Proceedings of the 1st workshop on the development of a multiborehole observatory at the Gulf of Corinth

Athens - October 26-28; 1997

sponsored by the

International Continental Drilling Program (ICDP)

organized by

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CONTENTS

Introduction

F.H. Cornet, Institut de Physique du Globe de Paris, France

The Gulf of Corinth is presently the fastest opening continental rift in the world with an opening rate somewhere between 10 and 15 mm/year and the tilting and uplift of its southern shore at a rate of about 1 mm/year. This fast opening is associated with a shallowly northerly dipping seismic zone located at depths ranging from 6 to 9 km. Five events of magnitude larger than 6 have been observed in this region within the last 30 years. But all the observed deformation cannot be accounted for only by the observed seismic activity. Yet the importance and mechanics of non-seismic deformation remains to be documented. It seems very likely that fluids play a most significant part in this deformation process. Accordingly, the Gulf of Corinth seems the ideal place for investigating in situ the mechanics of faulting in extension zones with particular emphasis on the relationship between earthquakes and fluids.

This proposition has been extensively discussed during the 3 days workshop which was held in Athens, October 26-28, 1997, under the sponsorship of the International Continental Drilling Program (ICDP). The purpose of the workshop was to discuss the potential interest of developing a multiborehole observatory in the Gulf of Corinth for understanding both the rifting process and the mechanics of faulting in an extension context. The workshop was organized in four main themes :

1. Mechanics, physics and chemistry of faulting and rifting,
2. Geodynamics and seismotectonic context of the Gulf of Corinth,
3. Integrated Experiments on In situ studies of faulting,
4. Development of a multiborehole observatory in the Gulf of Corinth.

50 participants from 8 different countries have been invited in order to have presentations from some of the most qualified experts in the relevant themes of the workshop. In these proceedings, first the agenda of the meeting is presented. Then abstracts of the presentations as submitted by their authors are stacked in their order of presentation during the meeting. No editing has been made except, when possible, for homogenizing the title of the presentation. Not all authors have sent abstracts of their presentation. Yet, the document issued from this compilation provides a sound basis for documenting the proposal for developing a multiborehole observatory in the Gulf of Corinth. The discussion which was held during the last day has helped focus the proposal. Then, exchanges between some of the participants has helped further refine the project. The presently prepared pre-proposal is presented in a separate document, for it will be subject to further changes as discussions proceed. It is based, today, on the idea of concentrating efforts within a 30 km x 30 km zone extending on both shores of the gulf in the area of Aigion and Eratini. It is hoped that the present proceedings will remain a good summary of todays understanding of the faulting and rifting presently occuring in the Gulf of Corinth. It is considered to constitute the base for further discussions of the pre-proposal.

Development of a Multiborehole Observatory at the Gulf of Corinth

Athens - October 26-28, 1997

Workshop sponsored by the
International Continental Drilling Program (ICDP)

AGENDA

Sunday, October 26, 1997

Introduction (Chairs: I. Vardoulakis and F.H. Cornet)

09h00-09h20	Opening session
09h20-09h45	Emmermann R. (GFZ Potsdam); The International Continental Drilling Program (ICDP)

Mechanics, Physics and Chemistry of Faulting and Rifting

Fluids and Faulting (Chairs: R. Sibson and R. Larson)

09h45-10h05	Sibson R.H. (Univ. of Otago, New Zealand); Fluid redistribution around normal fault systems; field evidence and models
10h05-10h25	Roeloffs E. (USGS-Cascades Volcano Obs.); Earthquake-related fluid pressure transients: Observations in shallow boreholes and speculation about seismogenic depths
10h25-10h45	Gueguen Y. (ENS Paris); Flow in fractured media
10h45-11h05	*Coffee break*
11h05-11h25	Boulegue J. (Univ. Paris VI); Permeability variations induced by fluid circulation in faults
11h25-11h45	Erzinger J. (GFZ Potsdam); Aspects of fluid sampling and gas logging in boreholes
11h45-12h05	Milanovski S. (Inst. Phys. Earth, Moscow), Fluids and thermal regime in the crust - Kola hole data
12h05-12h25	Garagash I. (Inst. Phys. Earth, Moscow), Listric fault - a porous saturated formation of the earth's crust
12h25-12h45	Taylor B. (Univ. of Hawaii) Papua-New Guinea: active low angle normal faulting and plans for drilling in 1998
12h45-14h15	*Lunch*

3D regional stress field determination and the brittle-ductile transition (Chair: G. Borm)

14h15-14h35	Zoback M. (Stanford Univ.); In situ stress measurements in active normal faulting environments in the western United States
14h35-14h55	Cornet F.H. (IPG Paris); An integrated method for mapping the regional stress field and the pore pressure
14h55-15h15	Exadaktylos G. (Univ. of Crete); Rock mechanics and fracture mechanics in seismology
15h15-15h35	Papamichos E. (IKU Petroleum Res. Trondheim); Continuous material characterization from acoustic logs
15h35-15h55	Alexeev A. (Comp.Centre Novosibirsk) Vibroseismic surveys for deep

	structures identification
15h55-16h15	*Coffee break*

Quasistatic and dynamic modelling of faulting and rifting (Chair: G. King)

16h15-16h35	Vardoulakis I. (NTU Athens); Modelling of geological structures formation using small scaled model experiments
16h35-16h55	Chery J. (Univ. Montpellier); The Gulf of Corinth: which style of rifting?
16h55-17h15	Madariaga R. (ENS Paris); Earthquake ruptures: what can we learn from a borehole ?

Monday, October 27, 1997

Geodynamic and seismotectonic context of the Gulf of Corinth

Tectonics and deformation measurements (Chairs: D. Papanikolaou and R. Armijo)

09h00-09h20	Armijo R. (IPG Paris); Is the Corinth Rift the tip of the North Anatolian Fault?
09h20-09h40	King G. (IPG Paris); The tectonics of the Gulf of Corinth and its relation to the evolution of the Aegean
9h40-10h00	Morewood N. (Univ. College London) The structure and kinematics of a normal fault boundary, Gulf of Corinth: implication for rift evolution
10h00-10h20	Ferentinos G. (Univ. of Patras); Offshore faults in the Gulf of Corinth
10h20-10h40	Rondoyanni Th. and P. Tsombos (IGME Athens); Neotectonics and seismic activity in the Gulf of Corinth
10h40-11h00	*Coffee break*
11h00-11h15	Papanikolaou D. (Nat. Cent. Marine Res., Athens), Comments on the neotectonic map of the Korinthos area
11h15-11h30	Papanikolaou D, V. Lykoussis and D. Sakaleriou (Nat. Cent. Marine Res., Athens); Comments on the submarine neotectonic map of the Korinthiacos Gulf
11h30-11h50	Billiris H. and G. Veis (NTU Athens); Geodetically derived crust deformations
11h50-12h10	Briole P. (IPG Paris); Present deformation of the Gulf of Corinth measured by GPS and SAR
12h10-12h30	Bernard P. (IPG Paris); Seismic and electric anisotropy versus deformation in the Corinth Rift
12h30-14h00	*Lunch*

Geophysical observations (Chairs: T. McEvilly and R. Madariaga)

14h00-14h20	Stavrakakis G. (Nat. Obs. Athens); A new telemetry seismographic network in Greece
14h20-14h40	K. Makropoulos (Univ. of Athens); The Gulf of Corinth: 15 years of seismological and geophysical studies
14h40-15h10	Lyon-Caen H. (IPG Paris) and A. Rigo (OMP-CRGS-CNRS Toulouse); Seismological studies in the Gulf of Corinth: constraints on the deformation mechanisms
15h10-15h30	Melis M.S. (Univ. of Patras); Studies of microearthquake rupture properties in the Patras-Corinth graben system
15h30-15h50	Hatzfeld D. (IRIGM Grenoble); Microearthquake seismicity west and east of the Gulf of Corinth

15h50-16h15	*Coffee break*
16h15-16h35	Sachpazi M. (Nat. Obs. Athens) and A. Hirn (IPG Paris); Reflection-refraction investigations of the crust of the Gulf of Corinth
16h35-16h55	Pham V.N. (IPG Paris); Electrical conductivity and structure of the crust around the Gulf of Corinth from magnetotelluric results
16h55-17h15	Jaupart C. (IPG Paris) and E. Koutsikos (Univ.of Athens); Heat flux measurements

Panel discussion

R. Sibson (Chair), D. Papanikolaou, G. King, P. Briole, R. Madariaga, H. Lyon-Caen

17h30-18h00

- On the existence of a shallow dipping decollement zone
- Regional stress field, brittle-ductile transition and the mechanics of listric faulting
- Fluids, faulting and seismicity
- Seismic/aseismic deformations
- Rifting and heat flux
- What can be learned from microseismic studies on the mechanics of larrge earthquakes

Tuesday, October 28, 1997

Proposal for a multiborehole observatory at the Gulf of Corinth

Integrated Experiments for in-situ studies of faulting (Chair: M.D. Zoback)

09h00- 09h30	Mc Evilly T. (UC Berkeley) and E. Karageorgi (Inst. Solid Earth Phys.- Athens); The Parkfield Experiment
09h30- 09h50	Stefansson R. (Icelandic Meteo. Off., Reykjavik); Continuous measurements of strain and hydrological effects in Iceland
09h50-10h10	Gariel J.C. (IPSN Paris); Earthquakes and water pressure changes. The Garner Valley (California) experiment
10h10-10h30	Bernard P. (IPG Paris), The GAIA Project
10h30-10h50	*coffee break*

Discussion on the development of a multiborehole observatory at the Gulf of Corinth (Chairs : F.H. Cornet and I.Vardoulakis)

10h50-11h10	Borm G. and Wohlgemuth (GFZ Potsdam); Technical aspects of scientific drilling at the Gulf of Corinth

Panel discussion

F.H. Cornet (Chair), M.D. Zoback, P. Bernard, E. Roeloffs, T. McEvilly, I. Vardoulakis

11h15-11h45	goals of a multiborehole observatory, identification of potential sites of interest
11h45-12h15	Identification of a financing strategy
12h15-13h 45;	*Lunch at Amarilia hotel*
13h45 - 14h30	Set-up of a project structure, identification of potential partners
14h30-14h45	**Closing session**

Involvement of Fluids in Normal Faulting: Field Evidence and Models

Richard H. Sibson**, **University of Otago, Dunedin, New Zealand

Geological information on the deep structure of large-displacement normal faults and the physical processes operating therein is derived from two principal sources, the exhumed footwalls of steep active normal faults (e.g. Bruhn *et al.*, 1994), and the structural assemblages characterising the very low-angle 'detachment' faults often associated with metamorphic core complexes (e.g. Lister & Davis, 1989). Both provide evidence for fluid involvement in the faulting process over a broad depth range, with implications for fault shear resistance and the mechanics of normal fault reactivation. A general downwards progression in fault rock assemblages (high-level *breccias* and *gouges* (often clay-rich) Æ *cataclasites* Æ *phyllonitic mylonites* at the onset of greenschist facies conditions near the base of the seismogenic zone) is generally inferred for normal fault zones developed within quartzo-feldspathic continental crust. Fluid inclusion studies in footwall assemblages from the Wasatch Front, Utah, and from Dixie Valley, Nevada, suggest a transition from hydrostatic to suprahydrostatic fluid pressures over the depth range 3-5 km, with some evidence for near-lithostatic fluid pressures and repeated lithostatic-hydrostatic pressure cycling, towards the inferred base of the seismogenic zone (Parry & Bruhn, 1990). Fluid interaction with normal fault zones involves a mixture of static and dynamic effects.

<u>Static Effects</u> **-** The first factor to be considered here is the *relative permeability* of the fault zone with respect to the country rock. In high-porosity country rock, faults often develop as low-permeability deformation bands to form hydrological barriers. In contrast, within low-porosity country rock, faults may be relatively high-permeability structures though their permeability may be time-dependent as a consequence of hydrothermal self-sealing, etc. *Juxtaposition effects* (e.g. a permeable sandstone unit faulted against an impermeable shale) may also determine whether a fault is transmissive to flow or acts as an impermeable barrier. In the near-surface. *Arrays of subvertical hydraulic extension fractures* may develop in association with normal faults under hydrostatic fluid pressures to depths determined by rock tensile strength. Competence layering in such settings promotes the formation of *fault-fracture meshes* through mixed-mode brittle failure (Sibson, 1996). Similar mesh-like structures may form at greater depths in overpressured portions of normal fault zones, especially in dilational jogs. Strong *directional permeability* may then develop in the subhorizontal s_2 direction parallel to intersections between minor faults, extension fractures, and stylolites.

<u>Dynamic Effects</u> **-** At least three mechanisms may contribute to fluid redistribution around normal faults coupled to the seismic cycle of shear stress accumulation and release (Sibson, 1994). In extensional settings, mean stress decreases as the shear stress rises on a normal fault, and increases when shear stress is released during seismic slip (Sibson, 1991). As a consequence, dilatational strains should develop during the interseismic phase (including the

opening of vertical hydraulic extension fractures), only to be relieved abruptly through the coseismic-postseismic period with expulsion of contained fluid (Muir-Wood & King, 1993). These effects should be especially strong in the near-surface zone of extension fracturing. Second, rapid coseismic opening of *dilational fault jogs* at any depth through the seismogenic zone may lead to intense localised reductions in fluid pressure through *suction-pump* action. Third, *fault-valve* behaviour may occur if the normal fault transects a sealing horizon capping either uniformly overpressured crust (as is known to occur in the Gulf Coast sedimentary basin - Roberts *et al*., 1996) or fluid overpressures localised to the lower portions of the fault zone itself. Such behaviour would lead to postseismic discharges in the vicinity of the fault accompanied by an increase in frictional strength which diminishes towards the next failure episode as the fault seals and fluid overpressures reaccumulate (Sibson, 1992).

The mechanical problems associated with the initial formation and continued reactivation of very low-angle normal faults ($d < 30°$) (Sibson, 1985) have been addressed by many researchers. One set of postulated solutions involves the deflection of stress trajectories from the vertical and horizontal either by topography (Abers et al., 1997) or magmatic bodies (Parsons & Thompson, 1993; Lister & Baldwin, 1993), or through stress refraction around locally overpressured zones (Bradshaw & Zoback, 1988), or from variations in boundary loading conditions (Yin, 1989; Spencer & Chase, 1989; Melosh, 1990). Wills & Buck (1997) provide a critical analysis of the problems associated with several of these stress deflection schemes. Others (Reynolds & Lister, 1987: Axen, 1992; Axen & Selverstone, 1994) have cited evidence for fluid overpressures within normal fault zones as a mechanism allowing their continued reactivation at high angles to subvertical s_1, while Bartley & Glazner (1985) invoke a combination of stress reorientation from topography, and localised fluid overpressures to allow low-angle slip at depth. Brittle failure mode plots demonstrate that reactivation of very low-angle normal faults under vertical s_1 trajectories is possible from fluid overpressures localised within the fault zone with $P_f > s_3$, provided the country rock retains significant tensile strength. It should be noted, however, that while localised fluid overpressures may conceivably assist the continued reactivation of low-dipping normal faults, they cannot by themselves account for their initiation at low dips.

A progressive programme of borehole investigations in the vicinity of the Gulf of Corinth with the aim of determining stress and fluid-pressure conditions over a broad range of crustal depths in the vicinity of active fault zones would allow the different hypotheses discussed here for fluid interaction with both steeply and shallowly dipping normal faults to be tested and evaluated.

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Earthquake-Related Fluid Pressure Transients: Observations in Shallow Boreholes and Speculation About Seismogenic Depths

Evelyn A. Roeloffs, U.S. Geological Survey, Vancouver, USA

Long records of fluid pressure in active tectonic areas are needed to study the mechanical role of fluids in the earthquake generation process. In particular, such records are required to determine how fault zone fluid pressure, porosity, and permeability vary before, during, and after earthquakes. Such pressure and physical property variations are hypothesized to influence aftershock timing and distribution, stress redistribution by earthquakes, mainshock-foreshock linkages, and remote triggering of seismicity. A small number of hydrologic precursors to earthquakes have been documented, and fluids are also suspected to cause electric or magnetic earthquake precursors.

Fluid pressure measurements as a proxy for strain measurement has been advocated for many years. To date fluid pressure records from active tectonic areas in the U.S., Japan, Turkey, China, and the Former Soviet Union are primarily water level measurements in boreholes with depths shallower than several hundred meters. These data begin to address some of the issues mentioned above, and have also revealed unexplained earthquake-related phenomena. Only observations at greater depth, however, can establish whether these phenomena also occur at depths where earthquakes nucleate.

Here I will summarize the important findings for shallow depths, and suggest goals for a program of deeper measurements. Although important exceptions will be described below, many shallow observations confirm that poroelasticity or simple fracture deformation models correctly predict the responses of water levels in wells to crustal deformation. Earth tide and barometric responses are consistent with poroelastic responses of 10-100 cm/ppm volumetric strain, with somewhat larger coefficients for boreholes intersecting deformable planar fractures. Fluid pressure changes of 1 cm per day can be distinguished from background noise, so fluid pressure changes in response to strain of 10^{-8} can be expected to be observed.

Vertical flow between shallow poorly confined aquifers and the water table significantly limits this sensitivity. Precipitation-induced changes in water levels are also marked at some sites and mask tectonic signals in strainmeter as well as water-level records.

Water level changes caused by fault creep and oscillations due to seismic waves may not be appropriate targets for deeper observation programs. Creep-induced water-level changes, possibly limited to California, primarily reflect shallow processes, and do not appear to be Earthquake precursors. Fluid pressure oscillations proportional to seismic wave amplitude could be a factor in remote triggering of earthquakes, and questions remain about their responses to shear waves as well as their limiting sizes. Recording these high-frequency waveforms against high background pressure would be difficult, although knowledge of peak pressure changes would be valuable.

Coseismic water level changes should be an important target of deeper fluid pressure observations, which could also facilitate the recording of the recovery phase of such changes. Magnitude 5 earthquakes at depths of 10 km are expected to impose permanent, instantaneous strains of 10^{-8} or greater at the surface. Borehole strainmeters have recorded many such strain steps (although some strain records also show unexplained changes in strainrate following earthquakes). Water levels in wells should show step-like coseismic changes, and several data sets, including the magnitude 5 Parkfield, California, earthquake in December, 1994, confirm that most wells do respond as expected. Such fluid pressure changes are expected to recover due to horizontal and vertical flow. This evolving fluid pressure field has been hypothesized to control aftershock distribution, and presumably influences the effective stress increments from which Coulomb Failure Function changes are calculated.

Current shallow observations reflect primarily flow to the water table, so that deeper observations are essential for recording this recovery phase. Coseismic water-level changes as large as 1 m that do not fit the poroelastic model are now well-documented to depths of several hundred m, but it is not known whether they occur at greater depth. Such changes have been observed at sites including wells several hundred m deep in porous aquifers as well as fractured crystalline rocks, in response to earthquakes as far as hundreds of km away. If they occur at seismogenic depths, these fluid pressure changes could be related to the remote triggering of seismicity. An open question is why certain sites exhibit these unexplained responses to earthquakes.

Among reported hydrologic precursors to earthquakes, water level increases in two wells prior to the 1985 Mw 6.1 Kettleman Hills, California, Earthquake constitute a fairly well documented example that would likely have been better recorded in deeper boreholes. These water level increases took place over three days, reaching an amplitude of 3 cm in a well 153 m deep, and could have been caused by strain due to pre-earthquake aseismic slip at a depth of 15 km. Dissipation of fluid pressure by flow to the water table probably prevented detection in one borehole; this problem can be greatly reduced by observing at greater depths.

Extending the depth range of continuous fluid pressure monitoring in active tectonic areas will provide scientific payoffs but is not without challenges. Besides the obvious benefit of being closer to deep sources, better isolation from the water table is a very significant advantage of deeper observations. On the other hand, lower permeability may reduce signal amplitude, higher ambient pressure will limit time and/or pressure resolution, and hot corrosive fluids will shorten sensor life. Suggested targets for deep continuous fluid pressure monitoring are therefore signals several cm in amplitude with durations of days to several months. These limitations should still permit recording of peak dynamic pressure associated with seismic waves, comparison of coseismic fluid-pressure and borehole strain transients, and the characterization of coseismic responses to distant earthquakes, including the recovery phase. Short-term fluid pressure variations prior to earthquakes, if they occur, should also be observable in deeper boreholes. Ultimately, continous fluid pressure measurements from seismogenic depths are required to answer fundamental questions about how faults generate earthquakes.

Flow in Fractured Media: a Modified Renormalization Method

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Abstract

We present a methodology to account for fluid flow from micro- to macroscales in fractured media. Renormalization Group (RG) theory coupled to a percolation approach provides a convenient tool allowing to deal with the complex connectivity of fracture systems and with the intricate relationship between the various scales involved and the observation scale. This method also provides us with a way to describe scale dependence of permeability (K). 2D- and 3D- calculations can be performed for broad distributions of *both* conductances and fracture lengths. Here we introduce what we call a "modified renormalization" method. This method is then tentatively applied to the upper crust where many scales of fractures are present. The results are discussed relatively to the 3-4 orders of magnitude increase in permeability which has been reported by some authors from sample scale to regional scale and we examine how our model could be used to predict possible scaling laws.

FROM CORE SCALE TO HECTOMETRIC SCALE

HOW TO RELATE THE SCALE DEPENDENCE OF PERMEABILITY (IF ANY) TO THE GEOMETRICAL PROPERTIES OF THE FRACTURE NETWORK?

We have to take into account:

- a broad distribution of hydraulic conductances
- a broad distribution of fracture lengths

3/D-RENORMALIZATION

The overall behavior is controlled by heterogeneities at <u>a particular scale</u> (scale of step 0)

fractures = bonds distributed over a network with probability p

Classical renormalization allows to answer 2 questions:

- *considering occupied bonds at a given scale,*
  how does a given network connect at a larger scale ?
- *what is the overall conductance ?*

ACCOUNTING FOR SEVERAL SCALES OF HETEROGENEITIES:

A MODIFIED RENORMALIZATION METHOD

How to build networks in full agreement with any distribution of both

- conductances ?
- fracture lengths ?

Method = overprinting of networks

At scale n : *contribution of all fractures of size < n (classical renormalization)*
plus contribution of fractures of size n (overprinting)

distribution of fracture lengths: $p_i \sim (l_i)^a$ with -1 = a = 1

or, equivalently,

number of fractures /unit area: $n_i \sim (l_i)^a$ with -3 = a = -1 a = a -2

Conclusions

- A METHOD TO ACCOUNT FOR HYDRAULIC PROPERTIES OF 2D AND 3D MEDIA IN RELATION WITH THE SCALE OF MEASUREMENT
- AN EFFICIENT TOOL
- A GEOMETRICAL NETWORK HIGHLY SIMPLIFIED
- NO PRECISE DESCRIPTION OF FLOW PATHS

Permeability Variations Induced by Fluid Circulation in Faults

Jacques BOULEGUE, UPMC, Paris, France

There are few direct informations available about the nature of fluids flowing in fractures and the evolution of their composition with varying T and p conditions encountered, as well as upon mixing with aquifers cross-cut by the fractures. The relations of the compositions of the fluids with the hydrogeological parameters is almost unknown.

For what concerns fluid circulation in faults, there are few measurements of p and T available to constrain modelling, except in some oil industry related areas (e.g., South Eugene Island off Louisiana; Southern Trinidad;). To acquire informations related to the composition of fluids flowing in fractures and the processes leading to their composition and evolution along fluid paths, we have studied mud volcanoes in several areas: South Trinidad, South-West Taiwan, Shabah. These mud volcanoes are located above well-known fault systems and enable sampling of fluids expelled along faults.

Expulsion of mud from a mud volcano is most probably triggered by seismic activity. Gases (CH4 dominant) are mostly expelled in the earlier activity.The compositions of the fluids are then issued from complex mixing of fluids expelled from deep reservoirs (in connection with basin aquifers) with fluids fom several overlying aquifers cross-cut by the faults. The most noticeable reactions are formation of calcite, silica and kaolinite in the fractures, leading to a decrease of permeability with time (10-100 years time scale after a given eruption of a mud volcano) by self-sealing. Modelling of fluids circulation in the South Eugene Island area has shown that the permeability of the fault system is strongly lowered within 10-300 years owing to self-sealing. The studies of chemical and isotopic properties of kaolinite, quartz and calcite cements, collected in loose rocks expelled in the early activity of the mud volcanoes, enable to acquire datas pertinent to the conditions at depth leading to the ascent of the deep fluids along the faults and their expulsion at the location of the mud volcanoes.

Experimental circulation in a fault system within granite , induced between deep boreholes (3500-3800 m depth; Soultz, France), has shown that the permeability control is mostly due to the variations of pressure and their effect on the formation of minerals such as quartz and calcite.

The understanding of compositions of fluids circulating in faults, of their evolution and of their relation with variations of permeability, requires p and T measurements in relation with a detailed survey of fluid chemistry in the fault as well as in the aquifers cross-cutted by the faults.

Aspects of Fluid-Sampling and Gas-Logging in Boreholes - The KTB Example -

Jörg ERZINGER, GeoForschungsZentrum Potsdam, Potsdam, Germany

Introduction

Fluids are responsible for almost all chemical, physical, mechanical and dynamical processes within the earth’s crust. They influence, for example, the rheological behaviour of rocks, seismicity, melting and crystallization processes, metamorphic reactions as well as the transport of matter and heat within the earth’s crust. A major problem in modern geochemistry is, however, the quantification of fluid flows in the earth’s crust.

The Continental Deep Drilling Program of the Federal Republic of Germany (KTB) offered the unique opportunity to draw direct samples of deep-seated formation fluids. It was thus possible to determine the volatiles of almost "fresh" rocks just drilled and to examine intensively the gas phase of formation fluids transported with the drilling fluid to the surface in the KTB pilot and main holes. The KTB-wells (KTB-Vorbohrung (KTB-VB) 4000.1 m deep and KTB-Hauptbohrung, (KTB-HB) 9101.0 m deep) are situated in the Oberpfalz (Bavaria, Germany) near the town of Windischeschenbach.

Our major goal was to obtain information on the amount of gases in the continental crust as well as their composition and depth distribution. In the KTB field laboratory, established at the drill site, a mass-spectrometrical on-line analysis of the gases dissolved in the drilling fluids was carried out. An interpretation of these data and the following mass balances required information on the gas contents of the rocks and the amounts of gases which could migrate on fissures.

Technical description and sampling methods

The gases dissolved in the drilling fluid have been analysed qualitatively and quantitatively around the clock and on-line during drilling of the KTB-VB and -HB. For the extraction of gases dissolved in the drilling fluid a degassing device with a free outlet was used in the KTB pilot hole and in the KTB main hole down to 3003 m. With this gas trap assembly only the volumetric portion of each gas could be determined but not the amount of gas entering the borehole. Below 3003 m a newly developed closed by-pass system was installed at the KTB-HB. A constant portion (about 80 l/min) of gas-bearing drilling mud was pumped through a by-pass line and ran directly into an air-tight twirl degasser. The gases were led from this degasser into the nearby automatic gas mass spectrometer where they are quantitatively analysed for N2, O2, Ar, He, CO2 and CH4. In addition, C2H6, C3H8 and C4H10 were analysed using a gas-chromatograph, and Radon was quantified spectrometrically.

In order to quantify gases entering the borehole known quantities of pure and mixtures of gases were injected into the mud circulation system. While the drilling mud is equilibrated with atmospheric air before being pumped down into the borehole, the "outlet-mud" shows a corresponding atmospheric gas composition (with the exception of oxygen) if natural gases have not entered the borehole from wall rock.

Results

The continuous drilling fluid analysis in the KTB-Hauptbohrung indicated several significant fluid inflow zones with high concentrations of methane and helium. From 1980 - 2200 m in the KTB-VB a cataclastic shear zone with graphite-rich paragneisses was drilled. Even though the largest part of the methane penetrated via fissures into the borehole, the rocks of this zone, which were investigated using high vaccum degassing techniques, are very rich in gas. The cataclastic zone was characterized by long-lasting degassing features, hence the drilling fluid was enriched with methane down to about 2500 m. Below 3400 m (KTB-VB) several fluid inflows with high methane concentrations could be observed. In contrast to the graphite-rich cataclastic zone (1980 - 2200 m), in this case, the fluids entered the borehole abruptly via fissures of some centimeters in width, which manifests itself in the gaslogs as short sharply limited concentration maxima. A longer-lasting degassing did not seem to have taken place.

In the KTB-Hauptbohrung two different types of gas-bearing horizons could also be generally distinguished. The first type included "dry" inflows (i.e. mainly gas, less brines) from graphite-bearing cataclastic shear zones, at 1445 m, 1530 m, 1960 m and 2416 m. The second type included "liquid" or "brine" inflows, was frequently related to open fissures within a prehnit-mineralized section and appeared below 3000 m.

In the Vorbohrung and Hauptbohrung, the "dry" inflows are characterized by high hydrocarbon contents, whereas helium was enriched in brine-bearing inflows (second type). In addition the composition of gaseous hydrocarbons from the cataclastic zones differ significantly with relatively high ethane contents (CH4/C2H6=14) from those of the fissure systems with lower C2H6 concentrations (CH4/C2H6=40). Apart from methane and ethane, propane and butane as well as traces of unsaturated hydrocarbons such as ethene and propene could also be detected down hole in the drilling mud.

In the Hauptbohrung the amount of gases entering the borehole through specific borehole fractures increased with depth while the methane/helium ratios remained relatively constant. In amphibolite and gneiss sections the methane/helium ratio was about 40 and 25 respectively, probably due to the higher radiogenic helium production rate in the gneisses.

At the end of 1991 more than 750 m3 of pure formation fluids were pumped from the open borehole section (3850-4000 m) in the KTB-VB with about 0.8 liter (STP) of gas per liter of fluid.

The gases are mainly composed of nitrogen and methane with minor amounts of helium, argon, hydrogen and carbon dioxide. Fluid-gas associations with such composition are typical for deep crystalline rock environments. However, the formation water was not supersaturated with respect to gases under the prevailing pressure (400 bar) and temperature (118 (C) at 4000 m depth.

With these data and addtional isotope studies it was possible to determine the potential sources, origin and pathways of crustal fluids.

Conclusion

The main geoscientific goal of this study was to work out background information on gas contents in continental crustal rocks, their composition, origin and depth distribution. The new concept for on-line determination of gases dissolved in the drilling fluid has proved successful. Using this method, applied for the first time in a borehole, almost complete depth profiles could be surveyed for methane and helium. Most of helium and methane in the drilling fluid entered the borehole through fissures and fractures from the surrounding rocks, only a small portion was released during drilling by crushing of the rocks. It turned out that methane and helium are very sensitive indicators for formation fluids entering the borehole during drilling. The helium/argon ratio in the "4000 m fluid" corresponds to typical ratios for U-, Th- and K-decay in average magmatic rocks. Furthermore, hydrogen in the drilling fluid was mainly artificially created during the drilling process itself. The nitrogen isotopic composition did not differ significantly from that of the atmosphere, thus we were not able to state on the origin of nitrogen.

As the Hauptbohrung was only partly cored, on-line gas analysis often represented the only possibility to gain continuous information on the gas contents of the drilled rocks. It was, in addition, an important help when the time arrived to decide if and to what depth rock or fluid samples should be taken. Furthermore technically problematic horizons, for example the cataclastic zone at 1990 m, could be recognized by a significant increase in methane and helium concentrations, before the drill bit reached those sections.

Whilst simultaneous sampling of drill mud fluids and solids as well as on-line gas analysis do not disturb drilling operation and allow immediate detection of fluid rich hole sections (help for quick operational decisions), drill mud analysis gives only a rough idea of formation fluid geochemistry.

Off-line formation fluid sampling with down hole fluid sampler, draw down and packer testing, or continuous pumping has the advantage of less fluid contamination through drill mud and allows trace element and isotopes studies. However, these operations are relatively expenive and need thorough before hand planning.

Fluids and Thermal Regime in the Crust - Kola Hole Data

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A joint study for geothermal, hydrogeological and metamorphic zonation for Kola (Baltic Shield) superdeep hole is presented. Hydrogeological zonation for Kola can be divided into 4 parts:

I. Permeable zone associated with exogenous fissuring. Meteoric water with low salinity in fractures (0-800)

II. Zone of joint (free and chemically bounded) waters, mainly chemically bounded, where free waters occurs only in a narrow fault zones and veins (800-4500m)

III. Zone of regional tectonic foliation and hydraulic desegregation of rocks, with free high saline waters belonging to metamorphic fluid with primary marine origin (4500-9200m)

IV. Zone of joint waters, mainly chemically bounded with vein-type reservoir for free water (>9200m)

Zones III and IV are associated with riftogenic evolution of Pechenga Greenstone Belt.

Fractures were formed during dehydration processes in a closed system. For the upper part of Kola section we can explain heat flow density increase with depth as a result of subvertical water flow with Darcy velocity 0.4 cm/year. Temperature effect by paleoclimatic variation was also evaluated. At depths greater than 4.5 km, rocks are fractured and water saturated.

For observed geothermal parameter (heat flow, thermal gradient, thermal conductivity) we need to check factors like refraction of temperature field, free water in the caving hole and in fractures, degree of representation of rock samples for in situ conditions, etc.

For understanding the deep peculiarities of heat flow variations we also investigated heat and hydrogeological fields in the area near Kola hole. On the Baltic Shield we have low average heat flow values. Very often these values have a large scatter. The dominant factor causing this phenomenon is fluid flow in the crystalline rocks. The observed complicated picture of the heat flow distribution can be explained by very irregular permeability (cracked-type) of metamorphic rocks on the shield. The permeability depends also on tectonic and lithological factors. The zone of exogenous fissuring about 800 m depth was established by hydrogeological study on Kola Peninsula. In the area of Kola hole we have the unique opportunity to investigate in details relationship between space peculiarities of thermal field, hydrogeology, stress field and fault tectonic. We present new data about thermal and hydrogeological fields around Kola hole. This information is used for the interpretation of deep heat flow in Kola hole and heat-mass transfer in the upper crust.

Evaluation of Optimal Form of Listric Faults in Non-Homogeneous Earth

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The faults that break up the crust into blocks to represent the bands of localized inelastic deformation [1]. With depth the slope of faults decrease and they take for the listric form [2]. The problem is to establish the form and orientation of the fault that would correspond to the given rheology and loading conditions.

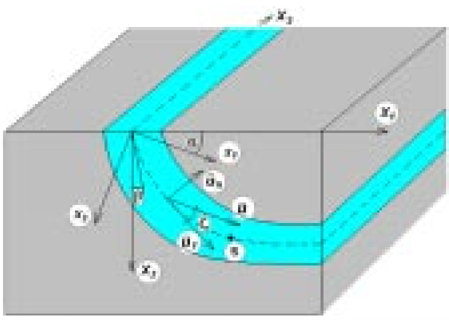

Fig.1 Scheme of listric fault

We shall consider planar deformation of a long, curved fault, with a width h in half-space $x_2 \geq 0$ in frame of the local system of coordinates n, τ and x_2 coinciding with the middle surface of the fault (Fig.1). Given the incremental displacement vector $\bar{u}$ across the fault

$$\bar{u} = u_n i_n + u_\tau i_\tau \qquad (1)$$

the normal ε_n and shear $\gamma_{\tau n}$ components of the deformation write as follows:

$$\varepsilon_n = u_n / h \quad , \gamma = u_\tau / h \ . \qquad (2)$$

Here $\bar{i}_n$ and $\bar{i}_\tau$ are unit vectors.

For incompressible material in the fault zone the intensity of the deformation have the form

$$\varepsilon_i = \frac{1}{\sqrt{3}}\sqrt{4\varepsilon_n^2 + \gamma^2} \ . \qquad (3)$$

Assume that the material in the fault zone is in the ideal plastic state and the yield strength in the earth crust σ_s is the function of cohesion σ_c, average pressure σ, pore pressure p and internal friction f,

$$\sigma_s = \sigma_c + (\sigma - p) f \qquad (4)$$

In this case the energy dissipation we will write in form

$$D = \frac{1}{\sqrt{3}} \int \sigma_f h \sqrt{4\varepsilon_n^2 + \gamma^2}\, ds \qquad (5)$$

Introduce another independent variable, the length of the arc S, and take into account that

$$u_n = u \sin\zeta \quad , \quad u_\tau = u \cos\zeta \qquad (6)$$

where $u = |\bar{u}|$ and ζ is the angle formed by the direction of the vector $\bar{u}$ and axis τ.

Having matched the zero point and the origin of coordinates x_1 and x_2 and directing axis x_1 along vector $\bar{u}$ that together with the axis x_1 forms an angle α, we get

$$\sin\zeta = dx_2/ds \quad , \quad \cos\zeta = dx_1/ds \qquad (7)$$

Using relations (2), (7), (8) the equation (6) will be finalized as

$$D = \frac{1}{\sqrt{3}} \int u\sigma_f \sqrt{1 + 3x_2'^2}\, ds \qquad (8)$$

We shall assume that out of the set of possible fault surfaces the one realized is that for which the functional (8) will have a steady-state solution. To find such optimal surface, we shall have to formulate and solve an Ostrogradsky-Euler equation:

$$\frac{\partial\Phi}{\partial x_2} - \frac{d}{ds}\frac{\partial\Phi}{\partial x_2'} = 0 \ , \quad \Phi = u\sigma_f \sqrt{1 + 3x_2'^2} \qquad (9)$$

It follows from (9) that

$$x_2'' - \frac{1}{3}(1+3x_2'^2)\frac{1}{(u\sigma_f)}\frac{\partial(u\sigma_f)}{\partial x_2} = 0$$
(10)

If σ_f does not vary with depth, then according to (11), $x_2 = const$, and the middle surface is a plane. If

$u\sigma_f = c\exp(-kx_2)$, (11)

the solution of (11) will be:

$$x_2 = \frac{1}{k}\ln[\cos\frac{k}{\sqrt{3}}(A+s)] + B \quad (12)$$

where

$A = -\frac{\sqrt{3}}{k}arctg[\sqrt{3}\cos(\alpha+\beta)]$,

$B = -\frac{1}{k}\ln(\cos\frac{k}{\sqrt{3}}A)$ are constants of integration.

Equations (12) and (7) allow to draw the fault's middle surface, with the given k and angles α and β.

According to the solution (12) decreasing of crust strength with depth leads to decreasing of fault slope. Fig.2 shows optimal middle surfaces of faults for $k = 10^{-2}\,km$ and different orientation angle β.

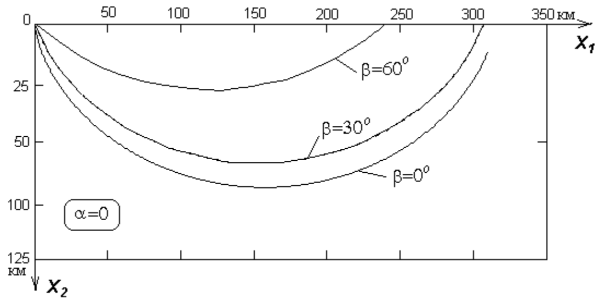

Fig.2 Forms of optimal listric faults for non-homogeneous earth crust

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Papua New Guinea: Active Low-Angle Faulting and Plans for Drilling in 1998

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The lateral variation from active continental rifting to seafloor spreading within a small region makes the western Woodlark Basin an attractive area to investigate the mechanics of lithospheric extension. Earthquake source parameters and seismic reflection data indicate that low-angle (~25-30°) normal faulting is active in the region of incipient continental separation. A low-angle normal fault emerges along the northern flank of Moresby Seamount, a continental crustal block with green schist metamorphic basement. Asymmetric basement fault blocks overlain by only minor ponded sediments characterize the margin to the south, whereas the margin to the north has a down-flexed pre-rift sedimentary basin and basement sequence unconformably onlapped by synrift sediments.

ODP Leg 180 will drill in June-July 1988 a transect of sites just ahead of the spreading tip: ACE-9a on the down-flexed northern margin; ACE-8a through the rift basin sediments, the low-angle normal fault zone, and into the footwall; and ACE-3c near the crest of Moresby Seamount.

The primary objectives at these sites are to: (1) characterize the in situ properties (stress, permeability, temperature, pressure, physical properties, fluid pressure) of an active low-angle normal fault zone to understand how such faults slip, and (2) determine the vertical motion history of both the down-flexed hanging wall and the unloaded footwall and, thereby, derive the timing and amount of extension prior to spreading initiation.

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Taylor, B., A. Goodliffe, F. Martinez and R. Hey, 1995, Continental rifting and initial seafloor spreading in the Woodlark Basin, Nature, 374, 534-537

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An Integrated Method for Mapping the Regional Stress Field and the Pore Pressure

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Many evidences have been accumulated during the last ten years concerning the role of interstitial fluids on the mechanical behavior of faults (see abstracts by Sibson , by Roeloffs, by Boulegue or by Garagash in these proceedings). However the various models proposed for taking into account the role of fluids remain speculative and there is a need to obtain in situ data concerning the various aspects of the coupling between fluid flow and the mechanical behavior of faults. These data should concern the chemical and the mechanical effects together with the transport characteristics.

We describe here a method for mapping the pore pressure from an analysis of focal mechanisms, when the regional stress field is known (Cornet and Yin, 1995). The method has been validated during an *in situ* forced fluid flow experiments at Le Mayet de Montagne experimental test site, in central France. Water has been injected in a 800 m deep borehole while the induced microseismicity was being monitored with a 15 three components seismic station network (Cornet and Julien, 1989). Flow conditions were monitored by running spinner logs and recording the surface injection pressure while the stress field has been determined by integrating Hydraulic Tests on Preexisting Fractures (HTPF) data together with focal mechanisms of observed microseismic events. A complete HTPF datum includes location and orientation of the preexisting fracture of concern together with the normal stress acting on it (Cornet and Valette, 1984). These data are obtained from borehole testing at selected intervals. Focal plane solutions yield two nodal planes one of which is the actual fault plane. The global inversion of focal plane solutions together with HTPF data identifies the regional stress field (assumed to vary linearly with the local coordinates) which satisfies best the normal stress measurements of the HTPF data and the observed slip vector direction within the fault planes defined by the focal mechanisms (Yin and Cornet, 1994).

For le Mayet de Montagne experiment, about 30 % of the microseismic events occurred at locations along faults where the stress is heterogeneous with respect to the regional stress field (angle between observed slip vector and computed resolved shear stress larger than the uncertainty on the slip direction determination). These heterogeneities have been documented later by direct in situ normal stress measurements conducted according to the HTPF technique. This has demonstrated that interpretation of focal mechanisms alone may not yield the correct regional stress field orientation. It has been concluded that it is only by coupling focal plane solutions with other independent stress field constraining data that the complete regional stress field at great depth may be determined with some accuracy.

Once the regional stress field is well established, those focal mechanisms which are homogeneous with it may be used as *in situ* piezometers. Indeed, the stress determination provides means to identify which of the nodal planes is the actual fault plane and then, for this fault plane, it provides an evaluation for both the normal and the tangential stress supported by the fault plane. Given the fact that friction coefficients for most faults are fairly well defined, the pore pressure required to induce slip motion can be computed for all those focal mechanisms which are consistent with the regional stress field. At, Le Mayet de Montagne, this mapping of pore pressure has provided means to identify which fractures are flowing (pressure gradient consistent with reasonable hydraulic conductivity) and those which are not (large pore pressure at long distances from the well bore). This conclusion has been validated then by confronting these results with direct flow measurements in the injection well.

Accordingly, when independent observations concerning either principal stress orientations or some stress component magnitudes are available from deep boreholes, the complete regional stress field (direction and magnitude of all 3 principal components) can be mapped within fairly large volumes by taking advantages of observed seismicity. Then, in turn, those focal mechanisms which are consistent with the regional stress field help to map the regional pore pressure.

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Rock Mechanics and Fracture Mechanics Theories and their Seismological Applications: The Gulf of Corinth Case and the Deep Drilling Problem

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Introduction

In order to study the mechanisms of faulting and earthquakes, as well as their interrelation, geophysicists normally rely on physical field measurements such as surface geodetic measurements, microseismic or seismic data. However, for the validation and regularization of these measurements scientists are seeking for direct measurements inside the Earth. These can only be achieved through deep boreholes appropriately positioned in the region under investigation with the aim of:

- correlation of subsurface structure with superficial structure,
- gain of scientific information about the Earth's interior (geology, rock mechanics, seismicity, fluids, wave propagation etc.),
- establishing an underground observatory for long-term monitoring of the earth's interior,
- studying seismic phenomena at depth.

The Gulf of Corinth area is one of the most rapidly extending areas in the world, where the local seismicity in the Gulf of Corinth is showing great activity with 5 earthquakes of magnitude larger than 6 over the last 30 years. Quite recently the seismicity of the Gulf of Corinth was manifested by two earthquakes, one of magnitude 4.1 and another of 4.3 with epicenter at North Elefsis (East side of the Gulf of Corinth, Nov. 3, 1997) which were followed by another major earthquake on Nov. 5, 1997 of magnitude 5.5 near Galaxidi at a focal depth of 20 km.The arguments in favor for drilling a system of deep boreholes and eventually an ultra-deep borehole at the Gulf of Corinth are the following:

- the Gulf of Corinth is located in Central Greece in a region of unique geological importance. It is the region where Peloponnesus separates from the mainland of Greece with a velocity of about 10 - 15 mm/year which is the world's greatest rate of separation within a continent. For this reason the Gulf of Corinth is referred to as one of the "world sites" of great structural geological interest.
- This area exhibits active seismicity manifested by small and large earthquakes.
- There is a complete record of large earthquakes that have occured over the last 103 years. Further, this specific region in comparison to other regions in Greece is extensively monitored in the past 15 years by the conduction of geodetic and seismological measurements, and a wealth of geological observations and neotectonic analyses carried out by IGME and others are available. Moreover, studies of microearthquake distribution in that area are available.
- The social-economic impact of such a project would be extremely important for this part of Greece. In the immediate region around the Gulf of Corinth live more than 6 million people, and large engineering projects have been carried out such as the management of underground water resources by the Mornos dam at the north side of the Gulf, or are currently under construction such as the Rio-Antirio bridge project

which will connect the south and north shore of the gulf, the future exploitation of hydrocarbons programme in the western side of the Gulf etc. Thus, the design of aseismic design of structures above and below ground level (e.g. bridges, tunnels etc.) as well as the seismic protection of urban areas around the Gulf of Corinth will have great impact on the development of that area, and information will be gained for similar methodologies to other areas with similar problems.

Rock mechanics and rock fracture mechanics play an important role in borehole stability analyses and stress interpretation theories. Two examples are given in the following.

Rock mechanics modeling: measurement of in situ lithostresses from borehole breakouts

Borehole breakouts occur under high in situ stresses when the tangential stress at the borehole wall overcomes the strength of the rock. Under unequal principal stresses failure is concentrated in two diametrically opposed zones parallel to the minor principal stress forming a notched shaped borehole. Such breakouts are valuable indicators of the direction of action of the principal horizontal compressive stresses, while their size and shape may provide information on the magnitudes of the maximum and minimum stresses relative to the strength of the rock. As the in situ strength of rock and its state of stress at great depths are difficult to determine, observations of the size and shape of the breakouts as well as the conditions under which they form will lead to an estimation of these parameters by appropriate inversion procedures.

Fracture mechanics modeling:

A gently dipping fault near a free surface in an extensional regime

The mechanical interaction between a stress-free fault and the earth's surface can be analyzed using two-dimensional displacement discontinuity schemes and principles of linear elastic fracture mechanics for a gently dipping fault buried beneath a horizontal free surface and subjected to far-field uniform extension (Fig. 1).

This geometric configuration may be seen as an oversimplified first-order model of the Gulf of Corinth with the detachment zone gently dipping to the north (10 to15°) at a depth of 10 km (Rigo *et al*., 1996). Uniform extension of the half-space creates an asymmetrical half-graben configuration manifested by a trough above the southward fault-tip followed by a hill to the north-side. The crack initiation and propagation conditions for the problem of the shallow fault has been investigated by using a maximum tangential stress criterion (Erdogan and Sih, 1962) resulting in an angle of crack departure equal to -74^o and to pronounced sliding mode over tearing mode. This clearly demonstrates the tendency of normal faults to climb to higher stratigraphic planes at high angle (Fig. 2, crack initiation from tip B) and is in accordance with the microseismic measurements of Rigo et al. (1996) at the Gulf of Corinth.

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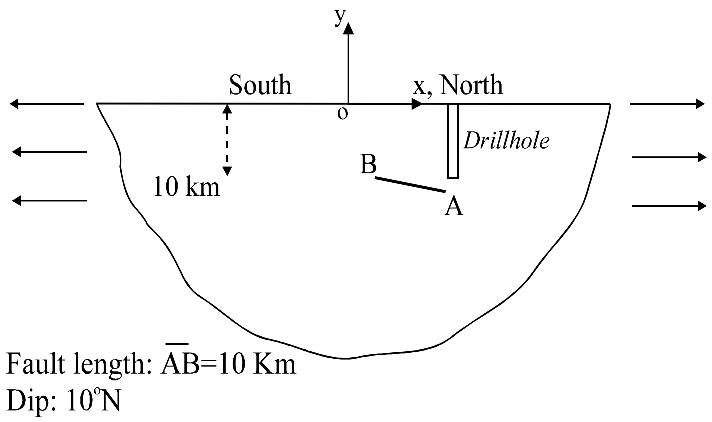

Fig. 1: Fault and free surface

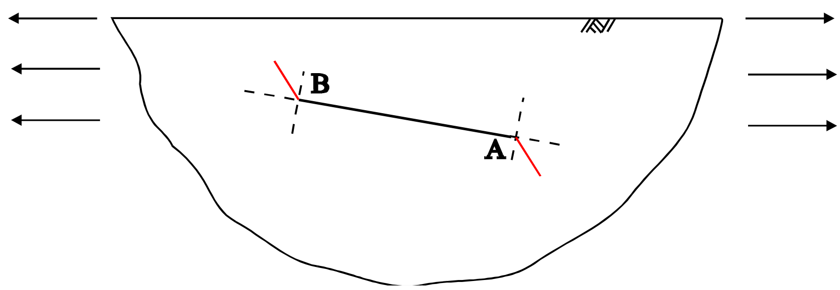

Fig. 2: Fault extension (crack) moving to higher stratigraphic planes (tip B) and the other moving downwards (tip A)

Continuous Material Characterization from Acoustic Logs

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A new method for estimating *in situ* mechanical properties from logs has been tested. The method - FORMEL - is based on a new constitutive model, describing processes which occur in rock during mechanical loading. The method has been compared with results from over 200 rock mechanical tests made on cores, and it compares favorably with direct correlations based on porosity or sonic compressional transit time. It works best for estimating strength at non-zero confining stress, and for porosities below 35 percent. Sand strength analysis using FORMEL has been compared with field sand production records, and it is concluded that the method is a valuable tool for sand prediction. A major strength of the method is that it is robust and may be applied with confidence to new wells and fields without re-calibration.

A knowledge of *in situ* rock mechanical parameters is needed for several applications in the petroleum industry. Uses include sand prediction, wellbore stability evaluation, and estimations of compaction and subsidence. The most direct way of obtaining rock mechanical data is from laboratory tests made on cores. However, there are several reasons why other methods are needed: first, core measurements can never provide a continuous strength estimate as a function of depth in a well; second, core tests may be unavailable because of the costs involved or because suitable core material has not been obtained; and third, the effects of stress unloading and core handling upon the quality of rock mechanical tests can be questioned.

Mechanical parameters cannot be determined directly from logging tools. Indirect methods (in which the strength and stiffness of the formation are inferred from other properties) must therefore be used. As the sonic log measures formation stiffness resulting from low-amplitude, high-frequency deformation, it is clear that acoustic logs are prime candidates for incorporation in methods for mechanical properties evaluation.

Two main issues arise from this:

- How can the low-amplitude, *dynamic* moduli given by acoustics be related to the large-amplitude, *static* moduli that are needed?
- Is there any relation between *moduli* and *strength?*

These questions are formidably difficult to answer theoretically, and no one should be offended by the statement that these problems, even today, are far from being solved. As a result of the lack of established theoretical models, most of the methods suggested for mechanical properties estimation from logs have been empirical. The idea behind FORMEL was to provide a description of the main processes occurring in a sedimentary rock during loading. Of special importance were mechanisms which give rise to differences between static and dynamic elastic moduli, since an understanding of these would facilitate the optimum use of sonic data. The aim was not to calculate rock behavior from "first principles", but rather to come up with a model which could be described by two sets of parameters: one set which can be estimated from well logs and other data available in a field; the other set being determined from a series of carefully designed and analyzed laboratory experiments. The latter set is expected to be the same for any given lithology, and may thus be determined "once and for all". This does not mean that calibration cannot be improved, but that the parameter set is not expected to change (significantly) as one goes from well to well or field to field.

The following mechanisms are included in the model:

Grain contact plastification or crushing. During loading, stresses are intensified at grain contacts. This means that irreversible deformation may take place at relatively low stress levels. This mechanism is valid even during hydrostatic loading, and gives the relationship between the static tangent bulk modulus K, the dynamic or elastic bulk modulus K^e and a parameter P quantifying the process of grain contact crushing and having a characteristic dependence on stress. The parameters controlling this dependence are determined from calibration experiments.

Closed sliding cracks. For shear loading, additional mechanisms may give rise to a difference between the static and dynamic moduli. One such mechanism is due to closed cracks or weak contacts, which may undergo shear sliding as a result of a static disturbance (large amplitude stress) but will not be activated by the acoustic waves (low amplitude stress). This mechanism gives a relationship between the static tangent Young's modulus E and the dynamic or elastic Young's modulus E^e with a parameter F which is proportional to the density of sliding cracks. F further depends on the friction coefficient for sliding of the cracks. F=1 corresponds to zero static tangent stiffness, i.e. peak stress, which defines the strength. The parameters controlling this dependence are also determined from calibration experiments.

The input parameters for FORMEL are a volumetric quantification of the formation, sonic P and S velocities, and estimates of the *in situ* stresses. In principle, a shear velocity is needed, but it is shown that in most cases it can be obtained indirectly from the compressional velocity. A more detail description of FORMEL is given by Fjær (1997), and Raaen et al. (1996).

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Vibroseismic Surveys for Deep Structure Identification

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It is always desirable to use seismic data in complex geophysical investigations of deep structures of the Earth's crust and mantle. The use of earthquake origins in seismology as sources of waves introduces many errors into some fundamental results, because the coordinates of the source and the moment of beginning of its action are unknown. These errors often exceed 20 km for the coordinates and 2 s for the moments. Explosions are also not appropriate for survey of time variations in the structures and properties of rocks. The forms of recurrent explosions are not identical. It is impossible to identify small changes of the properties of geological objects. For their identification it is necessary to have the accuracy of time determination equal to 1-5 milliseconds.

These basic limitations of seismology served as a motive for some researchers of three institutes of the Siberian Branch of the Russian Academy of Sciences to begin in 1977 development of the principles and instruments of active seismology which are presented in the present paper. We use the term "active seismology" for seismic investigations, in which powerful mechanical sources of seismic waves with precise control are employed. The accuracy in determination of the coordinates is 1-10 meters, and that of the origin time is 1-5 milliseconds. So, the conditions and the resolution in active seismology are close to those in seismic prospecting.

The potential advantages of this approach are evident :

- the coordinates of the source and the time of its action can be determined exactly
- multiple identical actions on the medium being studied (replication of experiments) are possible
- oscillations of desirable form and polarization can be excited
- experiments can be controlled on a computer
- there is no destructive action on the environment (environmental safety).

The main problems which can be solved by the method of active seismology using powerful sources are as follows:

- investigation and identification of inhomogeneities in the Earth's crust, mantle and core. Modern digital seismological networks and superpowerful vibroseismic sources can be used here.
- investigation of geodynamic processes by long-term observa-tions of the velocities and polarization of vibroseismic waves at fixed distances
- active monitoring of seismic prone zones for medium-range and short-range earthquake prediction
- active microseismic zoning of large areas
- investigation of stability of deep substructures in regions of exploitation of ecologically dangerous engineering constructions, large chemical enterprises, atomic power stations, dams in mountainous areas, etc.
- study of physical-mechanical and chemical properties of rocks and other materials under powerful vibroseismic actions

Some principles of radiation of seismic energy and construction of powerful vibrators have been established and tested in theoretical and experimental works during the last 15 years. An analysis of the mechanism of radiation of seismic waves at large distances (500 km and more) has shown that oscillations of large masses (approximately 100 tons) with large amplitudes (about 1-2 centimeters) are necessary. In this case the resonant regime of oscillations of the source joined with the upper layers of the ground occurs. Under such conditions the energy of seismic radiation is high. The principle of radiation from vibrators used in seismic prospecting does not satisfy these requirements.

We demonstrate two principles for construction of powerful vibrators: eccentric and hydroresonant. We also present some geophysical results, in which they are used (seismograms at a distance of 312 km, spectrograms at a distance of 520 km, tests for recurrence of signals obtained for seismic cross-sections by the common depth point method at a depth of 110 km, estimation of the errors of vibromonitoring).

The average time error is about 0.02% (approximately 0.005 s for 100 km), the average amplitude error is approximately 5%, and the phase error is 1.5 degrees.

The presented results on development of large vibrators and methods of seismic sounding show that the resolution and technology of processing used in vibroseismic surveys can be very close to that in seismic oil prospecting. Packages of solutions to direct and inverse problems for complex models of media have been created to interpret the data of active seismology including a 3D simulation package. Development of the concept of a multidisciplinary criterion for identification of the rheological flow and precursor for the appearance of the dilatancy zone is presented.

Connection Between Faulting and Base Detachment. Modeling Considerations

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1. Introduction

The Gulf of Corinth which is located in Central Greece is a region of unique geological importance. It is the region where Peloponnesus separates from the mainland of Greece. Billiris et al. Have measured in 1991 the Geodetic Extension Rate in N-S of the Corinthian Gulf to be 1. to 1.5 cm/yr (world's greatest rate of separation within a continent). For this reason the Gulf of Corinth is referred to as one of the three "world sites" of great structural geological interest where the unique phenomenon of rapid extension is observed. Furthermore, the local seismicity in the Gulf of Corinth is showing great activity with 5 earthquakes of magnitude larger than 6 R. the last 30 years. Quite recently the seismicity of the Gulf of Corinth was manifested by two earthquakes, one of magnitude of 4.1 and 4.3 with an epicenter at North Elefsis (East side of Gulf of Corinth) (November 3, 1997) which were followed by another major earthquake on November 5 (1997) of magnitude 5.4-5.5 at Galaxidi and at a focal depth of 20 km.

According to Rigo et al. (1996) the Gulf of Corinth is one of the most prominent acrive rifts in the Aegean area, with a history of repeated large earthquakes and with a high level of background seismicity. The observed seismicity is located between 6 and 11 km. The mechanisms indicate a nodal plane dipping 10-25^o due north and the inference of a deep detachment zone, where the major faults seen at the surface appear to root. There seems to be an absense of events shallower than 4 km.

Here a first effort is made to understand the mechanics of a detachment zone through modeling of geological structures formation using small-scaled model experiments. The central question is whether the detachment zone is connected directly to the major normal faults at the S-side and N-side of the Gulf of Corinth.

2. Scaling Considerations

We consider a large scale rock failure mechanism as below. From a purely mechanical point of view we recognize the following problem parameters :

- E_S,E_N : earth thrusts on faults [FL^{-1}]
- H: height of overlying rock [L]
- L: base displacement [L]
- γ: unit weight of rock [FL-3]
- G: dead load of wedge [FL-3]
- c: cohesion of rock [FL-2]
- ϕ friction angle of rock [-]

For simplicity it is assumed that elastic deformations are negligible as compared to plastic deformations. Thus elastic parameters are not entering the argument list of the earth thrust E and rock is described solely by its *strength parameters*. Thus we may assume that the earth thrusts are a function of the above listed parameters.

E=E(H,L,γ,c,ϕ)

By applying dimensional analysis (Hubbert 1937) we get

$$\frac{E}{\gamma H^2} = f\left(\frac{\delta}{H}, \frac{c}{\gamma H}, \phi\right)$$

We may now simplify the problem by assuming that cohesion forces are negligible as

$$\frac{E}{\gamma H^2} = f\left(\frac{\delta}{H}, \frac{c}{\gamma H}, \phi\right).$$

compared to gravity forces.

$$\frac{c}{\gamma H} << 1.$$

For example for $\varphi = 30^o$ and $(ucs) = 10 \quad MPa$ we get $c \approx 3\ MPa$ and with

$$\gamma \approx 27kN/m^3\ that\ \frac{c}{\gamma H} = 0.01.$$

Thus following these simplifying model considerations, we may conclude that rock masses of great extent in depth behave in a first approximation like a purely frictional material. In order to study large structures formation one may resort accordingly to 1g model tests with cohesionless sand as model material.

In order to study the mechanism of normal and antithetic fault formation due to detachment of the base a model experiment was constructed that consisted mainly of a box with glass walls to facilitate the direct observation and a sliding base to mimic the assumed tectonic movement

3. The Sliding Base Model Test

In order to decide which are the appropriate boundary conditions for the model experiment, we performed numerical studies using the code FLAC. As shown in the figure below, it was found that faults may emerge from either sharp discontinuities in the slope of the sliding base of from discontinuities in the assumed friction between overlying material and sliding base. The model tests confirmed the basic statements and have shown clearly the evolution of the global failure consisting of normal and antithetic faults and the dependence of the mechanism on the sliding-base displacement.

4. Concluding Remarks

These preliminary tests suggest that there is need for further detailed analysis of the nature of possible major tectonic mechanisms which may be accounted for the relation between normal and antithetic faulting on one hand and movement of a surface at the detachment zone. It is however clear that in the present preliminary study many important parameters have been left out. These are elasticity and cohesion, as well as structural properties of the rock. Contemporary research o progressive deformation localization has shown that in order to simulate faulting properly ine has to resort to the appropriate mechanical properties that describe microstructure (Vardoulakis & Sulem 1995). Microstructure is reflected in the thickness of the fault zone which in turn sets the appropriate internal length scale. Other properties which were left out and might be of significant importance in modeling are for example the effects of pore pressures and pore fluids (Vardoulakis 1996 a,b) and the effect of rate dependence of interfacial friction (Tullis & Weeks 1986) and strain softening (1992).

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The Gulf of Corinth: Which Style of Rifting?

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Continental extension results in a large diversity of tectonic styles, like narrow rifts of lithospheric scale (e.g. Baikal rift), distributed extension (e.g. quaternary faulting of basin and range), or localized extension at crustal scale (Gulf of Corinth, metamorphic core complexes). Thermo-mechanical explanations for the occurence of these different situations have been proposed [Buck,1991], but the relative weight of thermal and rheological properties of the lithosphere are only partially understood, as well as the role of the boundary conditions. Within this framework, a hot topic is the formation and the mechanical behavior of low angle faults which have been evidenced by geologists [Davis and Coney,1979; Wernicke,1981] but poorly understood using the classical theory of faulting [Anderson,1942] and rarely observed in term of seismic events [Jackson and White,1989].

Until recently, morphological and seismological observations in the Gulf of Corinth strongly suggested that a set of high angle faults controls both footwall uplift and hanging wall subsidence [Jackson,1982; Armijo *et al.,*1996]. The corresponding model would be a half-graben, with various degrees of sophistication [Vening-Meinesz,1950; King and Ellis,1990; Hassani and Chéry,1996]. This last model which involves elasticity, pressure dependent plasticity, viscosity, and frictional faulting, brings some predictions for half graben formation, that might be tested in the Gulf of Corinth:

- the friction coefficient seems to be lower than 0.4 if the internal friction angle of the upper crust is 30°,
- significant deformation always occur in the hanging wall, even if the friction coefficient is low,
- no decollement fault is needed to explain hanging wall subsidence.

However, there is now seismological and geodetical evidences that low angle faulting (10-30° dip) can occur at a depth of 8-10 km, at least in the West part of the gulf [Rigo and others, 1996; Rietbrock et *al.,*1996], and Bernard et al.*(in press).* The coexistence of these different fault types, high angle between 0-8 km depth, and low angle between 8-10 km, is difficult to understand with our present knowledge of lithospheric mechanics. For example, one can predict the occurence of severe problem of kinematic compatibility near the connection between high and low angle faults.

One way to investigate the tectonic behavior of the Gulf of Corinth would be to test two alternative hypothesis.

The first one is to consider the presence of a shallow dipping zone which could play the role of a detachment if a weak rheology (e.g. low effective friction) is used. The presence of such a pre-existing surface could correspond to a flat thrust herited from a compressive (alpine?) phase. Using this approach, the goal (and the difficulty) will be to find the rheological conditions to create a shallow high angle fault branched on the detachement surface.

The second approach is to postulate that a high angle fault develops in an initially homogeneous crust, and to seek the conditions for the *in situ* creation of a flat detachment below the hanging wall [Lister and Davis,1989].

In both strategies, the shape of footwall uplift, the subsidence pattern, and the distribution of horizontal extension will exert strong constraints on modeling.

We have tested the second hypothesis (initial high angle fault) using an elasto-visco-plastic crust cut by a Coulombian fault. The rheology is pressure, temperature, and stress controlled, that naturally leads to a pressure dependent plastic behavior in the upper crust, and to a temperature dependent viscous behavior (power law) in the middle crust. Stress analysis (figure 1) evidences the complexity of both stress orientation and intensity when a realistic rheology for the crust is used in conjuction with a relatively low friction coefficient (0.2).

According to previous results [Hassani and Chéry, 1996], this numerical experiment does not provide any low angle shear zone. 9The discrepancy concerns both the orientation of the shear zone in the middle crust (too steep), and its thickness (not a well defined shear band). We then varied parameters such as fault friction, crust-mantle density contrast, and basal shear stress. We did not find any combination of parameters allowing us to match topographic, kinematic, and seismological constraints together.

We think that this discrepancy between modeling and observations may be due to an inappropriate rheology to account for localized brittle-ductile shear bands. Indeed, power law rheologies as we use seem valid for only moderate strain, but do not probably hold for highly localized deformation influenced by strain or strain-rate softening. A next step will therefore involve appropriate laws for shear band development, that are probably grain size sensitive, due to dynamic recrystallisation (strain), and static recrystallisation (stress). These rheological effects might be one of the keys that control the tectonic evolution of the Gulf of Corinth. Discovering these mechanisms should improve our insights on continental rift zones, specially the metamorphic core complexes.

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What Can We Learn about Earthquakes from a Borehole ?

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The Gulf of Corinth is one of the most active seismic areas in the world. Although very large earthquakes are rare, many events of magnitude M>6 have taken place along the gulf in the last 30 years. Among these events, those of 1981 that took place in the eastern end of the gulf have fault planes dipping from 40-50 degrees. Those that occurred more recently in the central part of the Gulf had very shallow fault planes as determined from seismic, aftershock distribution, seismicity and geodesy. A medium sized event occurred in the week following the meeting. All this frequent seismic activity, associated to a local rate of extension of about 1.5 cm, takes place in an area less than 300 km in length by at most 50 km width. This earthquake concentration poses a number of fundamental problems in seismotectonics, the existance or not of shallow normal faulting, the mechanics of shallow earthquake slip, etc. Mainly though, it makes this area a natural laboratory for the study of earthquakes in Europe and the quantification of strong motion for earthquake resistant design.

The interest of drilling a borehole (or several of them) in this area is that we can observe earthquakes bellow the shallow diffracting layer that attenuates seismic waves. As shown by Abercrombie and others from observations in the Cajon pass borehole in the San Andreas fault, many events detected at depth can not be observed in the surface. The shallow layers of the crust, specially the sedimentary cover seem to diffract seismic energy strongly, attenuating and defocusing high frequency waves above 1 Hz. Installing broad band, high dynamic range seismic instruments at depth could provide relatively clean seismic waves with frequencies of several Hz. We would thus have an unobstructed view of seismic events at frequencies of a few Herz, when wavelengths become of the order of the gouge zone of faults (usually, a few 100 m). In my opinion, this would be a major advance is seismic studies.

Actually, at present most of our knowledge about seismic sources comes from strong motion data recorded on the "free" surface. These data are then low pass filtered at about 1 or 2 Hz (or even less for older instruments) and used in the inversion of the rupture process at the source. Down to these frequencies earthquakes appear as single ruptures propagating along well defined fault planes containing a finite number of discontinuities or jogs. The picture that emerges is close to the very traditional model proposed a long time ago by Haskell and that has reappeared under the name of Heaton. The main change with respect to these kinematic models is that rupture speed, rupture width of the "Heaton"pulses, as well as slip are strongly controlled by the stress distribution and rupture resistance at the beginning of the earthquake.

Recently, Olsen, Madariaga and Archuleta (Science, 31 Oct. 1997) showed that it is possible to explain all observations made after the Landers earthquake with a relatively simple model of a fault strip of about 70 km length by 12 km depth in which everything along the fault is homogeneous except the initial distribution of stress. The kinematics of rupture is almost the same as that recovered from seismic observations by several authors including Wald and Heaton, Cotton and Campillo or Cohee and Beroza. This model contained frequencies up to 0.5 Hz, roughly a wavelengths less than about 5 km for shear waves. This wavelength corresponds, for a standard model with stress drop of the order of a Mpa, to a slip of about 0.5 m. This is a very long scale, much longer than the estimated width of the gouge zone inside active faults. At this coarse scales earthquakes do not appear to be as rough as proposed in "toy models" like the self-organizing cellular automata of Bak and Tang, or the Burridge and Knopoff spring slider models. I think that it is clear that models of earthquakes look relatively simple because the resolution length is much too coarse.

Earthquake engineering and earthquake physics require that we understand seismic radiation at higher frequencies, beyond 1 Hz, say. For shear waves this corresponds roughly to wavelengths of less than 2-3 km, that is about 4 times less than the depth of the seismogenic zone. It seems quite obvious that at higher frequencies, when the length scales decreases bellow 1 km, the fine structure of the fault will become the dominating feature for seismic radiation. Studying radiation at these high frequencies requires that we separate source and propagation effects. In my opinion this can be done only by installing instruments at depth inside boreholes in order to reduce the destructive effect of diffraction on seismic waves. Otherwise we will continue looking at earthquakes trough a poorly polished mirror.

Is the Corinth Gulf the SW tip of the North Anatolian Fault ?

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We present geological and morphological observations at different scales to constrain rates of faulting and the distribution of deformation in the seismically active Aegean region. We focus first on the 130 km long Corinth Rift, an asymmetric graben where a flight of terraces of marine origin are uplifted. We show that the edges of the terraces lie in the footwall of the normal fault bounding the Corinth Rift and correspond to sea-level highstands of late Pleistocene age. Using detailed analysis of aerial and SPOT imagery supported by field observations, we have mapped ten terrace platforms and strandlines ranging in elevation from 10 to 400 m over distances of 2 to 20 km from the fault. The elevation of terrace's inner edges was estimated at 172 sites with an error of ±5 m. This data set contains a precise description of the uplift and flexure of ten different paleo-horizontal lines with respect to present sea level. To date the deformation we correlate the Corinth terraces with late Pleistocene oxygen-isotope stages of high sea-level stands and with global sea-level fluctuations. Using a thick elastic plate model consistent with our current understanding of the earthquake cycle and a boundary-element technique we reproduce the geometry of the shorelines to constrain both mechanical parameters and the slip on the fault. We show that the seismogenic layer behaves over the long term as if its elastic modulus is reduced by a factor of about 1000. All the terraces are fitted for fault slip increasing in proportion to terrace age and the component of regional uplift is found to be less than 0.3 mm/yr. Best fits give a slip rate of 11±3 mm/yr on the main rift bounding fault over the last 350 kyr. Other geological and morphologic information allows us to estimate the total age of the main fault (≈1 Ma) and to examine the mechanical evolution of the Corinth Rift. The minimum observed sediment thickness in the Gulf places an extreme check on the results of the modelling and a lower bound on slip rate of 6-7 mm/yr (40% less than estimated with modelling). Even this slip rate is nearly 10 times higher than for comparable features in most of the Aegean and elsewhere in the world.

At a larger scale, the spacing and asymmetry of the rift systems in the Aegean suggest strain localisation in the upper mantle with slow extension starting 15 Ma ago or earlier. The more recent (1 Ma), rapid phase of rifting in Corinth partly reactivates this earlier phase of extension. The younger faulting in Corinth appears to result from its present location in the inhomogeneous stress field (process zone) of the SW-ward propagating tip of the southern branch of the North Anatolian Fault. We extend these relations to propose a mechanical model for the Late Cenozoic evolution of the Aegean. As the Arabia/Europe collision progressed in eastern Turkey it caused Anatolia to move to the West and the North Anatolian Fault to propagate into the Aegean, where the early slow extension started to be modified about 5 Ma ago. The process of propagation dramatically increased the activity of some but not all of the earlier rifts. The model we present is compatible with tectonic observations, as well as with the seismicity, the paleomagnetic rotations and the displacement field now observed with GPS and SLR.

Geometry, Kinematics and Rates of Deformation in a Normal Fault Segment Boundary, Greece

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The geometry, kinematics and rates of deformation within a fault segment boundary between the ends of two major active normal fault segments have been investigated through examination of a faulted 126 ka marine terrace (Fig. 1).

Slip-vector azimuths defined by striations on the faults include N-S extension on ca. E-W faults, sub-parallel to those from earthquake focal mechanisms, together with significant and contemporaneous E-W extension on ca. N-S faults (Fig. 2). Summed rates of E-W extension along a ca. 550 m transect (0.17 mm/yr) are comparable with those for N-S extension (0.20 mm/yr) along a ca. 350 m transect. Our observations show that distributed non-plane strain extension occurs in fault segment boundaries and this should be noted when studying evolving fault geometries, fault-tip fracture toughness and regional deformation rates.

Offshore Faults in the Gulf of Corinth

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The Gulf of Corinth is a Plio(?)-Quaternary WNW-ESE-trending submar ine basin which occupies the northern side of the intensively faulted Corinth graben (fig.1a). During the last 15 years the Laboratory of Marine Geology and Physical Oceanography has carried out a number of marine geophysical surveys using Sparker and Airgun seismic profiling systems, which aimed at the study of the basin structure and the influence of active faulting on the coastal and submarine morphology and on the sediment processes. The surveys have shown that the basin is a complex asymmetric, ~900m deep, submarine graben, whose submar-ine morphology is characterized by three major physiographic units: (i) the shelf, (ii) the slope and (iii) the central basin or abyssal plain (fig.1b). The southern and northern margin of the Gulf of Corinth basin are bounded by a number of distinct fault segments separated by relay zones.

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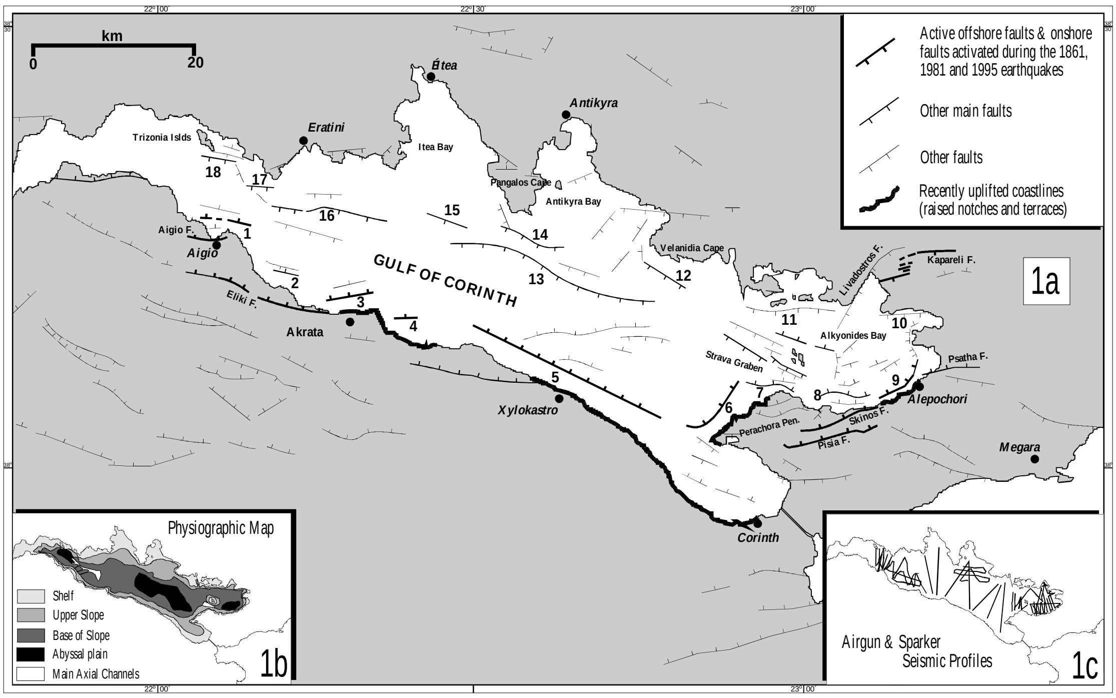

Fig.1: (1a) *Map presenting the faults of the Gulf of Corinth. Faults: 1.Valimitika, 2.Diakopto, 3.Akrata, 4.Aegira, 5.Xylo-kastro, 6.Perachora, 7.Strava, 8.E.Alkyo-nides, 9.W.Alkyonides, 10.Aigos-thena, 11.Domvrena, 12.Velanidia, 13.Antikyra, 14.Pangalos, 15.Itea, 16.Era-teini, 17.Tolo-fonas, 18.Trizonia (The onshore faults are adapted from Doutsos et al. 1988, Armijo et al. 1996).* ***(1b)*** *Physiographic map of Gulf of Corinth.* ***(1c)*** *Airgun & sparker seismic tracks*

In the western and central part of the Gulf of Corinth basin, the southern margin is bounded by five distinct right stepping fault segments (fig.1a). These are Valimitika, Diakopto, Akrata, Aegeira and Xylokastro faults. The faults trends range between ENE-WSW to WNW-ESE and their lengths are between 3 to 25km. They form north-dipping scarps whose heights increase from west to east from 200 to 600m, in accordance with the increase of the gulf's depth.

In the eastern part of the Gulf of Corinth basin this fault zone is shifted to the north by the Perachora fault and forms the southern boundary of the Alkyonides basin in the easternmost extremity of the gulf (fig.1a). The fault system in the Alkyonides basin consists of three fault segments: the Strava fault and the West and the East Alkyonides faults (fig.1a). The faults trends range from WNW-ESE to ENE-WSW and have a length of about 7km and dip northwards. Ten boundary faults have been recognized and mapped at the northern margin of the Gulf of Corinth basin (fig.1a). These faults establish the «antithetic» fault system which controls the formation of the basin

The Aigosthena, Livadostros and Domvrena faults (fig.1a), consist the northern boundary of the Alkyonides basin which shows a strong southward asymmetry, indicating that the faults in the south is the major fault system.

In the central part of the Gulf of Corinth basin the margin is bounded by four faults: the Antikyra, Velanidia, Pangalos and Itea faults. The dominant southward asymmetry of the basin indicate that in the central part of the basin the major fault system is in the south.

In the western part of the Gulf of Corinth basin, the northern margin is bounded by three main faults, which are the Trizonia, Tolofonas and Eratini faults (fig.1a). The faults lengths range between 3-15km and form steep fault scarps of about 300m in height. Here the basin is slightly asymmetrical to the north which indicates that the major fault system is in the northern side.

Raised notches and terraces along the southern coast of the gulf of Corinth (fig.1a) indicate episodic uplifting during the 300ka which suggests that the Akrata, Aegira, Xylokastro and E.Alkyonides faults have been active for long periods of time. The northern margin of the gulf of Corinth seems to be under a general subsidence regime, as is indicated by the presence of subsided wave-cut platforms and the fact that no raised notches or terraces have been yet found.

Neotectonic Structure of the West Korinthiakos Gulf and Geodynamical Phenomena Induced by the Egion Earthquake

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Introduction

The preliminary results of a research project on the active faults and the seismic risk of West Korinthiakos Gulf are presented. The project is financed by the Earthquake Planning and Protection Organization.

A total length of more than 2.000 km of seismic profiles were recorded (Fig. 1) during three cruises with R/V AEGAEO of NCMR, using various sound sources (AIR GUN 1, 5, 10 and 40 in^3, 3.5 kHz). Additionally, numerous gravity cores were collected in order to investigate the character of the recent sediments.

Special research was carried out in the epicentral area of the Egion earthquake (June 15, 1995, 6.1R) between Egialia and Eratini and more than 500 nautical miles of seismic profiles were recorded (Fig. 1).

Additionally numerous in situ observations were made along the coasts of the Gulf in order to combine the onshore neotectonic structure with the results of the evaluation of the seismic profiles.

Fault structures

Two main fault zones are responsible for the recent evolution of the West Korinthiakos basin. They run offshore the coasts of the Gulf along the slope of the basin in WNW-ESE average direction and are segmented to E-W trending faults, which are stepwise arranged (Fig. 2). The same arrangement display the sediment depocenters along the Gulf.

The total vertical displacement along the southern and the northern marginal fault zones increases eastward and exceeds 500m in the eastern part of W. Korinthiakos Gulf coinciding with the similar increase of the depth of the Gulf and the thickness of the deposited sediments towards the east.

Numerous synsedimentary (growth) faults are obtained along the central deepest part of the basin which also run E-W and create minor graben and horsts structures within the sedimentary basin. Their total vertical offsets do not exceed a few tens of meters usually.

Continental platform

Due to the very small distance between the present coast and the trace of the main offshore fault zones, the continental platform exists only in some areas (Fig. 2). In these areas the depth of the shelf break is not constant and varies between 74 and 110 m below present sea level. This variation is caused by the different vertical displacements along the active faults during Holocene and by the regression of the break due to extensive slumping and sliding of the outermost parts of the shallow platform downwards the slope. The latest is very characteristic offshore Egialia, where the shelf break lies at 35 to 55 m depth.

Submarine slumping

Very extensive slumping structures are observed along the slope of the basin offshore the southern and northern coast of the Gulf (Figs. 2 and 3). We interpret them as active complex slumping phenomena which reactivate episodically accompanying seismic activity or without it.

The reactivation of these submarine

slumps during the historical and recent eras initiated the tsunamis which are reported from the West Korinthiakos Gulf (373 b.C. Ancient Eliki, 551 Itea, 1402, 1748, 1817, 1861 Egialia, 1963 Loggos-Lampiri, 1996 Egialia).

Geodynamical phenomena induced by the Egion earthquake

Some of the faults located on the shallow platform offshore Egialia (Fig. 2) display strong evidences of very recent reactivation, since they offset the uppermost sediment layers and the sea bed. Additionally they are located in the extension of the areas where ground fissures, liquifaction phenomena and coastal sliding occured during the Egion earthquake. For these reasons we believe that the reactivation of these faults was very probably induced by the earthquake of June 15, 1995.

The tsunami which occured at the night of Dec.31, 1995 to Jan. 1, 1996, along the coasts of Egialia mainly can also be regarded as a late phenomenon caused by the Egion earthquake. According to the preliminary data from the evaluation of the seismic profiles of the area and our in situ observations, this tsunami was induced by the reactivation of a complex submarine slump located offshore the northern coast of the Gulf, southwest of Eratini, which became unstable due to seismic motion of June 15, 1995.

Present Deformation of the Gulf of Corinth

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Between 1990 and 1995, we carried out seven GPS campaigns around the Gulf of Corinth in order to monitor the spatial and temporal deformation of this seismic area. The network includes 51 first order points measured with an horizontal accuracy of 3mm (Figure 1) and 142 second order points measured with an horizontal accuracy of 10mm (Figure 2). Among these 193 points, 159 are also greek triangulation pillars measured between 1966 and 1972. The results obtained along a seven points profile installed in 1990 at the longitude of Aigion show that the extension between the North and the South coast of the Gulf is roughly stable at 14 ± 2 mm/year there except between 1994 and 1995 due to the effect of the 15 June 1995, Ms=6.2, Aigion earthquake (Figure 3). Extension rates deduced from the analysis of our different GPS data sets (Figure 4) are 14 ± 2 mm/year to the N9°E in the west, 13 ± 3 mm/year to the N in the centre and 10 ± 4 mm/year to the N19°W in the east of the gulf. At large scale, this result agrees with a 100 years estimation by Billiris *et al.* (1990) and the results of Clarke *et al.* (1997).

The triangulation data (Figure 5) indicate higher rates and less angular divergence : 25 ± 7 mm/year to the N4°E, 22 ± 7 mm/year to the N and 20 ± 7 mm/year to the N15°W. Both sets of data indicate a very narrow (10-15 km) deforming zone in the west that becomes 15-20 km in the centre and 20-30 km in the east. Analysis of the displacements observed after the Ms=6.2 Aigion earthquake (Figure 6) together with seismological and tectonic observations shows that it occurred on low-angle (35°) north-dipping normal faults located between 4.5 and 10 km depth in the inner part of the Gulf (Bernard *et al*., 1997). The existence of low angle faults in the inner-Gulf between the longitudes of Psathopirgos and Aigion is also supported by the results of Rietbrock *et al.* (1996) and Rigo *et al.* (1996).

Assuming that the deformation concentrates in relatively narrow deforming zones, a model of deformation in an elastic half-space indicates that the accumulation of strain observed between 1990 and 1994 can be explained by aseismic deformation in the uppermost kilometres of the inner rift, coupled with a continuous slip along a detachment zone located at the base of the faults. The model allows to evaluate the deformation accommodated respectively by the inner low angle faults of the Gulf and by the large faults bordering the southern coast of the Gulf. At Aigion, the model predicts that 10 mm/year of extension occurs across the inner-Gulf faults and only 4 mm/year across the large faults bordering the south coast of the Gulf. This corresponds to more than 65% of the total energy released by earthquakes in the inner-Gulf possibly similar to the one of 1995 (typical recurrence time of 70 years), the rest being absorbed by less frequent earthquakes (typically Ms=6.7, and 300 years recurrence time) occurring on the large southern faults.

Assuming that the 1995 earthquake is characteristic of the activity in the inner rift, the thickness of the seismogenic zone is 5.5 km there, located between 4.5 and 10km depth. The layer located above 4.5km depth in the inner Gulf of Corinth appears to deform aseismically. At the longitude of Xilokastro, our model predicts 6 mm/year extension across the inner-Gulf and 7 mm/year across the southern faults. This value agrees with the long term estimation of Armijo *et al.* (1996). The seismic moment release predicted by our model for 100 years (64 10^{18} Nm) is compatible with the seismic moment estimated by Ambraseys and Jackson (1990) with the last 100 years of seismicity in the Gulf (42 10^{18} Nm).

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Seismic and Electric Anisotropy versus Deformation in the Gulf of Corinth

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Shear-wave splitting studies on seismogram of local earthquakes in the Corinth rift has revealed a clear seismic anisotropy around the Gulf of Corinth. We investigated the characteristics of this anisotropy, for testing the model of a crack-induced anisotropy in relationship with the stress directions (Bouin et al., 1996; Bernard et al., 1997).

The data comes from thousands of records brought by several temporary field experiments: Aigion experiment (1991), Mornos delat experiment (1994), postseismic surveys of the 1992 Galaxidi and 1995 Aigion earthquakes (Bernard et al., 1997). Most of the sites show a fast S axis orientated WNW-ESE, thus perpendicular to the global extension direction given by the focal mechanisms (Rigo et al., 1996), the normal fault orientation (Armijo et al., 1996), and the GPS (Briole et al. , 1997). It is thus, to the first order, consistent with a crack-induced anisotopy with cracks orientated perpendicular to the least compressive stress direction. Delays of 0.05 s to 0.1 s between the fast and slow S suggest the existence of cracks down to a few kilometers, at least, with density of several percents.

A few sites give a different first S direction, WSE-ENE, which in some case can be explained by the presence of nearby fault segments with the same direction. Two of those sites deserved a particular sudy: the delta of the Mornos river, to the west of the rift, and the Psaromita cape, above the fault plane of the 1995 earthquake.

In the Mornos delta, the S polarization is striking N55+-25°. Magneto-telluric soundings in the frequency range 0.01 to 100 Hz showed a clear electric anisotropy, with a N55°+-10° conductive direction for the highest frequencies. This anisotropy spans through the whole layer of sediments, about 1 km thick. Comparison of the 1966-1972 triangulations and the 1991-1995 GPS positions of geodetic points in and around the delta showed rapid extension strain (2x 10^{-6} /year) in the direction N340°+-30°, perpendicular to the fast S and the highest conductivity directions, suggestive of a causal relationship between these observations. We thus propose that this strain controls the two reported anisotropies by the formation and maintainig of fluid filled, steeply dipping antithetic faults and fractures, and fluid-filled vertical cracks, all striking N55° +-20°. The source of strain is likely to be the active normal faulting near and under the delta, as independently evidenced by the discovery of nearby offshore faults, stiking about N60° (Papanikolaou et al., 1996), significantly different from the dominant E-W strike of the major faults of the gulf.

On the Psaromita cape, one site has provided anisotropy directions in 1991, 1992 and 1995. This direction has rotated clock-wise by 20° between 1992 and 1995, which we interpret as being related to the coseismic strain change of the 1995 earthquake: indeed, the calculated extension direction of the coseismic strain is perpendicular, within a few degrees, to the new fast S direction. We propose that at this site, before the 1995 earthquake, the upper few kilometers of the crust was relaxed, and that the coseismic stress resulted in a change in the dominant open crack system. Further work is carried on this preliminary interpretation.

Drillings at a few kilometers in depth would considerably help to better understand the relationship between seismic anisotropy, crack distribution, and crustal strain. Firstly, by providing direct tests of the validity of the EDA model, through the relationship between measured stress and detected anisotropy, and through the analysis of core samples. Secondly, by revealing the physical properties of anisotropic crack systems: size of cracks (microns, millimeters, ... ?); connetivity of cracks (permeability, electrical anisotropy); sensitivity to stress (depth distribution of cracks); sensitivity to stress perturbations (elasticity; crack growth and healing).

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The Gulf of Corinth: 15 Years of Seismological and Geophysical Studies

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In terms of tectonics and seismicity, the Gulf of Corinth is one of the most active areas of Greece, the country with the highest seismicity in Europe. Being a unique natural geophysical laboratory, the broader region of the Gulf has attracted widespread interest on behalf of geoscientists for many years.

The Department of Geophysics has been involved in academic and applied research in the broader area of the Gulf of Corinth for over 15 years. Research topics included seismotectonics, seismicity monitoring and analysis, earthquake source analysis, seismic wave propagation, earthquake risk and hazard analysis, magnetotelluric investigations of the geoelectric structure, geothermal research, regional gravity studies, GPS monitoring of crustal deformation and numerous small scale investigations, the latter being part of services offered to local government and private organisations. The first large scale experiment conducted by the department was the study of the extensive and intense 1981 seismic activity at the eastern end of the Gulf (the Alcyonides - Kaparelli sequence with events of Ms 6.6, 6.2 and 6.4 and long aftershock activity). Ever since, the Department has been actively and continuously occupied with in-depth in seismological and geophysical research, and has participated in almost every national and international experiment conducted in the area, the largest of which were carried out in 1986, Peloponnese and the Ionian Islands; 1988, Peloponnese and the South Aegean; 1989, Western Greece and the Ionian; 1991; Western Gulf;1993, Eastern Gulf; 1996-1997, broader area of the Gulf. To the above list, one should also include two international expeditions to study the aftershock sequences of the 11.18.92 M6 and Galaxidi, and the 6.13.95 M6.2 Aigion earthquakes respectively.

The Department of Geophysics is also committed to the systematic monitoring and research on of crustal processes resulting to tectogenesis and seismogenesis in the broader area of the Gulf, by installing a number of seismological networks and geophysical observation posts. The existing instrumentation around the Gulf of Corinth comprises two permanent seismological networks of digital wireless telemetry, with short (CORNET - Corinthos Network), and broadband (ATHENET - Athens Network) seismometers and an accelerometric network of five 24-bit digital strong motion accelerographs (RASMON - Rio-Antirio Strong Motion Network). These are augmented by the telemetric, short period VOLNET (Volos Network), equipped with short period seismometers, and two telemetric, (via cellular telephony), permanent electrical and electromagnetic field observation posts. The complement of the Department’s networks is illustrated in Figure 1.

Results from such a systematic and continuous research have been published in various scientific fora (journals, congresses and symposia) and were outlined in the presentation. Crucial, yet still unresolved questions concerning the tectonic evolution of the Gulf, as well as problems pertaining to seismic anisotropy, site and directivity effects and the possible existence and location of a detachment zone in the west side of the Gulf (evident from low angle fault plane solutions) were also discussed. Finally, the need for data derived from deep boreholes (so as to avoid that the frequently intense and misleading distortion exerted by superficial layers) was emphasised.

Seismological Observations in the Gulf of Corinth

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During the past 7 years we performed detailled seismological studies in the area of the Gulf of Corinth through french and european projects in collaboration with the Universities of Athens, Grenoble and Munich. We presented the main conclusions from these studies by stressing the existing constraints on active seismic faults given that the geometry of these faults is a key point concerning the evolution of the Gulf. Although the major E-W striking faults bordering the southern coast of the Gulf are known to be responsible for major destructive earthquakes, most probably involving slip on 45°-50° north dipping planes (e.g. the Ms ≈7, 1861 event on the Helike fault), the recent seismic activity reveals a somewhat different picture.

Fig 1. shows all reliable shallow fault plane solutions of magnitude larger than 5.5 for the Gulf of Corinth area. The 1981 sequence of earthquakes to the east is well known (e.g., Jackson et al., 1982; Hubert et al., 1997). All fault plane solutions from this sequence represent normal faulting on 45-50° dipping planes and the three largest events are associated with observed ruptures on known faults. To the west, 4 events of magnitude 5.7 to 6.2 have fault plane solutions representing almost pure E-W striking normal faulting with one steeply (55-65°) south dipping plane and one shallow (28-35°) north dipping plane. Contrary to the 1981 earthquakes, none of these events have created large enough surface ruptures that could be associated with the earthquakes. The most recent event, the 1995 Ms=6.2 Aigio earthquake has been studied in details using teleseismic body waves, GPS coseismic displacement, SAR interferometry image and local seismological observations (Bernard et al., 1997). The relocated position of the hypocenter (Fig.2) together with the GPS derived coseismic deformation field and the SAR interferometry image, makes it impossible for the steep south dipping plane to be the rupture plane. Moreover, GPS coseismic observations clearly indicate that rupture stopped about 4 km beneath the surface. Aftershocks location of the 1992, Ms=5.8 Galaxidi earthquake, obtained with a local network, strongly suggest that the 30° north dipping plane was the active plane for this event. No local observations are available for the 1965 and 1970 events but considering the similarity of the fault plane solutions with those of 1995 and 1992, their hypocenter location, and the fact that no surface rupture has been observed, these two events may well also involve slip on the shallow north dipping plane.

In 1991, we conducted a dense seismological experiment in the western part of the Gulf of Corinth, in the Patras - Aigion - Navpaktos region. The temporary network included 51 digital stations (21 one-component stations and 30 three-component stations) that operated for 2 months, covering an area of 40 x 40 km2, with an average distance between stations of 3-6 km. Among the 5000 recorded events with ML ranging between 1.0 and 3.2, we precisely located 774 events, with an accuracy of about 1 km.We determined 148 well-constrained focal mechanisms using P-wave first motions. Of these, 60 also have mechanisms obtained by joint inversion of the P-wave first motions and the S-wave polarization directions. The accuracy obtained in strike and dip for the nodal planes of the final set of fault-plane solutions is about 10-15° . The seismicity is mainly located between 6 and 11 km depth (Fig.3). It is located beneath the Gulf of Corinth and on its northern side with three major clusters: one east of the city of Aigion which was very active during the two months of the experiment, most probably triggered by a ML =4.5 event that occurred a few days before the installation of our network; two on the northern side of the Gulf, one in front of the Psathopyrgos Fault (cluster CL2 on Fig.4) and the other in front of the Helike Fault (cluster CL3 on Fig.4). Most of the fault plane solutions correspond to E-W striking normal faulting, as we expect for an extensional tectonic setting. In the western part of the network, in front of the Psathopyrgos Fault, most of the well-constrained fault plane solutions have a nodal plane dipping 10-15° to the north and a steep south-dipping plane. In the eastern part of the network, the fault plane solutions have E-W striking nodal plane dipping 45-60°. The asymmetry observed for the western set of focal mechanisms is also seen in the seismicity distribution and in the overall geological structure of the Gulf. To explain all these observations, we propose a detachment zone at depth, a structure where the major southern normal faults seen at surface appear to root. A large part of the microseismic activity clusters in regions near the junctions of the main faults with the proposed detachment zone. These intersections of faults zones would be a likely place for increased fracturing in the crust and thus for generating microseismic activity. The seismicity could also be associated with slip on small antithetic faults corresponding to the nodal planes dipping steeply to the south. A network of such antithetic faults with the geometry given by the observed seismicity distribution would also accommodate the overall strain compatible with the proposed detachment zone. However as discussed below this does not seem to be the case and slip occurs on the shallow dipping plane. Nevertheless, this detachment zone, which corresponds to the brittle-ductile transition in the crust, represents a shear deformation zone contributing to the redistribution of stresses at depth

The clustering of the observed microseismicity allows to study in more details the faults geometry by relocating multiplets. Differential P and S travel times are obtained using waveform cross-correlation techniques with a precision less than 0.01s, leading to relative location precisions of about 40m in horizontal and 100m in vertical. One identified set of multiplets corresponds to cluster Cl2 beneath the northern coast of the gulf at about 9.5 km depth, were a detachment zone has been suggested. It includes earthquakes that have a common fault plane solution with a steeply (~ 75°) south dipping plane and a ~15° north dipping plane. Relocation of the 12 cluster events indicates that within location errors, these events lie on a 10-15° north dipping plane coinciding with one of the nodal plane of the fault plane solution (Fig.5, Rietbrock et al., 1997). This is for us a clear indication that normal faulting did occur, at least on a 1km2 small patch, on a shallow 10-15° north dipping plane. Further indication that the shallow dipping plane is an active plane is given by the analysis of 2 other events within the same cluster using empirical Green functions to identify the rupture plane by Courboulex et al. (1996).

Seismological observations indicate that active normal faulting in the western part of the Gulf of Corinth occurs on 30° north dipping fault planes located beneath the Gulf of Corinth and not outcropping on land. In addition, detailled microseismicity observations show that a large part of the activity occurs within a zone at depth between 7 and 10km. We suggested that this zone may be a detachment surface gently dipping north because both the precise geometry and observed fault plane solutions of some events indicate that seismic slip do occur on such a surface. What are the mechanical relationships between the 45-50° dipping normal faults observed at the surface, the 30° dipping normal faults beneath the gulf and the detachment zone? How is slip partitionned between all these active faults? What is the extension of this zone? What is its importance for the long term deformation of the Gulf? Does this surface corresponds to a lithologic contrast? These are questions that cannot be answered at present. The present topography of the Gulf seems difficult to reconcile with an active detachment over few hundred thousand years or more (see presentations by G. King and J. Chery) suggesting that the low angle active faults we are observing are quite recent and may be restricted to the western part of the Gulf. This may not be very surprising given that the Gulf of Corinth has been evolving very rapidly and propagating in the last million years (Armijo et al., 1996) and that the present strain rates are very high (see presentation by P. Briole). In any case our observations indicate that peculiar mechanical conditions must exist at depth to allow normal slip on shallow dipping planes and likely fluids and/or preexisting structures at depth play an important role.

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Microseismicity West and East of the Gulf of Corinth

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The Aegean as a fast deforming area

The Aegean is a region of intense and rapid deformation located between the two major lithospheric plates of Europe and Africa. Because of the small horizontal dimensions (smaller than 1000 km) and the wide range of geophysical and geological information available, it offers a unique opportunity to study in detail continental deformation.

Since 1984, we conducted a systematic investigation of the seismotectonics of the Aegean. We installed, in collaboration with the Universities of Thessaloniki, Athens, and Paris, temporary networks of portable seismological stations for period of several weeks to record local earthquakes with a greater accuracy than the regional seismological networks. We investigated most of the active regions of the Aegean. We mapped thousands of earthquakes and computed hundreds of focal mechanisms that we compare with the recent active faults. Some faults are not seismic (mostly the NW-SE trending faults that are located west of the Aegean sea), some seismicity is not associated with any known major fault. We suggest that, due to the important amount of internal deformation, the localization of the deformation changes with time and a precise timing of the recent faults activity is necessary to correlate with present day deformation. Reverse faulting is restricted to the narrow active boundary, both for the continental collision and for the active subduction. Along the active boundary, the progressive rotation of the direction of shortening from Epirus to Rhodos suggests that internal deformation takes place within the South Aegean. The consistent N-S trend of the T-axes within the North Aegean and along strike of the Hellenic arc confirms the internal deformation. This homogenous strain pattern across blocks of different size and orientation is similar to an analogue model of spreading in response of buoyancy forces, and suggests that the surface tectonics of the Aegean is controlled by viscous deformation of the lithosphere as a whole.

The Gulf of Corinth

Within the Aegean, the Gulf of Corinth is certainly one of the most active region which clearly exhibit N-S extension at a rate that is likely greater than 1cm/year. Furthermore the Gulf of Corinth is one of the most tectonically active fault region of Greece, and surface features are clearly associated with seismic activity. EW striking normal faults that are of several tens of km long are visible on the southern border of the Gulf. Some antithetic faults, but less developed, are also visible in some places at the northern edge of the Gulf.

Around the Gulf of Corinth, we participated and conducted several microearthquake surveys around Patras in 1991, and around eastern part of Corinth in 1993. We also conducted several post-seismic interventions after several large earthquakes that occurred within the Gulf during the last 10 years.

A summary of our results clearly confirm the asymmetric shape of the Corinth Gulf that is bounded to the South by North-dipping normal faults. The two extremities of the Gulf (around Rio-Antirio and around Corinth) are certainly the most active places. The central part of the Gulf (related to the Xilokastro fault?) looks more quiet. The seismicity dips toward the North with an angle which is comprised between 40 to 15 º, but it is not possible at this time to decide if this low-angle dipping seismicity is due to low-angle dipping faults beneath the Gulf of Corinth or to a gently deepening of the brittle/ductile transition in the crust.

Beside seismicity that is not constraining enough the geometry of the fault plane, we plotted the dip of the inferred fault planes for all the mechanisms that were precisely computed for the microearthquakes during our different experiments. This plot clearly shows that, most likely, the fault planes dip about 35º northward, consistent with the dip of the fault plane of the Corinth 81, Galaxidi 92, Aigion 95 mechanisms precisely computed by body-waves modeling technics. We suggest therefore the main faults to dip individually 35º north, and the apparent shallow dipping seismicity to be due to scatter in seismicity and multiple faults

The western part of the Gulf, however, looks more simple than the eastern part (where the 1981 earthquake sequence occurred). In the west, most of the seismic activity seems to be related to the Helike fault, even the Ms=6.2 1995 Aigion event ruptured the Aigion fault. The Psathopyrgos fault does not look seismically active. During the 1992 Galaxidi earthquake, we recorded very little aftershocks that suggested us the earthquake to be related to a possible asperity between the Helike and the Xylokastro faults. Conversely, in the east, the antithetic faults that bound the Gulf both on the North and on the South, limit a graben of relatively small dimensions that vanish eastward. West of Patras, the tectonics is also more complex, a few strike slip mechanisms, computed both for microearthquakes and moderate magnitude events cannot be related to any active faults at the surface.

Conclusion

The Gulf of Corinth is certainly a very active extensional structure. Most of the active faults are located to the South of the Gulf and dip northward. The western Gulf (around Aigion) looks more simple than the eastern Gulf (Corinth). Most likely the dip of the active faults is about 35º toward the North.

New Reflection and Refraction Seismic Investigations in the Region of the Gulf of Corinth

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Introduction

In the frame of the Greek-French SEISGREECE experiment in January 1997, the N/O Le Nadir of IFREMER shot a single-bubble air-gun array every 50 to 75 m in the part of the Gulf to the East of Eghion. The signals were recorded by 6 OBS of ORSTOM, seismometers which were operated at sea bottom in the Gulf, as well as by over 12 seismometers at station sites on land. The 96-channel, 2400 m long seismic streamer of the vessel could be deployed to record a vertical reflection profile with 24-fold coverage, but only along the axis of the Gulf because of stormy weather. Processing of the data is still in progress at this early date after the acquisition, and the elements of interpretation hereafter are provisional; the current status of the results should be checked with the authors before use in further interpretation or planning.

Background

Greece is characterized by strong earthquake activity and the Aegean domain is in rapid extension. The Corinth Gulf has received particular emphasis in the study of seismogenesis and of present extension, because of its high level of seismicity and because geological investigations can be applied here on the flanks of the Gulf, to the seismotectonic problem.

In the eastern part, inferences on the upper crustal structure have been made from modeling of the tectonic response to normal-faulting. They used the upwarp of marine terraces near Corinth at the eastern end of the Gulf (Armijo et al., GJI, 1996). In the western part inferences on upper crustal structure come from micro-earthquake locations (Rigo et al., 1996, GJI) and interpretation of the source parameters of the 1995 Eghion earthquake (Bernard et al., 1997, J. Seism.).

Aims

The modeling of footwall upwarp of the Xylokastron fault in the East, from surface geological evidence had lead, under assumption of a single high-angle normal-fault, to a model which predicts that a young sedimentary basin of over 5 km thickness is located under the Gulf in the hanging-wall of the fault. Across the Helike-Eghion fault in the West microearthquakes have been interpreted to occur on high-angle faults but it has been suggested that these would merge into a shallow-dip detachment, with relatively low-angle slip, which was also the fault-plane of the large Eghion earthquake. Alternatively, the cut-off depth of microearthquake locations could correspond to a rather shallow position of the brittle-ductile transition.

The aims of the present study accordingly were to measure by seismic methods:

- the depth of the recent basin in the East and compare it to models
- to test whether the Xylokastron fault was the single structure controlling the

basement deformation

- to explore for interfaces within the upper crust which could be interpreted as flat tectonic structures, like the seismogenic detachment suggested in the West.

Design of the experiment

To measure the upper crustal layering, in particular the thickness of recent basins in order to constrain seismotectonic models, several OBS (Ocean Bottom Seismographs) were deployed with small spacing and a system of shot lines providing reversed in-line, as well as fan, observations. This was in order to provide a section of the basin just north of the major border fault at each end of the Gulf, Xylokastron in the East, Helike in the West, where the other data, earthquakes and geology had already been studied.

Mutichannel reflection seismic could be carried out (but only on one line along the axis of the Gulf since the experiment coincided with the major winterstorm of the last decades, of January 13, 1997) with the aim to interpolate the depth of the post-alpine basement between the two ends of the Gulf where OBS would identify the layering by providing seismic velocities. This line was also recorded by the OBS (and land stations) at a range allowing penetration into the basement.

Wave identification and structural layering

After filtering and deconvolution, the display of variable-offset record-sections allows to identify a series of wavegroups due to multipathing in a layered structure. Traveltime curves of conspicuous branches can be correlated as follows:

- The refraction-diving wave into a gradient layer just beneath sea-bottom, of unconsolidated sediments with seismic velocity V1<2km/s
- The reflection on, and diving refraction into the underlying layer of sediments presumably of the recent extensional stage, V2 from 2 to 3 km/s
- The reflection on top and refraction-head wave into a V3>4.5 km/s medium, interpreted as the basement after the Hellenic orogeny and before extension, that is the top of the Alpine nappes
- Headwaves or refractions at around 6 km/s velocity at depth in the deeper crystalline or metamorphic level within the post-alpine basement.
- Intrabasement wide-angle reflections are conspicuous as second arrivals on the variable offset lines at distances over 10 km, on OBS and also on land stations. Their amplitude can be modeled with synthetic seismograms. However, when sampled from different stations, they do not as yet indicate a single reflector (or then with notable relief), but rather are turned back from more than one reflectors in the 4 -8 km depth range.

The marine multiple coverage normal incidence reflection profiling is in the course of processing. Samples of a 24-fold, very brute stack, obtained from the 96-channel records of the 50 m spaced airgun shots shows late energy (more than 6s TWT) to be dominated by waterwave echoes on the basin-bordering fault scarps and the coast. The first seconds of the data however very clearly show good signal penetration and resolution to the basement. The infill of stratified soft recent sediments is clearly bounded at depth by a strong interface. The very diffractive low frequency response identifies this level as a basement, formerly outcropping topographical surface, presumably the post-alpine basement, top of the nappe pile resulting from convergence. The sediments show more than a single sequence, and only part of them may correspond to the present style of activity. They are limited to 3s TWT, i.e. 3 km beneath sea-level. The recent sediments exhibit a very variable thickness in relation to variations in the depth to the post-alpine basement

Preliminary results

(1) The upper crustal layering is clearly identified. On the multichannel, vertical reflection line, under a well-stratified sedimentary sequence, a strong reflector shows diffraction images characteristic of a basement surface. This interface is also identified as a main refractor on the OBS, with a velocity on the order of 5 km/s. Accordingly it can be interpreted as the postalpine basement, i.e. the level which formed the topographical surface on top of the pile of nappes.

Two other refractors are documented. A shallower one separating two gradient layers the average velocities of which are respectively lower and higher than 2.3 km/s. A deeper one where velocity increases to over 6 km/s, this is inside the postalpine basement, presumably the base of the alpine nappes, or a particularly high velocity one of the sheets (mesozoic carbonates?).

(2) The present topography of the postalpine basement is distinctly constrained by the data to have three deeps along the axis of the Gulf. They also correspond to three recent depocenters. There is evidence from seismic stratigraphy for half-graben subsidence. We take tentatively this evidence to suggest that there are three faults which control the deeper, southeastern edge of each of the basins which are at an angle to the axis of the sea-bottom trough. The extreme ones are the faults of Xylokastron and Eghion-Helike mentioned previously from other studies.

The third fault, in intermediate position, also extends down into the basement level. We suggest that it is the deep expression of the feature mapped from the surface into the upper part of the basin by Brooks and Ferentinos (1984, Tectonophysics) from a grid of single-channel seismic lines (and suggested as a listric growth fault in the sediments). Then its geometry allows to suggest that this deep-reaching fault in the Gulf can be prolongated towards the coast in continuation with the Derveni fault on land.

(3) Clearly, only a denser grid of profiles would allow to really constrain the geometry in map view. The three fault-bounded basins are probably parallel and en-echelon, although we do not have a grid of profiles to define their shape. The three sedimentary basins have a basement at about 3 km depth below sea-level, and an infill of about 1.5-2 km of recent sediments.

(4) Intrabasement reflectors are conspicuous in the wide-angle data. Although they will have to be carefully corrected for upper crustal heterogeneity they do not appear to correspond to a single continuous level as could have been expected for a detachment, but they are turned back from within an interval between 4 and 8 km depth.

(5) Late, deep reflections under the western part of the Gulf, the first to have been recorded in this region to our knowledge recall that the crust may be over 40-45 km thick, still bearing the mark of Alpine convergence and thickening, although extremely rapid rifting occurs now at the surface.

Electrical Conductivity and Structure of the Crust around the Gulf of Corinth from Magneto Telluric Sounding (MTS) Results

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The geological structure around the Gulf of Corinth consists of a W-verging stack of flat-lying nappes belonging to the Hellenides range, striking NNW-SSE. These thrusts have been deformed and folded during the EW compression phase, then uplifted and cut by the normal faults related to the Neogene extension phase, resulting in a set of nearly perpendicular structures.

In order to bring additional information on the crustal stucture of the rift, IPGP and NOA conducted a magnetotelluric survey in October 1995: 15 MTS stations have been operated with 11 sites to the north, west of Itea, and 4 sites to the south, near Aigion. We present here the results for the LAK-AMI profile, about 38 km long, crossing the Gulf. Figure 2 shows the geoelectrical section of the LAK-AMI profile.

The first striking observation is the existence of a relatively conductive zone of about 7 km thick below 9 to 12 km depth. This is due to the presence of fluids in zone of ductile shear. The top of this zone coincides with the decollement zone

Rigo et al. (1996) showed that the microseismicity is mainly located between 6 and 11 km in depth, suggesting the existence of a decollement zone under this seismogenic layer at around 10 km depth dipping 15° (+10°) northwards and corresponding to a transition from the lower semi- brittle (or ductile) zone to the upper brittle zone.

deduced from microseismicity study. However, it does not present any evidence for a northward low dipping angle. Furthermore, this conductive zone is not restricted to the root of the active normal faults, but exists under all the studied area. It could be therefore related to tectono-metamorphic processes due to the pre-Neogene activity of the thrusts. This inherited ductile zone would currently favour the decollement of the upper brittle crust and the rifting.

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Enhanced Observations with Borehole Seismographic Networks.

The Parkfield, California, Experiment

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The data acquired in the Parkfield, California experiment are unique and they are producing results that force a new look at some conventional concepts and models for earthquake occurrence and fault-zone dynamics. No fault-zone drilling project can afford to neglect installation of such a network early enough in advance of the fault-zone penetration to have a well-defined picture of the seismicity details (probably at least 1000 microearthquakes - an easy 2-3 year goal for the M<0 detection of a borehole network).

Analyses of nine years of Parkfield monitoring data have revealed significant and unambiguous departures from stationarity both in the seismicity characteristics and in wave propagation details within the S-wave coda for paths within the presumed M6 nucleation zone where we also have found a high Vp/Vs anomaly at depth, and where the three recent M4.7-5.0 sequences have occurred. Synchronous changes well above noise levels have also been seen among several independent parameters, including seismicity rate, average focal depth, S-wave coda velocities, characteristic sequence recurrence intervals, fault creep and water levels in monitoring wells. The significance of these findings lies in their apparent coupling and inter-relationships, from which models for fault-zone process can be fabricated and tested with time. The more general significance of the project is its production of a truly unique continuous baseline, at very high resolution, of both the microearthquake pathology and the subtle changes in wave propagation.

In a series of eight journal articles since 1991 (see references) we have presented the evolution of a new and exciting picture of the San Andreas fault zone responding to its plate-boundary loading. Abstracts from two recent articles are useful summaries of our present knowledge:

Karageorgi, E.D., T.V. McEvilly and R.W. Clymer, Seismological Studies at Parkfield IV: Variations in Controlled-Source Waveform Parameters and Their Correlation With Seismic Activity, 1987-1994, Bull. Seism. Soc. Am., 87, 39-49, 1997.

Since June 1987 at Parkfield, California the ten-station borehole network of three-component sensors has been illuminated 52 times using a shear-wave vibrator in three orientations at seven source points, in a search for temporal changes in elastic wave P and S velocities, anisotropy or attenuation. The monitoring interval includes the beginning and end of a severe three-year drought and four earthquake sequences, two of which produced the only A-level alerts to date in the Parkfield Prediction Experiment. A comprehensive study of the entire data set reveals a progressive travel-time advance in the coda of S-waves propagating in a localized region southeast of Middle Mountain. The anomalous wave field exhibits high apparent velocities suggesting deep penetration of the fault zone, although similar changes are not seen in waveforms from repeating similar microearthquakes. Accompanying the changes in travel-time were systematic variations in spectral content and polarization in the same segments of the wavefield. These variations correlate well in time and space with significant features of seismicity, fault creep and water levels at Parkfield. A preferred mechanism for the phenomenon is changing hydrologic conditions along the affected stretch of the fault zone, possibly deformation-induced, that perturb the shallow-propagating S coda in the upper few hundred meters of section.

Nadeau, R. M. and T. V. McEvilly, Seismological Studies at Parkfield V: Characteristic Microearthquake Sequences as Fault-zone Drilling Targets, Bull. Seism. Soc. Am., 87, December, 1997.

Studies at very high resolution of microearthquakes at Parkfield, CA since 1987 reveal a systematic organization in space and time, dominated by clustering of nearly identical, regularly occurring microearthquakes ('characteristic events') on 10-20 m wide patches within the fault zone. More than half of the 4000+ events in our 1987-1996 catalog exhibit this trait. In general, recurrence intervals (0.5 to 2 yr.) scale with the magnitude of the repeating events for the on-scale range (Mw 0.2 to 1.3) in this study. The similar waveforms, superimposed locations, quasi-periodic recurrence and uniform size of these characteristic events permit relative hypocenter location accuracy of meters and predictable occurrence times within windows of a few months. Clustered characteristic events occur at depths as shallow as about 3 km, and these are feasible targets for deep scientific drilling and observation at the focus of a subsequent small earthquake within an active plate-boundary fault zone. At Parkfield the achievable location accuracy to which a hypocenter can be specified as well as the predictability of its occurrence time appear to be uniquely favorable for in-situ fault zone measurements.

A third paper presents even more tantalizing results:Nadeau, R. M. and L. R. Johnson, Seismological Studies at Parkfield VI: Moment Release Rates and Spectrally Independent Rupture Dimension Estimates for Small Repeating Earthquakes, Bull. Seism. Soc. Am., 87 (in press), 1998.This last paper considers implications of the small areas and moment-dependent recurrence times of the characteristic events for the process of fault slip, deriving self-consistent scaling relationships among moment, area and stress drop that appear to hold over at least six orders of magnitude (up to the M6 events).Their dramatic and inescapable conclusion is that stress drop is clearly proportional to moment over that range, and that the smallest magnitude microearthquakes having slip surfaces no larger than a square meter must have stress drops of kilobars. This is a significant conclusion, often proposed and debated in the past, but without the convincing data provided by the Parkfield network.

The obvious implication (also often proposed before but unsubstantiated) is that the estimation of source radius from the displacement spectral corner is confounded by attenuation effects. The borehole data show convincingly that at magnitude in the range 0.5 to 1.0 the source-dependent corner frequencies exceed 100 Hz (see Nadeau et al., 1994). An interesting corollary to the scaling work is that the recurrence times represent slip rates on the fault surface at the cluster locations. These are seen to vary systematically in space and time, and further, they are clearly synchronous with the larger episodes of seismicity on the fault. These tiny clusters microearthquakes, observable only with borehole instruments and having recurrence times of months, thus can be viewed as local indicators of slip rate on the fault. It should now be evident that the nature of this data set -- borehole sensors in a quiet region giving a large magnitude range of on-scale recordings with high signal-to-noise ratio and minimum near-surface site effects, coupled with the clustered nature of the seismicity -- make it ideal for studies of fault zone dynamics and for seeking evidence of identifiable precursory phenomena prior to large earthquakes. Arguably the Parkfield experiment is the most significant and perhaps the only effort that will ultimately provide a definitive answer to the precursor question. The series of papers we have published with the borehole data at Parkfield illustrate what can be done to characterize at very high resolution an active fault zone.

The Corinth Rift Zone promises equally revealing and exciting discoveries if we can install a borehole network of several stations a few years before the deep drilling commences.

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Continuous Measurements of Strain and Hydrological Effects in Iceland

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Continuous measurements of volumetric strain in boreholes has been carried out since 1979 at 7 sites in and around the South Iceland seismic zone (SISZ). The most significant results are the observations of slow strain changes before and during 2 eruptions in the volcano Hekla and before and after an earthquake of magnitude 5.8 on the eastward prolongation of the SISZ. In both cases strain signals observed to a distance of up to a few tens of kilometers could be used for modelling volcano and earthquake related processes with duration of hours to days.Long lasting changes are seen in the strainmeter monitoring records after careful cleaning of athmospheric and tidal effects. However it has so far not been possible to verify these changes by other measurements. Increased compression is observed in the SISZ after 1990, lasting for one or two years. It has been suggested that a sequence of seismo/volcanic epizodes in SW Iceland between Reykjanes peninsula and Hekla in this time period is related to this observed increase in compression. There are also indications for increased compressive strain rate during early 1996 to the north of SISZ and simultaneous decreased strain to the south of it, while no change is seen in the SISZ itself. At the same time increased compression was inferred from observations of shear wave splitting near the SISZ, which has been related to dyke injection in in the Vatnajökull area in the preparation stage of the Vatnajökull eruption of October 1996.

A program for monitoring radon in borehole wells in the SISZ was initiated in 1977. Up to 9 stations were monitored and the length of the time series varies from 3-16 years. Samples were taken every 1-3 weeks. A significant correlation was found between radon signals, especially increase, and small earthquakes, i.e. the earthquakes following the signal within 6 weeks. It was observed that some measuring stations are more sensitive than others and some anomalies are observed at great distance from the earthquake which they are considered to be related to. This can possibly be explained by that both the radon anomaly and the earthquakes are related to a common source.

The radon measurements were discontinued in 1993 because of lack of funding. It is intended to start them again partly with a support from and as a part of the ongoing PRENLAB project in Iceland (EU supported).

A new project is now being planned in Iceland named: A search for earthquake precursors in South-Iceland geothermal reservoirs. The aim of the project is to find and to monitor possible earthquake precursors in South-Iceland geothermal systems. It is planned to install simple pressure, temperature or vibration devices near periodic eruptive geysirs or in deep geothermal wells or to collect similar signals from already operating monitoring systems of a few district heating systems in S-Iceland. It is considered that the deep roots of geothermal systems are likely to be sensitive to changes in stress conditions in the crust. There is historical evidence for such a precursors in Iceland, and P.G. Silver and N.J. Wakita, 1996 and P. G. Silver and N.J.Valette-Silver, 1992 have reported in Science changes shortly before large earthquakes in groundwater- and hydrothermal-systems.

This project is planned as a cooperation between the National Energy Agency of Iceland, which does thermal energy prospecting and research and the Icelandic Meteorological Office, which would provide monitoring facilities, which is the SIL system. The project is linked to the PRENLAB project although there is no direct input from PRENLAB funds to the project. The project is a low budget project based on good-will of the hydrothermal power companies and utilizing in some cases monitoring facilities that are already in use.

Hydrological effects are now observed indirectly by observations based on the SIL microearthquake system in Iceland. The SIL system is an automatic seismic acquisition and evaluation system. It automatically provides information on epicenters, fault plane solutions, moment magnitudes and other source related parameters of even very small earthquake. In a part of the system where station spacing is 20-30 km it is almost complete down to magnitude zero. By multievent analysis, relative accuracy of hypocenter locations is within 10 meters. The analysis methodology used, also improves the absolute accuray considerably, especially the depth. The relative accuray achieved, if errors are small compared to the fault planes, makes it possible to map active fault segments at depth. In this mapping and comparing with fault plane solutions the arrangement of planes for individual microearthquakes across the main fault plane shows a character which very difficult to explain without taking into account fluid activity, hydrofracturing, in the process.

The significance of microearth-quakes in studying earthquake processes has been clearly demonstrated in Iceland. They occur almost continuously both in time and space, so automatic evaluation to the degree which is possible is necessary. The acquisition facilities necessary for the microearthquake acquisition and evaluation can then easily cope with all the slower acquisition like strain and hydrological effects.

Some notes or advices based on the discussion in Athen October 26 - 28, related to the Corinth Multiborehole observatory. A fundamental objective of the project should be to create a better understanding of this very active earthquake area. The knowlegde aquired creates a better basis for mitigating earthquake risk in the area. This requires continuous research work after the end of this project and continuous monitoring of ongoing activity. To understand earthquake processes we need long term monitoring. The aim of long term monitoring is twofold. Firstly to create basis for earthquake prediction research or better hazard assessments. Secondly the monitoring system must carry out real time evaluation which is based on the ever groving understanding of the earthquake processes. We must take into account that science may in near future increasingly be able to provide useful warnings. In cases where this is possible it would be catastrophic for science not to act because of technical difficulties, i.e., the scientists might not make use of the modern computer technology for automatic evaluation. Research and being on the alert must go hand in hand. Real time monitoring and evaluation is in general significant to be able to inform the public about ongoing activity.

In cases that drilling of boreholes would be significant for improving the real time monitoring they should be drilled with the twofold objective of real time monitoring and of performing of in situ measurements.

For real time monitoring I see as most significant the creation of a well designed microearthquake system covering a large part of the area around the Gulf of Corinth:

Objectives

Detection and location of earthquakes down to magnitude zero and finding fault planesolutions. This must be done automatically. Mapping of active faults with relative errors less than 10 meters. Various other evaluations can be based on the above results.These objectives can be achieved by:

A minimum of 6 three-component seismometers with a spacing of about 20 km in the area. Increasing the number of stations would rather be for better coverage of the area as a whole than for denser station spacing. For the most possible sensitivity of the system a net detection is recommended (single station phase detection and multistation event selection). The digital signals must have better than 1 ms time accuracy. Adequate sampling frequency is 100 sec. 140 db resolution is recommended, 24 bit. To be able to cope with the enormous amount of data expected. the system must be highly automatic, both as concerns acquisition and evaluation. Low operation cost is a very significant condition for continuous future monitoring. The system design must be careful to avoid all sorts of high freq. noise as much as possible. It will probably lower the noise, in most cases, to put geophones into boreholes. Both for keeping the initial cost and the operational cost down it is however significant not to overdue here. This applies also for the geophones, i.e. how broad band they are. For the objectives listed above, a good 1 sec. geophones would certainly be good enough for the great majority of the earthquakes. A few more broad band seismometers, lower frequencies, should be included in the system for the larger earthquakes.

The SIL system, which has been in development in Iceland since 1988, and has been in automatic operation to carry out the above kind of processes since 1991, would be a very good choice, having overcome many communication and signal association problems during 7 years of automatic operation. Several other applications of the seismic system can be utilized besides those mentioned above, like sudies of anisotropy based on shear wave splitting and 3 dimensional inversions for seismicwave velocities of microearthquake residuals.

Besides its application as a seismic system in Iceland it is already being applied for a drillingexperiment. That experiment is a EU supported experiment under FERMI (an EU project). The purpose of the SIL system in that project is to study the effects, fractures created, when a drill hole is pressuraized by pumping water into it for increasing its efficiency.

Strainmeters

A good advice, based on Icelandic experience, is a careful study of the boreholehole in advance, f.ex. by monitoring with cheaper measurements for example millidegree thermometers or hydrophones. The purpose would be to see how sensitive the hole is for disturbances, especially rain. It is more significant for lowering noise to avoid water carrying veins or cracks than simply to drill deeper. In Iceland we have only used boreholes that were available because of other purposes. We have used with good results holes in depth range between 100 and 400 meters. The reason not to use deeper holes is partly that it is expected that both start cost and long term operation cost would be higher. Continuous waterlevel and temperaturemeasurements in the boreholes should always be included in the long term operation of strainmeters.

The GAIA Project:

A European Test Site for Earthquake Precursors and Crustal Activity at the Gulf of Corinth

E.C., DGXII, Environment Program, Seismic Risk
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The GAIA project started the instrumentation for a multiparameter observatory for crustal instabilities and earthquake precursors in the most seismic, continental region of Europe: the Gulf of Corinth, in Greece.

The Gulf of Corinth is a recent, asymetric rift, 120 km long and 10-20 km wide, opening at 1.5 cm/year according to GPS surveys (Briole et al., 1997), with a corresponding strain rate of 10^{-6}/year, and one earthquake with magnitude greater than 6 every 5 years. The major normal faults are dipping north, outcropping onshore as well as offshore near the southern coast (Armijo et al., 1996). Microseismicity is restricted between 5 and 10-12 km in depth (Rigo et al. 1996). MT surveys conducted within the GAIA project have detected the presence of a high conductivity layer below 10 km in depth, suggestive of ductile rheology (Pham et al., 1997). The last destructive events are the M=5.8, 1992 Galaxidi earthquake (Hatzfeld et al., 1996) and the M=6.2, 1995 Aigion earthquake (Bernard et al., 1997). A magnitude 5.5 earthquake occured the 5 November 1997, near the hypocenter of the Aigion earthquake - 10 days after the workshop. Several European or national projects are presently working on the structure of the rift: detailed bathymetric studies (Papanikolaou et al., 1996), seismic reflection and refraction (Sachapzai et al., 1997), and lithospheric seismic structure (Tiberi et al., 1997).

For the GAIA project, we leave to one side the premature question of earthquake prediction, and concentrate on the physical processes at work in the deformation of the crust, considering that the precursors to earthquakes, as well as the earthquakes themselves, are part of crustal instabilities with a large range of time and spatial scales. We therefore do not restrict ourselves to earthquake precursors - if any - , but consider the more global framework of coseismic (earthquake rupture), postseismic (crustal relaxation), and interseismic phases (precursory events, short term instabilities, and tectonic secular loading). The project will contribute to define optimal methodologies in terms of instruments, site selection, data analysis, and physical modeling for the detection and understanding of these seismic and aseismic instabilities. One originallity of GAIA is that it focusses on a system of faults - and not on an individual segment-: in the long term, it may provide valuable results on mechanical coupling between these faults.

Several tens of sensors have been already set up in multiparameter sites with continuous monitoring:

- 5 telemetered seismometers, covering the central eastern part of the gulf, to be completed by two seismometers to the west, providing a global coverage of the Gulf
- 9 accelerometers (5 more are planned in 1998) in the central-western part of the gulf, which will allow waveform inversion for earthquake ruptures with magnitude greater then 5.5
- 1 geophysical observatory in a natural cave, near Galaxidi, on the northern coast: 3 strainmeters in a decametric crack, 6 tiltmeters, droplet counters under stalactites,2 tide-gages in the lake (connected to the sea), pressure, temperature, rain
- 5 boreholes, 10 m deep, for the installation of tiltmeters (planned early 1998).The sites are located on the northern coast, where short or long term tilt is expected to be dominant, and where outcropping limestone provides hard rock conditions. Site spacing is about 10 - 15 km, for
- allowing spatial correlation for deep sources of strain
- 1 gravimeter in Delfi, with data retrieved in Athens by phone line. A second gravimeter will be installed more to the west, closer to the active zones.
- 1 tide-gage site near Galaxidi. A second site is planned on the southern coast.
- several sites for radon measurements in soil and in ground water: on the Helike fault scarp, in particular with radon (and hydrogen) sensors in a dry borehole 30 m deep; on the Aigion fault scarp; near Kalithea (nothern coast), where a radon anomaly occured three days before the Galaxidi 1992 earthquake; and on two large, karstic springs, near Itea.
- 4 sites for electromagnetic measurements: electrotelluric lines (4 sites), radio-receivers (2 sites), magnetometer (1 site). Three sites are on the northern coast, one is to the south near the Helike fault.

The GAIA project should be considered as the first stage in a long term research project: the multiparameter geophysical monitoring of the Corinth rift, with the aim to track and model its present deformation processes which couples seismic activity, fluid flow, and aseismic deformation. It is therefore very closely linked to some of the scientific objectives of the proposed deep drilling project, as monitoring geophysical parameters at large depth and/or within fault zones might bring major observations on these processes. This is thus an excellent opportunity for opening the GAIA project to a broader international community.

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Deep Borehole Drilling for Integrated Geoscientific Studies

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The UAT.DGG has been involved in academic and applied research in the broader area of the Gulf of Corinth for over 15 years. Research topics included seismotectonics, seismicity monitoring and analysis, earthquake source analysis, seismic wave propagation, earthquake risk and hazard analysis, magnetotelluric investigations of the geoelectric structure, geothermal research, regional gravity studies, GPS monitoring of crustal deformation and numerous small scale investigations, the latter being part of services offered to local government and private organisations.

The UAT.DGG operates permanent seismological networks, (digital wireless telemetry), which enclose the Gulf and allow for the detailed and precise monitoring of seismic activity. These include the CORNET, (Corinthos Network), and VOLNET, (Volos Network), equipped with short period seismometers, the ATHENET, (Athens Network), equipped with broad band seismometers and the RASMON, (Rio-Antirio Strong Motion Network), equipped with strong motion accelerographs. The total number of stations in the UAT.DGG networks is 24, with 16 located in the immediate vicinity of the Gulf.

The drilling of deep boreholes will provide a wealth of data and direct evidence to confirm or refute models, predictions and expectations derived from hitherto work, as well as answers to several important questions concerning the physical processes leading to seismogenesis in extensional geotectonic settings, such as is the Gulf of Corinth. Many theories regarding active tectonics, crustal deformation, anisotropy, seismicity, earthquake sources and earthquake premonitory processes are now based on assumptions, data from shallow boreholes or, on laboratory measurements. Deep boreholes provide the opportunity for *in situ, multi-disciplinary* measurements yielding, in turn, constraints to theories and quantitative studies.

The Gulf of Corinth is an ideal candidate for the proposed programme. The high seismicity of the area is a major factor in such a long term monitoring programme, since it provides data in a short period of time. Moreover, there exists extensive background information from previous national and international studies; this data will be extremely important in guiding the progress of the project in the pre-drilling and drilling phases. In addition, the rift zone of the Gulf of Corinth is in the proximity of the Athens, Patras and Corinth metropolitan areas and is easily accessible from both the north and south shores.

The objectives which will be met during this program may also have direct practical applications on issues of protection and mitigation of earthquake and geological hazards, inasmuch as the available data will improve the understanding of processes involved in the response of ground or slopes to shaking.

One of the most significant benefits with scientific, as well as national importance, is the development and application of new acquisition systems, field measurements, processing, analysis and modelling techniques. This implies technology transfer and experience/know-how exchange between the participants.

In concluding, we expect that the results will be fundamental in improving our understanding of problems pertaining to tectogenesis, seismogenesis, earthquake prediction and protection against natural hazards..

Technical Aspects of the Gulf of Corinth Scientific Drilling

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Abstract

The structure and organization of the scientific drilling project at the Gulf of Corinth depends on the specific geoscientific goals and drilling constraints which include drill site conditions (ownership, duration of drilling, environmental issues), the individual boreholes (number, diameters, depths, directional steering, casing scheme), drill cores required (coring method, sections, diameters, core orientation technique), and the intended scientific investigations (inhole experiments, logging program, on-site geoscience).

Motivation and conception, planning and realization of the drilling project is a multi-step iterative process:

Before establishing the large-scale interdisciplinary research and development program of scientific drilling, a thorough pre-site-survey on the regional and local structural geology and tectonics must first be carried out. Based on the various goals of this drilling project as well as on environmental and transport restrictions and the infra-structure in general, these pre-site-investigations will lead to the selection of an optimum site for the borehole(s). Subsequently borehole and surface measurement programs and the development of appropriate technologies will be defined and initiated.

Organisation and planning of this drilling project comprises the definition of the technical and operational design, clarification of management and financing strategy as well as training of expert personnel. Technical aspects range from drill site location with its structures and drill rig to the actual drilling scheme and logging and coring programs. In addition, the organisation and set-up of a compatible data base system from the start is a most important task. Establishment and management of funding sources as well as industrial support and cooperation covers a broad spectrum of economic and political aspects. However, the technological spin-off resulting from this scientific drilling program as well as a crucial boost to already existing knowledge, e.g., in seismic hazard mitigation is hoped to later compensate investments for this project.

Drilling operation requires suitable drilling technology, selection of an optimum (water-based) drilling mud, and the establishment of a field laboratory. The drilling and casing scheme depends strongly on the type and mechanical stability of rock encountered, on the coring sections, logging campaigns and in-hole experiments. After completion of the active drilling phase, a deep observatory for seismological, hydrological, geohydraulical and geomechanical long-term measurements should be installed at the bottom of the borehole for post-drilling investigations.

The integrated interpretation of all drilling and logging data can be achieved by computer network processing including visualisation of the data profiles through a standardized data base system such as the GEOLOG^{GFZ}-program. This can also be used in future, e.g., to acquire and disseminate stress data in the earthquake prone area of the Gulf of Corinth.

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