gagnanetsins, að meðtöldum launum rafeindaverkfræðinga á uppbyggingarskeiði, alls: 3.911.500 S.kr.
Rekstrarkostnaður að hluta til meðan á uppbyggingu stendur, alls: 633.800 S.kr.
Rekstur kerfisins 1989 til 1991, að meðtöldum kostnaði vegna norræns rannsóknarstyrkþega, á ári alls: 782.600 S.kr.

Álitið er nauðsynlegt að norræni styrkþeginn verði frá öðru Norðurlanda en Íslandi. Sama á a.m.k. að nokkru leyti við um verkfræðinginn eða verkfræðingana meðan á uppbyggingu stendur. Þetta er óhjákvæilegt, bæði til að flytja inn reynslu og sérþekkingu frá hinum Norðurlöndunum og einnig til að tengja átak þetta fastar samsvarandi starfi í hinum löndunum.

Í þessari skýrslu gerum við enga áætlun um norræna samvinnu á þessu sviði eftir 1991. Samt sem áður efumst við ekki um, að þetta átak verði upphafið að nýju skeiði í samstarfi norrænna jarðskjálftafræðinga og nýr áfangi í velheppnaðri samvinnu Norðurlanda.

# 1.c INTRODUCTION

In this document we outline a cooperative Nordic project aimed at mitigating earthquake risk and promoting earthquake prediction. The basis of this 6 year project is the building of a seismic data acquisition system in an earthquake zone in Iceland and the development of methods for fast evaluation of physical parameters related to earthquake generation and thus significant for earthquake prediction. The successful execution of this project will be of great benefit to Iceland, but its aim is also to accumulate new experience and knowledge for the benefit of other Nordic countries and indeed the whole world, in their efforts to mitigate earthquake risk.

In many parts of the world, earthquakes are the cause of death, human suffering and enormous economic loss. With the fast development of modern technology, earthquake risk is relevant to human activities to an ever increasing degree.

These facts and recent advances in the geosciences and technology, make the development of earthquake prediction methods a challenging goal for all concerned, not least scientists.

The international community has recently taken significant steps towards cooperation in this field. In Europe, a common effort towards this goal was proposed in a resolution from the the European Council, with recommendations to concentrate efforts on five earthquake "test-areas". One of the proposed areas is the South Iceland Lowland (SIL), Suðurlandsundirlendið. This is the basis for the present proposal for Nordic cooperation in earthquake research.

SIL is the part of Iceland where earthquakes in the past have caused the most damage and destruction. We know that such earthquakes will occur again in the future.

In the cooperative project proposed here, highly developed techniques and technology from the Nordic countries will be combined with experience acquired in monitoring frequent natural hazards in Iceland. The project will be a concerted effort towards mitigating earthquake risk in the South Iceland Lowland and also towards earthquake prediction.

In Chapter 3, we describe the geological setting of the SIL area, the nature of the earthquake activity and the zone of major seismic damage, as inferred from historical documents and recent observations. There is also a short description of already ongoing and planned investigations in the area. These investigations, which have been intensified during the last decade, are of great advantage to the project proposed here, which is based on these earlier investigations. Its goal is to supplement, and add new dimensions to those ongoing observations.

In Chapter 4, we discuss in some detail the scientific objectives of this proposal. In short, the objectives are to collect and evaluate geophysical data, with the aim of gaining a better understanding of the physical properties of earthquakes, where and when great earthquakes can occur. This we consider to be a basis for reducing losses in earthquakes as well as for earthquake prediction.

Iceland is of special interest in such investigations, not only because of the severity of the earthquakes which can occur, but also because of the varying physical conditions which influence crustal deformation and the generation of earthquakes. Therefore research in Iceland is relevant to attempts to model earthquake generation anywhere in the world.

In our judgement, the study of microseismicity; i.e. small earthquakes which occur frequently, is of central importance for this project in Iceland. Therefore we propose to design and build a high quality seismic data acquisition system for the recording and fast evaluation of microseismicity in the area. However, the network is designed such that it will be easy and cheap to add to it observations of other geophysical data, which are significant for the project.

In Chapter 5, we outline the scope and design of the proposed data acquisition system. The production of a final detailed design is the main task to be undertaken during the first part of the project.

The system must be capable of recording and evaluating a large quantity of earthquake data recorded in the South Iceland Lowland in a near real time. A data bank relevant to earthquake prediction will be continously accumulated, which will reflect the dynamic state of the seismic area. Methods will be developed for the routine comparison of current observations with background material.

In this way techniques will be developed for earthquake prediction, concurrent with necessary accumulation and evaluation of real data.

Another feature of the system is that it can easily be extended to record other kinds of geophysical data, and thus will enable the observation and recording of other parameters significant to earthquake research.

The system is also designed in such a way that it can be extended to handle data from the whole of the country, which of course is of interest for Iceland, but is also of interest for the success of this project in general.

Besides the preliminary evaluation of data, the data center will be equipped for storing data in such a form that they will be easily available to other scientists, together with archived background material.

In Section 5.6, the required dynamic range of the system is discussed; i.e. what sizes of earthquake motion must be covered by the seismic network. In Section 5.7, an estimate of the seismic rate is given, this being about 2.000 events per annum on the average. However, as earthquake activity in Iceland is very episodic in character, the network must be capable of storing up to hundreds of earthquakes per day.

The fast development of computer techniques in recent years has made it possible to build an observational system fulfilling the requirements stated above in a far cheaper and more efficient way than before.

As described in Section 5.8 a "personal computer", PC, will be installed at each observation site. The system will be capable of event detection; i.e. finding and selecting significant events for transmission to the central station. This is done by these site computers, and by interfacing these and the central computing facilities. Transmission to the central station in Reykjavík will be through the local telephone network and through a commercial data link.

In Chapter 6, the time schedule of this project is presented, starting in 1986 and finishing in 1991.

The proposed project has been the subject of discussion for some years by Nordic seismologists, and at the beginning of 1985, the Icelandic Committee for Earthquake Research presented a general proposal along these lines for the Icelandic members of the Nordic Council. At the Nordic Council meeting in Copenhagen in March 1986, a similar proposal was presented by members.

With the economic support of NOS-N and "Nordisk kulturfond", a meeting was organized in Oslo in April 1986, and the work of designing the proposed seismic network and the research program was started.

The 6 year project, which we are proposing therefore started in reality early this year. Although it has been possible to take such preparatory steps, the successful conclusion of the project in 1991, will depend upon the timely raising of the necessary funds.

The time schedule is shown in Table 6.1. The first 3 years are devoted to designing and construction of the system, while the last 3 years are spent developing scientific methods applicable to earthquake risk mitigation and earthquake prediction.

In Chapter 7, there is a detailed cost estimate. The total cost of this 6 year project would be 6.893.100 Swedish kr.

This may be broken down as follows:

| | |
|---|---|
| The cost in 1987, including a part of 1986 | 677.000 S.kr. |
| in 1988 | 3.568.300 S.kr. |
| in 1989 | 1.082.600 S.kr. |
| in 1990 | 782.600 S.kr. |
| and in 1991 | 782.600 S.kr. |

The budget may also be broken down by subject:

Designing, materials costs and construction of the system, including a technical engineer during the construction period, total 3.911.500 S.kr.

Partial operation cost, during the construction period, total 633.800 S.kr.

System operation, from 1989, 782.600 S.kr. per annum until 1991, including a Nordic research fellow.

It is considered necessary that the Nordic research fellow comes from a Nordic country other than Iceland, and the same applies partly to the technical engineers during the construction period. This is necessary in order to import specialized skills, to enable the exchange of experience between the Nordic countries and to encourage connections between this project and parallel activities in the the whole of Scandinavia.

Plans for Nordic cooperation in this field after 1991 are not detailed herein, but the authors are in no doubt that this project would mark beginning of a new era of Nordic seismological cooperation, and a milestone in the success of Nordic cooperation.

# 2. NORDIC COOPERATION TOWARDS EARTHQUAKE PREDICTION

## 2.1 The background of the present proposal

Earthquakes strike suddenly and the larger ones with disastrous consequences. Could their occurrence be predicted, enormous human suffering and material damage could be avoided. From the dawn of seismology, prediction has presented a challenging goal.

Earthquake prediction in its broadest sense, means the prediction of where and when an earthquake will occur, and its effect at various places. In all these aspects of prediction there has been progress, although the prediction of time is usually most difficult. In seismic risk analysis, a kind of time prediction is expressed as a statistical probability of the likelihood of a damaging earthquake occurring within a certain number of decades, based on a historical accounts. Such risk analysis is extremely valuable and is the basis for building codes etc. However, in the sense of earthquake prediction, this is not satisfactory. The ultimate goal of earthquake prediction is to be able to predict the occurrence time with a few days accuracy. Several early attempts of such exact time predictions based on periodicities of earthquake occurrence failed, causing pessimism regarding the possibility of a more precise prediction of the time of occurrence. The main barrier is a lack of understanding of the physical processes leading to earthquakes. The breaking of this barrier would represent a remarkable breakthrough in the field of earthquake prediction.

At the beginning of the sixties, reseachers around the world found that seismology had developed so much that renewed efforts towards prediction were worthwhile. Groups were formed in Japan, the United States, and U.S.S.R. aiming at solving the problems of earthquake prediction. Several important discoveries followed, each time raising much optimism, but still prediction has remained an elusive goal.

On a broader scale, it was vital that Europe should have an earthquake prediction programme. After a preparatory ad hoc working group submitted a proposal, the Council of Europe in 1980 set up a working group, CAHRT, to prepare such a programme. The group, headed by L. Mendes Victor (Director of the Meteorological Institute, Portugal), enlarged the scope to include the mitigation of earthquake catastrophes.

In the resolution of the committee, special emphasis was placed on concerted research efforts in five so-called test areas, among them the South Iceland Lowland.

The ad hoc group recommended that the test areas be visited by missions formed by members. The mission to Iceland was composed of the chairman, L. Mendes Victor, and Dr. Ola Dahlmann (Sweden), who also wrote a report on this visit.

The Dahlmann - Mendes Victor report describes the problems of Icelandic seismicity, a short review of the research already initiated, and an overview over such activities that could be supported by international participation. The operational part of the report is found in the subparagraph: "Possible cooperative research projects." This paragraph is further divided into:

a) Earthquake source studies
b) Ground investigations
c) Risk analysis

CAHRT finalized its work by the end of December 1983. The Council of Ministers submitted the CAHRT programme to COST for further action. The EEC has also taken notice of the programme and the commission is considering action. However, these initiatives do not include the Icelandic test area.

In the Dahlmann - Mendes Victor report the importance of the SIL test area is stressed. This area is one where very significant geophysical processes are occuring, and furthermore, as a potential site of destructive earthquakes, any steps towards prediction, would be of great importance to Icelandic society.

During a meeting of Nordic seismologists in Tällberg in 1984, concerted efforts in this area were discussed, and a group emerged to specify a project which could provide the background to an application to the Council of Nordic Ministers.

This group met in Oslo in April 1986 and decided to concentrate its efforts on "Earthquake source studies" as the most fundamental problem. The research programme presented here is the result of that meeting.

# 3. THE SOUTH ICELAND SEISMIC ZONE

## 3.1 Earthquake activity

Most of the seismicity of Iceland is related to the mid-Atlantic plate boundary that crosses the country. The centers of spreading are expressed on land by neovolcanic zones that are connected to the submarine spreading centers by complex zones of lateral motion (Fig.1). This motion is taken up along the Tjörnes fracture zone on the north coast of Iceland and in the south by the seismic zone of the lowland of South Iceland.

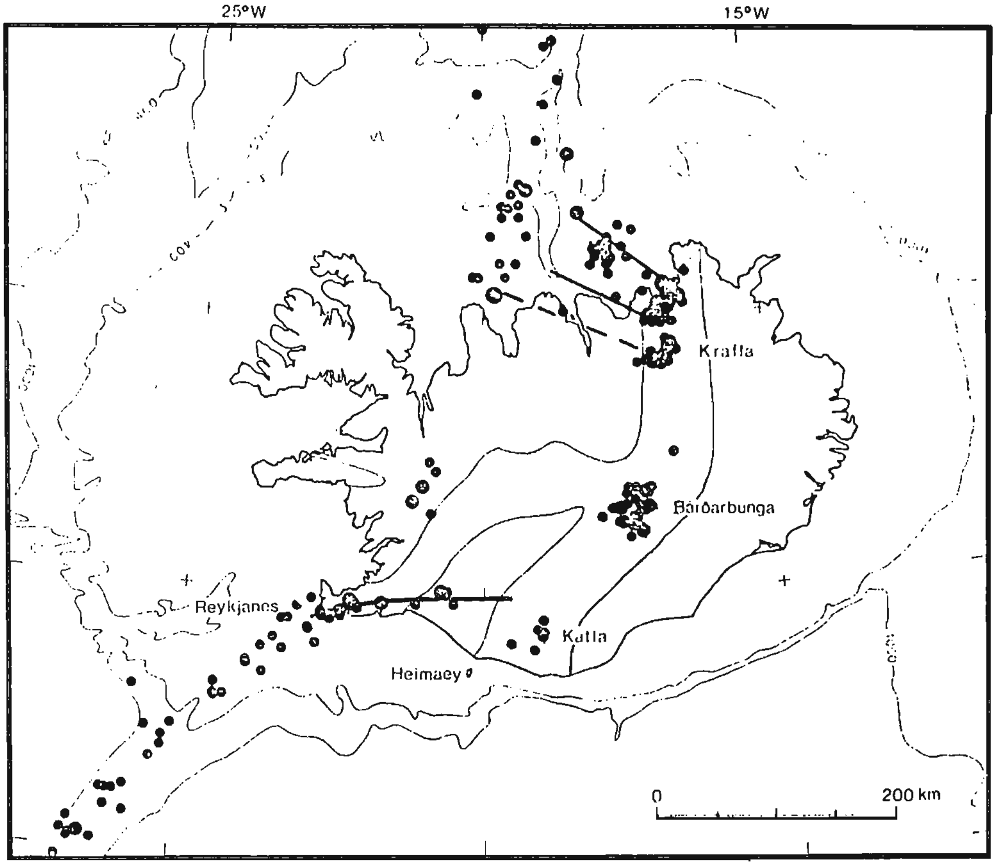

Fig.1 Epicenters in the Iceland area. Data from the PDE lists of the U.S. Geological Survey for the period 1963 - 1981. Only epicenters determined with 10 or more stations are included. Larger dots are events of Mb = 5 and larger. The volcanic zones are stippled, and thick lines lie along the seismic belts in the fracture zones, both in South Iceland and off the North Iceland coast.

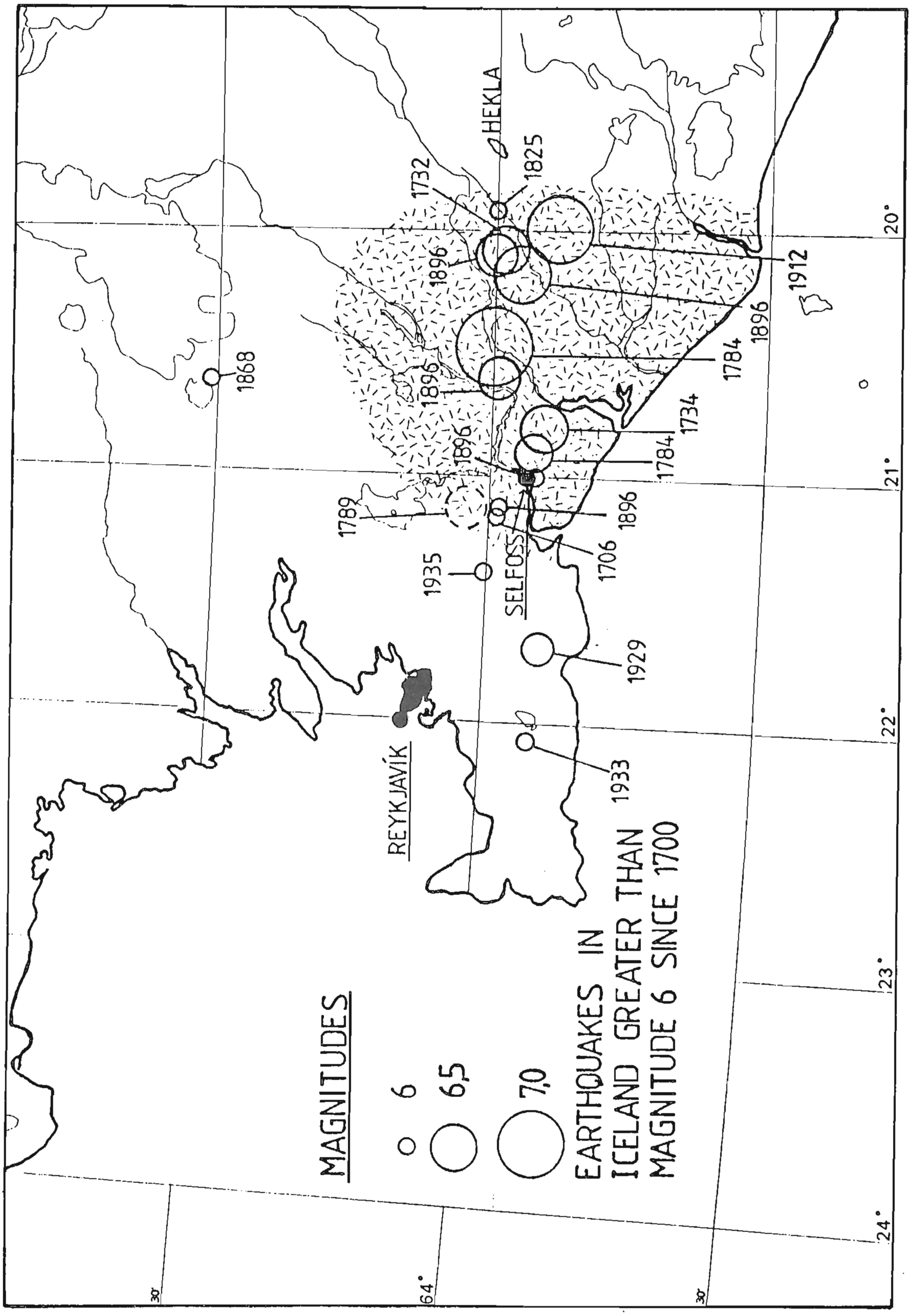

Fig.2 Epicenters of large earthquakes in SW-Iceland since the year 1700. Magnitudes before 1912 are interpreted from written documents about the destruction which they caused. The South Iceland Lowland (SIL) is shaded.

The majority of destructive earthquakes in Iceland since its settlement in the ninth century have occurred within the South Iceland seismic zone, which is about 70 km long and bridges the gap between two branches of the volcanic zone. The seismic zone crosses relatively densely populated farmland and urban areas (Fig.2). Increasing investment in the area is progressively increasing the damage potential of future earthquakes.

Maps of destruction zones of historical earthquakes as well as recent microearthquake monitoring, show that the zone is aligned E-W. Surface fracturing during past earthquakes shows, on the other hand, that each individual earthquake is associated with right-lateral strike-slip faulting on N-S striking fault planes arranged side by side within the zone (Einarsson and Eiríksson, 1982; Einarsson et al., 1981). The same is shown by the N-S elongation of the destruction areas of individual shocks.

Strain built up in the South Iceland seismic zone is released in sequences of large earthquakes with recurrence time of the order of 100 years, and with magnitudes slightly exceeding 7 on the Richter scale. The earthquakes tend to be larger in the central and eastern part of the zone than in the western part. Some examples are known of sequences starting in the east and migrating westward. The last sequence of this type occured in 1896, and the last earthquake of magnitude 7 occurred near the eastern end of the zone in 1912.

In Fig.3 are shown contours of maximum intensities in the South Iceland Lowland since the year 1700, as inferred from historical sources. This map gives an indication of what accelerations are to be

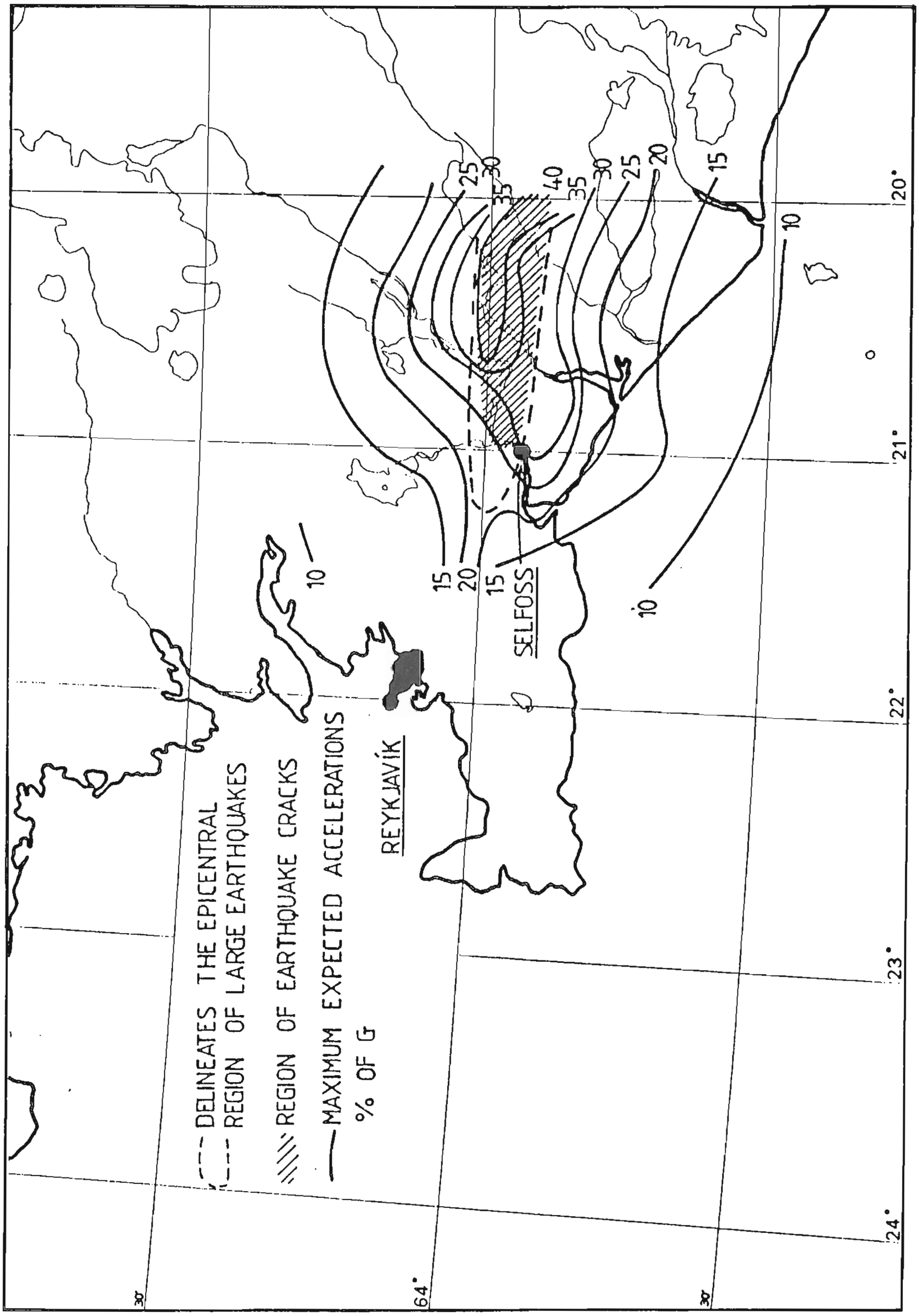

Fig.3 The epicentral region of large and catastrophic earthquakes in the South Iceland Lowland, and the expected maximum ground accelerations in the area.

expected in this region, but without taking into account the special effects of surface breaks and existing cracks in the epicentral area. The area, where cracks from historical earthquakes are known, is shaded in this figure. In this area, considerably larger accelerations can be expected than those indicated by the contour numbers. The dashed line indicates the extent of the epicentral zone of earthquakes larger than 6.

## 3.2 Current investigations

Several research projects are being conducted in the region in an effort to monitor crustal movements, assess seismic hazard and predict future activity. The largest of these are:

a) Seismicity monitoring
b) Continuous monitoring of strain
c) Radon monitoring
d) Geodetic measurements
e) Strong motion recorders
f) Mapping of earthquake fractures

Fig.4 is an overview of observational sites in the South Iceland Lowland.

### 3.2.1 Seismicity monitoring

A country-wide network of about 40 seismological stations is run as a cooperative effort between several institutes and agencies. Most of the stations are equipped with a short-period vertical motion seismometer. The signal is recorded with pen and ink on paper. Four stations are within the immediate epicentral zone in South Iceland, and eight more stations are within 50 km distance. The set of locatable earthquakes is complete above magnitude 2, but smaller

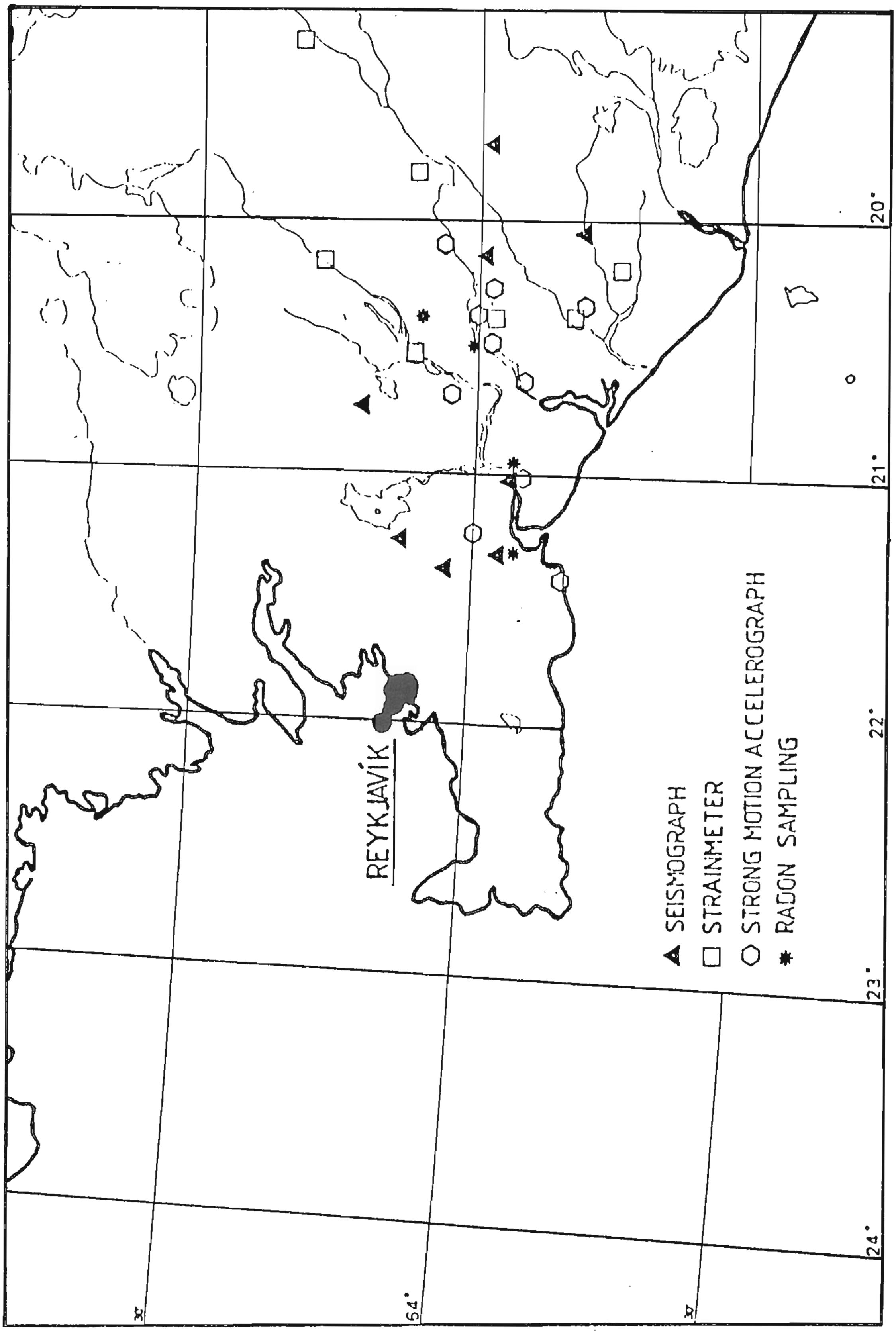

Fig.4 Existing network of monitoring of earthquakes and related geophysical processes in the SIL area.

earthquakes are often detected.

### 3.2.2 Continuous monitoring of strain

Since 1979, Sacks-Evertson volumetric strainmeters have been operated at seven sites within and close to the South Iceland seismic zone. The strainmeters have shown a relatively constant strain build-up interrupted by events of faster strain changes, which sometimes can be traced from station to station. In spite of the low seismicity of the region since the installation, a few examples are already known of distinct strain events, before or after small shocks. The data are now sent to Reykjavík as 12 bit digital words with a sampling rate of 71 samples/sec and recorded on magnetic tape after filtering. The equipment has an option to detect events, in which cases all data are stored, up to 71 samples/sec for each channel. This project is run by the Icelandic Meteorological Office, in cooperation with the Carnegie Institution of Washington.

### 3.2.3 Radon monitoring

The discrete sampling of geothermal fluids for radon determination was initiated at eight sites in South Iceland in 1977. Samples were taken every 1-2 weeks and sent to Reykjavík for analysis. Several anomalies have been observed prior to earthquakes (Hauksson and Goddard, 1981), in particular at one station. A continuously recording radon monitor was installed at that station in 1980. Sampling at other stations has been reduced due to lack of funds. This project is run in cooperation between the Science Institute in Reykjavík and the Lamont-Doherty Geological Observatory in New York.

### 3.2.4 Geodetic measurements

Some baselines were measured with a geodimeter in 1977, 1979, 1981 and 1983 to monitor possible crustal strain build-up. These measurements were greatly increased in number in 1984, when a geodetic network was measured, covering most of the seismic zone, by the National Energy Authority and the Science Institute in Reykjavík. A total of 90 km of leveling lines was measured in 1984 - 1985, and 50 gravity stations were occupied with a LaCoste-Romberg gravimeter. A major project of satellite geodesy was started during the summer of 1986 involving the use of 11 GPS-receivers. About 350 baselines were measured, covering large parts of Iceland. The expected accuracy is 0.1 ppm.

### 3.2.5 Strong motion recorders

Strong motion accelerographs with event triggering have been installed at nine sites in the seismic zone and its immediate neighbourhood. Three instruments record analogue (Kinemetrics SMA-1) and seven instruments record digital data (Geotech A-7000, Sprengnether DR 100). Almost no strong motion records exist of Icelandic shocks to date.

### 3.2.6 Mapping of earthquake fractures

The systematic mapping of surface faults associated with postglacial earthquakes has been in progress since 1977. Large parts of the seismic zone have been mapped, but some areas are still left. The most prominent features of the faults are tension gashes that are arranged in en echelon patterns, suggesting strike-slip motion at depth. Evidence for surface faulting can be found throughout the zone, and also in a few places outside of the main areas of destruction in historical earthquakes.

# 4. SCIENTIFIC OBJECTIVES OF THE PRESENT PROPOSAL

## 4.1 General considerations

This earthquake monitoring project aims to reduce losses due to damaging earthquakes, primarily by achieving a deeper understanding of where and when great earthquakes can occur. It is our judgement that the best results can be achieved by acquiring a knowledge of the physics and dynamics of the crustal deformations taking place in the region. The acquisition of such knowledge and its use for earthquake risk assessment by deterministic modeling of the dynamics of the area, will result in scientific advancement of general interest and of value to other earthquake-prone regions in the world.

The physics of crustal deformation processes will therefore be one of the main targets in this project. The choice of Iceland as one of the European earthquake research sites is partly due to its extreme geological and geophysical conditions. Thus the influences of the very different physical conditions in Iceland on the crustal deformation and earthquake generation will show the importance of the different physical mechanisms, that are presently discussed in relation to earthquakes. This is of direct interest for the attempts to model the earthquake generation at any place on earth.

For the study of the crustal deformations a variety of geological and geophysical data are needed; geodetic measurements [high precision levelling and triangulation], measurements of strain, stress and tilt, and gravimetric and seismic measurements. In addition, it is desirable to know the crustal structure and geological history.

In this report, the installation of a general data acquisition system capable of collecting high quality seismic data is proposed. In our judgement, the study of microseismicity is of central importance to the success of this project and it is proposed that the system will be operated for the continuous monitoring of microseismicity. The design of the system, however, allows for the acquisition of other kinds of geophysical data.

As the proposed high quality network also allows studies of fault mechanisms and stresses relaxed by microearthquakes, there will be several new possibilities for prediction. For instance changes in the stress field, which are expected to precede major events, may be detected.

It should also be pointed out that study of the microseimicity means that the seismic wave propagation in the crust also must and will be studied, and information about the crustal structure will be obtained. This opens up the possibility of making extremely accurate measurements of seismic wave velocity variations, which are expected to be related to crustal stress variations.

## 4.2 Information yielded by the microseismicity

Microseismicity (numerous small earthquakes, too small to be felt) can be monitored by a dense network of seismometers. If the network produces high-quality digital data (using well-calibrated seismometers and amplifiers, good time accuracy and a dynamic range that prohibits overloading), extremely valuable data about the crustal conditions and about the crustal deformations, stresses and movements can be obtained. For example the results of microseismicity studies in southern Sweden and Denmark, based on data from the FOA network, show that even very small earthquakes - less than ML = 1 - may be related to the regional tectonic stress field. This is of central importance and implies that data extracted from microseismicity give direct information about ongoing crustal deformations that may be the same process that produces damaging earthquakes.

The following parameters can accurately be estimated from the earthquake recordings of a dense network:

i) The time and location (including depth) of the seismic sources.

ii) Fault mechanism solution; i.e. the orientation of the possible fault planes and the direction of the slip.

iii) The orientation of the stresses relaxed by the earthquake slip at the source.

iv) The size of the fault sliding as given by the seismic moment (the product of the fault area and the length of the slip).

v) The corner frequency of the ground motion, which can be used to give estimates of the size of the faulting surface and the static stress drop. This gives the size of the slip, when combined with the seismic moment.

vi) The relative location of aftershocks and swarms. This is a more direct way to estimate the size and the orientation of the fault surface and thereby also achieve more reliable estimates of the static stress drops.

If the area covered by the network is seismically active, within a relatively short time large amounts of data may be accumulated. The

FOA network in southern Sweden and Denmark gave some 200 earthquake source mechanisms, now being geologically interpreted, within five years of operation. Such a large amount of data allows a detailed interpretation of crustal deformations, movements, stresses, fault pattern and block structure. This knowledge is of fundamental importance in any attempt to simulate the geodynamics of the area by numerical geomechanical models.

There are several indications that major earthquakes are preceded by changes in the microseismicity. One frequently described phenomenon is increased activity around the epicentral area, starting months or even a few years before a major earthquake.

## 4.3 Other types of measurements, observations and investigations needed for the study of the crustal deformations and movements

Only part of the crustal deformation and fault sliding take place as sudden unstable slip events (earthquakes), and there is consequently need for monitoring also the stable deformations and faulting of the crust. If the geodynamic process is known and understood, then improvements in the earthquake prediction may be reached rather straightforward.

As described above, the data acquisition system proposed is well suited for collecting all kinds of geophysical data up to sampling frequencies of a few hundred Hz. The following types of on-line measurements are of interest in the attempts to study non-seismic crustal movements:

i) Strainmeters (deformation and stress changes)
ii) Tiltmeters (tilt and deformation)
iii) Gravimeters (height)
iv) Temperature (flow of water and/or magma)

Note also the discussion of monitoring the crustal stresses by checking the seismic wave velocities in Section 4.1.

Much information about crustal deformations within the area come of course from geological observations. These data must also be compiled and integrated in a model of the general features of crustal deformation.

Direct geodetic measurements may be of great value in this area of fairly fast deformation. Precision levelling and triangulation covering the area should be done repeatedly.

All the results of the geological/geodetical/geophysical deformation analysis will be used to produce a picture of the general pattern of crustal deformation. The information from the microseismic study will then be used to study details and variations in the deformations related to the unstable part of the fault sliding.

Most of the nonseismic measurements will be undertaken as part of the more regular geological studies of the area but will also make use of the proposed data acquisition system.

## 4.4 The expected scientific and practical outcome

The operation of the network will produce seismic measurements of high quality from a large number of earthquakes.

Analysis of recordings of the microearthquakes will give their fault plane orientations, the faulting areas, directions and size of the slips, the orientation and size of the relaxed stresses, in addition to the locations, focal depths, and seismic moments.

The combined analysis of the microseismic source data given above and of the accumulated knowledge based on other geophysical, geological and geodetical observations is expected to clarify the nature of crustal deformation processes.

The wave propagation data will be used in seismic inversions to calculate crustal structure.

Variations in the microseismicity and wave propagation will be studied in the search for indicators of variations in the crustal stress field.

If large earthqukes occur the microseismicity will be studied in search for variations useable for prediction.

The seismic activity observed and analyzed will be related to the crustal structure, to other geophysical information, to the geology of the area and to laboratory observations of sliding under high pressure and temperature. This is a step in the understanding of the processes causing unstable slip in the crust.

The ground shaking associated with earthquakes will be studied together with attenuation. These aspects are important in the seismic hazards analysis.

New seimic hazard estimates will be produced.

# 5. THE EARTHQUAKE DATA ACQUISITION SYSTEM

## 5.1 The design goals of the system

The basic objective of the system is to provide high quality data from local earthquakes occurring in the South Iceland Lowland. A significant feature of the system is the automatic evaluation of a large amount of earthquake data such as epicenter location, magnitude and other significant source parameters. The system must be secure in saving all significant data in a form easily accessible for later evaluation and research. The system must also have a large dynamic range; i.e. provide quality records for earthquakes of very different sizes.

Although the main objective of this programme is the recording and evaluation of local earthquake data, the system must have the capacity for collecting and evaluating other types of geophysical data, such as strain changes, tilting, changes of radon content in water, electrodynamic anomalies due to stress changes, etc. Such measurements involve, in general, a much lesser data flow than seismic measurements and can therefore easily be included in the observational end of the system.

It is also significant that the system can be extended to cover similar monitoring for the country as a whole. This has both a scientific and an economic advantage.

In order to fulfill the above requirements the system is based on digital recording and transmission.

## 5.2 The observational sites

The observational sites are basically eight, each consisting of a cluster of short period (1 sec) seismometers. In most cases the cluster would consist of 3 components of geophones, in other cases of 3 vertical instruments at close distance. The suggested observational sites are shown in Fig.5. The ninth cluster in the figure; i.e. the one furthest to NE, will be included in the network at an early stage and will be costed by another source. The preferred dynamic range of the observational equipment is 140 dB; see Section 5.6.

## 5.3 Software of data acquisition system

Although many seismic data acquisition systems are in operation, a basic weakness is often that the associated software is not sufficiently sophisticated to enable efficient and flexible field operation. This in turn means that even when high quality data are collected, the ensuing analysis is tedious and laborious and precludes that the objectives of the operation project are fully met. In other words, the data acquisition system in which the software constitutes a crucial part, must be designed in such a way that not only the data collection in the field, but also their subsequent analysis are assured and in thorough and effective manner. With this in mind, the seismic monitoring system for SIL is required to achieve the following:

i) To record and store data in the field.

ii) To check the incoming data for earthquake occurence.

iii) To analyze the detected signals, and store the associated signal parameters and raw data on a disk file.

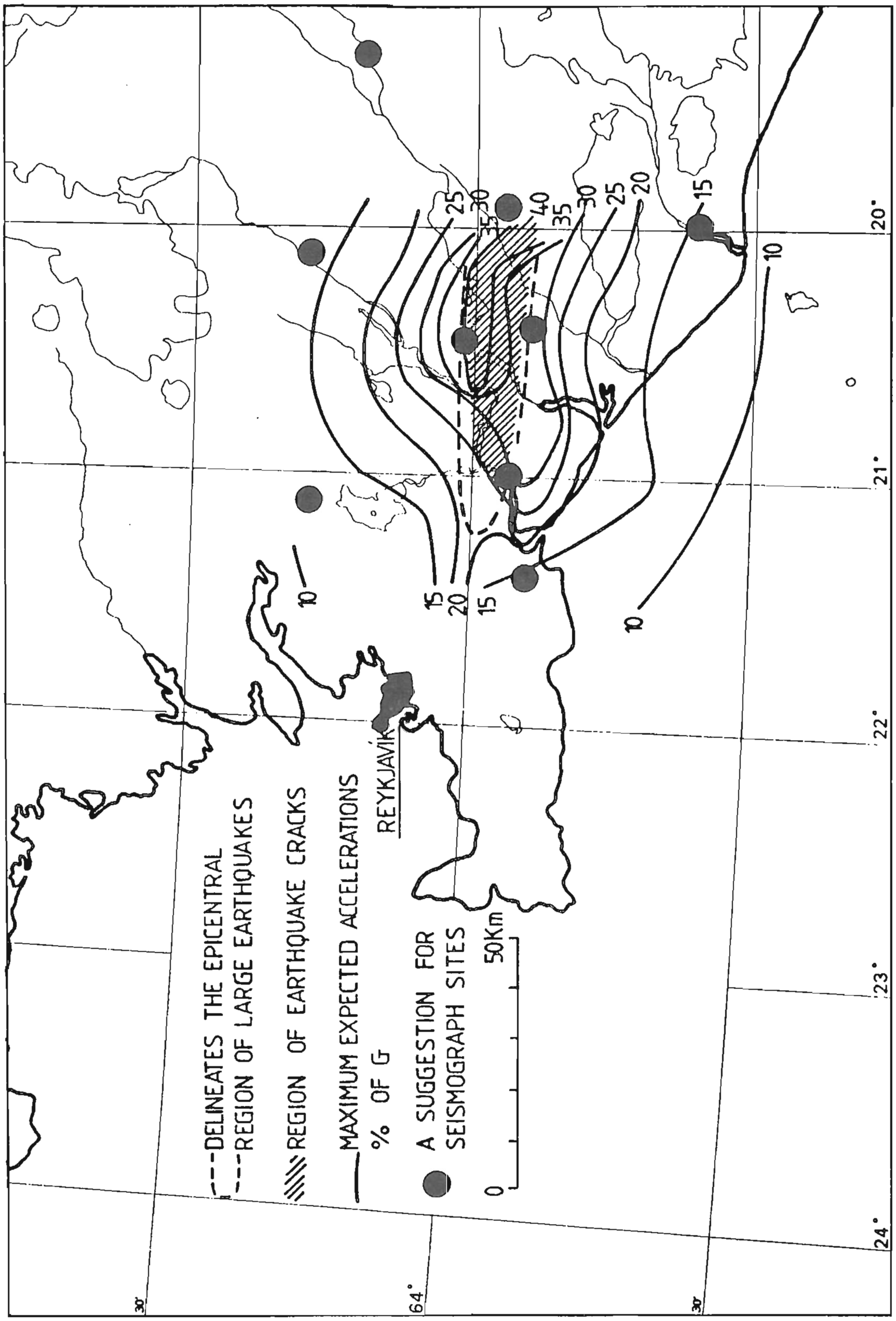

Fig.5 The configuration of the observational sites of the proposed network, shown in relation to the epicentral zone of destructive earthquakes.

iv) To send disk file data automatically and routinely to the data center in Reykjavík, or when requested from Reykjavík.

v) To change the characteristics of the field operation, instrument calibration and "watch dog" functions etc., by remote control.

In this way, a near real-time monitoring of earthquake activity in the SIL area can be achieved. In addition, if more extensive data analysis is required in Reykjavík, this would be feasible as well, because the original data would be archived.

Design of an appropriate field data acquisition system meeting the above requirements is now nearly complete and the necessary details on these developments are given in Section 5.8.

## 5.4 Data center functions and daily operation

The data center in Reykjavík would serve as the hub of the field data acquisition system and its central role would be to ensure that the monitoring of the earthquake activity in SIL is carried out in an efficient manner. The specific operational tasks of the data center reflecting rapid (signal detection and associated raw data) and slow (completed tasks) would be as follows:

i) To merge detection files from individual stations for rapid event locations and source mechanisms solutions.

ii) To extract from information under i), data relevant for earthquake prediction, and add it continuously to a data bank, reflecting the dynamic state of the seismic area. By routine analysis this can be compared to current observations in order to find prediction anomalies.

iii) To generate event files; i.e. merge recordings from individual stations for the detected events.

The data center operation would be automated to such a degree that one analyst should be able to handle around a 100 earthquakes daily. Experience acquired in data center operation should make further extensions and automation feasible in the future. To ensure data center operation along the above lines, a comprehensive software package is required. For the present proposal this should not be a big problem since within the Nordic countries much of the software is already available.

## 5.5 Analysis and synthesis of network data

More fundamental problems related to earthquake prediction are too complicated to handle on a routine basis. A significant part of the network routine would be to provide data for dealing with such problems and thus encourage earthquake prediction research. In this connection, following two approaches would be considered:

i) Generating "snapshots" of the dynamic state of the SIL areas.

ii) To establish an infrastructure to earthquake prediction research and ensure that it is available to scientists, both within the Nordic seismological community and elsewhere.

Point i) above refers to the extraction of earthquke parameters on a routine basis, such as maps and graphic displays of detected deformations within SIL, change in activity rate, hypocenter migrations, possible velocity changes in terms of topographic mapping.

Information in this form should be easily available from the data center staff and would provide clues to earthquake precursory phenomena. In addition to this a comprehensive data base should be available for anyone wanting to pursue such problems in greater depths. We foresee that such a set-up would make it attractive to prominent researchers to conduct part of their research dealing with earthquake prediction on the basis of data from the SIL area.

## 5.6 The amplitude range to be covered

In Fig.6 we try to demonstrate what amplitude range has to be covered by the South Iceland Lowland network. This figure shows the amplitude levels for different magnitudes at 10 and 20 km from the epicenter. The figure also indicates the noise level during the quieter half of the year.

The amplitudes of the signal levels in the figure are inferred from the local magnitude scale. They are in general agreement with a spectral study of large numbers of earthquakes of magnitude 4 - 5 observed at the Carnegie broad band station at Akureyri from the Krafla-Öxarfjördur tectonic event in 1975 - 1976. The corner frequencies indicated in this figure are in agreement with the above and in general agreement with the increase in corner frequency with diminishing magnitudes, observed in other parts of the world. The high frequency cutoff at 10 Hz is a guesstimate. For Iceland this cutoff frequency is probably not higher than 20 Hz, indicating that the frequency coverage of the system does not need to be higher than about 40 Hz. The microseismic noise level is inferred from visual inspection of short-period paper records, and is also in general

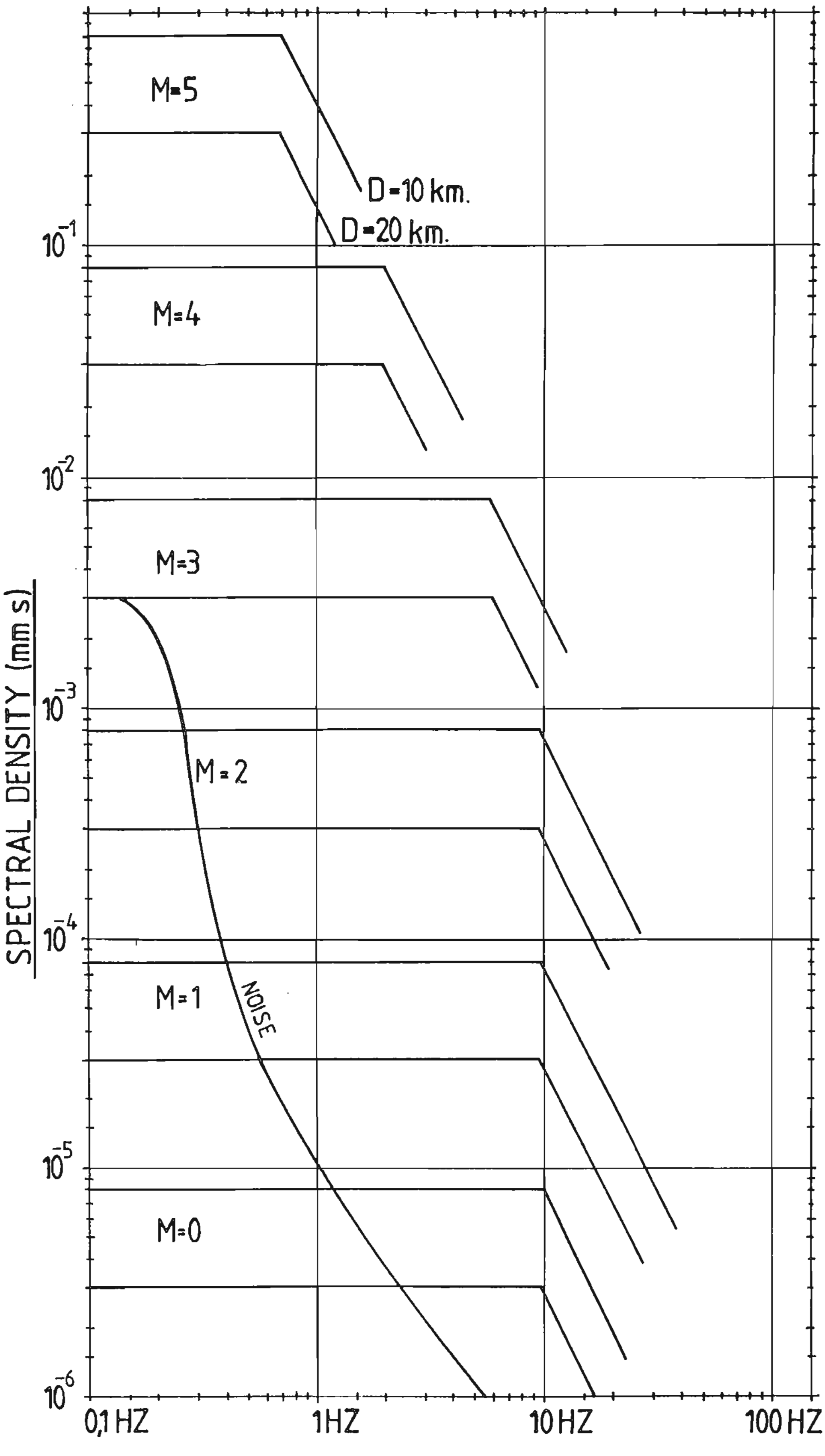

Fig.6 The amplitudes (in terms of spectral density), and the frequency content of earth motion for different earthquake magnitudes, expected at 10 resp. 20 km distance from the epicenter.

agreement with the mentioned spectral study (Stefánsson, 1979). It should be pointed out that the information in the figure is not based on spectral studies of recordings from the SIL region, since no such observations are at present available.

In the seismic network described here, 10 km is certainly the minimum epicentral distance for which registration by three stations is possible. The figure indicates that the detection threshold aimed at is M = 0. The reasons for this are as follows: Automatic detection would be very difficult for signals much below the 1 Hz noise level, since it is also a requirement to record true signals for periods well above 1 sec. Also good signal analysis requires that the noise be one order of magnitude less.

## 5.7 The number of earthquakes to be expected

Here we try to estimate how many earthquakes can be expected to be recorded by the network. This is significant both for designing the capacity of the system and for estimating the cost of operation. It is, however, difficult since we intend to record smaller, and thus many more earthquakes than before.

The following formula is most commonly used to describe the relation between magnitudes and the number of earthquakes: $\log N = a - bM$, where M is Richter`s magnitude and N is the number of earthquakes equal to or larger than M, and a and b are constants, that mainly depend on region.

From a homogenous set of earthquake data down to magnitude 2.5

from the SIL area for the period 1960-1980 (Skaftadóttir, 1981), the value of b in the formula was found to be 0.77. This would mean that we should expect 450 earthquakes of the magnitude ML = 0 originating in this area, assuming that the above time period is an average period. However, it is known that the activity varies. We have estimated that during the last 280 years the number of earthquakes of magnitude 6 or larger in the region is 4 - 8. Applying the above value for b indicates that the number of earthquakes of this size would be 590 - 1.170 each year. A better average value thus should be close to 800 per annum of magnitude zero earthquakes or larger.

Another source of data is the Hengill volcanic area at the western end of the SIL area. Here the 1960-1980 set of data quoted above indicates a b-value 1.07 and 800 earthquakes per annum equal to or larger than M = 0.5, which is a probable recording threshold for this area. A three month recording period using a dense network in 1981 (Foulger, 1984) yielded a b-value of 0.76 and 100 shocks larger than or equal to 0.5 magnitude, which does not contradict with the above conclusion.

For earthquakes from other parts of the country a rough estimate can be made based on a paper by Tryggvason et al., 1958. From the Reykjanes Peninsula 600 earthquakes down to magnitude 1.0 - 1.3 can be expected per year. From close areas to the north and northeast, Langjökull and Borgarfjörður, we expect 50 earthquakes of magnitude 1 and 50 earthquakes of magnitude down to 1.5 - 2.0 from the Vatnajökull area in NE direction. From North Iceland and off the north coast and from the Reykjanes Ridge, 150 earthquakes can be expected down to magnitudes 2.0 - 2.5.

Adding the above numbers for expected earthquakes we obtain an estimate of 2.500 for the whole country. In reality this number would be reduced somewhat because the system would not be triggered by many of these earthquakes, especially those from the greater distances. Bad weather conditions would also preclude recordings at times. We therefore assume that the real number of earthquakes of useable size recorded by the network will be 2.000.

However, it must be borne in mind that aftershocks of large earthquakes and intense swarm activity for short periods of time can surpass the average seismic rate by orders of magnitude with data containing information of enormous value. For this reason it is necessary to design the system in such a way that on such occasions it can store the continuous data of several hours, although it would be impossible to evaluate all of them at once.

## 5.8 Technical realization of the network

### 5.8.1 Basic requirement

The goals of the system and the nature of the data sets to be dealt with, governs the design and implementation of the network. As discussed in Chapter 5.1, the network is not only intended for seismological data but also for various other types of geophysical data. Although this requires more flexibility in the design of the system it is the seismological data that govern the sophistication of the network, both hardware and software. The following table shows some technical specifications of the instrumentation needed to handle the signals from the sensors:

Frequency range: dc to 30 Hz
Voltage range: 1 µV to 10 V
Signal to noise ratio: > 70 dB
Time accuracy: 1 msec

The total dynamic range of this signal (140 dB) is far above what is easy to transmit longer distances in analogue form. This means that digitization must be done at the site, close to the sensor. To achieve the required signal to noise ratio, a 12 bit analogue to digital converter is needed. Gain ranging must then be applied to cover the total dynamic range of 140 dB. This must be done in no more than 6 dB steps to keep the signal to noise ratio above 70 dB.

### 5.8.2 Centralized or decentralized network

Basically two architectural designs are realistic for the SIL network, centralized and decentralized. The first requires that all digitized data from the sensors are transmitted in real time to a central computer where the first data reduction is done. In the second, which is to some extent a decentralized design, the first steps of data reduction are done at the observational site. The centralized design requires relatively simple instrumentation at the observation site but an advanced communication network. The decentralized design on the other hand requires more complex instrumentation at the sites but can use the standard telephone network for communication.

### 5.8.2.1 The centralized configuration

Each sample can be represented by two bytes, 12 bits for mantissa and 4 bits for gain information. The data rate for one channel at 100 samples per second is then 2200 baud (including start, stop and parity bits). This means that a standard 2400 baud link can transmit each channel and a 9600 baud link could carry four channels of signals as specified above. The telephone network in the area cannot be used for data transmission at higher rate than 1200 baud. Radio links for these data rates are commercially available but due to the difficult topography and the maintenance problems associated with running such system under Icelandic climatic conditions, this would probably be a relatively expensive solution in the long term.

### 5.8.2.2 The decentralized configuration

If the standard telephone network is to be used, considerable data reduction must be carried out at the observational site. This can only be done by installing computer facilities at each site. Personal Computers (PC`s) which are increasing in sophistication concurrent with falling prices, would be suitable for this purpose.

Data from four sensors must be reduced to 14% before transmission through a 1200 baud line and this would keep the line busy 100%. On a long term basis the area is estimated to have data of interest 0.07 to 0.15% of the time. A perfectly functioning detector would then produce data at the rate of 13.2 baud (4 x 2200 x 0.15 / 100) and occupy the telephone line 1.1% of the time. Of course such a detector cannot be realized, but reasonable estimates would be 2 to 5%

occupation of the telephone lines. This could be achieved by dividing the detection activities between the site computer and the central computer.

### 5.8.3 The proposed system

The final details of the configuration of the network would be the goal of the scientists employed on the project during first few months. However, we are convinced that the decentralized architecture is the most suitable for the SIL network. The rapid development of microcomputers and the steady decrease in price has given the PC the best cost-to-performance ratio available. Based on this and on the current implementation of new telephone stations in the SIL area, it is possible to propose a decentralized system taking full advantage of the flexibility offered by such a system.

As shown on Fig.7 the proposed network is divided into three basic parts; Cluster, Node Computer [NC] and the Central Computer [CC]. The Cluster which is stationed at the observational site consists of sensors, Analogue Signal Processing [ASP], Time Receiver [TR], Personal Computer [PC] and a Modem. The PC is the brain of the Cluster, which receives the continuous data flow from the ASP and stores it in a ring-buffer on a disc. It stores data from the last 12 hours available for possible request from the NC. An algorithm for event detection is executed in the PC on all incoming data. Possible events are reported to the NC in the form of short messages. These events are then stored on a cartridge tape recorder where up to 5 days of data can be stored. This is to avoid data losses in case of failures in other parts of the system. Whether the gain range

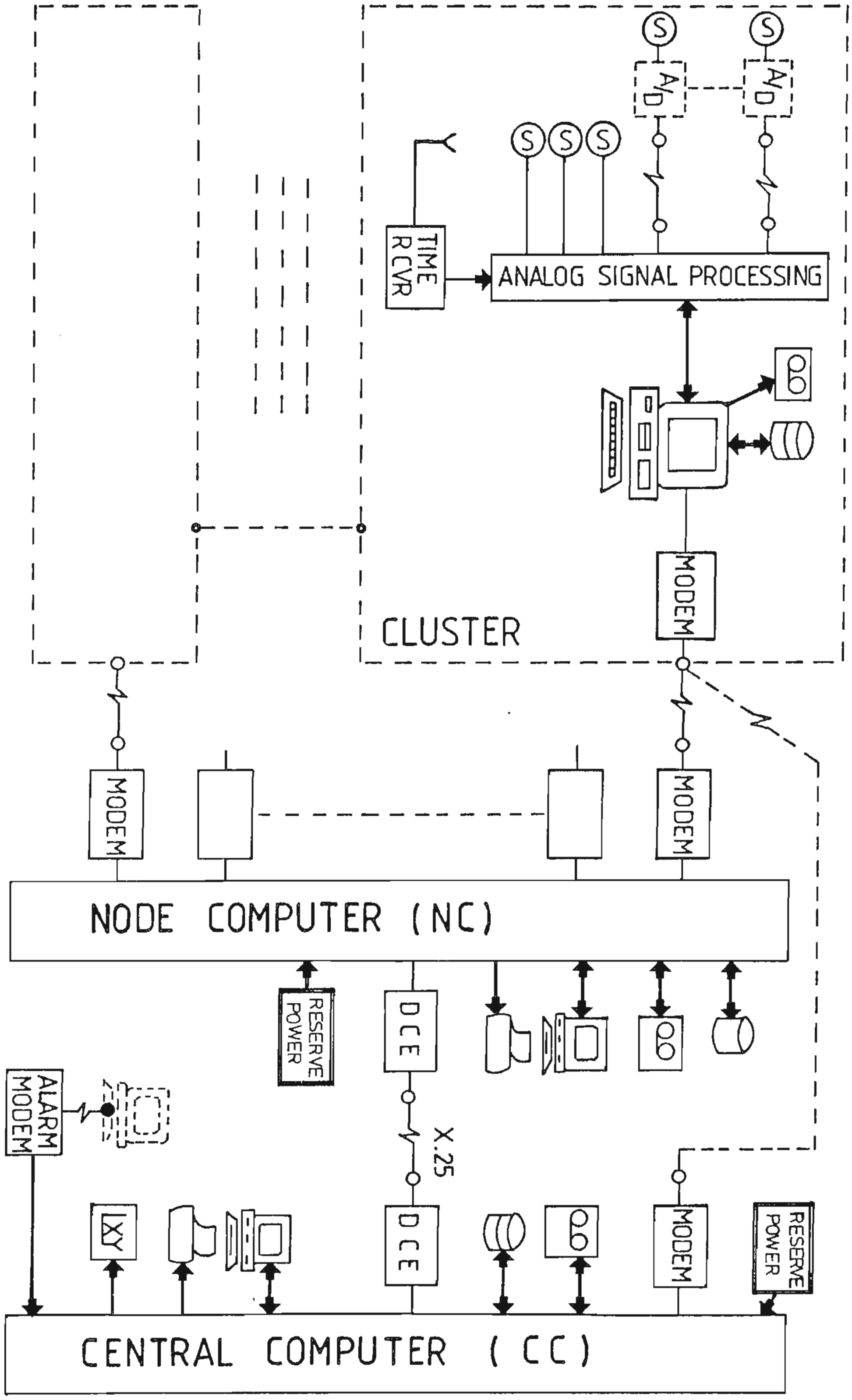

Fig.7 An overview of the data acquisition system from the Cluster at the observational site to the Central Computer in Reykjavík.

procedure and the time detection and synchronization is to be directly controlled by the PC or by a sub-processor in the ASP has not yet been decided.

The required time accuracy of 1 msec can be achieved by using a stable crystal oscillator synchronized with radio signals from Rugby (60 kHz), Omega (10 kHz) or Loran-C (100 kHz). By summing the difference between the second pulses from the radio receiver and the crystal oscillator over a period of time, a control signal is obtained. This can be used to adjust the crystal oscillator and the result is a time-base with the short-term characteristics of the crystal oscillator and the long-term characteristics of the radio signal.

The NC as shown in Fig.5 is connected to the Clusters through modems and to the DC through a data-link (X.25). Its existence in the network is strictly for practical and economical reasons. By moving the tasks involving the communications with the Clusters, and thereby the major data reduction, into the SIL area, a considerable reduction of the cost of communication is achieved as well as an increase in reliability. The NC is a powerful microcomputer capable of serving up to 8 Clusters receiving the short messages and deciding if data is to be extracted from the Cluster for further transmission to the Central Computer in Reykjavík.

The Central Computer in Reykjavík is a general purpose 32 bit minicomputer with all the peripheral units and software packages a seismological research group would need. As data is received from the NC it is stored on disc and various algorithms for further evaluation of the data, possible alarm etc., are executed. More details of the data center functions are given in Section 5.4.

# 6. TIME SCHEDULE FOR THE PROJECT

## 6.1 The steps already taken

The initiative of the European Council, mentioned earlier in this report, led to productive discussions about Nordic cooperation in the South Iceland Lowland earthquake research, during the Nordic Seismological Seminar in Sweden in March 1984. Encouraged by that, the Icelandic National Committee for Earthquake Research presented a proposal to the Icelandic parliamentarians in the Nordic Council at the beginning of 1985. This in turn resulted in the parliamentarian proposal at the Nordic Council meeting in Copenhagen in March 1986.

In order to facilitate and to speed up the realization of this timely idea, eight scientists from the five Nordic countries applied for funds to "Nordiska kulturfonden" and to NOS-N to hold a 3 day meeting in Oslo. The aim of the meeting was to prepare a more detailed proposal for Nordic cooperation on this project. The funds were granted and the meeting took place in April 1986.

The first draft of the programme appearing here was a result of that meeting.

It was further discussed at the seminar of Nordic seismologists (The 17th Nordic Seminar on Detection Seismology), which was held at Laugarvatn, South Iceland, 18-20th of June this year.

## 6.2 The next steps

Table 6.1 shows the main features of the time schedule. This schedule is dependant on necessary funds being made available in due time.

Work on designing the detailed parameters of the system has started and if funds are made available to accelerate this work near the end of this year, it is expected to be finalized in March 1987.

A prototype station (a cluster station or observational station) is scheduled to be ready in March 1988.

During the following five months, all the eight stations will be installed in the South Iceland Lowland, and the earthquake data acquisition system will be finalized in August 1988 and full scale operation will start in January 1989.

It is planned that this project as a whole will be finished by the end of 1991. The period 1989 to 1991 will be the time for the development of methods, a deepening the understanding of the processes leading to earthquakes in the region and facilitating the evaluation of parameters significant for earthquake prediction.

During the first period of the project a highly qualified technical engineer or engineers will be needed, with prior experience with such data acquisition systems. During the later period the need for permanent technical staff will be less, when on the other hand the need for geophysical and seismological expertise will increase. A full

Table 6.1 Time schedule

| | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 |
|---|---|---|---|---|---|---|
| Preparation of programme: Meeting in Oslo in April 1986. Presentation of a draft at the 17th Nordic Seminar on Detection Seismology in Iceland in June 1986. Final document presented for Nordic Council of Ministers, for NOS-N and the Nordic Cultural Foundation in September 1986. | ▨ | | | | | |
| System parameter design finished in March 87 | ▨ | ▨ | | | | |
| Prototype remote station finished in March 88 | | ▨ | ▨ | | | |
| SIL seismic network construction, finalized in August 88 | | | ▨ | | | |
| Partial operation and testing, August 88-December 88 | | | ▨ | | | |
| Full operation of the system from January 89, development of scientific methods. | | | | ▨ | ▨ | ▨ |
| | | | | | | |
| Technical engineer | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| Geophysicist | | | ▨ | ▨ | ▨ | ▨ |
| Nordic research fellow | | | ▨ | ▨ | ▨ | ▨ |

time geophysicist will be needed and a "Nordic research fellowship" is strongly suggested in order to facilitate Nordic participation in this part of the project and for future cooperation. (This would be similar to the Nordic research fellowships granted by the Nordic Volcanological Institute).

The main features of the time schedule are described in Table 6.1.

# 7. PROJECT BUDGET

## 7.1 Division of the cost

The estimated cost of the 6 year project of design and installation of the South Iceland earthquake data acquisition system together with its refinement and the development of scientific procedures is given below. It is subdivided in three main parts: "Design and construction cost", Table 7.1; "annual running cost", Table 7.2; and "partial operation cost", Table 7.3. The total sum of the whole 6 year project is assembled in Table 7.4.

The "annual running cost" becomes effective from the beginning of 1989. It consists to a large degree of salaries for scientists, who are mainly analyzing and interpreting data produced by the network. Their duties will also include assisting other institutions and visiting scientists, besides installing new instrumentation into this very powerful acquisition system.

The "partial operation cost" is the cost of operating the system and of gradual expansion of the seismic network during the construction period.

## 7.2 Estimate of salaries

The standard rules in paying wages at Nordic institutions for common Nordic projects is that they should be in accordance with the rules of the host country. Exceptions can be made, in cases where it is crucial to attract workers from other Nordic countries where the salary scale is higher.

In the following, we explain how the main parts of the salaries have been estimated, referred to June 1st, 1986:

i) A geophysicist, paid in accordance with Icelandic BHM 141, 8th step. The basic salary would be 589.500 I.kr. per year, added to this wage related cost (x 1.12) makes 660.240. In Swedish kr. (1 S.kr. taken as 5.8 I.kr.) this makes 113.834.

ii) A technical engineer after finishing the construction of the seismic network is estimated in the same way as the geophysicist, 1/2 service.

iii) A project leader, paid in accordance with Icelandic BHM 144, 8th step, a one year salary with wage related cost is 124.388 S.kr. His other work is estimated to be 1/4 of full service, making 31.097 S.kr. per year.

iv) A Nordic research fellow: A scientist with about 10 years of experience. It is of vital importance to the project that this person comes from outside Iceland, since this would result in the importing of experience already acquired in other Nordic countries in automatic earthquake data evaluation and also linking the project to the other Nordic countries. The salary of this worker is estimated here in accordance with Swedish wages, 192.000 S.kr. per year, and with the salary related cost according to Icelandic norms this makes 215.040 S.kr. Added to this 25.000 S.kr. in local subsidy and 20.000 S.kr. in transportation to and from Iceland, this makes 260.040 S.kr. per year.

v) An electronic engineer: During the construction period it is of a vital interest for the project to import technical experience in this field to Iceland, and therefore, using the same arguments as for the research fellow we estimate this post as before in accordance with Swedish wages to 260.000 S.kr. per year. Work will be done in cooperation between technical engineers from Iceland and persons from other Nordic countries, but as the division of work has not yet been decided, we estimate all in accordance with Scandinavian norms. We estimate the work under this post to require 2.4 years of work.

## 7.3 Explanations of some miscellaneous items

We consider it necessary to procure some finance to cost the meetings of a Nordic steering committee. Although we consider the authors of this report to be a provisional steering committee, this is not formally finalized in the event of the project being funded. However, we do not consider it necessary for the whole committee to meet each year. The sum estimated here is sufficient for 3-4 persons to meet once a year.

As seen in Tables 7.2 and 7.3, two data network connections are planned, from the Central Computer in Reykjavík, which is expected to be in the Icelandic Meteorological Office. One of the connections is for the Node Computer in Hvolsvöllur in South Iceland, the other leads to the Science Institute of the University of Iceland. This is considered necessary, both for achieving data from there to the network and for supplying data to the Science Institute.

Regarding the estimate of the telephone service cost; from the observational sites (the Clusters), this is called modem traffic cost, and from the Node Computer station, it is called data net traffic cost. The calculation of traffic cost is based on an average estimate of 2.000 useful recordings of earthquakes per year, including a certain number of false detections and recordings of events which are not useful. It is very difficult to estimate the number of these false detections. With the techniques used in this system, these can certainly be kept at a very low level, but being a new development, we cannot say how low. However, the system is so designed, that in case of too many "false alarms" or too many earthquakes, we can economize on the telephone cost without losing data. Such data would just arrive later by post. The telephone traffic cost estimated here is therefore realistic, the exceptions of course being years of enormous and exceptional earthquake activity.

In Table 7.1 the item: Upgrading of the Central Computer, refers to a part of the Central Computer facilities that will be bought later or after start of the network operation. This is a necessary increase in the capacity of the Central Computer after reaching the evaluation state of the programme. As progress in computer technology is very fast, it will certainly be practical to delay this upgrading until latest possible date.

## Table 7.1 Design and construction cost

| | | | | |
|---|---|---|---|---|
| Technical labour: | S.kr. | S.kr. | | |
| Technical engineers | 2.4 x 260.000 | 624.000 | | |
| External consulting | | 65.600 | | |
| Assistant manpower | | 12.000 | | |
| | | | 701.600 | S.kr. |
| One Cluster station, hardware: | S.kr. | S.kr. | | |
| PC w/hard disk | | 51.700 | | |
| Tape station | | 10.300 | | |
| Analogue unit (ASP) | | 53.400 | | |
| Cables and connectors | | 5.200 | | |
| Geophones | 3 x 11.500 | 34.500 | | |
| Power backup | | 6.000 | | |
| Furniture | | 4.300 | | |
| Transportation and travel | | 2.800 | | |
| Telephone line set-up | | 900 | | |
| Modem | | 3.100 | | |
| Subtotal: | | 172.200 | | |
| Eight Cluster stations: | 8 x 172.200 | | 1.377.600 | S.kr. |
| Central and Node Computers: | | S.kr. | | |
| Central Computer incl. peripheral equipment | | 1.000.000 | | |
| Upgrading of the Central Computer | | 300.000 | | |
| Installation (carpentry, furniture etc.) | | 3.400 | | |
| Data net connection set-up charges (x2) | | 5.700 | | |
| Modem line set-up charge | | 900 | | |
| Node Computer incl. peripheral equipment | | 400.000 | | |
| Installation (carpentry, furniture etc.) | | 3.400 | | |
| Data net connection set-up charges (x1) | | 2.900 | | |
| Modem line set-up charges (x8) | | 6.000 | | |
| | | | 1.722.300 | S.kr. |
| Tools and material: | | S.kr. | | |
| Electronic tools | | 51.000 | | |
| Software tools | | 43.000 | | |
| Experimental materials | | 16.000 | | |
| | | | 110.000 | S.kr. |
| Total design and construction cost: | | | 3.911.500 | S.kr. |

## Table 7.2 Annual running cost estimate after the construction period

| System: | S.kr. | S.kr. | | |
|---|---|---|---|---|
| Project leader | 0.25 x 124.400 | 31.100 | | |
| Administration overhead | | 51.000 | | |
| Geophysicist | 1 x 113.800 | 113.800 | | |
| Technical engineer | 0.5 x 113.800 | 56.900 | | |
| Technical requisites (tools etc.) | | 20.700 | | |
| Travels (annual meeting etc.) | | 40.000 | | |
| | | | 313.500 | S.kr. |
| Central Computer: | S.kr. | S.kr. | | |
| Maintenance contract | | 50.000 | | |
| Data storage material (tapes etc.) | | 3.400 | | |
| Printout cost | | 1.700 | | |
| Data net connections | 2 x 4.500 | 9.000 | | |
| Data net traffic cost | | 900 | | |
| Modem line connection | | 500 | | |
| | | | 65.500 | S.kr. |
| Node Computer: | S.kr. | S.kr. | | |
| Maintenance contract | | 15.000 | | |
| Data storage material (tapes etc.) | | 900 | | |
| Data net connections | | 4.500 | | |
| Data net traffic cost | | 9.000 | | |
| Modem line connections | 8 x 450 | 3.600 | | |
| Modem traffic cost (outgoing) | | 1.700 | | |
| Accommodation (incl. power) | | 4.100 | | |
| | | | 38.800 | S.kr. |
| One Cluster: | S.kr. | S.kr. | | |
| Caretaker and accommodation | | 6.000 | | |
| Data storage material (tapes etc.) | | 200 | | |
| Modem line connection | | 500 | | |
| Modem traffic cost (outgoing) | | 3.800 | | |
| Hardware maintenance (excl. labour) | | 2.600 | | |
| Subtotal: | | 13.100 | | |
| Eight Cluster stations: | 8 x 13.100 | | 104.800 | S.kr. |
| Nordic research fellow: | | | 260.000 | S.kr. |
| Total annual cost: | | | 782.600 | S.kr. |

Table 7.3 Partial operation cost

| System: | S.kr. | S.kr. | |
|---|---|---|---|
| Project leader | 2 x 31.100 | 62.200 | |
| Administration overhead | 2 x 51.000 | 102.000 | |
| Geophysicist | 1 x 113.800 | 113.800 | |
| Travels (annual meeting etc.) | 2 x 40.000 | 80.000 | |
| | | | 358.000 S.kr. |

| Central Computer: | S.kr. | S.kr. | |
|---|---|---|---|
| Maintenance contract | 0.5 x 50.000 | 25.000 | |
| Data storage material (tapes etc.) | | 2.600 | |
| Printout cost | | 1.400 | |
| Data net connections | 2 x 0.5 x 4.500 | 4.500 | |
| Data net traffic cost | | 1.700 | |
| Modem line connection | | 500 | |
| Modem traffic cost (outgoing) | | 2.600 | |
| | | | 38.300 S.kr. |

| Node Computer: | S.kr. | S.kr. | |
|---|---|---|---|
| Maintenance contract | | 15.000 | |
| Data storage material (tapes etc.) | | 1.400 | |
| Data net connections | | 4.600 | |
| Data net traffic cost | | 9.000 | |
| Modem line connections | 8 x 450 | 3.600 | |
| Accommodation (incl. power) | | 4.100 | |
| | | | 37.700 S.kr. |

| One Cluster: | S.kr. | S.kr. | |
|---|---|---|---|
| Caretaker and accommodation | | 6.000 | |
| Data storage material (tapes etc.) | | 200 | |
| Modem line connection | | 500 | |
| Modem traffic cost (outgoing) | | 3.800 | |
| Hardware maintenance (excl. labour) | | 2.600 | |
| Subtotal: | | 13.100 | |
| Eight Cluster stations: | 8 x 2/3 x 13.100 | | 69.800 S.kr. |
| Nordic research fellow: | 1/2 x 260.000 | | 130.000 S.kr. |
| Total partial operation cost: | | | 633.800 S.kr. |

## Table 7.4 Total project cost

| | | | |
|---|---|---|---|
| Design and construction | | 3.911.500 | S.kr. |
| Partial operation (until 89.01.01.) | | 633.800 | S.kr. |
| System operation (89.01.01. - 91.12.31.) | 3 x 782.600 | 2.347.800 | S.kr. |

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| | | |
|---|---|---|
| TOTAL PROJECT COST: | 6.893.100 | S.kr. |

# REFERENCES

Christoffersson, A., E. Husebye and S.F. Ingate. Phase identification on the basis of particle motion structure in 3-comp. seismograms, to appear in Geophys. Journ. Royal Astronom. Soc., 1986.

Dahlmann, O. and L. Mendes Victor (1983). Report of visit to the test zone of the Lowland of South Iceland, European Council, special report, CAHRT (83)4, pp. 1 - 14.

Einarsson, P. (1979). Seismicity and earthquake focal mechanisms along the mid-Atlantic boundary between Iceland and the Azores, Tectonophysics, 55, pp. 127 - 153.

Einarsson, P. Seismicity along the eastern margin of the North American plate, in Vogt, P.R. and Tucholke, B.E., eds. The western North Atlantic region: Boulder, Colorado, Geological Society of America, the geology of North America, in print, 1986.

Einarsson, P. and J. Eiríksson (1982). Earthquake fractures in the districts Land and Rangárvellir in the South Iceland seismic zone, Jökull, 32, pp. 113 - 120.

Einarsson, P., G. Foulger, R. Stefánsson, S. Björnsson and Þ. Skaftadóttir (1981). Seismicity pattern in the South Iceland seismic zone, earthquake prediction - an international review, Maurice Ewing series, 4, American Geophysical Union, pp. 141 - 151.

Flóvenz, Ó.G. (1980). Seismic structure of the Icelandic crust above layer three and the relation between body wave velocity and the alteration of the basaltic crust, Geophys. J., 47, pp. 211 - 220.

Foulger, G.R. (1984). The Hengill geothermal area: Seismological studies 1978 - 1984, a special report, Science Institute - University of Iceland, pp. 1 - 196.

Halldórsson, P. Seismicity and seismic risk in Iceland, in preparation, 1986.

Hauksson, E. (1981). Radon content of groundwater as an earthquake precursor: evaluation of worldwide data and physical basis, J. Geophys. Res., 86, pp. 9397 - 9410.

Hauksson, E. and J.G. Goddard (1981). Radon earthquake precursor studies in Iceland, J. Geophys. Res., pp. 7037 - 7054.

Husebye, E., E. Thoresen and S.F. Ingate (1984). Seismic arrays for everyone, Terra Cognita, 4, pp. 413 - 422.

Ingate, S.F., E. Husebye and A. Christoffersson (1985). Regional arrays and optimum data processing schemes, Bull. Seism. Soc. Am., Vol. 75, No. 4, pp. 1155 - 1177.

Pálmason, G. (1971). Crustal structure of Iceland from explosion seismology, Soc. Sci. Isl., XL, pp. 1 - 187.

Pálmason, G. (1973). Kinematics and heat flow in a volcanic rift zone, with application to Iceland, Geophys. Journ. Royal Astronom. Soc., 33, pp. 451 - 481.

Petersen G., G. Gunnarsson, H. Bjarnason, Ó.P. Halldórsson, S. Thoroddsen and S. Björnsson (1978). Landskjálfti á Suðurlandi, a report of a working group on South Iceland earthquakes and defense measures against them, Almannavarnir (The Civil Defense), Reykjavík, pp. 1 - 54. In Icelandic.

Ruud, B.O., E. Husebye, S.F. Ingate and A. Christoffersson. Event location at any distance using seismic data from a single 3-comp. station, to appear in Bull. Seism. Soc. Am., 1986.

Skaftadóttir, Þ. Earthquake catalogue for the South Iceland Lowland, Hengill, Hekla, and the Reykjanes Peninsula, unpublished.

Slunga, R.S. (1981). Fault mechanisms of Fennoscandian earthquakes and regional crustal stresses, Geol. Fören. i Stockholm Förhandlingar, 103, pp. 27 - 31.

Stefánsson, R. (1979). Catastrophic Earthquakes in Iceland, Tectonophysics, 53, pp. 273 - 278.

Stefánsson, R., I.S. Sacks and A.T. Linde (1979). Stress field changes during a tectonic episode in northern Iceland, Carnegie Institute, Yearbook, 78, pp. 320 - 325.

Stefánsson, R., I.S. Sacks and A.T. Linde (1981). The Hekla eruption of 1980 - the mechanism of a ridge volcano, Carnegie Institute, Yearbook, 80, pp. 511 - 514.

Stefánsson, R., A.T. Linde and I.S. Sacks (1983). Strain signals in Iceland, Carnegie Institute, Yearbook, 82, pp. 512 - 514.

Stefánsson, R. and P. Halldórsson. Strain build-up and strain release in the South Iceland seismic zone, in preparation, 1986.

Sæmundsson, K. (1979). Outline of the geology of Iceland, Jökull, 29, pp. 7 - 28.

Sæmundsson, K. Geological structure of the South Iceland Lowland, in preparation, 1986.

Tryggvason, E. (1973). Seismicity, earthquake swarms and plate boundaries in the Iceland region, Bull. Seism. Soc. Am., Vol. 63, No. 4, pp. 1327 - 1348.

Tryggvason, E., S. Thoroddsen and S. Þórarinsson (1958). Greinargerð jarðskjálftanefndar um jarðskjálftahættu á Íslandi, with a summary in English: Report on earthquake risk in Iceland, Tímarit Verkfræðingafélags Íslands, 43(6), pp. 81 - 97.

Tryggvason, K., E. Huseby and R. Stefánsson (1983). Seismic image of the hypothesized Icelandic hot spot, Tectonophysics, 100, pp. 97 - 118.