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PEOPLE
MARIE CURIE ACTIONS

Marie Curie Initial Training Networks (ITN)
Call: FP7-PEOPLE-ITN-2008

PART B

QUANTITATIVE ESTIMATION OF EARTH'S SEISMIC SOURCES AND STRUCTURE

"QUEST"

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B.1 LIST OF PARTICIPANTS

Table 1: List of academic and industrial partners (level of involvement in [], see Guide for Appl. p. 11). A * indicates a letter of support attached.

Partner		**Legal Entity**	**Department**	**Person-in-charge**
1	LMU	Ludwig-Maximilians-Universität München DE	Computational Geophysics	Prof. Dr. H. Igel
2	SCR	*Schlumberger Research Cambridge UK **[1,2,3]**	Exploration Geophysics	Dr. J. Robertson
3	SSZ	*Spectraseis AG Zurich CH **[1,2,3]**	Research and Development	Dr. B. Artman
4	IPG	Institute de Physique du Globe Paris FR	Seismology	Prof. Dr. J.-P. Montagner
5	ING	Istituto Nazionale di Geofisica IT	Geophysics and Volcanology	Prof. Dr. A. Morelli
6	ETH	Federal Institute of Technology Zurich CH	Geophysics	Prof. Dr. D. Giardini
7	UOX	University of Oxford GB	Earth Sciences	Prof. Dr. J. Woodhouse
8	UUT	University of Utrecht NL	Earth Sciences	Prof. Dr. J. Trampert
9	UCD	National University of Ireland Dublin IE	Geological Sciences	Prof. Dr. C. Bean
10	UJF	Universitè Joseph Fourier de Grenoble FR	Geophysics	Prof. Dr. M. Campillo
11	CUB	Comenius University Bratislava SK	Mathematics, Physics	Prof. Dr. P. Moczo
12	CUP	Charles University Prague CZ	Geophysics	Dr. J. Brokesova
13	OGS	Istituto Nazionale di Oceanografia Trieste IT	Exploration Geophysics	Prof. Dr. G. Seriani
14	UEA	University of East Anglia, Norwich, GB	Environmental Geosciences	Dr. A. Ferreira
15	UPO	University of Potsdam DE	Mathematics	Prof. Dr. M. Holschneider
Associated Partners				
IBM		*IBM Zurich Research Lab CH **[2,3]**	High-Performance Computing	Dr. Alessandro Curioni
MSI		*MicroseismicInc Houston USA **[2,3]**	Passive Imaging	Dr. L. Eisner
RZG		*RZG Garching / DEISA Project DE	Grid Computing	Dr. S. Heinzel
UNC		Univ. of Nancy/GOCAD Consortium FR	Numerical Geology	Prof. Dr. G. Caumon
TUM		Munich Computational Science Centre	Computational Science	Prof. Dr. H. Bungartz
CAL		Cal. Inst. of Technology Los Angeles, USA	Earth Sciences	Prof. Dr. J. Tromp
ANU		RSES Canberra AU	Geodynamics	Prof. Dr. B. Kennett
TOK		Tokyo University JP	Earth and Planetary Sciences	Prof. Dr. R. Geller
UCB		University of California, Berkeley USA	Seismology	Prof. Dr. B. Romanowicz
UAU		University of Austin USA	Computational Earth Sciences	Prof. Dr. O. Ghattas
LAN		Los Alamos National Laboratory USA	Parallel Computing, Time Reversal	Dr. L.J. Huang
CAM		University of Cambridge	Deep Earth Structure	Dr. A. Deuss
ENS		Ecole Normal Superieure Paris FR	Earthquake Rupture Processes	Prof. Dr. R. Madariaga
UHH		University of Hamburg DE	Earthquake Source Inversion, HPC	Prof. Dr. T. Dahm
UNA		University of Naples IT	Volcano Seismology	Prof. Dr. A. Zollo

Note[1]: This ITN is a re-submission with substantially revised work programme and participants. The proposal emphasizes industrial applications and supercomputing, joining lead scientists in the fields of exploration seismics, seismology, applied mathematics and high-performance computing, volcanic and seismic hazard, earthquake physics, physical inverse problems, geodynamics, from Departments of Mathematics, Physics, Earth and Computational Sciences, Oceanography and Exploration Geophysics. The consortium is complemented by the formal partnership of the leading supplier of geophysical technology to the oil and gas industry (Schlumberger Research) and an expanding new company (Spectraseis AG, Zurich). In order to foster pan-European exchange and open up the job marked outside Europe the network is complemented by associated partners in the US, Australia and Japan. Moreover, an alliance between QUEST and partners, the IBM Zurich Research centre, the DEISA project (a.o.) ensures the achievement of training and research goals in supercomputing issues. The QUEST lead-scientists are or have been involved in numerous EU funded activities such as the SPICE, NERIES, VOLUME, SESAME, and others. **This is the first EU-wide project of its kind focusing on the scientific and technical challenges of the seismic imaging problem in the PetaFlop age employing 3-D high-performance computing methodologies.** The substantial size of the network and training components is justified by the rapidly increasing demand of Earth scientists in the industry with sound training in computational applications and high-performance computing (HPC) methodologies.

[1] Acronyms are explained at the end of the proposal.

B.2 PROJECT OVERVIEW AND OBJECTIVES

Storing CO_2 in the subsurface to reduce global warming, finding hydrocarbon and other resources and monitoring their extraction, generating energy with Earth's internal heat, and forecasting natural hazards (earthquake-induced ground motion, volcanic eruptions, tsunamis) requires high-resolution tomographic images of the Earth's interior. Seismic waves are the most informative source of information on subsurface properties due to the short spatial wavelengths involved and the high efficiency of elastic wave propagation in the Earth. **The main goal of QUEST is research and training in the development of strategies for automated seismic imaging using the increasing power of 3-D simulation technology**. Existing methodologies are currently subject to a revolutionary change: While so far the observed information was severely reduced and approximate methods (e.g., ray theory) were used to determine Earth's structure, the massive increase in available computational resources allows us now to make use of the complete information contained in the observations. The actual application to real data and the Earth in its full three-dimensionality is at the beginning and the QUEST partners are at the leading edge of the corresponding research domains. The QUEST objective is to integrate the various elements (wave propagation, high-performance computing, inverse problems) exploiting the synergies of the network expertise and develop the next generation of imaging tools for use on all spatial scales.

With narrowing resources and increasing energy prizes the exploration industry is seeking highly skilled young scientists capable of driving the new computational technologies towards industrial problems. Earth Science graduating students in general are lacking profound theoretical and practical training in numerical methods and high-performance computing in connection with simulation and inversion software. QUEST intends to fill this gap offering the students excellent prospects in industry and academia as the combination of skills to be trained are highly in demand. The training and research on HPC solutions in seismic tomography will not only have an impact on industrial applications. We expect substantial progress in understanding the dynamics of our planet, the quantification of natural hazards such as earthquakes, tsunamis, volcanic eruptions and the associated risks to our societies. Without automated data analysis schemes on HPC systems our community will not be able to handle the dramatically increasing data volumes generated by existing and planned observational networks (e.g., NERIES, EPOS).

QUEST will link world-leading scientists in methodologies such as computational wave propagation (e.g., IPG, LMU, OGS, CUB), the theory of inverse problems (e.g., IPG, UOX, UUT, UJF), global tomography (e.g., UOX, UEA, ETH, ING), with two of the best industrial research laboratories world wide (SCR, IBM) and two expanding smaller companies (SSZ, MSI) both employing some of the most innovative monitoring technologies today. The network is complemented by associating the GOCAD Consortium, involving both industry and academia which has a unique expertise in geometric modelling and gridding of geological structures and representing their heterogeneities. In addition, we associate with the European DEISA project, and a cluster of high-profile Computational Science institutions in Munich (MCSC). These associations – together with IBM - will allow the QUEST researcher direct access to training and other facilities in the area of HPC.

QUEST will have a lasting impact on the practice of seismic tomography, leading to sustainable HPC solutions applicable to industrial and academic challenges, and a generation of young researchers capable of producing better Earth images that help us tackle the challenges of future energy-resource management and natural-hazard related research. **Making full-waveform modelling a standard tool will revolutionize seismology and related Earth science domains.**

B.3 S&T QUALITY

Proposed Research and Technological Area

What will help scientists to (1) reliably track fluid and gas fronts inside reservoirs over time, (2) monitor the temporal variations of magma flow inside volcanoes, (3) accurately predict strong ground motions for potentially damaging earthquakes, (4) develop consistent physical models for earthquake sources, or (5) understand the dynamics of the Earth's interior?

The answer to all of these questions is, we need **high-quality images of the physical properties** of Earth's interior on all scales and quantitative assessment of their accuracy. Finding the physical properties (isotropic, anisotropic, viscoelastic parameters) of the Earth's interior (and its seismic sources) by extracting information from observed ground motions (seismograms) provides the highest resolution images of all indirect physical methods. To date the standard "imaging" procedures are still based on highly simplified assumptions, even though modelling capabilities are rapidly evolving. That is, despite substantial progress in modelling seismic wave fields through complex three-dimensional structures only a tiny fraction of the observations in this "data-rich" field of natural sciences is used for the image recovery. The primary goal of QUEST is developing strategies for automated seismic imaging using the increasing power of **3-D simulation technology**. We will train a generation of Earth scientists that will be skilled in handling the ever increasing data volumes by making use of efficient algorithms and the developing high-performance computing e-infrastructure in Europe. By pursuing an open-source philosophy, we expect that QUEST will have a strong impact on the scientific output from many current and future "data-rich" projects in seismology and applied seismics.

Despite the progress in scientific software developments and supercomputer hardware, the Earth science community is far from making efficient use of these developments with negative impact on the scientific outcome of data processing. **Earth science communities and computational scientists are not as closely linked as they should be.** This results in a general lack of rigorous training in computational methods and the necessary expertise to use HPC facilities. This is further amplified by the **increasing complexity of computational hardware**. The future of HPC is in pooling the resources in a heterogeneous hardware network (e.g., DEISA) and making these resources accessible to the scientific community. This requires the adaptation, testing, and verification of central applications that can be used in a stable fashion on multiple platforms (e.g., IBM Blue Gene or SGI Altix systems). The long-term goal of QUEST and associated projects is – in addition to the specific scientific goals - to establish standard applications, codes of practice and training programs so that the European HPC-infrastructure in the upcoming Petascale age can be used with high efficiency by the Earth science community. This is of paramount importance in a field in which Terabytes of observational data are being acquired each day.

State of the Art and Objectives

Seismic imaging is currently far behind its potential capabilities, given the recent advances in simulating seismic wave fields through complex three-dimensional Earth models. Progress will depend on an efficient incorporation of these modern simulation technologies into the imaging problem and its automation.

Seismic experiments produce tremendous amounts of data volumes due to the high-frequency nature of seismic wavefields and the required high sampling rates with which observations are discretized. The primary goal is to understand Earth's structure (or processes related to earthquakes) by extracting a maximum amount of information from seismograms. The basic procedure is to model aspects of the observations (e.g., travel times of seismic body waves, surface wave dispersion curves, wave amplitudes or waveforms), and to minimize the misfit between theoretical predictions and the observations. Despite the fact that the resulting images constitute the backbone of many fields in Earth Sciences and in industrial applications the methodologies employed to provide solutions and to assess the accuracies are today far from optimal. In basically all geo-scientific areas the state of the art of seismic imaging[1] is not yet taking full advantage of the developing computational power and well-advanced simulation technology.

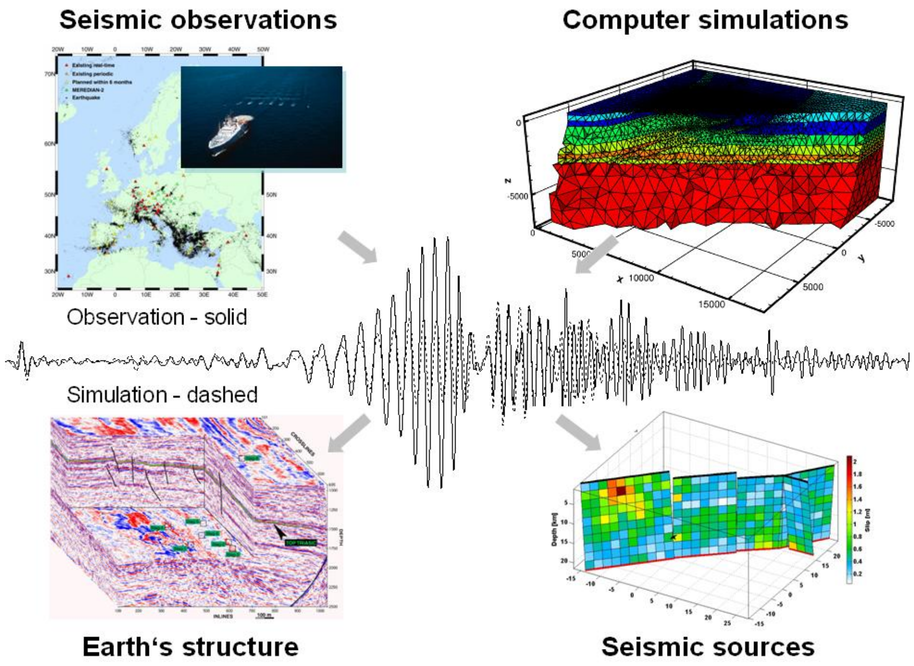


Figure 1: Fundamental concepts of QUEST research: Seismic networks, or temporary arrays (top left) observe vibrations (middle, solid line). These vibrations contain information on the structure of the Earth's interior (seismic impedances, bottom left) as well as the source (here: slip evolution and final distribution on a fault after an earthquake, bottom right). In QUEST this information shall be extracted by fitting simulated seismograms (middle, dashed line) through advanced 3-D simulation technology (computational grid shown top right).

Imaging requires high-quality data observed in dense **seismic arrays** and/or local/global **seismic networks**. It is important to note that with large-scale projects like NERIES (structuring European seismic networks), USArray, and many others, massive quantities of seismic waveform data are becoming available. This implies that data mining becomes an issue for high-performance computing systems. The last decade has seen a paradigm shift from seismic event-based observations to permanent observations of ground motions including ocean- and atmosphere-driven background *noise* (micro-seismicity and seismic hum). The analysis of noise has led to a new methodology to image the Earth's interior without the need for earthquake sources. Event-based and virtual source data – if processed properly – may change our view of the Earth. The seismic networks are becoming so dense that – at least in principle – high-resolution imaging of the Earth's interior and of seismic sources is becoming possible on all scales.

Currently, the standard way of analysing seismic observations in industry and academia to obtain the physical properties of the Earth's interior is ray-based **tomography**. It is now well accepted that in many cases the ray-based assumptions cannot be justified and will lead to erroneous or incomplete images. Consequently, a large amount of information on Earth structure or earthquake sources, contained in seismograms, is currently not exploited. One of the main goals of QUEST is to use most or all information in the seismograms. Despite the fact that some of the fundamental concepts concerning modelling and inversion (see Fig. 1) are well understood, the actual **application in 3-D is a tremendous challenge** particularly in connection with implementation on HPC systems! Because of the potential impact it is an **emerging and rapidly expanding field**. The

[1] We mostly use the term „imaging“ for the remainder of the proposal. Other expressions used in this context in the literature are "inversion, parameter estimation, data assimilation, data fitting, tomography, inference".

technical challenges equally apply to problems on all spatial scales (e.g., reservoirs, volcanoes, continents, planets).

A central tool of seismology is the calculation of synthetic seismograms that can be compared with observations. The only way to generate ‘realistic’ synthetic seismograms for complex three-dimensional models is by means of numerical methods (e.g., finite differences, spectral elements) implemented on supercomputer hardware. QUEST partners have been leading this field in Europe and beyond for several years and numerous algorithms that solve the wave propagation problem on reservoir, regional and global scales are available and implemented on supercomputers. **One of the most important points and the central motivation for QUEST is the fact that only now computational power has reached a point where many such “forward calculations” (i.e., simulations of wave propagation) can be done making it feasible to perform the imaging by trying to fit complete waveforms** (rather than travel times). This methodology - full waveform imaging - represents the primary goal all work packages in this proposal are jointly working towards.

There are several scientific problems that would greatly benefit from advances in seismic imaging:

- *Energy management - discovery, monitoring of reservoirs, CO_2 sequestration.* As the seismic method is the one that allows the highest-resolution mapping of physical properties it is the physical principle of choice for many applications. The sequestration of CO_2 may be part of a solution to anthropogenic climate change. The seismic method plays a central role in current experiments investigating the flow process after injection (4-D seismics). High-resolution imaging may considerably improve the monitoring of the sequestration process and the understanding of the feasibility of it in various areas. For all industrial applications moving to a more physics based approach means improved quantitative assessment of uncertainties with potentially a considerable economic impact. One of the key challenges is to recover the changes to the rock mass due to fluid flow. This requires the incorporation of appropriate rheologies (e.g., poroelasticity) in the modelling and inversion process.

- *Natural hazards – earthquakes, volcanoes, tsunamis.* The reliable forecasting of earthquake-induced strong ground motions strongly depends on the availability of high-quality subsurface imaging. 3-D sedimentary basins can substantially amplify ground motions. The relevance of the particular earthquake source behaviour for the surface ground motions (and their power to generate tsunamis) and the associated risk in particular areas is only now beginning to be addressed in a fully quantitative way. Therefore the imaging of the earthquake source is important to generate realistic earthquake scenarios. Similarly, the temporal changes of volcanic structures and the precise location of seismic activity on volcanoes is a key tool to monitor the state of the volcano’s eruptive state. Seismic energy is also generated by landslides, glacial earthquakes, and non-volcanic tremors. Using full-wave form back-projection (time reversal) – analogous to adjoint techniques – through complete 3-D Earth models can be used to constrain their locations and understand the underlying processes.

- *The dynamic processes of the solid Earth – mantle convection, crustal deformation.* On the regional and planetary scale the understanding of the dynamics of Earth’s interior rests on the best possible image of the current state of flow in the mantle. Despite the substantial progress with ray-theory we suggest that considerably sharper images are possible using full waveform methodologies that should allow much tighter constraints on the physical processes that shape our planet. Substantial progress can be expected with the increasing station density and campaign data (e.g., USArray) becoming available. A major challenge is to quantify the domains of application of full-waveform imaging in terms of source-receiver distribution, quality of starting models (in particular the Earth's crust), and frequency range of the data.

From a more technical point of view the recent discovery of the possible **structural imaging by correlating ambient background noise** (atmosphere-ocean driven micro-seismicity) is revolutionizing tomography for industrial (e.g., through innovative companies like SSZ) and academic applications (some of our partners have pioneered these methods, e.g., UJF, IPG). The implications are tremendous: one does not have to wait for earthquakes or active artificial sources radiating seismic waves but one can use seismic waveforms constantly excited by atmosphere and oceans to image internal structures. The two approaches – imaging using actual and virtual sources – complement each other and can partly be used for cross-validation. This is a newly emerging field in which QUEST partners are playing a world-leading role. The applications of this new methodology reach from reservoir scale over imaging of volcanoes to the imaging of sedimentary basins. QUEST will consist of a training network in which the development of both approaches can be pushed in a joint effort, and tested and compared in the same geographical regions with data sets provided by our industrial partners.

The key **scientific objectives** derive from the above considerations on the current state of the art and can be summarized as follows:

- **Improve the quality of structural and source images** derived from seismic data by incorporating 3-D simulation methods into the imaging process employing HPC solutions
- **Image seismic velocities, anisotropy, attenuation, and fluids** using information in waveforms and amplitudes
- **Develop novel approaches using passive imaging** that make use of virtual sources, investigate and broaden their domains of application on all scales.
- **Demonstrate the improved imaging power** through applications on a reservoir scale (CO_2-sequestration, geothermal energy), volcanoes, active seismic faults, and planets.
- **Disseminate the developed methodologies to the user community** through an open source software repository and web-interfaced benchmark facilities.

Participation of Industry

Seismic tomography is one of the key technologies in resource exploration industry, geothermal energy projects, and in geotechnical problems. It is important to note that all major exploration companies currently are **investing in full-waveform modelling technology** and are increasing the size of internal groups developing and applying this methodology. It is precisely for this reason that we are convinced that this is the right time to closely link the developments in academia with those in the industry and train young researchers capable of applying the methods.

Schlumberger Research Cambridge (level 1,2,3). QUEST is able to partner up with the biggest oilfield services contractor worldwide and its research laboratory in Cambridge, UK. Schlumberger employs over 80,000 people of more than 140 nationalities working in approximately 80 countries and has been an important employer for graduates in Earth Sciences. SRC is leading or being involved in several projects with academia (e.g., ASAP, AEGIS). Schlumberger's seismic division, WesternGeco, is a leading provider of geophysical services, with integrated activities from development of new acquisition systems for seismic and EM surveys to reservoir characterization. The industry, and Schlumberger in particular, recognize that the scientific and technical goals of QUEST are well aligned with their business interests of improving the reliability of geophysical prospecting methods, and therefore there is an obvious mutual interest in co-operation. In addition to applying the methodologies developed in QUEST to industrial data sets we will generate a qualitatively new level of synthetic industrial benchmark data using the leading-edge forward simulation tools recently developed within the consortium (LMU, IPG, OGS). This will serve as test data set to quantify and improve the resolution of seismic tomography. Schlumberger will provide special training in industry related scientific topics and complementary skills.

Spectraseis AG (level 1,2,3). Passive imaging is currently the most innovative new technology in seismology with applications on all scales. Spectraseis AG, Zurich, is utilizing this technology to extract information on reservoirs with the implication that the surveys have virtually no environmental impact and are suitable for use in sensitive land and marine environments, as well as locations where conventional seismic surveys are costly or impractical. Spectraseis is the leading provider of this so-called low-frequency technology. Spectraseis is rapidly expanding particularly in the technical areas. They will offer access to data sets and their seismic instrument pool, that we will use during one of the training practicals, and provide training in technical and complimentary skills.

IBM, Zurich Research Laboratory (level 2+3). IBM is the leading company for HPC hardware and software solutions today (more than 40% of HPC systems in the top500 list are from IBM). The Deep Computing (DC) initiative of IBM Zurich, created in 1999, aims at solving particularly complex technological problems faced by IBM, its customers and its partners by making use of (large-scale) advanced computational methods applied to large data sets. The DC initiative promotes and coordinates activities, which imply advances in hardware, software and the development of innovative algorithms, as well as the synergy of all three components. The expertise at IBM Zurich in computational physics and chemistry with applications in materials science and biochemistry is recognized throughout the world. This activity involves diverse technical steps: development of new algorithms, code optimization, particularly for massive parallel computing, data analysis, selected applications aimed at unravelling the physics and chemistry of the systems under investigation, virtual design of novel materials for advanced technologies, development of interfaces for Grid computing. Through the partnership of QUEST with IBM this expertise shall be applied to the seismic problem for all areas of application.

MicroseismicInc (level 2+3)*,* located in Houston, USA, will join QUEST as 2nd associated industrial partner. MicroSeismic Inc.'s proprietary PSET® technology utilizes wide aperture arrays, either on the surface or in the near-surface, to map the microseismicity associated with hydraulic fracturing and other dynamic reservoir activities. PSET® arrays obviate the need for monitoring wells, and provide the capability to map the full extent of fracture growth and fault activity with relatively constant resolution over a large survey volume. Already well established in hydraulic fracture monitoring, MSI is expanding its services to include PSET® based reservoir monitoring to assist oil and gas recovery operations. MSI will provide the opportunity for placements, access to industrial data sets and will be involved in the training workshops. MSI is also rapidly expanding hiring up to 5 research scientists every year.

The specific involvement of the industrial partners is more detailed in sections B4 and B5.

Research Methodologies

To solve the seismic imaging problem we need (1) an algorithm that solves the ***forward problem*** *and produces theoretical seismograms for a given earth model with complex geometries and realistic rheologies; we need (2) to parallelize the algorithm, generate computational grids and implement them efficiently on* ***High Performance Computing*** *systems and (3) we need to formulate the* ***inverse problem****, i.e. prepare and parameterise the data for the imaging process, employ a* *theory that tells us if an Earth model is good or bad by comparing theoretical predictions to observations, and pursue a strategy to search for models that explain our observations.*

The forward problem. Today, research in seismic wave propagation and imaging is entering a new era. The nineties were dominated by the expansion of broadband seismology (GEOSCOPE, IRIS, GEOFON, MedNet) and by the classical use of approximate methods like normal-mode or ray theory, to solve the forward problem, i.e. **calculate theoretical seismograms** and scan tomographically the interior of the Earth. Since the beginning of the new millenium, the massive use of a new generation of powerful parallel computers (clusters of PCs, GRIDs, Earth Simulator, BlueGene) makes it possible to routinely employ new, purely numerical (and, in principle, exact) methods to simulate the propagation of seismic waves in a realistic, 3-D Earth: the spectral element method and the arbitrarily accurate discontinuous Galerkin method, among others, are examples. As a result, the inverse problem of imaging the Earth's interior can rely on "adjoint" methods, based on the efficient, repeated simulation of seismic wave propagation for a variety of source-receiver geometries. Finite-frequency effects will thus be properly taken into account, with a theoretical breakthrough in the formulation of the imaging problem that will necessarily enhance tomographic resolution, and our understanding of the Earth.

High-Performance Computing. In QUEST research topics computational simulations will play the leading role in hypothesis testing, data modelling, and the development of new theories. Computational scientists are predicting a new era of supercomputing: After the “microprocessor era” with ever increasing clock rates, we are now entering an era with heterogeneous “multi-core” architectures that will impact hardware from large-scale shared-memory machines (SMP) down to mobile phones, PC processors and clusters. These developments require a paradigm shift in the approach to “*cpu-rich*” applications (simulation technology) particularly in the Earth Sciences. This implies that qualitatively a new level of co-operation with computational science is necessary. In addition to the existing links between the QUEST network partners and their local supercomputing centres we associate with the IBM Zurich Research Centre, the European supercomputer grid infrastructure through DEISA, and the Munich Computational Science Centre. With putting HPC at the centre of our methodological workplan we pursue the following goals: (1) training QUEST researcher from the beginning in professional software development tools, in parallel computing and the necessary expertise to debug (e.g., totalview), optimize and implement software on current supercomputers; (2) learn from computational sciences (CS) and develop best practices for code development, grid generation and visualization from an early stage in the scientific career; (3) by teaming up with software engineering experts at the supercomputer centers (e.g., through existing DEISA-DECI projects, and joint projects with our CS partners) to optimize the implementation of specific QUEST software. It is important to note that with the currently available flavours of seismic modelling tools (e.g., spectral elements, finite differences, discontinuous Galerkin approaches on hexahedral and tetrahedral grids, partly with options for space-dependent accuracy and time stepping), the efficient implementation (e.g., load balancing) has become so complex that the close cooperation with computational sciences is a prerequisite for efficient use of (and thus access to) the European Supercomputer Grid.

The inverse problem. Whenever we make observations in physical sciences we seek to explain those with predictions from a theory. The solution of the forward problem allows a direct comparison with the observations, e.g. comparing theoretical and observed seismograms sample by sample. The most elegant and general way of formulating the imaging problem is by means of probability theory: data and model spaces are formulated as probability density functions and the solution to an imaging problem are models that have a certain probability of explaining the observations. This approach was pioneered by one of our project partners (Prof. A. Tarantola, IPG). The probabilistic approach allows a quantitative assessment of data and model uncertainties at every stage of the imaging process. Despite the success of the theory the practical implementation of this approach in realistic applications is difficult and has not been rigorously employed (e.g., computational limitations, lack of prior knowledge). In QUEST we intend to go far beyond the current standards, use novel ways to parameterize waveform and amplitude misfits, and develop ways to recover both long-wavelength and short-wavelength Earth structures with as much automation as possible.

As mentioned above the "forward problem" of seismic wave propagation from point-like or finite earthquake sources is well understood in theory with remaining challenges in connection with grid generation, rheologies, and efficient implementation. Having a theory that allows us to assess the quality (likelihood, probability, goodness) of *one* model to explain the data, we are faced with the problem of finding those models that do have a high quality and are thus likely to be close to reality. The space of possible models for the problems we want to solve is immense! With today's supercomputers we are capable of running 3D models with >1 billion degrees of freedom, i.e. computational grid cells, with each cell having a number of physical properties (e.g. anisotropic elastic parameters, density, attenuation). The seismic imaging problem for source and structural properties exhibits everything from mildly to strongly non-linear behaviour. Depending on the degree of non-linearity a specific methodology to search in the model space has to be employed. The focus of QUEST research will be on adopting local search methods using gradient techniques to find subsequent model improvements.

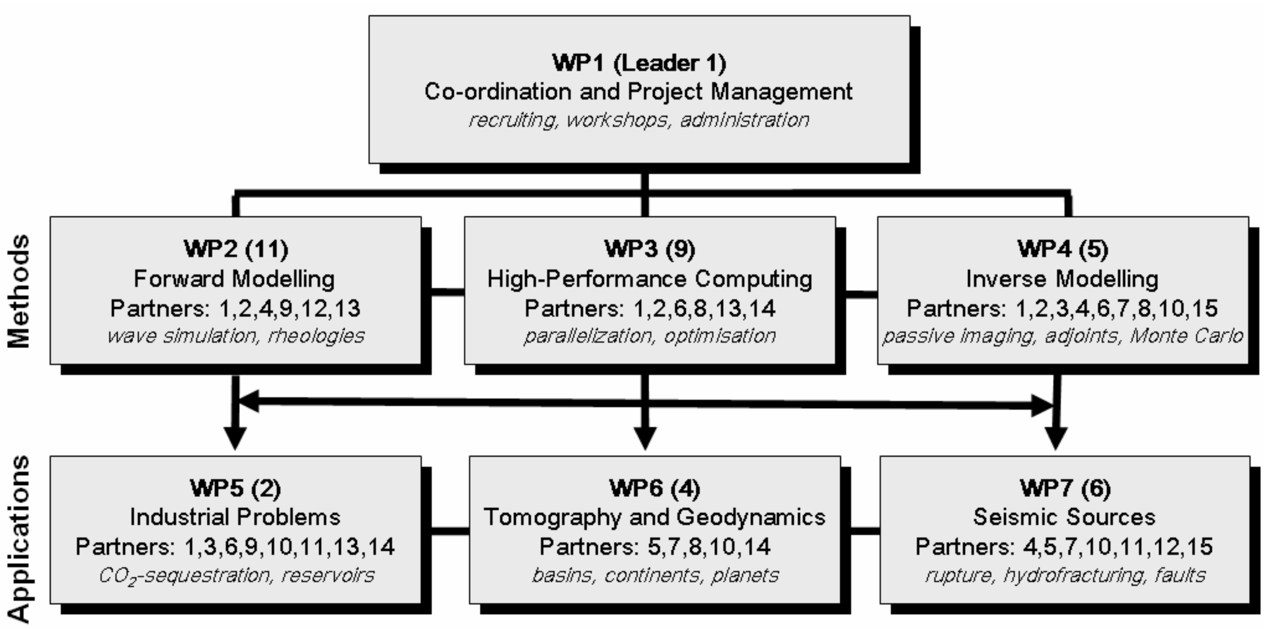


Figure 2. Work packages (WP) and titles, WP leading institutions (please refer to the table in section B1), main partners involved in the WPs and key issues.

Work Program – Integration of researcher projects

The scientific rationale of QUEST and the required methodologies naturally lead to the following work packages (WPs, see Fig. 2). Because the work program and the individual research projects are detailed in section B5 we restrict ourselves to a general discussion here. The WPs motivate the content and timing of the scientific training to be introduced in the next section. The primary scientific goal of QUEST is to develop and utilize novel simulation technology to achieve better images on all scales ranging from reservoir scales (WP5, energy, CO_2 sequestration) to sedimentary basins, continents, and planets (WP6, seismic hazard, geodynamics) to the detailed reconstruction of the location and behaviour of seismic sources (WP7, hydrofracturing, earthquake sources, shaking hazard). The scientific goals shall be achieved through methodologies developed in work packages structured as the methods section above: In WP2 the key ingredient to seismic tomography shall be developed and combined with the theoretical developments in inverse problems of WP4. The resulting computational algorithms shall be optimized, implemented through WP3 that will join up with HPC expertise through direct cooperation with IBM, the local supercomputer centres, DEISA, a.o. As will be shown below the workshop training program as well as the individual ER and ESR projects are timed such that the methodological parts will start first, staggered in time with the subsequent project and training parts focusing on specific industrial and scientific applications.

The individual research projects (ER and ESRs) will in general comprise elements of the objectives of several work packages. The projects – detailed in section B5 – will combine developments on more technical issues (e.g., optimization of forward and inverse simulation software, parameterization and search algorithms in model spaces) with specific applications of inverse methodologies (e.g., passive imaging, adjoint method, structural and source inversion) to real data sets from both industry-related campaigns, earthquake induced ground motions, and ambient noise recordings. It is the combination of an in-depth understanding of the methodologies and the experience and difficulties working with real data (not one alone) that creates the skills Earth scientists need today.

Role of Associated Industry and other Partners

Our associated partners fall into three categories: (1) industrial partners (IBM, MSI), (2) partners and consortia focusing on computational science and high-performance computing (UNC, RZG, LAN, UAU, TUM), and (3) leading international universities or research schools in Earth Sciences (CAL, ANU, TOK, UCB, ENS, UHH, UNA, CAM).

The association to the IBM Zurich Research Laboratory is of particular value to the project, as the implementation of parallel software, optimization, and the development of web interfaces into HPC facilities are central QUEST research goals. MSI is offering placements to QUEST researchers and access to one of the best industrial data sets available today with thousands of closely spaced seismometers. One of the most important aspect of the industrial partnerships is the opportunity for the visiting QUEST researchers to participate in in-house training on industry-related complementary skills. We consider the partnership with the consortia GOCAD (UNC), DEISA (RZG) and the association with one of the most prestigious US supercomputing laboratories, where the currently fastest computer is located (IBM Roadrunner, Los Alamos National Lab, LAN) as central to achieve our training and research goals in the field of computational science and high-performance computing. Through GOCAD we will have direct access to training in the domain of computational grid and model generation that will play a major role in the next generation of inverse problem solving. The association with DEISA will allow accessing the courses offered (with automatic access to HPC infrastructure through participation). Wherever possible we aim at space-time clustering of DEISA, GOCAD and QUEST training activities (see section B4). Participation in at least one training event offered through DEISA will be mandatory for the QUEST researchers. The 2nd project phase of DEISA has just started and dates for training events have not yet been fixed. The cooperation with IBM and the Munich Computational Science Centre through joint ER and ESR project aims at the specific engineering of a few computer programs with the most promising prospects for wide use by the scientific community. The decision on the programs will be made by the Science Board.

Finally, the associated international research institutions (CAL, ANU, TOK, UCB, UAU, LAN, CAM, ENS, UHH, UNA) have long histories of collaborations with the QUEST partner institutions and represent world-leading expertise in specific complementary areas (e.g., volcano seismology, dynamic rupture, time reversal, etc.). Their lead scientist will be involved in the workshop training programme (see section B4), the supervision of specific research projects, and will allow QUEST to have tight connections to ongoing international projects of similar scope. Experience with other large Earth Science projects has shown that by involving non-European institutions, holding special sessions and information meetings at the largest annual meeting in Earth Sciences (Fall Meeting of the American Geophysical Union) the visibility, exchange of expertise and scientists, and impact of such projects can be considerably increased at the expense of travel funds to one international meeting outside Europe per year.

B.4 TRAINING

Why should young Earth scientists be trained in the field of seismic imaging? As motivated in the research section the recovery of subsurface images and their evolution over time will be an increasingly important task for problems of energy (seismic exploration), environmental problems (near surface imaging), climate issues (e.g., CO_2-sequestration, glacial earthquakes), seismic, volcano, tsunami and landslide hazard and the understanding of the evolution of planets. The methods to be trained are just taking off as tools in the industrial research labs and thus the demand in skilled personnel is rising. The mathematical methodologies (adjoint methods, parameter estimation, search methods, data assimilation etc.) are used in many other fields (e.g., meteorology, oceanography, physics, medicine, economics, and engineering) and are easily transferable. In addition, the computational aspects of the training (numerical methods, computational physics, code parallelization) are increasingly important in all fields of natural sciences. In our experience high-quality training in these technical aspects has made young researchers highly attractive for employers in industry and the economy. In addition, fundamental knowledge of these technical aspects are today one of the prerequisites for a successful academic career in the natural sciences. In the QUEST project, young researchers have the opportunity to be embedded in a network with numerous direct connections to industry through collaborative projects as well as connections of the lead scientists to the top universities worldwide. **In short, this ITN offers a broad training programme in methods and skills which can be subsequently applied in a wide range of industrial and academic environments.** The specific skills that QUEST intends to train in addition to the topics already covered by the workshops will be defined by the supervisory board in response to any changes to the work plan or internal or external evaluation of the project.

In our view, now is the right time to propose a training programme with a strong focus on the imaging problem: (1) the theory of the *forward* problem of seismic wave propagation for 3-D media is well understood with key remaining issues in connection with high-performance computing; (2) only recently computational power has reached a state where imaging with 3-D “full waveform” simulation technology is feasible; (3) Earth sciences are being inundated with increasing volumes of seismic data from networks, and large experimental projects; and (4) entirely new imaging methodologies are emerging (passive imaging) that are absent in any curricula but are likely to play a major role in the future. In the past decades a prohibitively small part of the seismic data was exploited to investigate Earth’s structure and seismic sources. **With QUEST we want to establish a new quantitative level of seismic imaging and train young researchers who will be in charge of modelling the vast amounts of data in the future using sophisticated computational modelling techniques.**

The training and research goals of QUEST are not achievable on a national level. The specific expertise in the domains of the theory of inverse problems, the computational solution to the forward problem, earthquake source physics, passive imaging, etc. is scattered across Europe. In addition, it is important to note that recent years have shown an important cross-fertilization between seismic imaging on the smallest (e.g., reservoirs) and largest scale (global tomography) or between physics and seismology (diffuse fields, passive imaging, time-reversal techniques). Adjoint methods previously applied only in the context of reservoir scale applications are now being adopted to the problem of regional and global tomography. Computational tools for wave propagation and imaging problems are similar across a wide range of fields, a fact that calls for transnational cooperation and developments, common standards and exchange of ideas and experiences between disciplines.

The QUEST training programme is scheduled such that students subsequently are taken from the fundamentals of seismic imaging, via mathematical and computational skills, to the actual imaging using large data sets followed by the interpretation in the wider geo-scientific context. By providing the course and practical material through open web interfaces students (also from outside QUEST) will continue to have access to the training material. The variability of scientific and technical foci of the network partners underlines their complementary nature in both research and training aspects and highlights the interdisciplinary nature of the problem requiring expertise in mathematics, computational science, geology, and physics. The network gathers the strongest groups in Europe in support of the field of forward and inverse wave propagation and earthquake source physics. **The central training goal for all QUEST researchers is to be able to solve structure and source imaging problems from raw data sets to the final images using sophisticated 3-D simulation tools.**

Structure of Training Programme

Training in the QUEST network will happen on three levels: (1) Network-wide training will be organized through yearly **one-week training workshops**. In those workshops the categories will be trained in a logical sequence (see below). (2) Open meetings will be held in connection with the **WPs** defined above. Due to the strong interactions between the various WPs these meetings are expected to be visited by a substantial part of the QUEST researchers. Training in those meetings will focus on the individual research projects in connection with the WP objectives. (3) **Local training** at the partner institutions will involve the specific scientific and technical expertise of the partners. Most QUEST lead partners offer courses and seminars on a graduate level in the area of their expertise (e.g., numerical methods, HPC, inverse problems, rheologies, seismic wave propagation, etc.). The individual project supervisors will decide which courses are appropriate for their training in addition to network-wide opportunities. In addition, appropriate (e.g., short) courses with topics not covered by the workshops shall be offered to the network researchers, if possible.

A central template for soft skill training will be distributed by the management panel at the beginning of the project containing an extensive list of skills that should be covered. This list will be prepared by the network administrator and sanctioned by the Supervisory Board. Local soft training courses shall be advertised network-wide to allow participation from partners without such training options. However, a substantial part of the training on complementary skills will be delivered through the annual workshops (see Table 1).

Training of early-stage researchers (ESR). Full Ph.D. projects shall be supervised by scientists of two different QUEST partners (see section B5). QUEST employed researchers will spend at least two months per year at one or more other partner institutions. Each individual project will be evaluated at the yearly training workshops. QUEST students will be involved in the organization of local and network-wide meetings (e.g., WP meetings) as part of their soft skills training programme.

QUEST training workshops

The yearly one-week training workshops are the most important network-wide meetings. Training topics and partners´ responsibilities for those workshops are given in Table 1. We envision the workshop format as follows. The mornings are dedicated to lectures, while afternoons will be spent on computer and field lab exercises that closely track the theory taught in the mornings. Training of complementary skills will be distributed over the whole week and will add up to approximately one full day per workshop. At every workshop, industry partners contribute core modules to both the scientific and complementary skills training, as detailed below. In terms of S&T content, the workshop sequence follows the philosophy of the work programme with a stronger focus on methods in the early stage of the project leading into the applications in the latter part. Scientific poster sessions will be part of every workshop. In order to maximize the exposure and feedback with focus on student presentations, we plan to emulate the session format of Gordon Research Conferences. We have found them to generate particularly intensive interaction and exchange, both on scientific and networking levels. Posters will be posted in the main common room/lounge area, and will stay up all week. Official poster session hours are daily in the late afternoon. The regular social hours after dinner take place in the poster room so that scientific discussions may continue casually. Thus we want to lower students´ thresholds for striking up conversations with “famous strangers”.

All our workshop activities are geared towards encouraging and ensuring that students make broad use of the “human capital” assembled at their fingertips, both for their scientific and career development. We feel that this must be the fundamental value that a networked program such as QUEST adds, above and beyond a regular Ph.D. program. To this end, almost all of the complementary training will be delivered from within the network, and the boundaries between classroom teaching and personal mentoring will be fluid. We will teach formal skills such as publishing strategies, self-marketing and applying for jobs. However, we will put equal emphasis on conveying “soft knowledge” and people skills, in sessions on Ph.D. advisors´ expectations, being a valued collaborator, time management and fighting procrastination, dealing with a research crisis, and the role of mentors.

Table 1: QUEST Training Workshops

Workshop 1	**Introduction to QUEST: Fundamentals of Seismic Imaging**
Date: Month 9 **Location:** Smolenice, Slovakia **Local organisation:** CUB Bratislava **Trainers + Contributors:** SCR, CUB, OGS, UCD, CAL, IBM **External participants**: 150 researcher days	**PART I: Who is Who, and Why Are We Collaborating:** **Objectives:** Students get to understand the elements common to all seismic inverse problems, and the potential for cross-fertilization within QUEST. Students meet their external academic advisors from partner universities, and they explore opportunities for the mandatory industry internships. **Lectures:** • Introduction of QUEST work packages and how they relate to each other • The role of High-Performance Computing in seismic modelling and inversion • Different applications but similar methods in industry and academia • Internship opportunities **PART II: Tomographer´s Toolbox: Numerical wave simulation codes for forward modelling** **Objectives:** Students get to know cutting-edge wave propagation codes from a user´s perspective, and learn to recognize when and how things can go wrong. **Lectures:** • Numerical Methods (finite differences, finite elements, spectral elements) • Accuracy, Convergence, and Stability • Computational Geometry, Mesh Generation • Available Algorithms and Software **Computer Labs:** • Introduction to SPECFEM 3D as an example of a community forward-modeling code • Introduction to finite-difference/finite-element simulation tools from industry **Complementary Skills:** Getting what you came for: What does it take to earn a Ph.D.? Formal and informal coaching about advisors´ expectations, role of mentors, becoming a valued colleague, ethics in science, publishing, time management, coping with a research crisis, getting it done and moving on.

Workshop 2	Scientific High Performance Computing
Date: Month 21 **Location:** near Zurich, Switzerland **Local organisation:** ETH Zurich **Trainers + Contributors:** ETH, IBM, LMU, DEISA, UPO, UNC, LAN, TUM **External participants**: 150 researcher days	**Objectives:** Introducing basic and advanced concepts of parallel computation in science. In computer labs, students learn to parallelize one or two algorithms that play central roles in seismic inverse problems. **Lectures:** • Concepts of Parallel Computers and Computation • Designing Parallel Algorithms • Quantitative Basis for Design • Software Tools • Parallel Programming • Grid generation • HPC Infrastructures in Europe **Computer Labs:** • Sample application: Seismic wave equation • Sample application: Inversion of large matrices **Complementary Skills:** • Professional Proposal Writing: Project formulation to access HPC resources

Workshop 3	Seismic tomography: ray theory, banana-doughnut kernels, and waveform inversion
Date: Month 33 **Location:** Italy **Local organisation:** OGS+ING **Trainers + Contributors:** UOX, SCR, MSI, ING, UEA, CUP, CAM, Queen's Univ. **External participants**: 150 researcher days	**Objectives:** Understanding and carrying out all steps to generate a tomographic image of the subsurface from raw waveform data. We emphasize the understanding and use of computationally sophisticated measurement, forward-modelling, and inversion tools. **Lectures:** • Measurement procedures and their implied sensitivities: geometrical rays, banana-doughnut sensitivities, and waveform kernels. • Relative benefits versus computational costs of different methods, depending on experiment geometry and frequency content. • Tools for computing sensitivities, with an emphasis on the adjoint method • Tools for solving the inverse problem: Efficient inversion of large sparse matrices; Newton and conjugate gradient methods • Inversion for seismic sources (seismic hazards, hydrofracturing in industry) • Handling huge data sets **Computer Labs:** Waveform inversion in the frequency domain: Cross-hole body-wave tomography or wide-angle seismic refraction survey in 2D. • Picking of P-wave arrivals from a real waveform data set (from industry) • Generating a robust starting model: Classical ray-theoretical inversion of traveltime data • Pre-processing of seismograms for waveform inversion. Efficient selection of frequency bands. • Computation of waveform kernels using the adjoint method • Waveform inversion: Iterative solution with conjugate gradients. **Complementary Skills:** • Getting it done: attitudes and strategies for writing research papers and a Ph.D. thesis without the excruciating pain. • Publishing your research results: when, where and how? • The view from industry: why they, too, value your good writing skills and habits.

Workshop 4	The noisier, the better: Imaging with cross-correlation methods, ambient noise, and coda waves
Date: Month 45 **Location:** Cargese, Corsica **Local organisation:** IPG **Trainers + Contributors:** SSZ, IPG, UJF, UUT **External participants**:	**Objectives:** Imaging with noise is a new and rapidly developing field that is barely covered in standard curricula. Here, students get to know various methods in theory and practice. **Lectures:** • Fundamentals of diffuse wavefields; theoretical basis for recovering Green´s functions from ambient seismic noise • Cross-correlation and convolution techniques • Applications at various spatial and temporal scales • Time-lapse surveys using noise • Virtual sources and sensors **Computer Labs:** • Extracting and interpreting Green´s functions from realistic data sets (crustal scale, reservoir-scale, non-destructive testing) • Tracking temporal changes (time lapse interpretation)

150 researcher days	• Exploring the effect of non-randomly distributed sources (synthetic data) **Field Lab:** • Deploying Spectraseis broadband seismometers in the field. Using this noise data set as one of the examples in the computer labs. **Complementary Skills:** • Putting your science to work in industry, government, or academia: What kinds of jobs are out there? What kinds of jobs are right for me? • Self-marketing skills: applying for industry/public service jobs versus applying for academic jobs

Training contributions from academic, industry, and associated partners

Scientific lectures will be taught in large part by the network´s academic and industry partners. Industry partners will also be heavily involved in the computer and field labs. CAL and SCR will provide modeling software and exercises for Workshop 1, respectively. IBM will teach training modules in workshop 2 and will offer a visit to their Research Centre during the workshop to be held near Zurich. SCR and MSI will contribute training modules in workshop 3. SSZ will provide broadband seismometers for a field experiment in workshop 4, as well as exercises and expertise to interpret the data. Prof. Jeroen Tromp from Caltech will teach computer labs sections on the SPECFEM modelling code in workshop 1. Prof. Gerhard Pratt from Queen´s University, who is acclaimed for his hands-on workshops on adjoint inversions, will teach the computer labs of workshop 3. The complementary training is geared toward skills desired by both industry and academia, and is jointly taught wherever possible. We explicitly include sessions that will help students determine what kind of career is right for them. The QUEST workshops will be coordinated with workshops of other EU-wide projects in Earth Sciences such as DEISA. Additional joint workshops (or WP meetings) will be organised to improve the dissemination of QUEST research, and to provide even more student/researcher interaction.

Distribution of person-months. In addition to the coordinating institution most partners with WP leadership are allocated one experienced researcher for 12 months. Partners with expertise in two main research areas (structural or source imaging) are allocated person-months corresponding to two doctoral projects. Two one-month visiting scientist positions (Prof. Tromp, Caltech, USA, Prof. Pratt, Queens University, Canada, see section B6) are foreseen. Both scientists will prepare and carry out major parts of the training program at the QUEST workshops. Individual research projects are detailed in section B5.

Table 2: Distribution of person-months

Partner	ESR	ER	VS	Total
LMU	36	36	1	73
SCR	36	0		36
SSZ	36	0		36
IPG	72	12		84
ING	72	12		84
ETH	72	12		84
UOX	72	0		72
UUT	36	0	1	37
UCD	36	12		48
UJF	36	0		36
CUB	36	12		48
CUP	36	0		36
OGS	36	0		36
UEA	36	0		36
UPO	36	0		36
Total	**684**	**96**	**2**	**782**

Mandatory industry internships and HPC training. Students spend at least one summer as interns with one of our industry partners or associates. All industry partners commit to offer summer internships for Ph.D. students in the QUEST network. The industrial partners (SCR, SSZ, IBM, MSI) commit themselves to offer a total of 40 person-months of placements. This will allow the 19 ESRs to spend at least two months at an industry lab in the lifetime of their project. Cooperation between ERs and industry will be through collaborative scientific projects (see work plan). Universities and companies work together to formulate meaningful summer projects that apply methods from a student´s academic field of research to relevant topics in industry. QUEST researchers will participate in at least one HPC training course (e.g., IBM, DEISA, or local computer centres). The administrator will make sure information on those courses is distributed as soon as available.

Role of ER and ESRs. QUEST is employing methods (numerical approximations to wave propagation problems, inverse theory, and high-performance computing) that are technically very difficult, and as motivated in the introduction, Earth science graduates are usually insufficiently trained to immediately get started on the problems. While QUEST is aiming to provide the required initial training to the ESRs, the ERs will have the task to help get the work packages started (each WP has an associated ER). Because of previous or current EU projects we are optimistic that we can hire highly skilled ERs equipped with the methodological expertise required in QUEST. The ITN scheme allows hiring ER at the early stage of their career. In addition to the technical and scientific training the ERs will receive from their lead scientists, the workshops and the other training options, a specific focus for the ER mentoring will be to prepare them specifically for the responsibilities to be expected in permanent positions in either academia and industry. This involves leadership and organizational skills, as well more science specific activities such as the review process for articles and proposals, proposal writing and interaction with funding bodies.

B.5 IMPLEMENTATION

In this section we present (1) the management structure, (2) the capacities of the network, and detail (3) the work plan, and (4) the deliverables.

Organisation and Management Structure

***The Coordinating Institution**:* Ludwig-Maximilians-Universität (LMU) München is one of the leading research universities in Europe, with its president, Prof. Dr. Huber, currently chairing the League of European Research Universities. LMU recently received an additional €180 million by the German state to support outstanding graduates, establish research clusters and implement a comprehensive institutional strategy through 2011. To ensure that LMU Munich maintains its high level of research, particular emphasis has been placed on promoting exceptional graduates and emerging young academics from all over the world by offering a broad variety of training options: Besides the traditional individual professorial supervision of PhD candidates, LMU Munich runs a growing number of structured doctoral programs. National and international candidates can apply for one of our multidisciplinary Research Training Groups funded by the German Research Foundation or the international Masters and doctorate programs within the Elite Network of Bavaria (LMU Geophysics runs such an elite graduate college called THESIS). In addition, LMU has very strong links within the international training networks supported by the European Commission. Since 2002 LMU Munich has been participating in 17 Research Training Groups of the Marie Curie program. Seven of those networks have been coordinated by LMU scientists. On the more administrative side additional support is given by the newly founded GraduateCenter-LMU. Its most prominent aim is to strengthen the appropriate infrastructure for structured PhD programs. It helps interested graduates to apply and enrol for a PhD program at LMU Munich and offers training for professional skill development and personal training for young scientists from all disciplines. Moreover, they profit from Munich’s exceptionally diverse academic environment – with three universities and eleven Max-Planck Institutes –, allowing them to develop even beyond their specific professional qualifications.

***QUEST coordinator and administrator**:* The QUEST co-ordinator, Prof. Dr. Heiner Igel, is the vice-head of the Department of Earth and Environmental Sciences at LMU and Director of the Seismological Observatory in Fürstenfeldbruck. He coordinated (1) the 14-partner MCRTN SPICE between 2004-2007 with 5.5 Million Euro overall funding one of the largest RTNs at the time, (2) the International Quality Network – Georisk (IQN) (2001-2003), funded by the German Academic Exchange Service (DAAD), with 15 multi-national partners worldwide. He also co-coordinates the Elite Network THESIS: Theory, Experiment and Simulations, studies of Earth's dynamic processes, funded by the Ministry of Science, Bavaria, Germany (2005-2011). Prof. Igel is Executive Secretary for Theoretical Seismology of the European Geosciences Union. The coordinator will be assisted by the experienced MCRTN administrator Greta Kueppers, who administered the second half of the SPICE project. Her position as administrator entailed a wide variety of administrative, financial, and communicative duties such as the production of management reports, international advisor for newly recruited postdocs and PhD students with respect to career development, visas, housing, language courses, further academic opportunities, upcoming conferences, etc. The work package WP1 related to management is illustrated in the table below and will be detailed further in the text.

Table 3: Work package 1

WP1: Coordination and Management (LMU)
Objective: Scientific and financial administrative tasks to implement the project. Establishing of supervisory and science boards. Organization of recruitment, project web pages with general info, training material and software repository, central dissemination of project publications, public relations, career planning and industry liaison. Assembly of training material into e-learning course. (Co-) Organization of project workshops, special sessions and project display stands at international conferences. Building links to other EU projects (NERIES, DEISA, PRACE). Internal and external project evaluation and quality control. Preparation of project reports.
Milestones and Deliverables: Project content-manageable www structure (M3), annual workshops and supervisory board meeting (M9,21,33,45), final international workshop (M48), special QUEST sessions and meeting of supervisory board (European Geosciences Union, every April).

The QUEST network will be steered by a Supervisory Board (SB) and a Science Board (ScB) and Table 4 highlights their composition and tasks. The regular meetings of the Supervisory Board and Science Board will be the main instrument to ensure proper administration of the QUEST network and coordination between the teams. As indicated in the tables several of the Board members have special tasks. (1) The speaker for the industrial partners has the task to ensure the proper inclusion and influence of the industrial partners (all levels) on the project objectives and their deliverables, is bringing any industry-related issues to the attention of the supervisory board (e.g., employment issues, intellectual property, etc.); (2) The speaker for academic career planning is the contact person for all network scientists for academic career issues, ensures access to worldwide job data bases through the network web pages, and posts individual job offers to the appropriate mail lists; (3) Speaker for industry career planning. Same tasks as (2) (in this case through someone with career experience in Europe and USA); (4) Experience has shown that it is important to have a contact person (here: ombudswoman) to deal with complaints/appeals of researchers, including those concerning conflicts between supervisor(s) and researchers. Such procedures should provide all research staff with confidential and informal assistance in resolving work-related conflicts, disputes and grievances, with the aim of promoting fair and equitable treatment within the institution and improving the overall quality of the working environment.

Communication. A primary form of communication within the network will take place by means of a monthly newsletter, containing information on finances, deadlines, upcoming meetings, special sessions, training opportunities. This information will be also made accessible to the QUEST consortium through a password protected intranet site on the project web page. The main QUEST web pages will be essentially for external communication and will advertise upcoming network wide and external meetings and workshops, list publications, overview of research objectives, job postings, information on new developments and provide links to informal partners. It is important to note that through the use of a "content-management-system" each partner institution (and each involved scientist) can add information to the project www structure at any location with internet access. Active and continuous communication among the QUEST research teams will be ensured through video conferencing, where possible, allowing thus a real-time distribution of information. In order to maximise the benefits of the QUEST partnership, best practise recommendations will be presented during the management section of each network meeting ensuring that all participants are familiar with financial protocols and individual rights and responsibilities.

Table 4: Supervisory Board and Science Board

Supervisory Board (SB)	
Members and special administrative tasks: Prof. Dr. H. Igel (LMU, Coordinator, chairman) Dr. J. Robertson, SCR (Speaker for industrial partners) Dr. B. Artman, SSZ Prof. Dr. J.-P. Montagner, IPG Dr. A. Morelli, ING Prof. Dr. D. Giardini, ETH Prof. Dr. J. Woodhouse, UOX Prof. Dr. J. Trampert, UUT (Academic career planning) Prof. Dr. C. Bean, UCD Prof. Dr. M. Campillo, UJF Prof. Dr. P. Moczo, CUB Dr. J. Brokesova, CUP	**Members (cont'd)** Prof. Dr. G. Seriani, OGS Dr. A. Ferreira, UEA (Speaker ERs and ESRs, Ombudswoman) Prof. Dr. M. Holschneider, UPO **External representatives:** Dr. A. Curioni, IBM Dr. L. Eisner, MSI (Industry career planning) Prof. Dr. G. Caumon, UNC -> GOCAD Prof. Dr. H. Bungartz, MCSC Prof. Dr. J. Tromp, CAL
Tasks: The Supervisory Board will ➢ settle the skills requirements of the QUEST recruited researchers in agreement with the industrial and academic demands ➢ guarantee the exploitation of the partners' complementary scientific and technical know how ➢ guarantee the balance between scientific and technological training and complementary skills training of the QUEST young researchers, according to their needs ➢ appoint the Selection Committee in charge of recruitment strategies ➢ make decisions concerning financial affairs and intellectual property rights ➢ decide upon working program modification on the Science Board's advice ➢ ensure a constant and dynamic connection and exchange of best practice between the QUEST members	
Meetings and Rules: Supervisory Board Meetings shall take place twice a year, (1) at the Annual Meeting of the European Geosciences Union Meeting in Vienna, (2) during each QUEST network-wide Training Workshop. Prof. H. Igel, the Co-ordinator, will convene and chair. The Co-ordinator as chairperson will give notice in writing (e-mail with acknowledgement of receipt) of the meetings to each Supervisory Board Member at least 45 calendar days preceding the meeting. The invitation will be sent by e-mail to each representative of the QUEST Supervisory Board and will include a written original agenda with the current Network training, management and/or scientific issues that need to be discussed and decided upon. The QUEST members will be represented by their Supervisory Board representatives. In case a Supervisory Board member won't be able to attend the meeting, he/she may appoint a substitute for its representative to attend and vote at the meeting. In order to deliberate and decide validity, 2/3 of the Supervisory Board's members must be present or represented. Each member of the QUEST Supervisory Board present or represented in the meeting will have one vote. Each Supervisory Board member will be duly authorized to deliberate, negotiate and decide on all items listed above under "Tasks". Decisions will be taken by a quorum of 2/3. Written minutes will be produced of each meeting. Prof. Igel will send the draft minutes to the QUEST members within 10 calendar days of the meeting. The minutes will be accepted if, within 7 days from sending, nobody of the QUEST members will object in writing to the chairperson with respect to the correctness of the draft minutes. Prof. Igel will send the accepted minutes to all members of the QUEST consortium.	

Science Board (ScB)	
Members: **Prof. Dr. J.-P. Montagner, IPG, (SB Chairman)** Prof. Dr. H. Igel, LMU Prof. Dr. C. Bean, UCD Dr. J. Robertson, SCR	**Members (cont's)** Prof. Dr. D. Giardini, ETH Prof. Dr. M. Campillo, UJF Dr. A. Morelli, ING Prof. Dr. P. Moczo, CUB Prof. Dr. H. Bungartz, TUM
Tasks: The Science Board will ➢ monitor the effective and efficient implementation and global progress of the QUEST project in compliance with the network working program and, in case of weaknesses, propose modification of the working plan to the Supervisory Board ➢ initiate, coordinate activities of the corresponding Work Packages ➢ alert the Supervisory Board in case of delay in the performance of the activities in the Work packages	

➢ support the coordinator/Supervisory Board in preparing related data, deliverables and the scientific and financial reports concerning the different research teams ➢ prepare the content and timing of press releases and joint publications ➢ organize highly competitive recruiting in agreement with the principles set by the Supervisory Board ➢ settle the scientific organization of training workshops and special sessions
Meetings: The Science Board will meet at least twice a year before the SB Meeting. Prof. Dr. J.-P. Montagner, IPG, will convene and chair all meetings of the Science Board. The same rules as for the SB apply to the ScB.

Recruitment: Campaign, selection criteria and procedure. QUEST will launch recruitment by publishing ESR and ER positions in specialized journals such as EOS – the most widely read weekly journal in Earth Sciences published by the American Geophysical Union and the corresponding CS and HPC journals, on the EC jobs portal EURAXES, on the QUEST and DEISA websites, on the industry partners' websites, through flyers and posters presented at the EGU and AGU symposia respectively in spring and fall. The existing e-mailing list of seismological and geophysical laboratories as well as the industry partners' mailing list will be also used for advertising the vacancies. The QUEST vacancy notices will contain a clear, concise, and gender neutral job description, will provide information about working conditions, entitlements and career development prospects, will illustrate briefly the recruitment process and will outline the knowledge, skills and attributes required by the candidates in order to fulfil the selection and eligibility criteria.

The selection criteria against which QUEST applicants will be assessed are given in Table 5:

Selection criteria
➢ ***Qualifications***: High level of education and examination standard, particularly of applicants from countries with academic systems different from most European countries ➢ ***Experience***: according to type, level and quality. Excellence of the QUEST candidates will be evaluated qualitatively as well as quantitatively. Not only number of publications but also teaching, supervision, teamwork, knowledge transfer, management of research and innovation and public awareness activities will be key evaluation criteria. In case of applicants with an industrial background, particular consideration will be given to any contributions to patents, development or inventions. ➢ ***Knowledge, Skills and Competencies***: specialist/specific knowledge and skills such as fluency in a European language the QUEST candidates should bring to the post ➢ ***General Attributes***: aspects of personality such as creativity, level of independence, good interpersonal skills to develop and maintain effective working relationships that help to carry out the duties of the post

Placement of ESR and ER adverts will be the matter of the QUEST Supervisory Board, which will also appoint a Selection Committee, composed by the network co-ordinator Prof. Dr. H. Igel, by the network administrator Greta Küppers, by one representative of the academic sector Prof. Dr. Montagner and by one representative of the industrial sector Dr. Artman. The QUEST Selection Committee will first check eligibility and gender issues of the received applications. All the applications considered eligible will be then evaluated according to the selection criteria defined in the vacancy notices. The Selection Committee will examine the profiles of the applicants and assess their relevancy for the post in question. The best qualified and most suitable candidates will be then recommended by the Selection Committee to the different lead scientists, who will take the final decision on the appointment of the successful applicant. The Selection Committee will also take care of informing the unsuccessful candidates about the weaknesses of their applications.

Career development. Lead scientists will draw up a specific career development strategy for the researchers they hired. It will include the availability of mentors involved in providing support and guidance for the personal and professional development of the researchers, thus motivating them and contributing to reducing any insecurity in their professional future. This will be done in close cooperation with the two members of the SB in charge of career issues in academia and industry.

Gender Issues. The QUEST Supervisory Board will take particular care in promoting the application of female researchers by explicitly inviting them in the post adverts to apply for the position. In order to make working conditions appealing to women, the QUEST consortium will pay particular attention to allow flexible working hours. QUEST lead scientists will be responsible to make female researchers aware of any local schemes supporting young female researchers. The QUEST Selection Committee will ensure that gender issue will NOT take precedence over quality and competence criteria.

Internal and External Quality Control. One of the main tasks of the supervisory board and the external participants in particular is to ensure excellence in research and training throughout the network. Every year the external members will be asked to provide a brief SWOT report (strengths, weaknesses, opportunities, threats) on the project as a whole. This report shall be based on quantitative indicators (number of publications, patents, etc.) and qualitative indicators (e.g., management of research, teaching/lecturing, supervision, mentoring, national or international collaboration, administrative duties, public awareness activities and mobility) as can be derived from reports and participation at the workshops. Our experience with previous networks has shown that evaluation of workshops and work package meetings by the participants as well as online surveys had positive impact on subsequent network events and gave network scientists the opportunity to shape and improve activities. The administrator will take responsibility to analyze the results and distribute the results to the network.

Dissemination of project information and results. The classic way of disseminating project results is through (jointly-authored) publications by QUEST researchers in internationally leading journals. A digital library will be developed with interactive web structure that can lead to highly visible project elements and allow scientists worldwide to benefit from project results, where applicable. For example this refers to workshop training and practical material that shall be stored online and/or scientific software and computational tools that can be used by the scientific community. QUEST will pursue – where possible – an open-source philosophy to distribute the software to be developed to interested academic institutions (license issues to be negotiated for each software package individually). In case of funding the QUEST project and its objectives shall be advertised in the weekly EOS journal of the American Geophysical Union that is distributed to most Earth scientists worldwide. At both the EGU and AGU Meetings we intend to have special project stands distributing job opportunities, information on training opportunities, and general information on QUEST. A **final international meeting** (deliverable #23) will be organized in co-operation with other initiatives of similar scope, the exploration industry and companies involved in energy (geothermal) and other relevant activities (e.g., CO_2-sequestration). The title of the meeting will be “Seismic Tomography on Supercomputers: Exploiting the Waveforms”. The goal of this meeting is to disseminate the experience of QUEST to potential users for the inversion technology (seismic data interpreters, large seismic campaigns in academia and industry, government agencies) and link to other disciplines. The meeting also serves as a job market for QUEST researchers.

Intellectual Property Rights. With direct and associated industrial partners, joint PhD projects, use of in-house data sets and software, intellectual property rights become an issue for the consortium. One of the key tasks of the inaugural meeting of the supervisory board will be to formalize co-operation between the academic and industry partners. The supervisory board will develop a consortium agreement with the help of the legal departments of one or several universities and the industrial partners that will be signed by all partners. Given the participation of several industrial partners rules might be considered that QUEST students will not be allowed placements in more than one of the industrial partners. These issues will be decided upon at the first Board meeting.

Financial management. The Community financial contribution towards management-related expenses will be used to pay the salary of a network administrator, Greta Küppers, who will assist the co-ordinator, Prof. Dr. Igel, with this task. The network administrator will be in charge of re-allocating Community Financial Contribution received from the European Community to each of the partners without unjustified delay after the receipt of the Community Financial Contribution and according to the overall Network budget breakdown. Each QUEST Partner will specify to Greta Küppers a bank account to which the corresponding amount of the Community Financial Contribution shall be transferred. The network administrator will verify the validity of the Partners' bank details yearly and previously to the allocation of the estimated amount. In her role of financial manager, Greta Küppers will supervise by means of a computer-based accounting system that the expenses of the QUEST network are appropriate, economically efficient and in agreement with the initial financial planning. The network administrator, through the co-ordinator/supervisory board, will promptly ask the European Community for advice, in case a budget re-allocation among the Network members would come into question. Each QUEST Partner will manage the allocated budget according to its own usual accounting principles and practices. The allowed overheads will be used to arrange for local accounting assistance within each partner's institution. The granted funds will be primarily used to pay salaries, mobility expenses and research and training activities costs to young scientists during their stay at the host institution according to the rules set by the European Commission.

Capacities of the Network

The table below summarizes the capacities of the network in terms of scientists involved, expertise, the available infrastructure and training facilities, highlights, and publications. To demonstrate the complementarity of the network expertise we subdivide into six categories: (1) the mathematical foundations of imaging problems (M); (2) aspects of computational modelling and data processing (C); (3) seismic imaging of subsurface structure (S); (4) earthquake physics (E); (5) passive imaging (P), and (6) complex rheologies (R). Note also the various spatial scales (reservoir, continents, planets) on which inverse problems are studied in the network.

Table 5. Information on Partner institutions, involved scientists and expertise

Ludwig-Maximilians-University Munich DE – C,E,M,R	
Involved scientists, involvement and expertise: **Prof. Dr. H. Igel** (50%) computational geosciences, rotation Prof. Dr. P. Bunge (10%) geodynamics, geocomputing Dr. K. Sigloch (25%) finite frequency tomography Dr. M. Käser (25%) computational wave propagation	*Infrastructure, training:* Access to supercomputing and HPC training programmes, 150 node Linux cluster, structured graduate training programmes. University-wide soft skill programme. Several parallel wave propagation solvers and adjoint methods.
Highlights: HI coordinated the EU-MCRTN Spice Project focusing on computational wave propagation. LMU Geophysics has been running structured international graduate college for several years (THESIS). HI is Executive Secretary for Theoretical Seismology of the European Geosciences Union.	
Publications: (1) Fichtner A., B. L. N. Kennett, H. Igel, H.-P. Bunge, (2008). Theoretical background for continental and global scale full-waveform inversion in the time-frequency domain, Geophys. J. Int., in print. (2) De la Puente, J, M. Dumbser, M. Käser, and H. Igel (2008), Discontinuous Galerkin Methods for Wave Propagation in Poroelastic Media, *Geophysics*, in press. (3) Igel, H., A. Cochard, J. Wassermann, A. Flaws, U. Schreiber, A. Velikoseltsev, N. D. Pham (2007), Broad-band observations of earthquake-induced rotational ground motions, Geophys.J.Int., 168(1), 182-197.	

Schlumberger Research Cambridge GB – C,M,R,S	
Dr. J. Robertsson (10%) wave simulation Dr. C. Kostov (10%) inverse problems Dr. P. Childs (10%) inverse problems Dr. C. Thomson (10%) ray theory, theoretical seismology	In-house 3D finite-difference codes, in-house paraxial ray-tracing code, seismic processing system (Omega), seismic visualization and interpretation system (Petrel), participation in internal (Eureka) technical community knowledge sharing initiatives, access to research from academic consortia sponsored by Schlumberger.
Schlumberger is the world's leading supplier of technology, project management, and information solutions to the oil and gas industry. Their mission is to understand the static and dynamic nature of the subsurface reservoir by integrating key disciplines. Characterize the full earth model and maximize productivity. SLB has strong links to university research and funds the Schlumberger Medal by the Society of Exploration Geophysicists (SEG) in applied geophysics.	

(1) C.H. Chapman (2004). Fundamentals of Seismic Wave propagation, Cambridge University Press. (2) C. J. Thomson (2005). Accuracy and efficiency considerations for wide-angle wavefield extrapolators and scattering operators, Geophys. J. Int., 163, 308-323. (3) Moczo P., J. O. A. Robertsson, L. Eisner (2006). The Finite-Difference Time-Domain Method for Modelling of Seismic Wave Propagation, pp. 421-516, in Advances in wave propagation in heterogeneous Earth (eds. R.S. Wu and V. Maupin) Vol 48, Advances in Geophysics(ed. R. Dmowska), Elsevier-Pergamon, Oxford.

Spectraseis AG Zurich CH – C,P,S	
Dr. B. Artman (15%) passive imaging Dr. A. Goertz (15 %) reservoir seismics Dr. E. H. Saenger (10%) finite-difference modeling Dr. M. Kelly (10 %) geophysical pattern recognition	Complementary skills training in financial management, law and social sciences, contact with the national and international oil and gas business, access to IT instruments and data sets facilities. Pool of broadband sensors for passive experiments.
Spectraseis AG is a passive seismic service provider to the oil and gas exploration/development industry world-wide. The team, which includes at the moment more than 7 PhD.s with a background in various sub-disciplines of seismology and geophysics, physics and computer science, consists of highly skilled researchers and project scientists with many years of experience in the seismic exploration industry. Strong emphasis on team work and an open office create a highly prolific research lab and learning environment. Spectraseis has won the 2007 World Oil Award for Best Exploration Technology.	
(1) Steiner B., E. H. Saenger, S. M. Schmalholz, (2008). Time reverse modeling of low-frequency microtremors: Application to hydrocarbon reservoir localization, Geophysical research letters, VOL. 35, L03307, DOI:10.1029/2007GL032097. (2) Saenger E.H., R. Ciz, O. S. Kruger, S. M. Schmalholz, B. Gurevich, S. A. Shapiro, (2007). Finite-difference modeling of wave propagation on microscale: A snapshot of the work in progress, Geophysics 72, SM293, DOI:10.1190/1.2753552. (3) Artman B., (2006). Imaging passive seismic data, Geophysics 71, SI177, DOI:10.1190/1.2209748.	

Institut de Physique du Globe de Paris FR – C,E,M,P	
Prof. J.-P. Montagner (50%) surface waves, time reversal Prof. J.-P. Vilotte (30%), computational seismology Prof. P. Lognonné (10%), elastic waves in planets Dr. N. Shapiro (10%), Seismic noise tomography Prof. A. Tarantola (10%) Theory of inverse problems	Structured courses within the Doctoral School in Seismology and in all fields of Earth Sciences, access to the local IT facilities and to the Global Seismological observatories.
IPG is one of the founding institutions for the probabilistic approach to seismic inverse problems (AT) and has played a world-leading role in computational wave and rupture propagation (JPV), surface wave tomography (JPM), exploration of planets (PL), and ambient noise studies (NS).	
(1) Delavaud E., J.-P. Vilotte (2008). 3D Spectral Element simulations of the seismic response of complex geometrical structures: application to the caracas (Venezuela) basin, Geophys. J. Int., submitted. (2) Madariaga R. (2007), Slippery when hot, **Science**, 316, 842. (3) Qin Y., Y. Capdeville, V. Maupin, J.-P. Montagner, S. Lebedev, E. Beucler (2008). SPICE Benchmarks for global tomographic methods, Geophys. J. Int., in press.	

Istituto Nazionale di Geofisica e Vulcanologia Rome, IT – C,E,S	
Dr. A. Morelli (30%), seismic tomography Dr. P. Danecek (50%), waves in complex media Dr. D. Stich (20%), waveform inversion Dr. A. Bizzarri (30%), sources and fracture dynamics	Access to large seismic and geodetic data sets. Several in-house clusters. Access to CINECA supercomputers.
Dr. Andrea Morelli is co-coordinating the EU Integrated Infrastructure Initiative Project NERIES focusing on networking the European seismic networks, improving access to data, allowing access to specific seismic infrastructures and pursuing targeted research developing the next generation of tools for improved service and data analysis. INGV is also responsible for the coordination of Italian geophysical observatories in Antarctica.	
(1) Stich, D., P. Danecek, A. Morelli, J. Tromp (2008). Imaging lateral heterogeneity in the northern Apennines from time reversal of reflected surface waves (in press). (2) Stich D., A. Morelli (2007). Reflection of seismic surface waves at the northern Apennines, Earth and Planetary Science Letters, 259, 149–158, doi:10.1016/j.epsl.2007.04.036. (3) Danesi S., S. Bannister, A. Morelli (2007). Repeating earthquakes from rupture of an asperity under an Antarctic outlet glacier, Earth and Planetary Science Letters 253, 151–158, doi: 10.1016/j.epsl.2006.10.023	

Eidgenössische Technische Hochschule Zürich CH – C,E,S,R	
Prof. Dr. D. Giardini (50%) seismic hazard Dr. M. Mai (25%) earthquake source inversion Dr. L. Boschi (25%) global tomography	Several large Linux clusters. High station density seismic network. Access to supercomputers of Swiss National Computing Centre.
Prof. Giardini is President of the Federation of digital Broadband seismograph networks, in charge of the worldwide seismic networks. He also is the coordinator of the largest EU project in Earth Sciences so far (NERIES).	
(1) Monelli, D., P.M. Mai (2008). Bayesian inference of kinematic earthquake rupture parameters through fitting of strong motion data, Geophys. J. Int., 173, 220-232. (2) Käser, M., P.M. Mai, M. Dumbser (2007). Accurate Calculation of Fault-Rupture Models Using the High-Order Discontinuous Galerkin Method on Tetrahedral Meshes, *Bull. Seis. Soc. Am.*, Vol. 97 (5), 1570-1586. (3) Peter D., C. Tape , L. Boschi, J. H. Woodhouse (2007). Surface wave tomography: global membrane waves and adjoint methods., Geophys. J. Int., 171, 1098-1117.	

University of Oxford UK – E,M,S	
Prof. J H Woodhouse (20%) global tomography Prof. S Das (20%) earthquake sources Dr. D P Robinson (10%) seismic inverse problems	Training in project and research management, in presentation skills, in developing research leadership. The IT Learning Programme (ITLP), which is part of the Learning Technologies Group of the

	Oxford University Computing Services, provides an important link between information technology and academic teaching and research.
Prof. Das is leader of the Seismology group for the Natural Environment Research Council, UK. A Consortium grant of £2m was endowed to her in ordert to study the 2004 great Sumatra earthquake.	
(1) Das S., (2007). The need to study speed, **Science**, 317, 905-906. (2) Deuss A, SAT, Redfern, K. Chambers, J.H. Woodhouse (2006). The nature of the 660-kilometer discontinuity in Earth's mantle from global seismic observations of PP precursors, **Science**, 311, 198-201. (3) Chambers K., J.H.Woodhouse (2006). Investigating the lowermost mantle using migrations of long-period S-ScS data, Geophys J Int, 166, 667-678.	

Utrecht University NL – M,S,R	
Prof. Dr. J. Trampert (30%) surface waves, inverse theory Dr. H. Paulssen (10%) body wave analysis Dr. A. Sieminski (10%), adjoint anisotropic tomography	Training courses on communication and presentation skills, management skills, and scientific writing in English, high level courses in parallel computing, Linux cluster, access to supercomputing.
JT is responsible for the management of NARS, a mobile seismic network whose stations are currently deployed around the Gulf of California, Mexico in the **NARS-Baja** project.	
(1) Meier U., A. Curtis, J. Trampert, (2007). Fully nonlinear inversion of fundamental mode surface waves for a global crustal model, Geophys. Res. Lett., 34, L16304, doi:10.1029/2007GL030989. (2) van Vossen R., J. Trampert, (2007). Full-waveform static correction using blind channel identification, Geophysics, 72, no.4, U55-U66. (3) Trampert, J., F. Deschamps, J. Resovsky, and D. Yuen. Probabilistic tomography maps chemical heterogeneities throughout the lower mantle. **Science**, 306 (5697), 853-856, 2004.	

National University of Ireland Dublin IE – E,P,S,R	
Prof. Dr. C. Bean (20%) scattering, HPC computing Dr. G. O'Brien (15%), Fluid-solid coupling, HPC, CO_2 seq. Dr. I. Lokmer (80%), source inversions, volcano seismology Dr. S Murphy (25%), slow slip/ruptures	Complementary skills courses in scientific and proposal writing, financial and legal issues, innovation and knowledge transfer co-ordinated and facilitated by the Graduate Studies Programme, training in computational methods and parallel programming, access to supercomputing facilities.
CB is currently coordinating the EU Project VOLUME aiming at increasing our understanding of how subsurface mass movement manifests itself at the surface, in turn revealing the significance of such movements as precursors to impending eruptions. In 2007 the UCD Geophysics Group were PI's on an award of €1.2m from the Irish Government (Co PI's from Coleraine, Northern Ireland) aimed at developing local capabilities for, and enhance understanding of CO_2 sequestration. This project is undertaken as part of the Irish National Geoscience Strategy.	
(1) Bean C. J., I. Lokmer, G. O'Brien, (2008). Influence of near-surface volcanic structure on long-period seismic signals and on moment tensor inversions: Simulated examples from Mount Etna., *J. Geophys. Res*., doi:10.1029/2007JB005468, in press. (2) O'Brien G. S., (2008). Discrete visco-elastic lattice methods for seismic wave propagation, *Geophys. Res. Lett.*, 35, L02302, doi:10.1029/2007GL032214. (3) Lokmer, I., C. J. Bean, G. Saccorotti, D. Patanè, (2007), Moment-tensor inversion of LP events recorded on Etna in 2004 using constraints obtained from wave simulation tests, *Geophys. Res. Lett.*, 34, L22316, doi:10.1029/2007GL031902.	

Université Joseph Fourier Grenoble FR – E,P,M	
Prof. M. Campillo (25%) imaging (noise & diffuse fields) Prof. F Cotton (10%) seismic source inversion Prof. J. Virieux (25%) tomography in time and in frequency Dr. E. Chaljub (10%) simulation of wave propagation	Doctoral school training, contact to several oil industry companies, access to IT instruments and data set facilities.
FC coordinated the EU Interreg IIIB Alpine space European project SISMOVAL. MC pioneered theory and first applications of passive imaging in seismology.	
(1) Brenguier F., N. M. Shapiro, M. Campillo, V. Ferrazzini, Z. Duputel, O. Coutant, A. Nercessian, (2008). Towards Forecasting Volcanic Eruptions using Seismic Noise, **Nature Geoscience**, doi:10.1038/ngeo104. (2) Pedersen H.A., M. Bruneton, V. Maupin, (2006). Lithospheric and sublithospheric anisotropy beneath the Baltic shield from surface-wave analysis Earth Planet. Sci. Lett., 244, 590-605. (3) Shapiro N.M., M. Campillo, L. Stehly, M. Ritzwoller (2005). High Resolution Surface Wave Tomography from Ambient Seismic Noise, **Science** 307, 1615-1618.	

Comenius University Bratislava SK – C,E	
Prof. P. Moczo (50%) computational seismology Dr. J. Kristek (50%) waves in complex media Dr. M. Galis (50%) high-performance computing Dr. M. Kristekova (50%), signal analysis	Linux cluster, strong collaboration with the Geophysical Institute of the Slovak Academy of Sciences running the Slovak national network of seismic stations.
PM is in charge of the coordination of the seismic hazard analysis for two nuclear power plants in Slovakia.	
(1) Galis M., P. Moczo, J. Kristek, (2008). A 3D Hybrid Finite-difference -- Finite-element Viscoelastic Modeling of Seismic Wave Motion. Geophys. J. Int., in press. (2) Moczo P., J. O. A. Robertsson, L. Eisner (2007). The Finite-Difference Time-Domain Method for Modelling of Seismic Wave Propagation. In Advances in Wave Propagation in Heterogeneous Earth, 421-516, Wu, R.-S., Maupin, V., eds., Advances in Geophysics 48, Dmowska, R., ed., Elsevier – Academic Press. (3) Kristekova M., J. Kristek, P. Moczo, S. M. Day (2006). Misfit Criteria for Quantitative Comparison of Seismograms. Bull. Seism. Soc. Am. 96(5), 1836-1850.	

Charles University Prague CZ – C,E,S	
Dr. J. Brokesova (30%) ray-theory	Courses on technology transfer topics, access to local computational

Prof. Dr. J. Zahradnik (10%), finite-difference modeling Dr. F. Gallovic (50%) evolution of seismic faults Dr. I. Oprsal (30%), simulation of wave propagation	facilities.
JZ coordinated the EU funded project MAGMA aiming at contributing to the co-ordination of research and education in dynamic phenomena of the solid Earth and atmosphere by adopting unifying mathematical viewpoint and multidisciplinary approach. CUB is also in charge of the coordination of the consortium research project Seismic waves in complex 3-D structures (SW3D), focused primarily on the fundamental issues of high-frequency seismic wave propagation in complex 3-D isotropic and anisotropic structures.	
(1) Gallovič F., J. Brokešová, (2007). Hybrid k-squared Source Model for Strong Ground Motion Simulations: Introduction, Phys. Earth Planet. Interiors 160, 34-50. (2) Kolínský P., J. Brokešová, (2007). The Western Bohemia Uppermost Crust Shear Wave Velocities from Love Wave Dispersion, Journal of Seismology, 11, 101-120. (3) Zahradnik J, A. Serpetsidaki, E. Sokos, G.-A. Tselentis, (2005). Iterative Deconvolution of Regional Waveforms and a Double-Event Interpretation of the 2003 Lefkada Earthquake, Greece, Bull. Seism. Soc. Am., 95, 159-172.	

Istituto Nazionale di Oceanografia e di Geofisica Sperimentale Trieste IT – C,S,R	
Prof. G. Seriani (50%) spectral element modeling Prof. J. Carcione (10%) rock physics, waves in real media Dr. G. Rossi (25%), CO_2 fluid reservoir monitoring Dr. D. Gei (35%), seimic processing, rock seismics	Local soft skill training courses, courses on all aspects of IT and HPC through the Cineca Supercomputing Centre, various Linux based Clusters, access to instruments for seismic data processing, access to HPC multiprocessors.
GS coordinated the national R&D project TREMOR: a modelling system for numerical seismic wave propagation in realistic geological structures for earthquake risk investigations. GS was local coordinator of EU funded EOS , GEOSCIENCE II, SPICE and is of CO2Geonet, an EU Network of Excellence on Geological Sequestration of CO2. Moreover, OGS coordinated EU funded projects GEOBIT, ENC, SINBUS, GEOBIT-EXT, SEISBIT 3D RVSP, TO3D, 4DTAIL, all related to exploration geophysics.	
(1) Rossi G., D. Gei, S. Picotti, J. M.Carcione (2008). CO2 storage at the Aztbach-Schwanenstadt gas field: a seismic monitoring feasibility study, First Break, 26, 45-51. (2) Carcione J. M., (2007).Wave fields in real media: Wave propagation in anisotropic, anelastic and porous media, 2d edition, Handbook of Geophysical Exploration, vol. 38, Pergamon Press Inc. (3) Seriani G., S.P. Oliveira, (2007). Optimal blended spectral-element operators for acoustic wave modeling, Geophysics, 72(5), SM95-SM106, doi:10.1190/1.2750715.	

University of East Anglia Norwich UK – M,S	
Dr. A. Ferreira (50%) normal mode theory, inversion Dr. T. Bagnall (10%) time series data mining Dr. J. Harold (10%), parallel computing, HPC	Local soft skill training courses (i.e. understanding the research environment, training for academic consultants, preparing grant applications in the sciences, scientific presentations, writing for scientific publication, patents and IPR, working with the media), supercomputing and HPC training programmes, formal research and career skills graduate training, Linux cluster.
The School of Environmental Sciences (ENV) at UEA is regarded as one of the very best research and teaching institutions in the world for interdisciplinary environmental sciences. ENV has the highest 5* grade in the UK Research Assessment exercise, denoting international excellence, and the highest government grading for teaching (Excellent).	
(1) Ferreira A.M.G., J.H. Woodhouse, (2007). Observations of long period Rayleigh wave ellipticity, Geophys.J. Int., 169, 161–169. (2) Ferreira A.M.G., J.H. Woodhouse, (2007). Source, path and receiver effects on surface waves, Geophys. J. Int., 168, 109-232. (3) Ferreira A.M.G., J.H. Woodhouse, (2006). Long period seismic source inversions using global tomographic models, Geophys. J. Int., 166 (3), 1178-1192.	

University of Potsdam DE – M,C	
Prof. M. Holschneider (50%) wavelets Prof. S. Reich (20%), high-performance computing Dr. G. Zöller (25%), statistical parameter estimations Dr. M. Kulesh (50%), wavefield separation	Local soft skill training programmes, access to supercomputing and HPC training programmes, Linux cluster.
MH is the director of the Interdisciplinary Center for Dynamics of Complex Systems whose goal is to further interdisciplinary research and teaching in the field of Nonlinear Dynamics and Complex Systems	
(1) Maraun D., J. Kurths, M. Holschneider, (2007). Nonstationary gaussian processes in wavelet domain: Synthesis, estimation and significance testing, Phys. Rev. E, 75. (2) Diallo S.M., M. Holschneider, M. Kulesh, F. Scherbaum, F. Adler, (2006). Characterization of polarization attributes of seisimic waves using continuous wavelet transforms. Geophysics, 71(3):67–77. (3) Diallo S.M., M. Kulesh, M. Holschneider, F. Scherbaum, (2005). Instantaneous polarization attributes in the time-frequency domain and wave field separation. Geoph. Prosp., 53(5):843–855.	

Exploitable Synergies

A few years ago problems in the exploration industry, seismic hazard analysis, volcanology, or global tomography would have been solved with very different methodologies. In fact, we are considered as vastly different research areas (in the general field of geosciences). With the increased use of computational methods and the power of 3-D simulation technology this has dramatically changed. To highlight the possible synergies within the network we will give a few examples how the expertise available in the network cross-fertilized. (1) A concept (cross-correlation of random fields) originally used in astronomy (helio-seismology), then successfully applied in regional seismology (UJF, IPG), is now applied with tremendous success in the exploration domain (SSZ, SCR). (2) The adjoint method, developed in the eighties of last century primarily for the use in reservoir problems (IPG) is now being adopted and applied on local, continental and global problems (IPG, LMU, CAL, UOX, UEA), likewise the classical method for reservoir seismics – migration – is just being applied to global seismology. (3) Grid generation, meshing and visualization tools such as GOCAD were also developed primarily for the exploration domain and are now being used for regional problems in connection with sedimentary basins and earthquake scenario simulations. (4) The synergies with HPC expertise has been highlighted before. Transfer of expertise to Earth sciences can only improve the scientific output of our data modelling studies. The QUEST network has the required ingredients that such cross-fertilization will continue in an oxygen-rich research and training atmosphere.

Scientific Workplan

In this section we detail the scientific and methodological work packages (WPs) introduced in section B3. In particular project topics, names of the supervising lead scientists, and project start dates are given. Project acronyms are given followed by the start month (e.g., WP2-A-3 for the first project in WP2 starting in project month 3). We define four cross-cutting goals to which all projects are directed towards.

- *Stable parallel adjoint inversion using finite-difference and finite (spectral)-element methodologies*. Two specific software packages shall be developed, one for industrial type problems (Cartesian geometry), one for regional and global problems (spherical geometry). WP2-4 will join forces to reach these objectives.
- WP5: *Passive vs. active imaging in industrial problems*. Application to two industrial data sets (land and marine data provided by the industrial partners).
- WP6: *A new model of the Earth's upper mantle and crustal structure* (continental and global). How sharper are the new models and what does it tell us about internal processes?
- WP7: *The Earthquake source: stable and unstable features* – quantifying the uncertainties. Application to large earthquakes observed with strong motion, broadband and geodetic instruments.

WP2-4 constitute the methodological part of QUEST. Key objectives are the merging/extension of forward modelling tools with concepts from inverse theory (e.g., adjoint techniques, time reversal) and the incorporation of state-of-the art computational science methods for program development, performance optimization, grid generation, and visualisation. In WP3 the cluster of Munich and Zurich institutions (LMU, TUM, RZG, IBM, ETH) in geophysics, computational sciences, and the supercomputer centre (in cooperation with all partners) will take responsibility to produce 2-3 imaging programs tested on multiple platforms, optimized, and available through a version control system (community code, to be distributed under appropriate licenses).

Table 6. Work packages 2-7.

WP2: Forward Modelling (CUB)
Objective: Developing the forward modeling ingredients to the inverse problem. Defining optimal strategies for geophysical model description with complex geometries (e.g., GOCAD). Computational grid generation for efficient wavefield calculations. Adapting novel numerical approaches to the seismic wave propagation problem. Defining optimal solutions (best practices) for specific problems (e.g., in terms of numerical approach, problem scale, computational grid type). Development of appropriate rheologies for structural and source inverse problems (e.g., anisotropy, poroelasticity, nonlinear strains).
Projects: ER (WP2-A-3) (Moczo, Holschneider) Hybrid finite-difference/element modelling on octree grids. **ESR (WP2-B-3)** (Moczo, Igel) Optimally accurate finite-difference scheme for viscoelastic media. **ESR (WP2-C-3)** Wavefield separation on joint

usage of wavelet dispersion and oscillation patterns (Holschneider, Capdeville). **ESR (WP2-D-3)** Near field ground motion modelling for structure generated with GOCAD (Vilotte, Caumon).
Links to other WPs and overall objectives: Essential for all inverse studies as forward modelling is the key ingredient for any seismic source or structural inversion. The methodologies developed here will benefit from progress in WP3 with focus on implementing and optimizing the methods developed in WP2 on HPC systems (-> DEISA).
Milestones and Deliverables: Web-archive with 3-D wave propagation solvers applicable to imaging problems, adjoint wavefields, finite sources (M12). Interactive benchmarking facility for numerical wave and rupture problems (M30).

WP3: High-Performance Computing (UCD)
Objective: Seismic imaging undertaken in QUEST will depend on heavy computations requiring HPC soft- and hardware solutions. Goals are the efficient implementation of parallel wave propagation solvers and their adaptation to adjoint wavefields (in coll. with IBM). The generation of computational grids for the specific applications (reservoirs, volcanoes, faults, planets) and the e-infrastructure to disseminate them to the network partners. Provision of access to local parallel clusters (specifically at LMU, ETH, UU, UCD) and European supercomputer infrastructure through national supercomputer centers (DEISA/DEGREE). This WP will also set up a web-infrastructure for the imaging benchmark exercises. Training on computational issues (e.g., parallel programming) shall be provided through this WP in collaboration with computational scientists of the local supercomputer centers and the training offered through DEISA.
Projects: ER (WP3-A-6) (Bean, Vilotte) Multiple-platform optimization of wave simulation codes. **ER (WP3-B-6)** (Curioni, Igel) Stabilization of 3D modelling codes for heterogeneous, anisotropic planets. **ESR (WP3-C-6)** (Igel, Bungartz) Load balancing of wave simulations with local time stepping and p-adaptivity. **ESR (WP3-D-6)** (Mai, Curioni) HPC for data mining, imaging and visualization of seismic data and models. **ER (WP3-E-24)** Web interfaces for seismic modelling (Igel, Curioni).
Links to other WPs and overall objectives: This WP provides the technical support for the scientific software packages used for all practical applications planned in WP5-7. In addition, this WP is responsible for distribution information on and providing access to HPC resources. The software solutions will merge methodologies developed in WP2 and WP5.
Milestones and Deliverables: www platform for training on and access to European HPC infrastructure (M6). Best practices for parallel wave simulation and inversion code development and implementation (M18).

WP4: Inverse Modelling – Active and Passive imaging (ING)
Objective: This WP will deal with fundamental questions of inverse/imaging problems. What are optimal strategies to compare data with theory for the various imaging applications? How should we combine local with global search methods? How should models be described and represented in digital form? How can a priori information be incorporated into the imaging process. What search methods should be used to explore the vast model spaces? How to describe the solution of the imaging problem (movie philosophy)? How can the information of data and model uncertainties be conveyed visually? How can we use probability theory to define model geometries? How can we formally combine information from different data sets (e.g. passive and active imaging)? Projects in this WP will investigate and develop optimal strategies using a probabilistic approach to structural and source imaging from a theoretical point of view. In addition this WP shall specifically develop and extend the theory of and the domains of applications of passive imaging using ambient noise and coda signals.
Projects: ER (WP4-A-3) (Morelli, Montagner) Quantification and visualization of uncertainties in waveform inversion problems. **ESR (WP4-B-3)** (Campillo, Artman) Seismic passive monitoring of fault systems, underground industrial activity, and stress changes. **ESR (WP4-C-3)** (Mai, Bean). Scattering properties of local scale Earth structures: model discretization. **ESR (WP4-D-3)** (Ferreira, Montagner) Optimal model space search for waveform inversion.
Links to other WPs and overall objectives: This WP provides the fundamental concepts for the inverse modelling of observed seismic waveforms to be carried out in WPs 5-7. Progress in this WP will impact the quality of the images on source and structure of all practical applications. WP4 builds upon the methodological solutions provides by WPs 2+3.
Milestones and Deliverables: Computational tools and best practices for model space search, calculation and visualization of uncertainties (M24). New model of the European subsurface structure (M36).

In WP5 we intend to apply all flavours of inverse methodologies to one or two industrial data sets, so that cross-validation is possible (DC2). More than one dataset is recommended because of the contrasting land and marine imaging problems, in particular aperture, sampling, noise and especially different medium properties proximal to the receivers (seabed, free-surface topography, etc.). Passive sources will also be considered. New synthetic benchmark data sets will complement the real industrial datasets, allowing quantitative assessment of the resolution power of the various methods with ideal and current survey geometries.

WP5: Industrial Problems (SCR)
Objective: Application of full waveform imaging methods to industry problems. Development of a new high-resolution, multicomponent, 4-D benchmark seismic data base for testing solutions and inverse algorithms (incl. anisotropy, poroelasticity and time-dependence of internal structures). Application on observed data sets in collaboration with industrial partners in the fields of CO_2-sequestration, monitoring and control of geothermal projects, imaging the time evolution of reservoirs under production (4D seismics). (Inter-) comparison and integration of active and passive imaging methodologies in a quantitative way. Problem-specific recommendations for the use of full-waveform modelling and inversion tools in industrial problems.
Projects: ESR (WP5-A-9) (Robertsson, Igel) Adjoint methods on a reservoir scale. **ESR (WP5-B-9)** (Bean, Seriani) Inversion for

temporal changes in reservoir anisotropy. **ESR (WP5-C-9)** (Artmann, Campillo) Low-frequency velocity inversion using passive seismic data. **ESR (WP5-D-9)** (Morelli, Thomson) Time lapse full waveform inversion for geothermal and CO_2-sequestration problems. **ESR (WP5-E-9)** Poroelasticity and waveform inversion (Käser, Eisner).
Links to other WPs and overall objectives: In this WP the methodologies of WP2-4 are applied in a Cartesian framework in reservoir scales. Strong interaction with the training programme for all students on industrial problems.
Milestones and Deliverables: New high-resolution benchmark seismograms for testing (M14). Computational toolbox for imaging on reservoir scales (M36).

The first full-waveform inversion schemes based on 3-D simulation methods are envisaged in WP6 for continental scales (e.g., Europe, Australia, US). Again the goal is to use passive imaging and invert earthquake source generated ground motions and cross-validate the results.

WP6: Tomography and Geodynamics (IPG)
Objective: Improve the resolution of structural images of seismic velocities, anisotropies and attenuation on continental and planetary scale. Discussion of impact on fundamental geodynamic problems (dynamic topography, mantle convection, plate tectonics, hot spot activity, crustal deformation). Application of the forward and inverse methodology on spherical meshes. Explicit vs. approximate treatment of crustal layers, oceans, topography on forward and inverse problems. Effect of approximate vs. full-waveform modeling on structural imaging as a function of frequency.
Projects: ER (WP6-A-9) (Montagner, Trampert) Global anisotropic mantle tomography. **ESR (WP6-B-9)** (Woodhouse, Bean) Mantle scatterers using radon transforms. **ESR (WP6-C-9)** (Trampert, Shapiro) High-frequency inversion for a global crustal model using 3D wave propagation. **ESR (WP6-D-9)** Automated waveform comparison for large broadband data sets (Morelli, Holschneider)
Links to other WPs and overall objectives: Application of HPC full waveform methodologies (WP2+3) to imaging on continental and planetary scale. Link to the more general Earth Science question in geodynamics.
Milestones and Deliverables: Full waveform inversion tools for continental and planetary scales (M36). New global high-resolution model for both P- and S-wave velocities (M40).

The recently demonstrated high degree of nonlinearity and uncertainty of earthquake source inversion motivates the objectives of WP7 to improve the quantitative estimation uncertainties in specific case studies and extensive blind imaging benchmark tests in collaboration with SCEC.

WP7: Seismic Sources (ETH)
Objective: This WP aims at advancing earthquake source imaging. The improved source-rupture models will in turn be critical input to studies of the mechanical processes of earthquakes and to developments of new source-characterization for shaking scenario simulations for ground prediction and seismic hazard. Specific research topics include the quantitative assessment of uncertainties and the development of fully nonlinear inversion schemes using the probabilistic approach; applying space and time adaptive inversion parameterizations; development of strategies to include the high-frequency part of the wave field into source imaging; direct inversion of dynamic rupture parameters; and the design of optimal experimental configurations (including borehole geometries) for source imaging by resolution analysis. These studies shall be complemented by "blind source imaging" exercises that will include researchers outside QUEST. This WP will also address the issue of high-resolution source location in the context of hydrofracturing (e.g. geothermal reservoirs, enhanced oil-recovery).
Projects: ER (WP7-A-9) (Mai, Vilotte) Complex earthquake sources embedded in 3-D. **ESR(WP7-B-9)** (Das, Bouchon) Earthquake rupture process from broadband recordings. **ESR (WP7-C-9)** (Brokesova, Bizarri) Inference of fault rheology from ground motions. **ESR (WP7-D-9)** Fluid migration, earthquake sources and seismicity (Bean, Eisner).
Links to other WPs and overall objectives: Particularly for continental scale and planetary scale inversion (WP4) finite sources is a key ingredient to progress instructural imaging.
Milestones and Deliverables: Kinematic source inversion blind test (M16). New data base with high-resolution source images combined with resolution information (M36).

We expect that – in addition to the network-wide training workshops – short open meetings of the institutions involved in the WPs will be held 1-2 times a year in support of the objectives to be reached. These meetings will be held either at partner institutions or in connection with the international meetings (e.g., EGU).

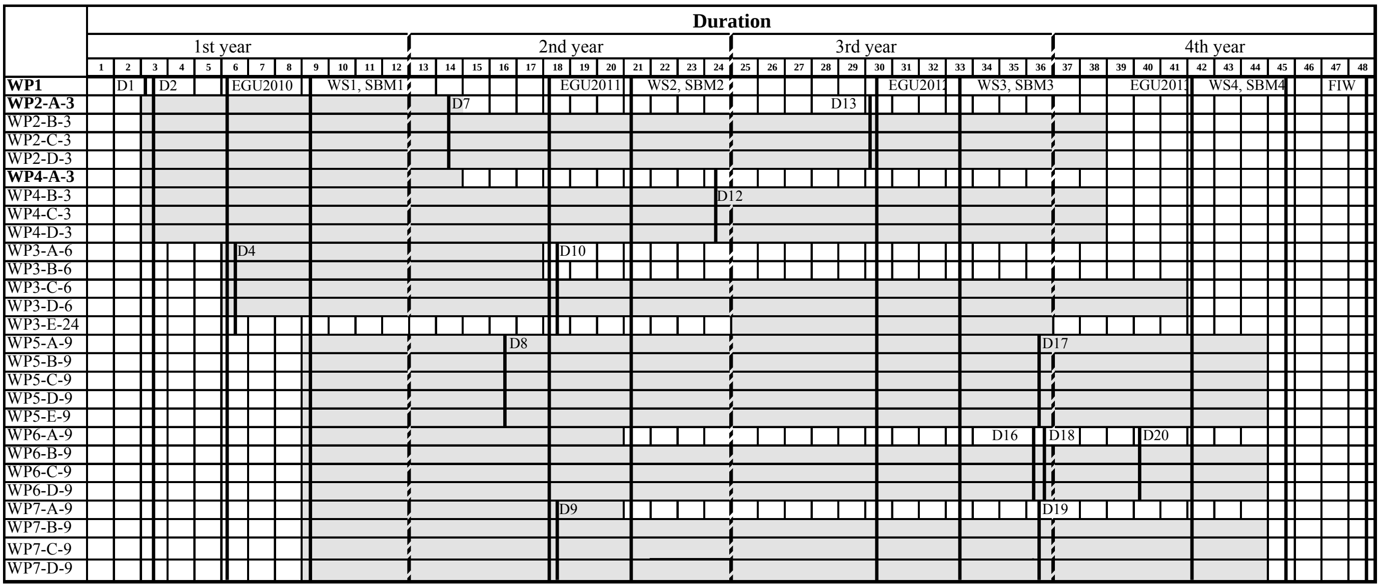
Deliverables

The following table summarizes the deliverables with types R (report), S (software), M (Meeting), W (web-structure) in chronological order. The WP columns only denote the responsible WP leaders.

Table 7. Information on the project deliverables

QUEST Project Deliverables				
#	**Title**	**WP**	**Date (mo.)**	**Type**
1	Project www structure, content management system, mail groups	1	3	W
2	Kick-off Meeting – Munich	1	3	M
3	Special session EGU 2010	1	6	M
4	Web-platform for HPC training and hardware access	3	6	W
5	1st Training workshop, Smolenice, SK	1	9	M
6	Special session EGU 2011	1	18	M
7	Digital library with forward solutions	2	14	S
8	New industrial benchmark data set	5	16	R
9	Kinematic blind source inversion facility	7	18	W
10	Best practices for parallel wave simulation	3	18	R
11	2nd Training workshop, Zurich, CH	1	21	M
12	Computational tools for inverse problems	4	24	S
13	Web-based interactive benchmarking for wave and rupture problems	2	30	W
14	Special session EGU 2012	1	30	M
15	3rd Training workshop, Venice, IT	1	33	M
16	New regional and global tomographic models	6	36	R
17	Toolbox for imaging on reservoir scales	5	36	S
18	Toolbox for imaging on continental and planetary scales	6	36	S
19	Earthquake source data base with uncertainties	7	36	R
20	New global high-resolution model	6	40	R
21	Special session EGU 2013	1	42	M
22	4th Training workshop, Cargese, FR	1	45	M
23	Final International Workshop, location tbd	1	48	M

The timing of individual projects (19 ESR and 7 ER) and deliverables are further illustrated in **Fig. 3** below. Please refer to Table 7 for deliverables D. Workshops and Supervisory Board Meetings are labelled WS and SBM, respectively. European Geosciences Union Meetings (EGU) are indicated for each year.



B.6 IMPACT

As indicated in the introduction the scientific domain QUEST is occupying can be described as immensely "data-rich". With ever-increasing station density of regional and global seismic networks with permanent multi-component observations with O(100Hz) sampling rates and field campaigns with hundreds of receivers the automated analysis of huge data volumes and the extraction of a maximum amount of information on structure and source is a problem of paramount importance now and in the future. The observational part of the required infrastructure in seismology is currently receiving attention through the NERIES project, in which access to the observational data will be coordinated and centralized for the first time. What is needed now is that Europe joins forces (1) to create the necessary sustainable computational tools to handle, process and interpret the observations, and (2) to train research scientists capable of further developing and driving these tools to do leading edge science. This applies to both industrial, academic problems, and also to government agencies working on aspects of natural hazards, energy, and climate problems. QUEST is targeting to achieve these goals with a strong focus on the training aspect.

Long-term benefits and collaborations. The proposed network is expected to create a number of career paths for the QUEST trained researchers in industries making use of seismic imaging technologies. This will have a long-term impact as this usually leads to strong links between the universities where the employees have graduated and the particular companies. This (1) facilitates and enhances collaboration on relevant research topics, and (2) creates links that enable easy access of graduating students to industrial placements. The QUEST network will also be used as a motor to devise future joint undergraduate and graduate multi-partner degree programs by recognizing mutually appropriate teaching modules.

Improvement of the career prospects. Simulation and inversion technology combined with HPC computing plays an increasingly important role in most natural sciences and Earth sciences is no exception. As Earth Sciences are an inherently multidisciplinary field the education at universities on undergraduate and graduate levels is primarily focused on providing the fundamentals in geology, physics, chemistry, maths, paleontology, biology, etc. Hence, there is little or no space for in-depth theoretical and practical training in numerical methodologies, computational sciences and high-performance computing. Nevertheless, if one carefully looks at the descriptions of job offers in academia, industry, and government labs (e.g., geological surveys) in recent years, the latter skills are often specifically sought for. In fact, many Earth Science departments (and industry labs) are re-focusing their positions with increasing emphasis on computational applications. QUEST tries to fill this gap in the academic training and provide exactly those skills combined with leading edge research projects for both academic and industrial problems. One of the key advantages is the fact that methodologies used in fundamental research and applied problems are now almost identical. This has led to more mobility of researchers in our field between industry and academia in recent years. In the light of this – and judged by the experience from other projects – we are convinced that the training provided by QUEST will lead to scientists with a spectrum of skills that will allow them excellent career opportunities not only in seismic exploration and general Earth sciences but also in adjacent fields such as physics, mathematics, computer sciences, and others. Through the interaction with the industry partners, the ER's will gain an impression on the specific work requirements and the "work climate" with the application-oriented industry; this may help early on to decide which career path to choose after graduation: academia or industry.

Improvements for the involved institutions. The technical developments envisaged in QUEST - in particular in connection with the development of stable, sustainable imaging software – cannot be achieved by single institutions or on a national level as the required expertise in forward modelling, inverse problems and computational aspects is widely scattered around Europe. Combining the efforts will considerably reduce the duplicative efforts in developing software in small projects leading to solutions that today are not easily maintainable due to the rapidly developing and increasingly heterogeneous computer architecture. From a technical point of view, participation in the network allows the institutions to have access to standardized software solutions, and be part of the effort to jointly increase the level of technical skills in our field, and make use of the network-wide assembled training material.

Impact on the scientific level of Applied Problems and Earth Science in Europe. We strive at developing a new generation of processing and imaging schemes extracting/incorporating much more information from observations than previously using the power of modern supercomputing. We expect this to have an impact on many levels: (1) for industrial problems it should lead to a more physics-based approach and improve the reliability of subsurface images. This should have a quantifiable impact on the reliable monitoring of CO_2-sequestration, the recovery of hydrocarbons, planning and controlling geothermal projects and others. (2) There are several regions in Europe that are at high risk from earthquake hazards, e.g., Italy, Greece, Turkey, and others. Mitigation of risks in the long term will rely on precise forecasting of ground motions and appropriate measures to reinforce structures in hazardous areas. This forecasting has to be based on high-resolution 3-D Earth models that we can obtain through the methods to be developed within QUEST. (3) On a larger scale we want to understand why and how the Earth'crust moves and this involves long-term processes (dynamic topography) that are connected with seismic velocity perturbations in crust and mantle that we can derive with greater accuracy with 3-D inversion methods. (4) A Europe-wide effort is on the way to develop a large observational and computational infrastructure to combine Earth Science disciplines in one European Plate Observatory System (EPOS). Needless to say that the gigantic data volumes to be gathered by such an infrastructure must be matched by appropriate modelling tools as proposed by QUEST. The proposed project can serve here as a first demonstrator that can be extended to other sectors (e.g., geodynamics, electro-magnetics, geodesy) in the future.

Visiting Scientists and External participants. In our training programme we involve two world-leading external scientists in the field of seismic imaging. Prof. J. Tromp (California Institute of Technology, soon to move to Princeton University), co-author of one of the basic textbooks in theoretical seismology, has pioneered the application of spectral-element methods to the imaging problem on global and regional scales using HPC systems. He is an excellent teacher and will be involved in our first workshop (preparing his course at UUT). Our second external trainer is Prof. G. Pratt (Queens University, Kingston), a world-leading expert in the application of frequency-domain imagines schemes and a highly gifted lecturer. He has long-term collaborations with industry and will focus on the application of imaging to industrial problems in the 3rd workshop. Other world-leading experts of our associated partners (e.g., Profs. Kennett, Romanowicz, Geller, Ghattas) will be invited to participate in the relevant QUEST workshops. We allocate 150 researcher days for external participants per year (30 participants per annual QUEST workshop).

All QUEST workshops will be advertised widely and are open to any interested young and experienced researchers. The number of participants will be limited and we will offer support for external participants on a competitive basis. Applications will provide information on their research projects and names of referees. Decision will be based on research excellence, however, giving some priority to researchers of less favoured regions.

B.7 ETHICAL ISSUES

	YES	PAGE
Informed Consent		
• Does the proposal involve children?		
• Does the proposal involve patients or persons not able to give consent?		
• Does the proposal involve adult healthy volunteers?		
• Does the proposal involve Human Genetic Material?		
• Does the proposal involve Human biological samples?		
• Does the proposal involve Human data collection?		
Research on Human embryo/foetus		
• Does the proposal involve Human Embryos?		

• Does the proposal involve Human Foetal Tissue / Cells?		
• Does the proposal involve Human Embryonic Stem Cells?		
Privacy		
• Does the proposal involve processing of genetic information or personal data (e.g. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)		
• Does the proposal involve tracking the location or observation of people?		
Research on Animals		
• Does the proposal involve research on animals?		
• Are those animals transgenic small laboratory animals?		
• Are those animals transgenic farm animals?		
• Are those animals cloned farm animals?		
• Are those animals non-human primates?		
Research Involving Developing Countries		
• Use of local resources (genetic, animal, plant etc)		
• Impact on a local community		
Dual Use and potential for terrorist abuse		
• Research having direct military application		
• Research having the potential for terrorist abuse		
I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	X	

ACRONYMS USED

Acronyms used in the proposal text	
AEGIS	Ability Enlargement for Geophysicists and Information technology Specialists
ASAP	Alberta Saline Aquifer Project
CIDER	Cooperative Institute for Deep Earth Research
DECI	Subproject of DEISA – DEISA Extreme Computing Initiative
DEISA	Distributed European Infrastructure for Supercomputing Applications
EPOS	European Plate Boundary Observatory
MCSC	Munich Computational Science Centre
NERIES	Network of Research Infrastructures for European Seismology
PRACE	Partnership for Advanced Computing in Europe
SCEC	Southern California Earthquake Centre
SESAME	Site EffectS assessment using AMbient Excitations
SPICE	Seismic wave propagation and imaging in complex media: a European Network
VOLUME	VOLcanoes: Understanding subsurface mass moveMEnt

Appendix A: Letter of support Schlumberger

Schlumberger Cambridge Research Limited

High Cross, Madingley Road
Cambridge CB3 0EL, England
Tel. +44 1223 315576
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www.slb.com

Schlumberger

European Commission
"PEOPLE"
Marie Curie Initial Training Programme

August 28th, 2008

Marie Curie Initial Training Networks (ITN) , Call: FP7-PEOPLE-ITN-2008
QUEST: QUANTITATIVE ESTIMATION OF **E**ARTH'S SEISMIC SOURCES AND **ST**RUCTURE

To whom it may concern:

This letter confirms the support of Schlumberger Cambridge Research Limited ("SCR") for the project proposal QUEST (the "Project") and SCR's intention to participate in the project as industrial partner.

Schlumberger is the major provider of oilfield services, employing 80,000 people worldwide, and SCR is a research center of Schlumberger located in the UK. The Geophysics department at SCR has about 25 researchers, working on research topics related to the characterization of the subsurface mostly for hydrocarbon exploration and exploitation, but including also CO_2 sequestration. We, at SCR, are developing new methods for seismic data acquisition and interpretation, using large-scale scientific computations during our research and product development process. We are well aware of the potential of cross-displinary research in the field of Seismology, and of the requirements and challenges in training young scientists, and have participated in several successful EU projects.

We have been impressed with the quality and relevance of the QUEST proposal and look forward to participate in the research, as well as in the training and collaboration activities of the network. Specifically, we plan to contribute to the project through

- participation in the organization of a workshop on numerical methods for large-scale simulation of wave propagation;

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Registered Office: 10 Duchess Street, London, W1G 9AB

- hosting and co-supervising a PhD student (36 months) working on industrial applications of inversion methods, and
- contributions to datasets made available for the evaluation and benchmarking of new algorithms as outlined in further detail in the proposal.

The PhD student working at SCR will receive training in technical and complementary skills, and he/she will be encouraged to develop professionally by taking full opportunity of the QUEST network as well as the Schlumberger Technical Community (Eureka) and other internal resources. The work experience at SCR should be a good preparation for the student's further career, whether in industry or in academia. Conversely, SCR as a prospective employer appreciates the possibility to host a student and interact with students and researchers from the QUEST network.

As a final note, our (SCR) contributions to the project are conditional to an agreement among the project participants, regarding intellectual property rights to and exploitation of technology developed in the Project, in accordance with the applicable guidelines for EU Marie Curie proposals.

Yours sincerely,

Robert Hughes Jones
Managing Director
Schlumberger Cambridge Research

Cc: Prof. Dr. Heiner Igel, LMU München

Appendix B: Letter of support Spectraseis

Spectraseis

Spectraseis AG
Giessereistrasse 5
8005 Zürich
Switzerland
Tel 41-43-500 5828 (direct)
Fax 41-43-321 3841
www.spectraseis.com

14 July 2008

European Commission
"PEOPLE"
Marie Curie Initial Training Programme

To whom it may concern:

This letter is in support of the proposal for a Marie Curie Initial Training Network (ITN) called "Quantitative Estimation of Earth's Seismic Sources and Structure" (QUEST) in which Spectraseis AG is planning to participate as an industrial collaborator.

Spectraseis AG of Switzerland is a small and fast-growing (40+ people) geophysical technology company serving the worldwide oil and gas exploration industry. The company applies and further develops a novel seismic technique, initially researched at the University of Zurich and published in 2003. Having spun off from university research ourselves, the idea of industry/academia collaboration for mutual benefit of young scientists and young companies is especially intriguing to us.

The research topics covered and methods trained in QUEST are well focused toward addressing the challenges of the world's growing energy demand while developing a sustainable, CO_2-neutral supply chain. The PI's of QUEST have identified a current gap in the technology to better and more completely image the Earth's interior. They intend to address this with research on imaging techniques such as waveform inversion, passive imaging and tomography. The techniques to be developed as part of the QUEST network have applications in imaging and understanding geothermal and hydrocarbon reservoirs, high-resolution monitoring of underground CO_2 storage, and time-lapse monitoring of seasonal underground gas storage reservoirs. Furthermore, the seismic exploration industry has always been an extremely data- and computing-intensive industry at the forefront of high-performance computing and high-performance computing is one of the focus topics of QUEST.

These issues are at the heart of the challenges of the oil and gas exploration industry, and well positioned among the problems that Spectraseis addresses as a company. Therefore, the QUEST training network will develop the talents required of new researchers in our fast-growing company.

The E&P industry is in dire need of people trained in applied seismology. Such professionals need to master very technical IT issues (e.g. parallel programming) and mathematically difficult methods (e.g. inversion) as well as the physics of wave propagation through complex media. The existing Earth science curricula can provide these cross-disciplined skills only to a limited extent. An integrated network involving host institutions covering all aspects of modern geosciences, coupled with industry partners providing real data and applications to real-world problems constitutes an excellent framework for such training.

A key benefit of this initiative is the opportunity for researchers to work within a client-centred organization solving immediately pertinent problems, and effectively communicating the solution to clients. This important aspect of education is often overlooked and cannot be conveyed through regular university curricula.

Within the QUEST framework, Spectraseis AG will provide training and advice by:

- Providing workspace and access to computing facilities for up to one early-stage researcher and one experienced researcher, committing to facilities for 36 and 18 person-months, respectively. Senior researchers within the company will provide guidance in day-to-day work and project scope, while partnership with a degree-granting University (ETH Zurich) will provide the curriculum to complete the educational experience.

- Providing data from a pool of 200+ broadband seismometers that is constantly (re)deployed throughout the world to record the ambient seismic hum that continuously propagates through the Earth.

- Providing training in complementary skills, such as project administration and planning, client interaction and presentations, budgeting, and field operations.

Spectraseis is continually searching for well-trained geoscientists. As such, we are intimately aware of the limited size of the global talent pool of competent geophysicists. In the current climate of high demand, and declining university enrollments in this area, we are firmly dedicated to helping address the shortfall of trained applied-seismologists within the scope of the QUEST initiative.

Yours faithfully,

Ross Newman
Chief Executive Officer

Dr. Robert M. Habiger
Chief Technology Officer

CC Prof. Dr. Domenico Giardini and Dr. Martin Mai, ETH Zürich
Prof. Dr. Heiner Igel, LMU München

Appendix C: Letter of support IBM

IBM Research GmbH
Zurich Research Laboratory
Säumerstrasse 4
CH-8803 Rüschlikon, Switzerland
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Fax +41 (0)44 724 89 11
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Prof. Heiner Igel
Department of Earth Sciences - Geophysics
Ludwig-Maximilians-University
Theresienstrasse 41
D-80333 München

Rüschlikon, August 25, 2008

QUEST (Quantitative Estimation of Earth's Seismic Sources and Structure) ITN project

Dear Prof. Igel,

With this letter we want to express IBM strong support to the QUEST project. We are convinced that development of predictive hazards simulations is bound to have large business and social impact. Moreover, the ability to design and re-engineer algorithms to exploit efficiently modern massively parallel supercomputers - which is key to the success of the project - is one of the competences of our Computational Sciences group that we intend to develop further.

For these reasons we would be eager to collaborate with the network sharing our experience in algorithm development for efficient scaleout on massively parallel supercomputers and would consider hosting PhD and post-doctoral students at our facility.

Sincerely,

Dr. Matthias Kaiserswerth
Director

Appendix D: Letter of support MICROSEISMICINC

MicroSeismic Inc.
The Unconventional Seismic Resource

800 Tully Rd., Suite 175
Houston, TX 77079
281-493-0032 (office)
866-593-0032 (toll free)
281-493-1557 (fax)

July 8, 2008

European Commission
"PEOPLE"
Marie Curie Initial Training Programme

To whom it may concern:

We would like to express our strong enthusiasm in participation in the project QUEST as the methodologies investigated in this project are of direct relevance to our current business project. QUEST offers a unique network bridging Earth sciences with modern IT technology. Both university and industrial research is overwhelmed by the rapid technical developments on the supercomputing front. Therefore, we have particularly strong interest in high-performance computing and passive seismic imaging in our application to oil and gas field monitoring (especially for hydraulic fracture monitoring), and climate related problems (CO_2-sequestration). We believe this technology can be also successfully applied to mitigation of natural hazards particularly in volcanology.

Our company is actively seeking the kind of people trained in the proposed network with very technical IT skills (such as parallel programming) and abilities to solve technically and mathematically difficult problems (inversion). Currently the Earth science curriculae at most of the universities do not provide this kind of training. Such project would be a perfect match for the current recruitment crisis initiated by the increasing energy prizes and needs of the trained geoscientists.

Our plan is to offer placements to QUEST scientists who will be able to work on unique datasets acquired in our company and provide them with specialized insight into data processing and proprietary technology. In this way we would provide them with hands-on practical training while we would gain their expertise from earthquake seismology. The trainees would also gain insight into non-technical skills such as management and client relations. As the datasets are proprietary (i.e., owned by various clients) and very large (requires our Houston computational facilities) this training would have to be carried in our facilities. Finally, we regard this training as an opportunity to recruit talented young scientists as we currently grow at rapid pace and we have recruited in this field five people in the last year.

PASSIVE SEISMIC MONITORING

MicroSeismic Inc.
THE UNCONVENTIONAL SEISMIC RESOURCE

800 Tully Rd., Suite 175
Houston, TX 77079
281-493-0032 (office)
866-593-0032 (toll free)
281-493-1557 (fax)

Sincerely,

Ron Warren
Chief Financial Officer
MicroSeismic, Inc.

Appendix E: Letter of support DEISA

Distributed
European
Infrastructure for
Supercomputing
Applications

Garching, 24th July 2008

Prof. Heiner Igel
Department of Earth Sciences - Geophysics
Ludwig-Maximilians-University
Theresienstrasse 41
80333 Munich
Germany

Subject: Letter of Support for the project QUEST (Quantitative Estimation of Earth`s seismic sources and structure)

Dear Prof. Igel,

Earth and Planetary Sciences constitute an essential user community in the European supercomputing scene, since hypothesis testing in this area today rests to a large extent on simulations of the physical system in 3-D requiring high performance computing solutions (HPC).

The training in HPC in those communities is basically not existent but has to be provided through link with the local supercomputer centers and European HPC projects. In this specific case DEISA can cross-communicate information on training programs and supercomputer access and/or organize joint workshops on HPC aspects of Earth Science simulation software. QUEST will enable training of a new generation of Earth scientist qualified to cope with HPC developments for upcoming Petaflop systems.

With a strong collaboration between DEISA and QUEST the Earth science community will be strengthened by improving the quality of HPC software through the development of stable and well engineered community scientific software.

Best regards,

(Stefan Heinzel)

Stefan Heinzel
Director of Computing Center of the Max Planck Society (RZG)
D-85748 Garching near Munich, Boltzmannstraße 2
Phone: 49-89- 32 99-1340, e-mail: stefan.heinzel@rzg.mpg.de

DEISA2 Coordinating Partner - http://www.deisa.org

ENDPAGE

PEOPLE
MARIE CURIE ACTIONS

Marie Curie Initial Training Networks (ITN)
Call: **FP7-PEOPLE-ITN-2008**

PART B

QUANTITATIVE ESTIMATION OF **E**ARTH'S SEISMIC SOURCES AND **ST**RUCTURE

"QUEST"