AlpArray

Probing Alpine geodynamics with the next generation of geophysical experiments and techniques

A European initiative to advance our understanding of orogenesis and its relationship to mantle dynamics, plate reorganizations, surface processes and seismic hazard in the Alps-Apennines-Carpathians-Dinarides orogenic system. The initiative will integrate present-day Earth observables with high-resolution geophysical imaging of 3D structure and physical properties of the lithosphere and of the upper mantle, with focus on a high-end seismological array.

Science plan of the AlpArray initiative, to complement national applications for funding

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1. General idea and purpose of AlpArray

Orogenesis is the main process responsible for creating the surface on which we live with its attendant geology, topography, active deformation and natural hazards. This is dramatically evident in Europe, where the centre of the continent is dominated by the active orogenic belts of the Alps and the Carpathians and its southern margin by the intertwined orogenic belts of the Mediterranean. Unravelling the dynamics of the Alpine-Mediterranean orogenic systems, with their constantly shifting patterns of deformation, is a daunting task, but one that is too important to ignore given the population density of these seismically active and hazardous regions of Europe. Challenges particular to the European orogenic systems centre on the variability of these small orogenic systems in space and time. In large orogenic systems like the Andes or Himalayas, structures in the crust or upper mantle can be traced continuously for hundreds, even thousands of kilometres. In contrast, the European orogenic systems are characterized by spatially limited subduction zones with diverse lateral terminations, detached and torn slabs, slabs that reverse polarity along strike, subduction of heterogeneous lithosphere with oceanic or thinned continental crust, and collision between continental lithosphere with thick crustal roots. This spatial heterogeneity changes with time – with constant shifting of plate boundaries and relative motion – resulting in a changing tectonic nature of the subduction, collisional and extensional plate boundaries and consequent seismicity.

The long history of geologic and geophysical research in the European orogenic regions has revealed the nature of this complex, transient orogenic system, yet complexity breeds controversy. There is hardly a lithosphere-scale process or structure that is not under debate or for which multiple hypotheses have not been proposed. Many of the controversies regarding complex orogenic systems may only be resolved by obtaining high quality images of the deep subsurface and integrating these with surface studies and theoretical and modelling work. High quality imaging of velocities and fabrics allows resolution of upper mantle structure and flow patterns and, in particular, permits mapping of the inclination, length and position of subducted slabs, or identification of tears, detachment and mantle zones of slab collision. This in turn provides information about the history of subduction and the nature of the subducted material. These, and other objectives outlined in the sections below, will go far in resolving current controversies regarding complex, European-style orogenesis and permit an updated characterization of the relationship between geodynamic processes, surface observables (uplift, topography, surface structures) and natural hazards (near-surface earthquakes).

Recent initiatives around the world have demonstrated new working models for large-scale geophysical experiments and their links to other disciplines. The USArray component of the US NSF EARTHSCOPE Project and the Chinese SINOPROBE are examples of geophysical experiments at a scale not yet seen in Europe. Yet, even at this scale, geophysical experiments today are not conducted in isolation. Earth Science moves forward most rapidly where conducted with multi-disciplinary teams: EARTHSCOPE and other programs such as *Continental Dynamics* and the *Frontiers in Earth System Dynamics* in the US and the TOPO-

EUROPE Program in Europe have demonstrated that this research model works. AlpArray seeks to combine components of these models to launch a new type of geophysical deployment in Europe that will provide highest-quality seismological and other Earth scientific data as well as serving as the intellectual stimulus for geologic and geodynamic studies addressing pressing scientific questions in Central Europe and, in particular, in the Alpine region. This European initiative combines several unique features:

- At present there is no European-scale funding agency available to finance and run this new type of cross-disciplinary seismological-geodynamical project. Hence a large group of institutions and individuals have developed the present science plan in a series of workshops held at ETH Zürich and EGU Vienna since 2011. The project will be coordinated by a Steering Committee and a Science Council, comprising representatives of the participating institutions (see Appendices A and B), and requests for funding will be submitted on a national basis. This initiative builds on experiences gained in various very successful cooperative projects in the past between surveys and academic institutions (e.g., European Geotraverse (EGT), EUROPROBE, TOPO-EUROPE).

- AlpArray is a multidisciplinary, research-oriented project that brings together national seismological and geological surveys and academic institutions in order to focus on the greater Alpine area, a region of common interest. Understanding the tectonics and geodynamics of the densely-populated greater Alpine region will have direct societal impact. The scientific questions to be addressed are of interest to the broader scientific community and the technological and scientific results will be portable to other parts of Europe and the world.

- AlpArray will provide in its core unified and homogeneous seismological coverage of the greater Alpine area with seismometers deployed at unprecedented high density (Fig. 1). This is indispensable for developing multi-parameter 3-dimensional mapping of structures and physical properties of rock volumes (seismic velocities and anisotropy, gravity, aseismic and seismic surface displacements, etc.). A similar coverage is also planned for a magnetotellurics (MT) experiment.

- AlpArray aims to better understand and quantify the current geodynamic state and the evolution of the greater Alpine area. It will combine the **AlpArray seismic network** (Fig. 1) with **AlpArray complementary experiments** and, additionally, **AlpArray collaborative projects** (see chapter 5 and Appendix A). This multi-pronged approach will go beyond seismic imaging and will involve all disciplines of Earth sciences (geology, modelling, gravimetry, MT, GPS, etc.) to produce new, self-consistent geodynamical models of large-scale mantle dynamics and plate reorganisations in the Alps-Apennines-Carpathians-Dinarides orogenic system.

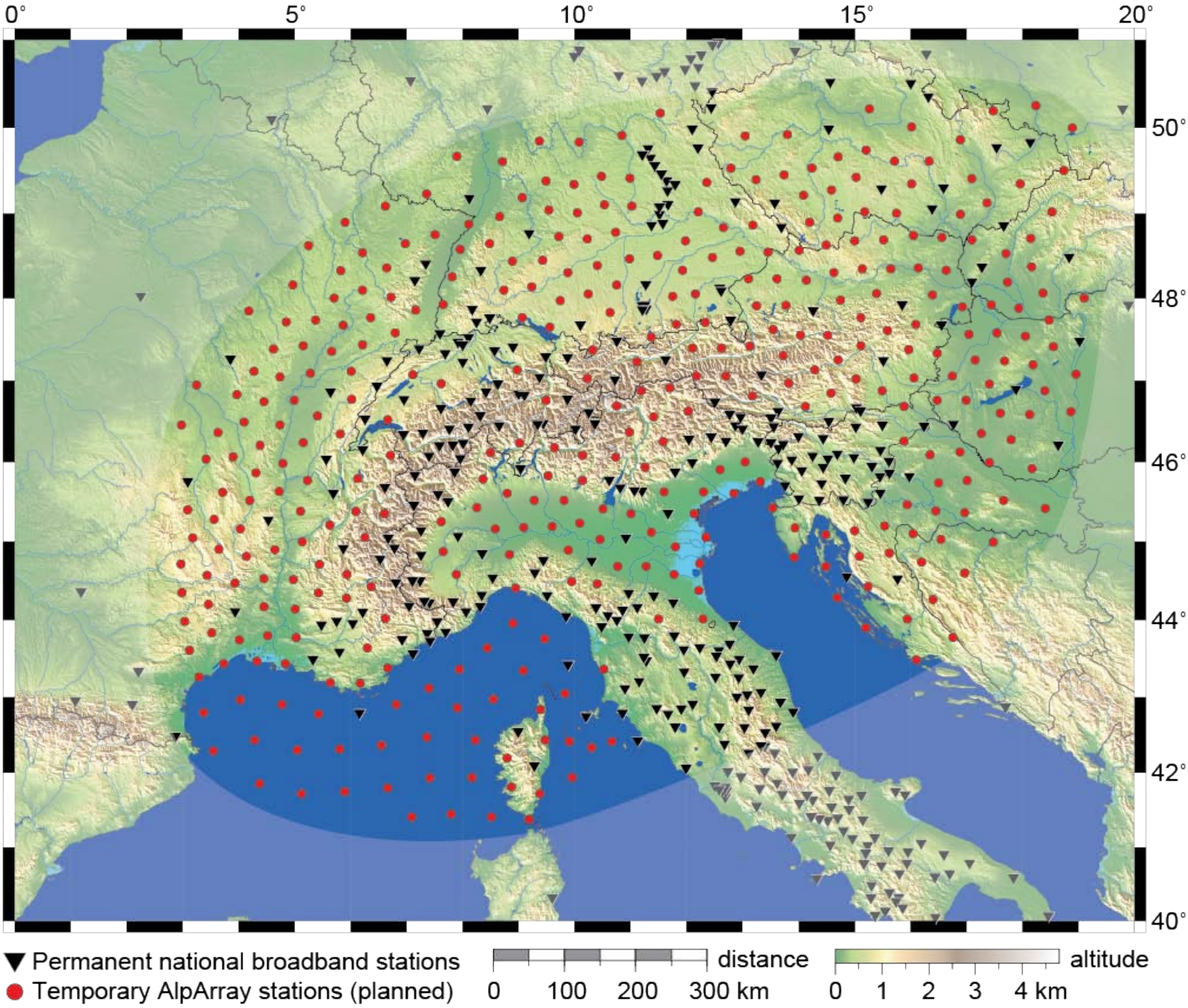


*Figure 1: Map of the greater Alpine area with permanent seismological network stations (in black) and the planned **AlpArray seismic network** (in red) which, together, will provide a unified and homogeneous coverage of the study area at 40 km average station spacing.*

2. Why the greater Alpine area?

The greater Alpine area is an ideal natural laboratory for studying on-going and past orogenic processes because:

- The greater Alpine area, comprising the Alps proper, their forelands and transitions into the Apennines, Carpathians and Dinarides (Fig. 2), is the site of significant earthquake-related hazard in a densely populated part of Europe (Fig. 3).

- The Alps are arguably the best-studied active mountain range in the world. The available geophysical-geological database is exceptionally large and provides a solid basis for advancing our general knowledge and understanding of orogenic processes on all scales.

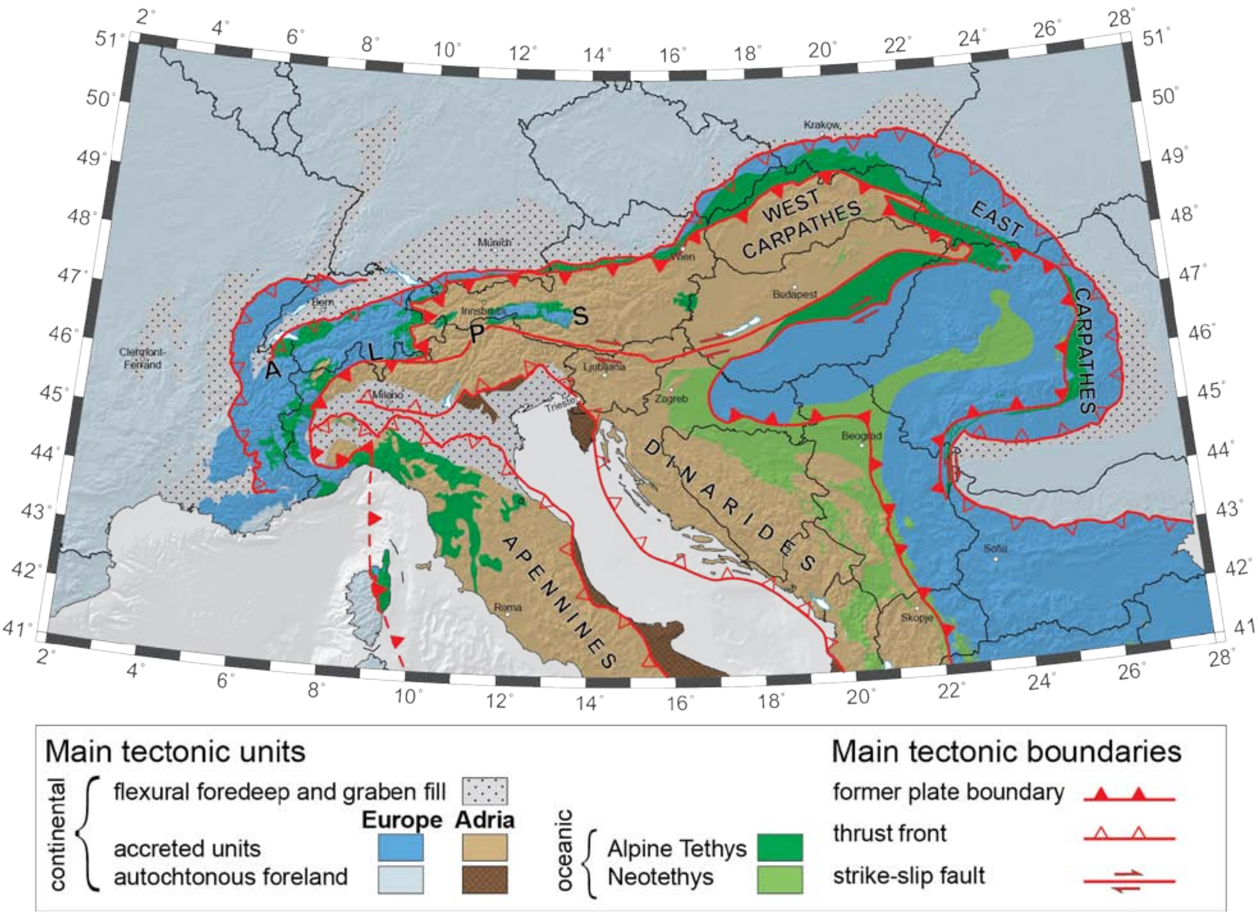


Figure 2: Tectonic map of the Alps, their adjacent orogens and forelands that result from the collision of two converging plates, Europe and Adria. The major units are coloured according to their overall provenance. Red colours mark the main tectonic boundaries that outline the complex geometry and geological history of the Alps. Modified from Schmid et al. 2008, Ustaszewski et al. 2008, Schmid & Slejko 2009, Handy et al. 2010 and Bousquet et al. 2012.

- A great diversity of geodynamic processes can be studied within the relatively small area occupied by the greater Alpine area: (1) interactions between large-scale Africa-Europe plate convergence and gravitationally induced slab retreat; (2) independent displacements and rotations of micro-plates in an overall regime of slow Africa-Europe convergence; (3) slow transient deformation of the asthenosphere-lithosphere boundary and the relationship to the highly complex crustal structure; (4) processes of slab tearing; and (5) slab polarity reversals which are taking place between the Alps and the Dinarides as well as the Alps and the Apennines.

- The greater Alpine area presents an orogenic system with a present-day 3-dimensional complexity that results from major plate reorganizations during the last 35 Myr – following Africa-Europe collision. It is a system that calls for a novel approach beyond the application of traditional plate tectonics and concepts that can incorporate significant deformation of the plates and include the role of micro-continents and micro-oceans.

- The greater Alpine area is characterized by various recent plate reorganisations, and therefore is highly suitable for studying transience in orogenic structure, i.e., changes through time, which can be inferred from state-of-the-art geophysical imaging combined with geological investigations and thermo-mechanical modelling.

- The exceptionally high quality of the geophysical-geological database, combined with seismological data of unprecedented resolution available through the AlpArray deployment, will provide a historic opportunity to produce self-consistent numerical geodynamical models of the Alps-Apennines-Carpathians-Dinarides orogenic system. This will capture first order complexities in the geological and geophysical structure and the processes that produced that structure. This opportunity is offered by the relatively small size of this orogenic system and recent advances in supercomputer power and numerical geodynamic modelling techniques.

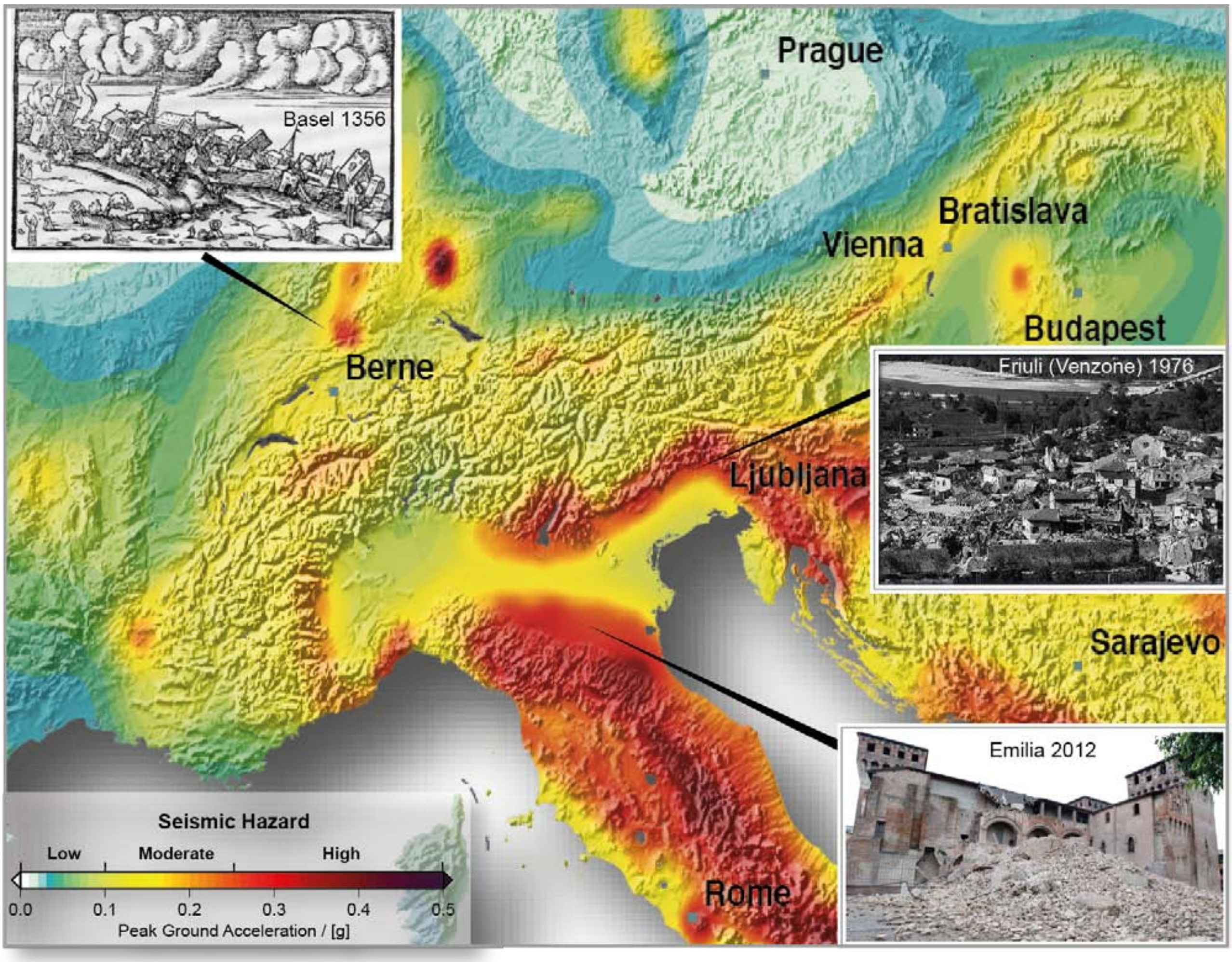


Figure 3: Seismic hazard in the greater Alpine area according to the recently released SHARE project (www.share-eu.org) model. Reality is depicted with the example of the historical Basel, the modern Friuli and the recent Emilia earthquakes.

3. Expected societal impact and outreach of AlpArray

- The Alpine mountain belts of Europe and the central Mediterranean area are the locus of intense tectonic and seismic activity with significant local variations (Fig. 3) in one of the most densely populated and industrialized parts of the world. Investigating the underlying causes of this activity is of paramount social and economic relevance. AlpArray aims for a deeper understanding of the underlying geodynamical processes that make certain parts of the greater Alpine area (e.g., Basel area, Friuli, Emilia region; Fig. 3) more prone to seismic hazard than others. The large-scale AlpArray seismic network provides the possibility of improving the monitoring of seismicity by alleviating the current magnitude diversity amongst the many permanent seismic observatories (SHARE project www.share-eu.org; Stucchi et al. 2012; Grünthal et al. 2013). A harmonized and homogeneous approach to locate and characterize earthquakes and, in particular, to estimate magnitude with a common velocity model provides the opportunity to calibrate magnitudes routinely provided by the different national seismic networks and institutions across a broad range of magnitudes starting at about M=1. Such a calibration of magnitude estimates can ultimately lead to improved earthquake activity rates and thus seismic hazard estimates. This effort may also reveal as-yet unidentified, "silent" fault zones that are creeping and produce only low-magnitude events. The strain field will be analysed for local co-seismic and aseismic components with a special focus on the regions of higher seismic and/or tectonic activity. Such studies will allow to refine the seismic hazard map of the entire Alpine area. In addition, understanding and quantitatively modelling long-term orogenic processes and the present-day geophysical-geological state of the area will provide a process-based model that complements evaluations of seismic hazard. So far, these evaluations are based on statistical methods founded primarily on instrumentally recorded seismicity and on archived of historical earthquakes.

- A better understanding of on-going orogenic processes in the greater Alpine area has potential for evaluating other than seismic natural hazards in areas characterized by high topographic gradients and tectonic deformation. Geological engineering applications that require risk assessment include the extraction of geothermal energy, extraction of gas enhanced by hydro-fracking, storage of gases, e.g., CO_2, and long-term storage of nuclear waste. Natural hazards associated with high mountain regions include landslides, rock falls, debris flows, and floods. All these processes are affected by erosion rates and the geological development of high relief mountain topography that we will understand better with the AlpArray project.

- Close collaboration of national seismological surveys and academia in the framework of AlpArray is expected to yield new techniques, for example, in data acquisition and joint inversion of different types of data. These applications are expected to have an impact beyond the AlpArray project in applied science performed by private industry and governmental agencies.

- The educational outreach of AlpArray will be considerable given that the Alps are Europe's best known mountain range and the source of much public interest. In addition, the Alps are a model orogen known throughout the scientific community and a key example in our understanding of orogeny. The public takes great interest in basic questions such as how the Alps were created, why they differ from region to region, and how the topography has evolved during past tectonic and climatic events. Practical information such as the relative hazards of specific regions will also be of great interest to the public and AlpArray will take a number of measures to communicate the practical as well as the discovery sides of the scientific results. Generally, AlpArray strives to raise the awareness of the population with regard to orogeny, earthquakes and natural hazards.

4. State of knowledge and outstanding scientific questions

The greater Alpine area (Fig. 2) comprises an orogenic system where two converging large (Europe and Africa) and a small (Adria) plates interact over time with various micro-plates of oceanic and continental provenance (not shown in Fig. 2 for simplicity) and several zones of post-35 Ma slab retreat (Alps, Apennines, Eastern Carpathians) in a particularly intricate way. From the geological literature it has long been known that the Adriatic plate forms the upper plate with respect to Europe in the Western and Central Alps and the Western Carpathians, while the same Adria plate forms the lower plate in the Apennines and the Dinarides (e.g., recent reviews by Schmid et al. 2008 and Handy et al. 2010). Travel-time seismic tomography in the greater Alpine area has allowed us to image velocity gradients in the crust (e.g., Diehl et al. 2009; Di Stefano et al. 2009, 2011) and upper mantle (e.g., Lippitsch et al. 2003; Piromallo & Morelli 2003; Spakman & Wortel 2004; Kissling et al. 2006; Mitterbauer et al. 2011; Giacomuzzi et al. 2011; Giacomuzzi et al. 2012). Such gradients reflect differences in several physical parameters, for example, rock composition and temperature. Imaging these gradients has spawned geodynamical interpretations which are often controversial. While most authors agree that mantle tomography has revealed the existence of mantle slabs which are spatially linked to both modern (at shallow depth) and ancient (at greater depth) zones of lithospheric subduction (Figs. 2 and 3), there remain considerable uncertainties in the geometry of slabs, their internal properties, slab tears and crust-mantle interface particularly in transitional areas between the Alps and adjacent orogens.

In the Apennines-Alps transition zone, for example, geophysical imaging of the deep structure is clearly insufficient because the existing data does not allow us to discern whether the change in subduction polarity between the two orogens is a lateral one that existed since at least 50 Ma ago (e.g., Faccenna et al. 2001; Piromallo & Faccenna 2004; Vignaroli et al. 2008, 2009) or, alternatively, a temporal one related to a recent (post-35 Ma) reversal of subduction polarity entirely triggered by slab retreat in the Western Mediterranean (e.g., Handy et al. 2010). Similarly, the exact outlines and origin of an enigmatic slab beneath the Eastern Alps, i.e., near the Alps-Dinarides transition zone, are subject of on-going controversy. Figure 4 depicts the interpretation of Lippitsch et al. 2003 and Kissling et al. 2006, but an alternative interpretation provided by Mitterbauer et al. 2011 attributes this slab to the European rather than the Adriatic plate. Solving this controversy is particularly relevant for the Friuli seismic hazard area, which is either located in the Dinarides foreland (if the Eastern Alps slab is an Adriatic slab) or in a retro-belt of the Alps (if the Eastern Alps slab is a European slab).

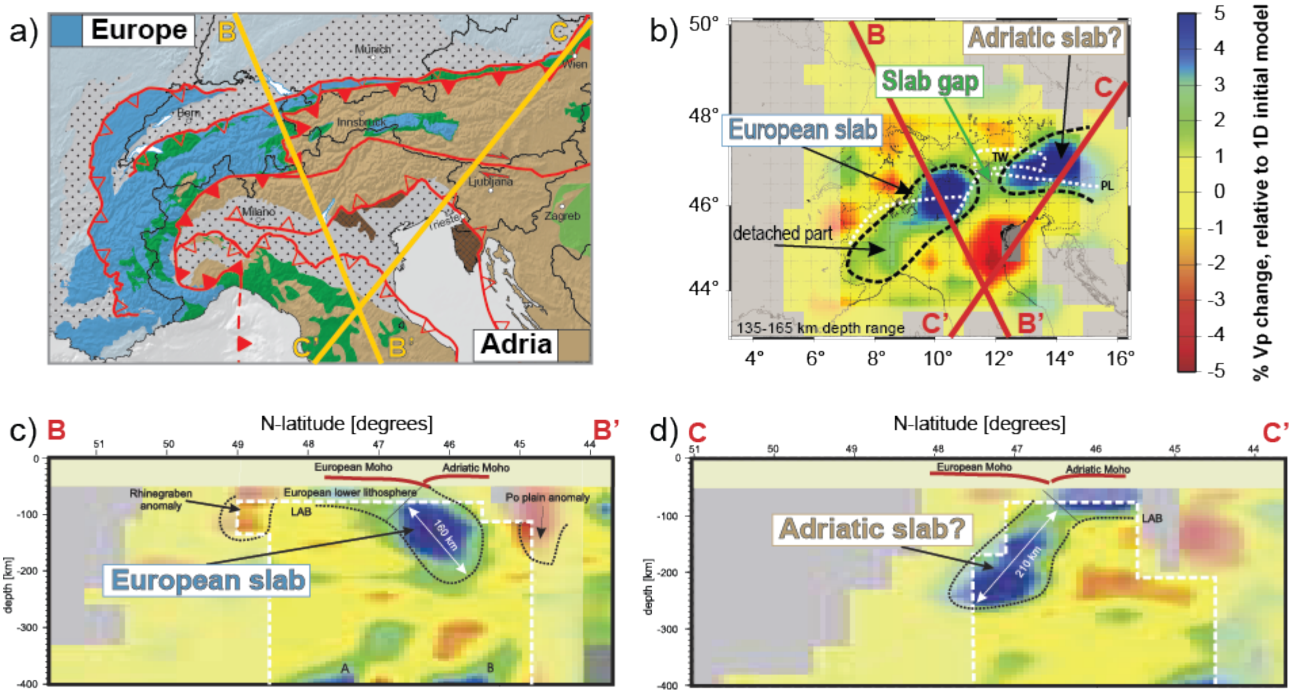


Figure 4: Linking the Alps' present to its past using geology at surface and seismic tomography at depth. (a) Tectonic map from Figure 2, with profiles BB' and CC' shown on other sub-figures; (b) Seismic tomography depth section showing two distinct slabs beneath the Alps: one European with a detached part, and one presumably but also debatably Adriatic, with a clear slab gap in-between; (c, d) Seismic tomography profiles along lines BB' and CC' showing the dip and depth extent of the slabs. Seismic tomography images of Lippitsch et al. 2003.

The combination of active seismic experiments performed at the end of the last century with geological interpretations has led to a better understanding of many parts of the greater Alpine area on a lithospheric scale; and example of this is the interpretation shown in Fig. 5 that relies on the data acquired by the ECORS-CROP experiment (Roure et al. 1996). However, many questions remain: does slab tearing, as postulated by the interpretation in Fig. 5 (and in many other parts of the greater Alpine area) really occur, or are these misinterpretations due to poor data resolution? Moreover, the details regarding the interface between mantle lithosphere and lower crust – the Moho (Di Stefano et al. 2011) – and regarding the deep structure of the plate boundaries (e.g., Brückl et al. 2010; Spada et al. 2013) are clearly insufficiently known. Encouraging results are now available from crustal tomography (e.g., Diehl et al. 2009) but do not cover the entire Alpine region. The purely passive experiments planned by AlpArray envisage a much more densely spaced array and provide an excellent opportunity for going beyond the existing knowledge of lower crustal structure and the crust-mantle interface, currently based on the controlled source seismology results of the last century. Furthermore, AlpArray will allow for imaging structural details and fabric of the mantle lithosphere and the lithosphere-asthenosphere boundary – the lower margin of the involved plates – that are currently rather poorly constrained beneath the orogens compared to few regions in the foreland (e.g., Plomerová et al. 2012).

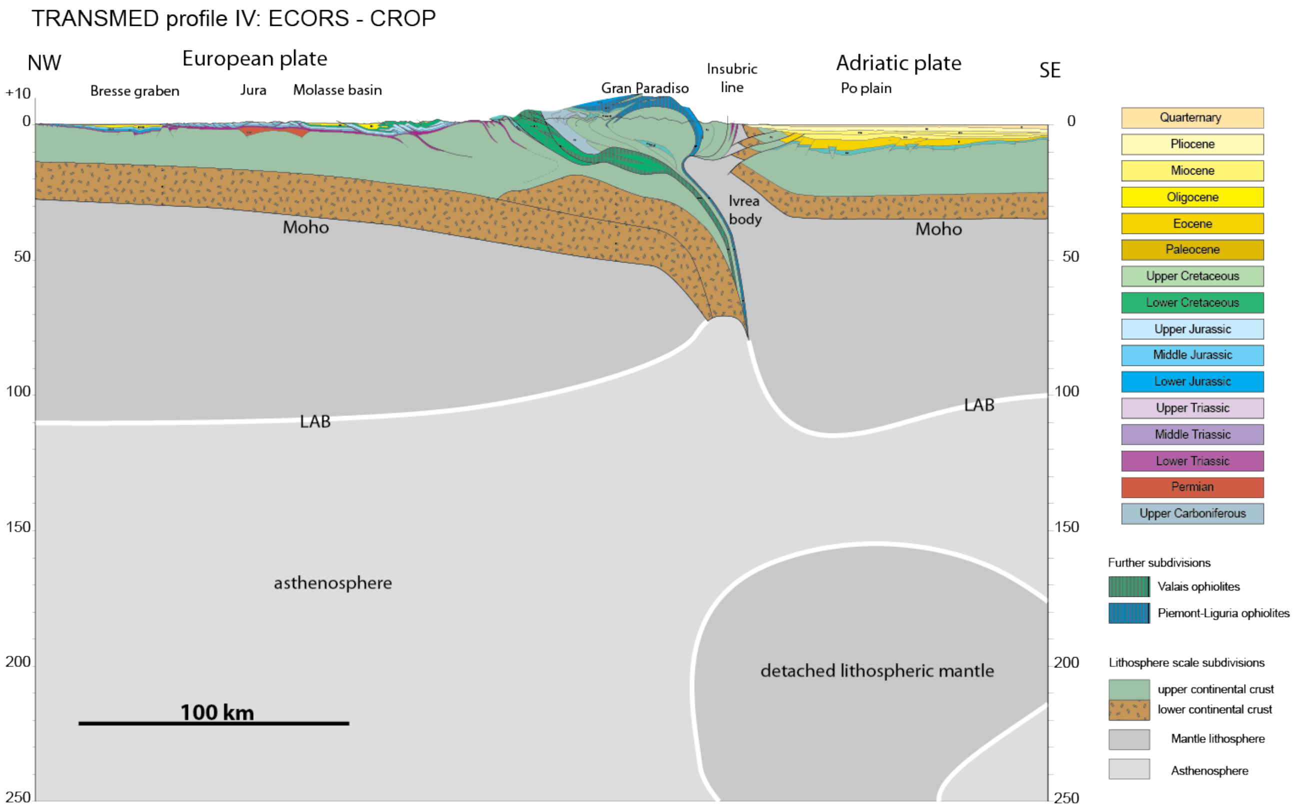


Figure 5: Crust-lithosphere-mantle structure along the ECORS-CROP profile across the Western Alps, exemplifying observations and interpretations across the scales (modified from Schmid et al. 2004).

Imaging the deep structure of the greater Alpine area offers a rare glimpse of different stages of mountain building, from juvenile stages along the Adria-Europe plate boundary in the Dinarides and the eastern part of the Southern Alps (Vrabec & Fodor 2006) to mature stages exhibited in the central and western parts of the Alps. The Western Alps may even be in a post-orogenic stage characterized by active extension (Sue & Tricart 2003) and isostatic uplift (Champagnac et al. 2007). Moreover, the deep structure of the Alpine forelands yield potential insight into how pre- to syn-orogenic rift structures, for example, the Upper Rhine–Bresse Graben, interact with subduction and collisional tectonics. Therefore, AlpArray will focus on the greater Alpine area including its forelands, with a special focus on the structure of the orogen at both ends (Figs. 1-5): (1) the arc of the Western Alps possibly overlies the partly detached, SE- to E-dipping European slab, which is spatially juxtaposed with the W-dipping Adriatic slab beneath the northern Apennines; and (2) the Eastern Alps, which overlie a N- to NE-dipping slab of controversial shape and origin (Adriatic or European?) that is separated from adjacent slabs by low-velocity gaps (Figs. 2 & 4). The target volume at the scale of the orogen extends down to the base of the mantle transition zone at 660 km depth. Determining seismic anisotropy directions in the crust and upper mantle and estimating the amount of accumulated oceanic and continental material in the mantle transition zone will help to reconstruct the current and past plate motions and dynamics in three dimensions. Previous studies of seismic anisotropy in AlpArray region mainly concern the Northern Apennines

(Margheriti et al. 2003, 2006; Plomerová et al. 2006; Salimbeni et al. 2007, 2008; Munzarová et al. 2013), where anisotropy measurements supported the hypothesis of an ending subduction or a differential trench retreat process. Kummerow et al. (2006) reported a peculiar anisotropy pattern beneath the belt in the Eastern Alps and Fry et al. (2010) in the Central Alps. Barruol et al. (2011, 2004) in the Western Alps interpreted anisotropy information as clear indication of the roll-back process in that region.

The Alps and neighbouring mountain belts present dramatic topographic expressions of orogeny, yet the relation of current tectonic processes of crustal shortening and isostatic uplift with topography evolution and erosion rates remain controversial. For example, the Western Alps show almost no evidence of convergent tectonics, yet contain the highest relief and the highest elevations in the Alps (Sternai et al. 2012). This high topography must be related to isostatic differences between the Western Alps and the central Alps, but it is not clear if this is because of changes in crustal structure and density, or because of a reduction in the downward pull of the slab beneath the Alps, possibly due to slab tearing under the Western Alps (Lippitsch et al. 2003). This idea has serious implications for the topographic history of the Alps, but remains controversial in the absence of better imaging of the potential slab tear. In a similar controversy, the Eastern Alps show evidence for renewed uplift in the last few million years (Wagner et al. 2011), but there is no obvious tectonic driver for this motion. Differentiating potential climatic drivers from deep originating geodynamic causes has important implications for the surface evolution of the Alpine region and requires additional constraints on tectonic and geodynamic processes.

The list of scientific questions discussed above makes it evident that time is ripe for a new generation of cross-disciplinary geophysical-geodynamical initiatives which will shed new light on the current state and long-term evolution of structure of the Alps at crustal and mantle depths, including its transition to neighbouring mountain belts. This cross-disciplinary project will provide both high-resolution geophysical data and corresponding, mutually-consistent quantitative geodynamic models to reach a major breakthrough in understanding orogeny in the heart of Europe.

5. AlpArray project

The complexity of the Alpine orogenic belt results from the interaction of oceanic and continental lithosphere in micro-plates that are caught between two large converging plates: Europe and Africa. In striking contrast to the wealth of geological and geophysical information on various local crustal structures and time periods of the orogeny, our present understanding of the mountain building processes that shaped the Alpine orogen is pitifully limited to a sequence of simplistic 2D plate tectonic scenarios mainly due to the lack of resolution and reliable information on mantle lithosphere and asthenosphere at regional and local scales. The challenge of the AlpArray initiative is to provide the opportunity for a breakthrough in our understanding of mountain building processes from initial to final phases including contemporary 3D-interactions of large plates with small plates and micro-ocean subduction. This demands a multi-disciplinary, multi-lateral, and international research approach. The core data for such an effort will come through the establishment and operation of a seismic array that combines the networks of a dozen seismological observatories with a few hundred temporary broadband stations covering the Alps, the Northern Apennines and their forelands. The scientific questions and challenges outlined above can best be addressed in a co-operative research initiative that includes the following components: **(1)** the **AlpArray seismic network** (Fig. 1), **(2) AlpArray complementary experiments** (networks, swaths and profiles, see examples on Fig. 6) including other geophysical methods like magnetotellurics, gravity and GPS, and **(3) AlpArray collaborative projects** (see also Appendix A). In combination, these components go far beyond seismic imaging and involve many disciplines of solid Earth sciences.

5.1 AlpArray seismic network

Many of the outstanding science questions will be addressed by data obtained through a pan-Alpine network of broadband seismic stations. Building on the skeleton of permanent national networks, the AlpArray seismic network will deploy stations to embody the needed seismological tool: a broadband station every 40 kilometres in the greater Alpine area (Fig. 1). This geographical coverage and station density, including at least 32 ocean bottom seismometers in the Ligurian Sea and the Gulf of Lion, is required to ensure an array with the required aperture and resolution for the multiple seismological methodologies to address the main scientific questions of Alpine orogeny outlined above. Seismological instruments from national pools will be deployed simultaneously on a temporary basis for at least 2 years and data will be merged with those from the permanent broadband stations operated in the region. This represents the largest experimental effort of the AlpArray project; therefore all AlpArray participating institutions will be expected to contribute within their abilities to establish and to maintain this network. Co-ordination regarding technicalities and a common data management strategy is already well advanced and the related protocol for seismic experiments is ready for use (see the document "Technical strategy for the mobile seismological components of AlpArray" on www.seismo.ethz.ch/alparray).

5.2 AlpArray complementary experiments

Some of the scientific questions require data at a finer resolution than that to be obtained from the pan-Alpine seismic network. Therefore a number of more local target-oriented complementary field experiments will be carried out within the frame of AlpArray project. Beyond acquiring seismological data, these complementary experiments will also collect other type of geophysical (gravity, MT, GPS) as well as geological data to constrain joint inversions and to aid multi-disciplinary interpretations, with the aid of e.g., high end numerical or analogue modelling studies. The acquisition geometry and duration of these networks will be specifically designed to tackle regional problems and the particular target in question. AlpArray complementary experiments will be typically organized by a few participating institutions and will form the core of one or more related AlpArray collaborative projects (see next section).

Both the larger, fieldwork containing complementary experiments and the more numerous and rather interpretative collaborative projects will be coordinated by the Steering Committee and the Science Council, as outlined in Appendix A. A few examples of complementary experiments are listed in the next sections and are shown in Fig. 6.

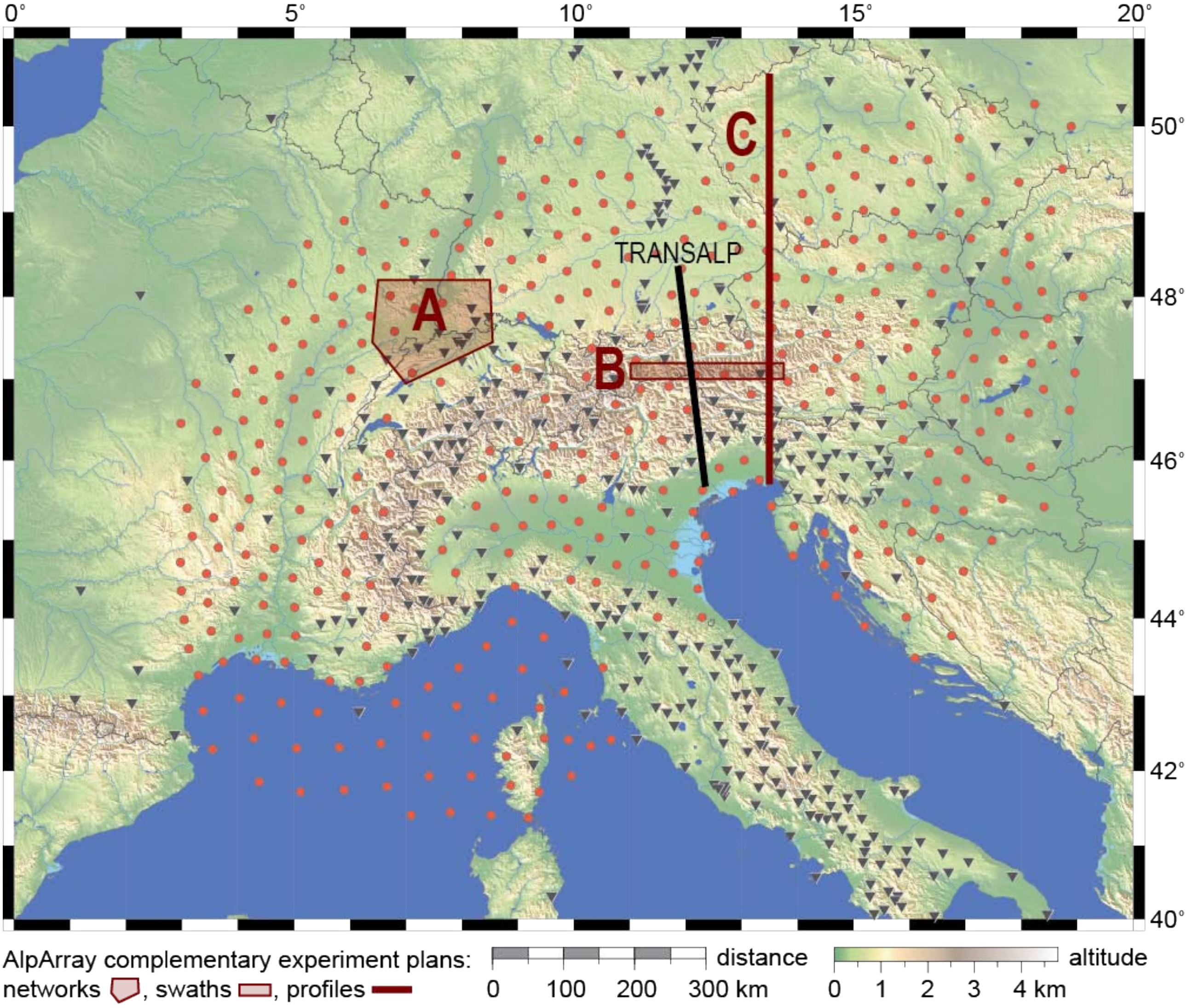


Figure 6: A few examples of AlpArray complementary experiments to be carried out in addition to the pan-Alpine seismic network (dimmed symbols). These experiments target special structures and regional-scale problems. See text for details.

5.3 AlpArray collaborative projects

The AlpArray collaborative projects involve many disciplines of solid Earth science combined to address a common scientific question and to yield comprehensive interpretations. Particularly, the 3D numerical modelling techniques have made enormous progress in the last few years and will make it possible, together with large-scale geological studies, to reach a major breakthrough in understanding orogeny.

The scientific research in AlpArray will be carried out in the framework of such collaborative projects, related either to the AlpArray seismic network or to one of the complementary experiments. A group of researchers will address a topic of common interest, share efforts in the analysis and interpretation of data or bring unique skills and methods to the collaboration. For an organizational overview, collaborative projects are initially grouped into four topical and three regional themes. These are listed below together with a few examples:

I. *Structure, fabric and flow of lithosphere-mantle system beneath the Alpine region*

Orogeny in the greater Alpine region is driven by subduction of a number of slab segments with complex geometry and characterized by rather small horizontal widths, as compared for example to Pacific subduction zones. Vertical tears are expected between segments and horizontal tears have been postulated beneath the northern Apennines, beneath the south-Western Alps, and the northern Dinarides, possibly giving rise to asthenospheric windows beneath these regions. However, the geometry of the horizontal tears, and even their existence, remains contested. Furthermore, the character of the slab segments is highly variable in down-dip direction: the slabs are made of oceanic lithosphere of different oceanic domains and even intermittent continental lithosphere may have been subducted. Older slab segments seem to rest beneath the western Mediterranean, the Alps and the Pannonian Basin (e.g., Lombardi et al. 2009; Hetényi et al. 2009). The existence of these slab segments has been shown by previous tomographic studies but their geometry and their internal properties remain to be resolved.

Downgoing subducted slab segments and large-scale continental deformation are accompanied by mantle flow of the surrounding material that presumably is less viscous than the slab itself. There are a number of questions regarding this mantle flow. Is it induced by plate motion and therefore parallel to the current plate motion direction? How is it deflected by the highly complex geometry of the subducted slab segments? How broad is the flow region affected by subducting slab segments? Is there active upwelling of less viscous material? Do these upwellings come from the boundary between the upper and lower mantle or do they originate from the subducted slab segments? Are they caused by hot temperatures or by fluids? Seismic imaging of AlpArray data will provide 3D models that are unprecedented in terms of resolution and reliability of lithosphere fabric, mantle isotropic velocity anomalies and of anisotropy as a key indication of mantle flow.

Though the crust in the Alpine region and its forelands has been studied by active seismic experiments along many profiles (e.g., Kissling et al. 2006; Brückl et al. 2010), the properties of lower crust and mantle lithosphere remain relatively poorly resolved. As it is commonly believed that orogeny is mainly driven and determined by dynamics and properties of these units, the geodynamic system behind the mountain building processes and the related geo-hazards are still poorly understood. By constraining all accessible properties of the lithosphere with a uniform resolution across the region we should gain a better understanding of the interplay between principle orogenic processes and their variations adapting to local conditions.

II. *Geodynamics of Alpine Orogeny*

Better understanding the geodynamic evolution of the Alps and its manifestation in the present day observables (surface motion, topography, strain, stress, seismicity, lithology, structure, gravity, heat flow, etc.) demands a multidisciplinary approach covering many fields in solid Earth science. Integration of diverse observations in a physically self-consistent manner requires geodynamic modelling through state-of-the-art laboratory analogue and numerical methods. Among the main tasks to be taken are: (1) Modelling the tectonic evolution on geological time-scales of the Alps and micro-plate orogeny in general; (2) Modelling the topographic evolution of the Alps and surrounding regions linking surface processes to deep driving processes. The first task comprises detailed modelling of the recent tectonic evolution since ~10 Ma as well as integrating tectonic reconstructions of the Alpine region (e.g., Handy et al. 2010) with the driving geodynamic processes since the Cretaceous. The second is key to improve our understanding of the relationship between surface deformation and upper mantle forcing, including the mechanical coupling at different levels within the lithosphere. Dynamic modelling of the crust-mantle system is relevant to seismogenesis, as well as rheology and structure of the lithosphere. To model the state of lithosphere (geotherm, petrology, fluids) and to assess the forces acting on plates and upper mantle during continent-continent collision (since 35 Ma) current strain and stress fields will be compared with geological strain measurements (rock fabric), with directions of strain and stress at every time-step of models, with P- or T- axes of the micro-earthquakes but also with 3D anisotropy tomography results. To bridge the large geodynamic spatio-temporal scales from the mantle to the fine grain of fault dynamics and topography evolution, development of high-resolution 3D surficial-seismo-thermo-mechanical numerical approaches will be further exploited.

III. *Seismicity, Seismotectonics and Seismic Hazard*

New AlpArray data will allow for studies of the regional seismicity and seismically active faults in the Alps. Source parameters (locations, source mechanisms, moment tensors, source time functions) will be determined. We will aim at a consistent determination of these parameters. The amount of tectonic force that can be transferred from a deformed/deforming mantle into the crust above it (and *vice versa*) depends on the degree of coupling. It is particularly relevant in the Alpine collision arc where the strain history needs extensive imaging and modelling in order to be better understood. The 3D strain and stress fields will be constrained, including the use of GPS data, and estimates of the seismic coupling will be carried out. Only a very detailed knowledge of the uppermost crust in the seismically hazardous regions will allow us to make the connection between lithosphere-mantle structure, the forces leading to seismicity and the related hazard. These results will be the basis for improved seismic hazard estimates locally and across the region. As an example, we envision a collaborative project targeting the seismicity and seismotectonics of the Upper-Rhine graben – Basel area (see complementary experiment A in Fig. 6). Finally, the definition of 3D crustal and upper mantle seismic reference models will allow improved standardized earthquake catalogues for the greater Alpine region.

IV. *New Methods and Opportunities in Seismic Imaging*

AlpArray will provide a state-of-the-art seismic image of the crust and upper mantle of the greater Alpine region, thereby providing a clearly focused snapshot of the geodynamic state of this collisional orogen. Clearly, data acquisition, processing and inversions are extremely challenging tasks that can only be tackled with techniques in the forefront of their domain that will need new adaptations or developments through collaborative efforts. In a first step, the different seismic data and data products (body wave attributes, dispersion curves, waveforms) will be inverted separately for 3D models of P-wave and S-wave velocities and various discontinuities – including the lithosphere-asthenosphere boundary – for the entire Alpine region. In addition to isotropic elastic velocities, parameters of anisotropic and anelastic wave propagation are to be determined in order to better constrain internal lithosphere fabrics (fossil or due to contemporary deformation) and asthenospheric flow. Furthermore, from seismic attributes the mineralogy and temperature should be constrained. Ideally, different data products (travel times, receiver functions, polarization, slowness, propagation directions, waveforms of direct and scattered body and surface waves) are jointly inverted. That implies multi-scale imaging with a spatially varying – but highest possible – resolution instead of a number of separate models with very different characteristics. A second step will aim at joint, multi-scale inversions of various kinds and scales and will demand significant methodological improvements. In addition to ray-theoretical tomography of high frequency body wave attributes, inversions should also include finite frequency tomography and waveform inversions of direct and scattered waves measured at the AlpArray seismic network and with AlpArray complementary experiments using denser station spacing. When embedding the resulting high-resolution models into regional and global models, the resolution has to be quantified and trade-offs (e.g., between isotropic and anisotropic parameters) need to be examined.

Besides aiming at the joint inversion of seismic data, we envisage as well the joint inversion of seismic data with other geophysical observables, such as potential field data (gravity, magnetotellurics), surface vs. deep deformation pattern (using GPS) and petrological observables. For example one such multi-domain inversion should best constrain petrophysical properties (seismic wave velocities and density) to identify the corresponding rock type and hence their origin and role in the evolution of the orogen.

V. *Western Alpine arc and Northern Apennines: resolving slab interaction*

The Western Alpine arc provides direct evidence for the coupling between mantle flow and lithosphere-scale tectonics (e.g., Faccenna et al. 2001; Vignaroli et al. 2009) in the region where the Alpine and northern Apennine slabs interact. In addition, this region features a number of key questions regarding the post-35 Ma Alpine orogeny such as, e.g., the role of the Ivrea body in collision tectonics (e.g., Schmid & Kissling 2000; Dumont et al. 2011); the relation between proposed European slab tearing and recent orogenic uplift history (Glotzbach et al. 2008) including the shift to horizontal extension in the western Alps (Sue et al., 2007); and subduction dynamics and retreat of the northern Apennine slab (Vignaroli et al. 2008). This region should become the target of a specifically designed AlpArray complementary seismic experiment to achieve high-resolution imaging of the Ligurian crust beyond the capacity of the AlpArray seismic network's 32 ocean bottom seismometers in the Ligurian Sea.

VI. *Eastern Alps, Dinarides and Bohemian Massif*

The seemingly 2D large-scale surface expression of the orogen in the Eastern Alps contrasts with complex geometrical relations of the plate boundaries in this region (e.g., Ustaszewski et al. 2008) and the relief of the lithosphere-asthenosphere boundary (e.g., Plomerová and Babuška, 2010). With the unique structure of the Tauern window and the oblique orientation and side-stepping of the Insubric line along the Giudicaria line, however, the geologic record clearly documents significant lateral variations along the orogen. Furthermore, at depth, complex Moho topography (Brückl et al. 2010; Spada et al. 2013) and the interpretation of the lithosphere slab geometry (Babuška et al. 1990; Lippitsch et al. 2003; Mitterbauer et al. 2011) are controversial see Fig. 4 and chapter 4). Recent gravity studies (Braitenberg et al. 2002; Ebbing et al. 2006;

Zanolla et al. 2006) conclude that present-day topography, uplift rate and crustal structure in the Eastern Alps may not be accounted for by conventional Airy-Heiskanen isostasy but require a load from the lithosphere mantle slab. Along the SW flank of the Bohemian Massif the maximal width (>120 km) of the Molasse basin is reduced to only a few km in the East where the northern Calcareous Alps almost join the southernmost tip of the Bohemian Massif. Still further East, the Bohemian Massif marks the former European plate southern boundary to the Pannonian Basin. The transition from the W-E striking Eastern Alps to the NW-SE trending Dinarides is equally complex and the structure at lithosphere depth is rather poorly known. Compared to the wealth of geologic data in the region, the Eastern Alpine crustal and lithosphere structure and, hence, their structural and geodynamic relations to the surrounding tectonic units are poorly understood. Note that based on instrumental and historical seismicity, the region along the southern border of the Eastern Alps and the transition to the Dinarides represents one of the highest seismic hazard in the greater Alpine region (Fig. 3).

In summary, significant improvement of seismic images and consequently constructed geophysical and geodynamical models are necessary to advance understanding of the Eastern Alps. As example complementary experiments and collaborative projects, we envision a new geoscience traverse including a high-resolution seismic profile along longitude 13.5°E from the northern Bohemian Massif to Trieste (see profile experiment C in Fig. 6) and a high-resolution swath (see swath B in Fig. 6) along latitude 47.2°N covering the length of the Tauern window and 50 km beyond its both western and eastern ends, also to link the new N-S transect with the existing TRANSALP transect.

VII. *Alpine forelands: establishing structure, composition and deformation history*

We aim at providing a consistent high-resolution lithosphere-mantle model of the orogen that includes not only the Alps and northern Apennines but also reveals their geodynamic relations to the forelands and, in particular, the Rhine-Bresse-Graben systems. This is of key interest for seismotectonics since the Alps have migrated significantly toward the European foreland during the post-collisional phase (e.g., Ford et al. 2006; Handy et al. 2010) and the N-to-NE migration of the northern Apenninic front is clearly documented by overthrust Miocene sediments in the Po Plain (Pieri & Groppi 1981). A new 3D high-resolution structural model of the lithosphere in the forelands will provide information of the utmost importance for quantitative modelling and understanding of the complex relations between extensional deformation of continental lithosphere – including the creation of small oceanic domains, subduction, continental collision – and the various orogenic episodes including orogenic collapse.

6. Concluding remarks

AlpArray builds on recent observational and methodological developments of passive seismic imaging – as illustrated for example by the success of USArray – in establishing the densest regional-scale seismological network ever deployed to provide unprecedented data quality for imaging the Earth. The AlpArray project will be in the tradition of successful, Europe-wide cross-disciplinary Earth science programs, e.g., the European Geotraverse (Blundell et al. 1992), EUROPROBE (Gee & Stephensen 2006), TOPO-EUROPE (Cloetingh & Willett 2013). The Alps and its environs provide the opportunity to focus on the most dramatic and, arguably, the most important geodynamic target in Europe. The large-scale seismic deployment and attendant geophysical, geologic and geodynamic studies will bring this state-of-the-art methodology to the continent. The combined geophysical-geological-geodynamical approach unifies a critical mass of scientific experts to jointly tackle well-defined problems with multi-disciplinary methods. The collaborative projects will be at the forefront of solid Earth science research and have the potential to reveal unseen details of Alpine structure at all depths (crust-lithosphere-mantle), to sophisticatedly model the geodynamic evolution of the orogen, and to create the first homogeneous, unified picture of Alpine seismicity, seismotectonics and seismic hazard. This project should add new chapters to textbooks on the Alps and on orogeny in general, and increase the awareness of the population regarding the natural environment in which they live.

Appendix A – Memorandum of Collaboration for AlpArray

AlpArray is a large collaborative project with the aim of carrying out cutting edge research using seismological as well as associated Earth sciences data in order to better understand the geodynamics of the greater Alpine area and the related seismic hazard. The main actions to realise this goal are:

1) collecting a top quality seismological dataset from a dense network of temporary seismic stations which complements the permanent stations to ensure homogeneous coverage of the greater Alpine area ("**AlpArray Seismic Network**");
2) deploying specifically designed temporary seismological arrays ("**AlpArray Complementary Experiments**") along profiles, swaths or networks that are devoted to the resolution of specific structures and targeted questions;
3) acquiring associated Earth sciences data (such as geology, gravity, magnetotellurics, etc.);
4) interpreting the collected dataset in multidisciplinary ways.

The research on the acquired data will be organised in "**AlpArray Collaborative Projects**". All participating institutions will be expected to contribute within their abilities to establish and to maintain the long-term **AlpArray Seismic Network**, but may also focus on shorter term **AlpArray Complementary Experiments** and/or contribute to **AlpArray Collaborative Projects'** research.

<u>Organization</u> (see Figure on next page)

The AlpArray Working Group (**AAWG**) consists of the involved members of all participating institutions. Scientific leadership of the **AAWG** is provided by the **Science Council** consisting of one representative per participating institutions. The **Science Council** elects the **Steering Committee** with the Project Manager (**PM**)(= "PI" = "general secretary") as its head, who is also member of the **Science Council**. In addition, four working groups (**WG**) will form:

- **WG1**: Procedures and Data Management: definition of best practices for operation procedures, data handling, storage and sharing;
- **WG2**: Deployment: detailed planning and supervision of field deployment and data acquisition;
- **WG3**: Analysis: scientific analysis, interpretation and synthesis, cooperation in **AlpArray Collaborative Projects**;
- **WG4**: Outreach: communication, dissemination, website, meetings and education activities.

The **PM** and **WG2** are responsible for timely coordination and decisions regarding the **AlpArray Seismic Network**. The **PM** must be able to commit up to 20% of his time to closely follow and overview the field deployments. Data quality control, archival and distribution of **AlpArray Seismic Network** data will be performed as outlined in the document entitled "Technical strategy for the mobile seismological components of AlpArray". Seismic data acquired by the temporary stations of the **AlpArray Seismic Network** belongs to and is open to the **AAWG** according to the approved Science Plan. All seismic data (**AlpArray Seismic Network** and **AlpArray Complementary Experiments**) will be archived and disseminated through EIDA (European Integrated Data Archive) to the **AAWG**. Three years after the official dismantling of the **AlpArray Seismic Network** or of an **AlpArray Complementary Experiment** the respective temporary station data becomes publicly available. Access to data from permanent stations remains unchanged. The collected data should not be used for commercial use. Data should not be transferred to any third party without written authorization of the **Steering Committee**.

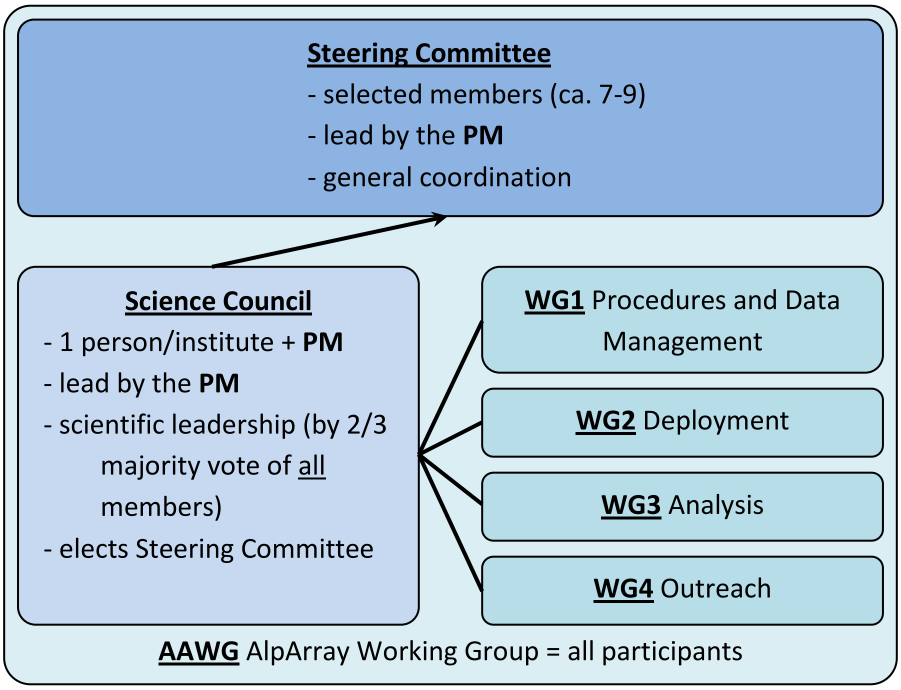
The **Steering Committee** is responsible for the coordination of all research activities of the **AAWG**, in particular of the PhD research projects and of the Science Plan. Decisions regarding research with **AlpArray Seismic Network** data, **Complementary Experiments** and **Collaborative Projects** are prepared by the **PM** and the **Steering Committee** and decided by the **Science Council** with 2/3 majority vote of all members (no response = disapproval), either at meetings or by electronic vote. New institutions wanting to join AlpArray after the official start date apply to the **Steering Committee** who will evaluate the request and prepare the decision of the **Science Council**.

AlpArray will include several **Collaborative Projects** and **Complementary Experiment**. **AAWG** members are encouraged to form special research groups within the **AAWG** dedicated to cooperate in **Collaborative Projects** and/or **Complementary Experiments** and to submit ideas for such projects and experiments to the **Steering Committee**. The **Steering Committee** will co-ordinate the submitted projects and experiments transparently by sharing them with all participants (by e-mail or secured webpage) and by providing regular updates of these activities as they become available. **AlpArray Complementary Experiment** and **Collaborative Project** research groups define their organisation and appoint a leader (member of the **Science Council** or **Steering Committee**) who acts as a representative in **AAWG** and reports to the **Steering Committee**. **AlpArray Collaborative Projects** and **Complementary Experiments** acquiring data beyond the **AlpArray Seismic Network** are encouraged to define a data dissemination policy analogue to that of the **Seismic Network**.

Authorship. Publications will include as authors the **active participants** of the **Collaborative Project**, followed by "and the AlpArray Working Group" and a link to the AlpArray website. This website will be independent of the affiliated institutions and managed by WG4. **Active participants** are those who contributed to the research (including data acquisition and processing). If the use of a "Working Group" as an author is not possible in a given media (e.g., AGU journals), a minimum requirement is a specified sentence (available on the AlpArray website) in the "Acknowledgments" section.

Participation in AlpArray requires (1) acceptance of the final version of this Memorandum by researchers and institutions by their signature, and (2) naming the representative of the institution into the **Science Council**.

The full **Science Council** will first meet in 2014 and elect the first **Steering Committee**, thereby officially founding the AlpArray project.



Appendix B – Interested institutions as of Autumn 2013

From 17 countries in total

BGR Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany
Charles University, Prague, Czech Republic
Christian-Albrechts Universität, Kiel, Germany
Comenius University, Bratislava, Slovakia
CEA Comissariat à l'Energie Atomique, France
Croatian Seismological Survey, Zagreb, Croatia
GFZ Deutsches GeoForschungszentrum, Potsdam, Germany
DIAS Dublin Institute for Advanced Studies, Dublin, Ireland
ELTE Eötvös Loránd University, Budapest, Hungary
EARS Environmental Agency of the Republic of Slovenia, Ljubljana, Slovenia
EOST Ecole et Observatoire des Sciences de la Terre, Strasbourg, France
ETH-ERDW Eidgenössische Technische Hochschule Zürich, Department Erdwissenschaften, Zürich, Switzerland
ETH-SED Eidgenössische Technische Hochschule Zürich, Schweizerisches Erdbebendienst, Zürich, Switzerland
Freie Universität Berlin, Germany
Friedrich-Schiller-Universität Jena, Germany
Geological and Geophysical Institute of Hungary, Budapest, Hungary
GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Germany
Goethe-Universität, Frankfurt am Main, Germany
HAS Hungarian Academy of Sciences, Budapest, Hungary
INGV Istituto Nazionale di Geofisica e Vulcanologia, Roma-Genova-Bologna, Italy
Insitute of Earth Sciences "Jaume Almera" CSIC, Barcelona, Spain
ISTerre Institut des Sciences de la Terre, Grenoble, France
IPGP Institut du Physique du Globe, Paris, France
Institute of Geophysics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
Institute of Rock Mechanics and Structure, Academy of Sciences of the Czech Republic, Prague, Czech Republic
Johannes Gutenberg Universität Mainz, Germany
KIT Karlsruhe Institute of Technology, Karlsruhe, Germany
Kövesligethy Radó Seismological Observatory, Budapest, Hungary
Landeserdbebendienst, Freiburg im Breisgau, Germany
Ludwig-Maximilians-Universität München, Germany
OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Udine-Trieste, Italy
Republic Hydrometeorological Service of Republic of Srpska, Banja Luka, Bosnia-Herzegovina
Royal Observatory of Belgium, Brussels, Belgium
Ruhr-Universität Bochum, Germany
SEIS-UK, Leicester, United Kingdom
Slovak Academy of Sciences, Bratislava, Slovakia
Università degli Studi di Genova, Italy
Università degli Studi di Padova, Italy
Università degli Studi di Trieste, Italy
Università degli Studi Roma Tre, Italy
Universität Hamburg, Germany
Universität Innsbruck, Austria
Universität Leipzig, Germany
Universität Wien, Austria
Université Claude Bernard Lyon 1 – ENS Lyon, Villeurbanne, France
Université de Franche-Comté, Besançon, France
Université de Lausanne, Switzerland
Université de Nice-Sophia-Antipolis, Valbonne, France
Université d'Orléans, Orléans, France
Université de Rennes 1, Rennes, France
Université Pierre et Marie Curie, Paris, France
University of Leeds, United Kingdom
University of Leicester, United Kingdom
University of Liverpool, United Kingdom
University of Ljubljana, Slovenia
University of Oxford, United Kingdom
University of Potsdam, Germany
University of Warsaw, Poland
University of Zagreb, Croatia
Utrecht University, Utrecht, The Netherlands
Westfälische Wilhelms Universität Münster, Germany
ZAMG Zentralanstalt für Meteorologie und Geodynamik, Wien, Austria

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Technical strategy for the mobile seismological components of AlpArray

Recommendations of the AlpArray Working Group 1 Procedures and data management

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1. Summary

AlpArray is an initiative to study the greater Alpine area with interdisciplinary research in an international context. A major component is a series of large-scale broadband seismological network deployments[1]: a main AlpArray Seismic Network ("backbone") and a number of dense, targeted networks known as AlpArray Complementary Experiments. The interested parties (currently 64 institutes in 17 countries) plan to combine their existing infrastructures into a transnational effort that includes data acquisition, processing, imaging and interpretation. The main experiment will encompass the greater Alpine area, from the Main River and the Bohemian Massif in the north to the Northern Apennines in the south and from the Pannonian Basin in the east to the French Massif Central in the west. We aim to cover this region with high-quality broadband seismometers by combining the ca. 220 existing permanent stations with an additional 500+ instruments from existing mobile pools and from specific national infrastructural efforts. The project will include both a uniformly dense backbone network (ca. 350 temporary broadband stations required) providing homogenous and high-resolution coverage, and a set of more dense targeted networks with broadband and short-period sensors along key parts of the Alpine chain (ca. 200 temporary stations). The current document describes standards that should be adhered to for temporary broadband stations in the backbone, and should be aimed at in the targeted networks. These land-based efforts will be combined with deployments of ocean bottom seismometers in the Mediterranean Sea; the standards for these OBS stations fall outside the scope of this document.

This report is prepared by the AlpArray Working Group 1 "Procedures and Data Management". AlpArray is organised into a number of different working groups, as seen in the overall AlpArray organisation structure in Figure 1. These recommendations will be acted upon by WG2 "Deployment".

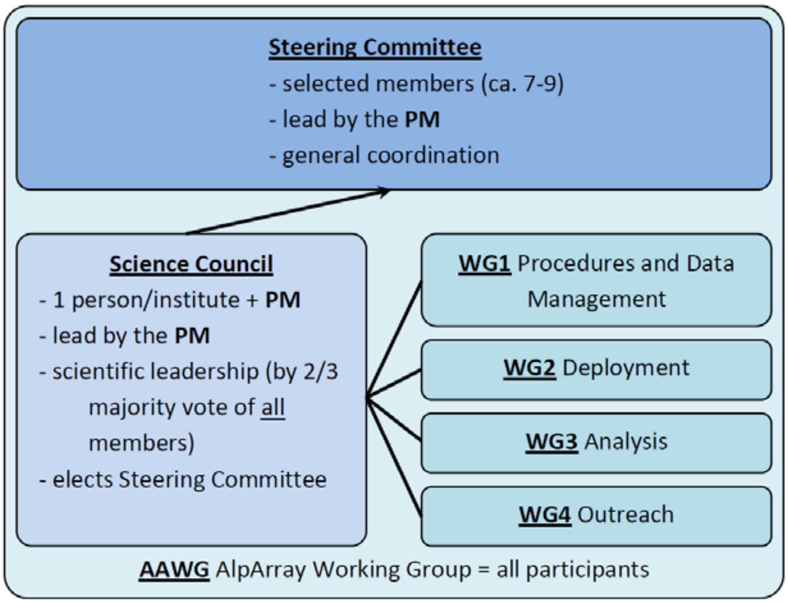

Figure 1: Organizational structure of the AlpArray project (see the Science Plan for more details)

[1] More information about AlpArray is at www.seismo.ethz.ch/alparray – including documents (as they become available) outlining the scientific goals and the proposed legal structure with the Working Groups.

Instrumentation for the AlpArray seismological experiments will be provided by participating nations from a combination of instruments from existing equipment facilities and from as yet unsecured funding opportunities. The hardware, software, manpower and level of support vary significantly between national facilities. Each facility or research group which deploys instruments is however responsible for providing the seismic instrumentation, technical assistance and support for data management. Although of significant size in certain cases, none of the national facilities are large enough to support such large-scale experiments without close collaboration with other facilities. Integration must be achieved at all levels, from field methods and data quality standards to data archiving and accessibility. This requirement was recognised at the early stages of the AlpArray initiative and this paper presents guidelines for optimising this integration. Although data acquisition can readily be achieved with a diverse set of instrumentation and techniques, a consensus must be achieved on data quality, products and access for end-users.

Responsibility for station operation (including stations permitting, station planning, station installation, station service, data recovery, data transfer, consumables, etc.) is in the hands of the group which deploys the instruments and the relevant PIs in the country in which the instruments are located (if different). The "Deployment" Working Group (WG2 – see Fig. 1) comprises representatives from each country participating with instrumentation or hosting stations.

It is expected within the data deployment phase that an AlpArray data management full-time employee (FTE) will be available to (1) ensure all AlpArray data is being retrieved in timely manner; (2) ensure metadata for stations is correct; and (3) coordinate quality control (QC) efforts, informing partners and management of problems with sites and equipment.

AlpArray will be founded on cross-community coordination spanning many nations and disciplines within seismology, and the adherence to standards. The concurrent EPOS[2] Preparatory Phase FP7 project attempts to build these ties and standards for the broader European solid earth community, and so AlpArray can be considered a flagship project demonstrating the viability of the EPOS concept.

[2] http://www.epos-eu.org/; The European Plate Observing System (EPOS) is the integrated solid Earth Sciences research infrastructure approved by the European Strategy Forum on Research Infrastructures (ESFRI) and included in the ESFRI Roadmap. EPOS is a long-term integration plan of national existing RIs.

2. Introduction

This document presents the recommendations of WG1 "Procedures and Data Management". The aim is to establish technical protocols and standards for participating institutions that will ensure the highest quality data. Although some of the recommendations presented here may seem overly prescriptive, challenges arising from the diversity of the participating facilities in this large-scale collaborative project can only be mitigated by significant synchronisation of experimental deployments and data gathering. Adherence to these protocols should significantly improve (1) efficiency in the deployment phase and (2) the final data quality. The ultimate goal is the capability to readily integrate data from permanent stations, large-aperture broadband deployments and more focussed localised studies.

We have split standards in to **compulsory**, **best practise** and **recommended**:

- **Compulsory** items will lead to the highest standard of data quality and returns and must be vigorously adhered to by all participants.
- **Best practise** items will lead to the highest standard of data quality and returns but may sometimes be inappropriate or unfeasible.
- **Recommended** items will in general not affect data quality but should assist participants to optimise procedures where currently multiple options exist.

We recommend that WG1 remains active, updated in composition and involved for the duration of the AlpArray initiative to enable assimilation and implementation of any future improvements to the recommendations presented here.

The strategy for data archival and dissemination will be to use the infrastructures defined and created by EIDA[3] (the European Integrated waveform Data Archives), the continually developing standard already operational within the permanent seismological network community. EIDA is currently built on ArcLink software distributed within SeisComP3, and includes documented standards for data archival, as well as access to the waveforms via a web portal or command line scripting.

Indeed throughout this document, we apply standards regularly adhered to by permanent broadband networks – the goal being that by encouraging best practice, the AlpArray project will gather data of the highest possible quality, that will be managed and offered to community in the most effective and cost-efficient manner possible. A major component of this effort is a highly recommended suggestion to centralise data quality control and metadata evaluation for the project. It is envisaged one of the national funding applications includes the salary to an AlpArray staff comprising at least 1 technician (FTE), who, in addition to undertaking the QC, can also maintain a web presence and take responsibility for ensuring the operability and visibility of the AlpArray data services (i.e., managing project sensor inventory; providing an overview of the incoming data managed and archived by the regional partners; NOT to manage the entire dataset).

[3] See http://www.orfeus-eu.org/eida

3. Recommended standards and methods

We address in turn all aspects of broadband seismic data acquisition and data management such that every step of the experiment cycle can be agreed and synchronized prior to the commencement of any experiment.

3.1. Station equipment and settings

Participating seismic equipment facilities house a diverse set of instrumentation. A seismic station consists of a sensor and a datalogger / digitiser (typically the digitiser and the datalogger are a single unit), with associated hardware for communications, power etc. Although the sensors and dataloggers available across Europe differ significantly in their origin and functionality, prescriptive methodology and data product management does not preclude utilisation of equipment from a range of facilities in a single experiment.

In order to ensure a minimum standard of data quality and to optimise data usage the following standards must be achieved:

Compulsory

1. Sensor must be 3 component and broadband: flat velocity-response in the frequency domain from at least 0.03 Hz (30 sec) to 20 Hz, preferable down to 0.008 Hz (120 sec).[4]
2. Digitiser must be >130 dB (24-bit technology) between 0.1 Hz and 10 Hz.
3. Known dataless SEED response for full system (both for sensor and datalogger) (http://www.iris.edu/manuals).
4. The digitizer must have GPS timing. GPS timing quality must be known and stored in SOH log file or be otherwise available for QC. Timing accuracy of at least 10 msecs during normal operation is required. GPS must be continuously on.
5. The digitiser must be set to record at 100 sps or higher sampling rate in order to ensure the data collected has the broadest possible scientific usage.
6. Datalogger must have rapid data-recovery for field maintenance, and a minimum storage capacity for the 100 sps continuous streams of 6 months.
7. Datalogger will locally store continuous waveforms in any format that is then converted to miniSEED by openly available, well-test tools to miniSEED format in an error-free manner prior to be sent to the data centre. Note that each data contributor will have to provide data to EIDA node in miniSEED format, and it is the task of the network running the station to ensure high quality miniSEED data acceptable to an EIDA node is made available.
8. All sensor / datalogger systems must be tested alongside another sensor of known response before deployment (huddle test) to ensure all components work and system meets the nominal calibration values.

Recommended

1. 1 sps data should also be locally recorded (or transmitted) to improve QC analysis.
2. Datalogger should be able to support real-time GPRS (mobile phone) communications (though this will not always be implemented).

[4] **Compulsory** for broadband experiments only: Not always appropriate, e.g., local seismicity studies where these standards can be regarded as **Best practise**. 30 s bandpass is sufficient for the local seismicity studies.

3.2. Vault types and site selection

The design of temporary seismic stations is highly dependent on local conditions and the availability of materials. We do not prescribe a compulsory pit design, but assign noise performance criteria instead. It is noted that at some sites, e.g., on sediments in deep Alpine valleys or in the sedimentary foreland basins and grabens, these noise criteria cannot be met without relocating the station by 10's of km, so common sense must prevail.

The individual agencies and institutions planning and deploying the stations need to strike a balance between ease of finding and permitting locations that will meet the noise requirements, and complexity of the installation (e.g., sites near settlements will be noisy, but will likely have mains power, security, communications and be easy to service; autonomous sites with low noise will be easier to find but more difficult to operate, and it may be too complex and costly to setup an appropriate vault with security and appropriate power, especially in the high Alps).

Examples for vault construction (including proper insulation, pressure tight housing, etc.) can be found in Appendix B.

As the AlpArray project progresses towards field installations, an AlpArray station installation and check sheet will be prepared and added as an appendix to the current document.

Compulsory *(mostly hard rock / rural sites)*

1. Installation: all deployments must be supervised by experienced persons (but not necessarily facility staff). An experience person is someone familiar with (1) preparation of high quality seismic vaults; (2) operation and configuration of sensor and digitizer (and communications equipment if this will be used); (3) field data analysis and data recovery, including analysis of state of health (SOH) data. This is typically **NOT** a student.
2. Site-noise levels, for all 3 components (*rock / rural site)*: 20dB lower than the high noise model up to 100s (excluding the microseism) (this can and should also be met by 30s sensors).
3. Tests using a broadband sensor for >1day must demonstrate the modal noise level for the station meets the agreed noise levels for that period. This should be done within 2 months (compulsory), better within 4 weeks (strongly recommended), even better before installation and within 10 m of the candidate site (best practice). If the agreed noise levels do not meet the criteria the station must be moved (compulsory).
4. When determining the orientation of station, the method of orientation should be recorded at each site, including degrees of declination if true North is used.
5. Due to security, access or power issues it is not always possible to locate stations exactly where required for optimal array coverage. For the backbone, we recommend that if the final site falls within 3 km of the planned site it is acceptable without further agreement. If the final site falls between 3 km and 6 km then the deployment team must check with the national coordinator. If the site lies >6 km from the planned location then this must be referred to the main AlpArray WG2 (Deployment) team. For the targeted networks, this criterion may need to be even stricter, depending on the purpose and station spacing, and will be decided on a case by case basis with WG2.
6. The method used to calculate the geographical coordinates, altitude and depth from free surface for the sensor (not the position of the GPS attached to the datalogger!) must be

recorded and made available (e.g., handheld GPS, Google Earth). Coordinate precision of 4 decimal places (~1 m is required). Coordinates must be measured in WGS84, elevation is above the ellipsoid. This might seem trivial with new stations with GPS but still ambiguities (ellipsoid vs. geoid) and coordinates read from old maps exist.

Recommended

1. Site-noise levels, for all 3 components (*basin / soft soil site*): lower than Peterson (1993) high noise model up to 100 s (this can and should also be met by 30s sensors).
2. Due to the diversity of site geology and local conditions a single specific vault design is inappropriate, therefore:
   a. The vault design will not be dictated but requires that the specified noise model be met: In general this will require avoiding inhabited buildings. Further, in order to minimise local structure-related site amplifications, buildings >1 story should be avoided, and if the deployment will be in an existing structure, the sensor must be installed in the basement.
   b. Site autonomy: Sites without mains power will require solar panels with battery backup. A minimum of 60 days autonomy without charge is suggested, e.g., battery capacity of 240 Ah for a 2 W system (potentially >100 days autonomy required in the high-Alps or high-latitudes where access is likely to be severely restricted during winter).
3. Standard methods for sensor orientation are prone to significant error, even at permanent installations (Ekström & Busby, 2008). We therefore recommend that wherever possible tools are acquired at the start of any large-scale project to minimize sensor orientation errors (e.g., gyroscopic compass). Potentially a handful of these systems would serve the entire AlpArray community for the duration of the initiative.
4. For security reasons, where possible private land should be used for deployment with agreement of the land-owner.

3.3. Communications and maintenance schedule

Although real-time data transmission is optimal for data recovery and quality control it is clearly not always feasible due to power and signal requirements, and typically high communications costs. Mobile communications would be the preferred real-time communications solution as in general, a mobile phone signal will be available at the majority of sites in the Alpine region except in extremely remote regions. Where mains power is available real-time data transmission through the mobile phone network becomes highly desirable. Where mains power is not available, real-time communication through the mobile network will result in significant power overheads which may make this prohibitive, although SOH transmission would still be feasible. Real-time transmission should be considered on a site-by-site basis but the following factors must be taken in to consideration. For off-line stations, a maintenance schedule which includes site visits every 3 months should be implemented. In the high Alps, site visits in the winter months will only be possible if the stations are located in the immediate vicinity of inhabited or otherwise supported areas.

1. Financial costs:
    a. In the majority of Alpine-region countries, **real-time data transmission** can be achieved for around €20 per month (up to €35 for reliable connections) with a hardware start-up cost of around €1,000 per station (though many mobile pools already have the required hardware). There is an associated cost with data centre manpower for array monitoring and data QC, dependent on array size: 4 man-days per month for 50 stations is realistic, ***equivalent to 40 man-days per year per 50 stations***. Additionally, network monitoring tools need to be setup so that communication dropouts, or other station problems that are indicated by monitoring the SOH data, can be tracked and appropriate automated notifications distributed.
    b. **Offline stations** result in major hidden costs: Consider for example a plan to provide periodic maintenance for an off-line mobile network comprising 50 stations - having a service interval of 3 months for each station. If we assume 2 stations can be serviced (including data download and minor repairs) per day, with 2 extra office days added for conversion and data QC, this requires ***120 man-days per year per 50 stations***. Additionally, the hidden cost of a significant increase in the proportion of lost data (see section below) must also be taken into account.
    c. Excluding the already-mentioned communications equipment, hardware and software for real-time data retrieval need not differ from that required for offline data processing and so is regarded as cost neutral.
    d. If sufficient spare parts are available, repairs of offline stations can generally be carried out during servicing and therefore are at no extra cost.
    e. Real-time station repairs would require additional site visits and must therefore be considered on top of these figures, especially if the array is not maintained by in-country staff. A contingency budget for such circumstances should therefore be considered. If real-time stations continue to deliver data without problems routine visits are not required. Real-time stations will also include a minimum of 6 months on-site recording, so if there are communications failures data will still be recorded locally. The manner of data archival in case of gaps in the transmission is to be dealt with the station operating networks; if a network does not already have a solution, the final archive should be the locally recorded and manually retrieved data.
2. Data recovery rates:
    a. A realistic expected data loss for offline seismic stations is around **10-20%**, usually a result of vandalism, instrument failure or power supply issues.
    b. Real-time data transmission allows station issues to be identified within hours or days of manifestation. Where issues cannot be resolved remotely site visits can be scheduled to ensure recovery in a timely manner. Data loss rates for well maintained real-time networks can be lower than **1%**.

3.4. Data recovery and security

EIDA is now recognised as the standard data exchange solution for European collaborative experiments. Eight EIDA nodes currently exist, a number of which are already AlpArray participants (e.g., GFZ, INGV, IPGP, ODC, RESIF, SED/ETHZ). The concepts behind EIDA or ArcLink, the underlying software, are followed for the archival and dissemination of all waveform data at numerous large seismological observatories (GFZ, SED/ETHZ, RESIF, INGV). EIDA is also used to distribute restricted datasets from mobile experiments. It is recognised that in order to be suitable for AlpArray, the EIDA software requires additional technical development and the community management structure needs to be formalised. These issues are currently being addressed and the resultant EIDA should be a viable and sustainable package that can be used at all European data centres. The following recommendations that directly relate to EIDA are subject to successful implementation of these improvements.

The general archival policy for AlpArray is that data collected within a particular country will be archived at the relevant EIDA node in that country, if existing. If no local EIDA node exists, the data will be archived at an EIDA node agreeable to both the PI's institute and the host country. In general, conversion to the final archive format (miniSEED) and associated data QC will be carried out by the PI, supporting instrument facility or responsible EIDA node data centre.

Compulsory

1. If native format is not miniSEED, data must be converted to archive-ready miniSEED format at the host institute within 1 month of the site visit. Host institute must work with relevant EIDA node to agree on what is "archive-ready" (typically quality controlled day-long miniSEED files).
2. Data must be at the nominated EIDA node and made available to project partners on the community portal within 2 months of site visit. Quality control *(see note below)* of all data is completed within this 2 month period and prior to sending the data to the nominated EIDA node.
3. Permanent data backups must be maintained by the PI or supporting facility.

Best practise

1. For off-line stations, site visits and data download should be made every 3 months for the duration of the deployment.

Recommended

1. Archive-ready miniSEED data from each station goes to the nominated data centre dependent on station location (e.g., miniSEED data from UK hardware operating in Switzerland are sent to the Swiss EIDA node for archiving).
2. If an experiment does not have a national EIDA node then arrangements must be made between participating groups or ODC prior to commencement of any experiment.
3. Real-time data are delivered in real-time to relevant EIDA node. Real-time data are quality controlled *(see note below)* with at minimum a weekly assessment of all available sites.

NOTE: Quality control standards and procedures will follow those of EIDA nodes. However, currently no standards yet exist across EIDA nodes. These should be developed before AlpArray is recovering data, but as there is no clear funding, it cannot be guaranteed it will happen. In case of delays, representatives of AlpArray WG1 and WG2 will convene in due time to set the standards (data availability, completeness and gaps, latency, PSD/PQLX plots, polarity reversal, component exchange, time stability, etc). Following the QC rules will be compulsory.

3.5. Data formats and access

Compulsory

1. FDSN network codes must be assigned to temporary stations with one code per deploying institution or mobile pool.
2. The virtual network _ALPARRAY_ will be attached to all projects. All data associated with AlpArray, including temporary and permanent stations, will be accessible using this mask.
3. All waveforms will be archived in miniSEED format. Standard SEED naming conventions must be followed. Metadata will be in dataless SEED or FDSN stationXML. Station naming will be AAxxx for temporary backbone stations, with “xxx” being numbers assigned by WG2 (a range of numbers can be given to an institution / a pool to allow flexibility), and all stations must be registered under ISC station registry. Examples:

Station name	Type	Network code	Equipment	EIDA node	Virtual mask
ZUR	permanent	CH	Swiss	Switzerland	_ALPARRAY_
AA101	temporary	XA	Swiss	Switzerland	_ALPARRAY_
AA201	temporary	XB	SEIS-UK	Switzerland	_ALPARRAY_
BUD	permanent	HU	Hungarian	ODC	_ALPARRAY_
AA202	temporary	XB	SEIS-UK	ODC	_ALPARRAY_

4. Metadata creation and QC is the responsibility of the facility or the EIDA node, as agreed before each project begins.
5. MiniSEED format can be either Steim 1 or 2 compression.
6. Huddle test and state of health data will be archived locally, and must be made available on request. Example of huddle testing can find at PASSCAL website: http://www.passcal.nmt.edu/content/huddle-testing-feedback-sensors-and-dataloggers.
7. Data archiving must be in a standard style: standard SeisComP3 SDS structure preferred unless other structure is already in use that is compatible with EIDA distribution. Reference as of October 2013: http://www.seiscomp3.org/wiki/doc/applications/slarchive/SDS

Best practise

1. A huddle test is required before the experiment. When freighting the instruments (potentially causing damage to them) an additional brief (>12h) huddle test is recommended in the country of installation. This also helps the local PI and project members to learn about the operation and functionalities of the equipment.

3.6. Data openness

Data will be openly available to all project partners within 2 months of data collection in the field. It is encouraged that data will be fully openly available immediately, but in recognition that this is not always possible (i.e., Ph.D. studies), a maximum delay of 3 years after data collection for the backbone (determined by the Steering Committee) or a targeted deployment ends, will be mandatory (see "Memorandum of Collaboration").

Data openness has recently become a significant issue for national funding agencies, and it is these agencies who will generally dictate any data-access restriction periods. There is increasing recognition that public data-access following a proprietary protection period for initial publication, usually 2 or 3 years, is beneficial. Within the seismological community, data openness following publication is generally accepted as being of significant benefit to all parties and has been undertaken for a number of years. Such openness is certainly compatible with the seismological community where publicly available software processing packages (database maintained by ORFEUS) and open processing environments, such as ObsPy, are commonplace. Prior to the period of data release, data sharing agreements are required between all participating groups and Memoranda of Understanding must be implemented prior to the commencement of any experiments. Though EIDA primarily follows an open access data policy, the distribution tools already supports restricting access of datasets to specific users.

In order to maximize benefit to the wider seismological community, a ***special event scenario*** is mandatory, facilitated by the implementation of EIDA nodes. In case of M5+ events inside or adjacent to the network, a 24 hour window (1h before event time to 23h after) of all data should be made publicly available as soon as possible.

Compulsory

1. Data is made available via EIDA to all partners within 2 months of data collection.
2. Data is made publically available via EIDA within 3 years of end of experiment, as determined by the Steering Committee.
3. For M>5 events inside or adjacent to the network all data from -1hr to +23hr from origin time is made publically available via EIDA as soon as possible.

Best practise

1. Data is made available publically via EIDA as soon as it is available.

3.7. Centralised data coordination

We recommend distributed data archiving but centralised quality control:

1. The archives are distributed across Europe, with centralised access services using EIDA.
2. Standard quality control applied locally, but coordinated centrally – for station noise (including PQLX), station uptime / gaps, SOH monitoring. See above for QC features.
3. Project management for the archives will be done centrally with a project website (maintained by the 1 FTE at the nominated data centre), including station quality reports, station information (including standardised deployment and servicing sheets), instrumentation availability, etc.

a. Instrument inventory optimisation can then be done using this web hub by project scientists.

Items 2 and 3 above require a significant amount of work across the duration of the AlpArray initiative, and as such we propose there is an "AlpArray data hub" which would be staffed by at minimum 1 FTE, to be funded through one national project, working at the corresponding institute with an ORFEUS Data Centre affiliation.

4. OBS data

OBS (Ocean Bottom Seismometer) data have not been addressed here directly. However, our proposals are consistent with a future integration of OBS data without significant effort. The integration of onshore and offshore facilities within Europe is currently underway and synchronization of data products is seen as an essential outcome of this. Details are outlined in the attached White Paper which resulted from a workshop targeted at the integration of onshore and offshore instrumentation facilities within Europe (Appendix A).

5. Discussion and Conclusions

We present here an outline plan for how the large-scale, international, seismological AlpArray experiment can technically be realized through integration of the individual European seismic facilities. Each participating facility retains its own national identity and operating structures but application of the guidelines presented here allow any number of these facilities to undertake this collaborative large-scale projects without any detrimental effect on data quality or scientific outcomes. A key component of the plan is the responsibility of the specific AlpArray working groups (backbone, targeted networks) for the station operation.

We have addressed the key components of the seismic experiment within the AlpArray project:

- Station equipment and settings
- Vault types and site selection
- Communications and maintenance schedule
- Data recovery and security
- Data formats and access
- Data openness
- Centralised data coordination

By agreeing to this set of standards and protocols prior to the initiation of the project, collaborating national facilities can mitigate against the problems associated with the diverse instrumentation and operational protocols. One significant barrier to collaboration on such large-scale experiments within the European Scientific Community, i.e. discrete national funding of instrumentation facilities rather than a centralised European seismic facility, is therefore overcome without any intervention by the project’s scientific participants. AlpArray is an ambitious concept yet is realistic in addressing the European environment, and by pooling the resources of the community, we can leverage a significant pool of mobile seismometers to do serious science without having to construct a centralised European mobile pool.

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Appendix A – Integrating Mobile European Plate Observing Systems: Seismology

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Introduction

Mobile networks of seismometers are required to answer fundamental questions about the formation, structure and dynamics of the European plate and to evaluate important risks and resources. With the European plate surrounded on 3 sides by water and containing major seas, marine seismometers must be an integral part of this network. The efficient use of these instruments depends not only on their existence, but also on the ease of their access by the seismological community.

We propose actions to make marine seismographs more accessible to the seismological community. A major action is the standardization of methods for requesting these instruments and for providing the data. We also propose a framework for better communication between European parks, which should ease standardization and improve the quality and availability of instruments. This initiative falls within the EPOS (European Plate Observatory System) framework, complementing the EMSO (European Multidisciplinary Seafloor Observatory) initiative in the same way that land-based mobile instrument parks complement permanent stations.

Motivation

The last two decades have seen an explosion in the availability and quality of mobile seismological systems. Whereas, 20 years ago, a "detailed" regional study might consist of deploying 10, mostly short-period, seismometers for a few months, the same region can now be studied using hundreds of smaller, easier to use and more sensitive systems. Also, collaboration between countries and their instrument parks allow more instruments to be applied to one problem. These advances allow seismologists to image sections of the European plate with unprecedented resolution. A recent example is the IBERARRAY-PYROPE experiment, in which Spanish and French seismometer parks combined forces to study the structure beneath the Iberian Peninsula and Pyrenees mountain chain.

Marine seismograph stations, commonly known as OBS for "ocean-bottom seismometer", have similarly advanced. Whereas, 20 years ago, there were no more than 100 academic OBSs in the world, almost all of them short-period, there are now about 1000 such instruments, many of them large- or wide-band.

Many studies aimed at studying seismic hazard, mapping the potential for natural resources, or addressing fundamental geodynamic questions should use a combination of land-based and marine seismometers. This is particularly true for Europe, which is surrounded on three sides by seas and which contains great inland seas. Europe's greatest seismic hazards are centred close to these seas and its most important energy resources are on continental margins. Even many land-based regions, such as the Alpine mountain range, are close enough to seas that a complete seismological coverage can only be obtained by including marine stations.

However, very few experiments use both land-based and marine stations, much less than should be expected. The land and marine seismological communities have developed somewhat independently,

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leading to different means of requesting each type of instrument in most countries. In addition, marine data is rarely made available on public seismological data archives, making it more difficult for this data to be used beyond the objectives of the initial projects, or for the data quality to be evaluated.

Marine parks are generally smaller than their land counterparts, and the costs per deployment higher, mostly due to the high price of ships for the deployments but also due to the cost of batteries for long-term deployments. The additional challenge of obtaining ships can also discourage scientists from trying to use marine instruments. Finally, marine measurements have a different (and generally stronger) background noise spectrum than well-installed land stations.

Our goal is to allow scientists to develop seismological experiments with the optimum geometry, scale and sensitivity for the problem, with a unified access to both marine and land instrumental pools and, ideally, ship time (or at least support in obtaining suitable ships for deployment).

Good Practices

Unifying marine and land-based seismological systems on a European level is currently unlikely for a number of reasons, including differing funding structures, diverse national priorities and heterogeneous hardware. As long as the instruments remain under national control, the best approach to assimilation is the clarification of the costs and harmonisation of the means of requesting instruments in each country. The key to successful integration is of course improved cooperation between facility managers.

The following is a list of "good practices" that should be implemented by marine parks to integrate marine and land-based seismological systems.

1. Organize yearly organizational or technical meetings between the parks.
2. Archive data in a European or national seismological data centre that can provide data over the web in a seismological standard format.
3. Develop and distribute tools for standard OBS data pre-processing (e.g., component orientation, clock correction verification and noise removal).
4. Encourage openness about data collection success rates and problems. Create tools to evaluate these parameters.
5. Lobby for a single (or at least coherent) process for funding and ship time.
6. Encourage rapid response / ship time mechanisms in countries with OBS parks.

Priority should also be given to integrating land and ocean instrumentation on a national level, making instrument requests and payment structures compatible. Some national parks have already united land and ocean facilities under a similar umbrella (e.g., the amphibious DEPAS pool in Germany and the NERC Geophysical Equipment Facility (GEF) in the UK).

Each national pool is free to set their own rules. For example, pools in countries with high seismic hazard might always want to retain a number of instruments for response to national emergencies. But these rules must be clear in order for European-level coordination to advance. And they must clearly state if they do not follow the "good practice" guidelines.

Data will be provided to the data archives in "raw" format (corrected for measured clock drifts, but not verified using cross-correlation, re-oriented using correlation or earthquakes, or noise reduced). These methods require resources beyond those of the individual parks and can moreover introduce supplementary errors if not correctly applied.

Although some bilateral agreements between the major OBS-parks already exist, true Pan-European coordination between OBS parks will bring additional benefits by simplifying the logistics of exchanging OBS capability and providing access to scientists from European countries which do not have their own national pool. European coordination will also provide benefits on a national level: it will allow local experiments to be more ambitious (using the ideal geometry instead of the one imposed by their local park), it will allow parks to function and prosper even in years where there is a dip in their national demands, and it will help parks to improve their instruments.

Action Plan

Implementing the above good practices requires means beyond those existing in the individual OBS parks. European-level support is needed to support coordination between the parks, increased visibility of the parks and clarify the use of their instruments. An infrastructure is also needed for developers that can transform the routines for data conversion and pre-processing already developed at some of the parks into tools that can be applied to all of the parks in two steps: (1) tools to convert data from each park into a standard seismological format and (2) tools to apply OBS-specific data pre-processing to these standardized data.

A Committee for the Harmonization of European OBS Parks (CHEOPs) has been formed to realize this goal. The principal tasks of this committee are (1) to educate the seismological community about the availability and capabilities of OBSs experiments and the resources needed to collect high-quality data; (2) to identify the need for OBSs in important scientific targets and make sure that the OBS parks can respond to these needs; (3) to better integrate OBS parks into national and European geoscience initiatives and structures; (4) to create a European-level infrastructure dedicated to improving and harmonizing European OBS parks (data quality, data access, usage requests).

Active seismic experiments

This paper focuses on passive seismological measurements because they are the most closely related to land seismological experiments. However, active seismic experiments are a major component of ocean-bottom seismology and have several links to integrating land- and ocean-seismology.

First, active seismic experiments can provide constraints on structure, fault geometry and properties of sediments, crust and upper mantle that can be crucial for understanding regional geodynamics and for better locating earthquakes and putting them into context. Indeed, there have been several land-sea active seismological experiments.

Second, even active seismic experiments that are not focused on issues of direct interest to passive seismologists may provide unique data in otherwise unexplored regions. Continuous data from these experiments should, if possible, be saved in standard seismological databases. This practice could also help the OBS parks, who usually provide shot-based data to their clients and must re-extract them if the clients recalculate the shot positions or times. If the continuous data are stored in a standard format, a standard tool could be developed for extracting shot-based data, and data validation methods developed for passive seismology could also be applied to these data.

Finally, OBSs used for active seismic experiments would also benefit from a greater collaboration on the European level, to improve their instruments and to have access to instruments from other parks for very large experiments.

Links to European Initiatives

OBS parks need to better coordinate with existing European and national seismology initiatives. Better integration is one of the major goals of the Earth Plate Observing System (EPOS) initiative, and we should take advantage of this infrastructure, if possible, to initiate the most pressing actions, such as the first technical meetings and possibly methods for requesting an OBS-specific infrastructure. OBSs have also played an important role in the European Multidisciplinary Seafloor Observatory (EMSO) and our developments can have a direct effect on the quality of their stations. Finally, ORFEUS strongly supports this initiative. Their ability to provide logistical/financial support is uncertain, but should be discussed.

Future directions

Instrumentation. It is at the current stage also not advisable to request a standard instrument to be developed, as different types of instruments provide important differences. For example, marine instruments need to store their own power, so there will always be a trade-off between the size of an instrument, the type of sensor, and the maximum deployment length. We do recommend, however, that instruments move toward at least wideband sensors (60s or longer), as the broader band is necessary for many seismological studies and new low-power sensors are nearly as compact as short-period sensors and have power consumptions (150 mW) comparable to or lower than the rest of the instrument electronics. Broadband sensors will be necessary for some experiments, but their higher power consumption (700-1000mW) significantly reduces their possible deployment time and their larger size can limit the number of instruments that can be transported by a research vessel.

Technological innovation. Although OBSs are already a useful part of scientific experiments, further advances can be made to make them better. We list a few below, some of which are already being developed in one or more of the parks. Coordination of these efforts would allow these problems to be attacked more efficiently:

- <u>Reduction of seafloor current noise</u>: Seafloor currents create a much higher noise signal on the horizontal channels than exists at land stations. Although this noise can be removed by burying the sensors, lower cost methods can also be developed, such as reducing the sensitivity of seafloor sensors to currents and independently measuring tilt in order to correct for the current noise. The UK's OBS park is working on the first problem, but future European help could be crucial to making advances that can be applied to all instruments. Studies of tilt and rotation funded by Europe could also lead to rotation being used as a seismological measurement in its own right, whose potential is currently being evaluated in land experiments.
- <u>Orientation of seismometer components:</u> Currently, OBS seismometers are almost never oriented, as compasses near enough to the sensor to be attached are too affected by the sensor's EM field, and other means, e.g., the use of gyros must be explored.
- <u>Data shuttles:</u> A means to send data capsules to the surface on command, would allow the verification of instrument/data quality from a small ship without having to recover an instrument and perhaps perturb its favourable emplacement. Potentially, expendable instruments could release shuttles at regular intervals.
- <u>Multiparameter measurements:</u> Each OBS deployment provides a measurement structure (power, data storage) in an isolated, hard to reach region. Numerous other important parameters (tilt, currents, magnetic field, temperature…) could also be measured at the same time.
- <u>High sampling rates:</u> These would allow studies of other phenomena, such as marine mammal migrations, other near biological activity and hydrothermal vent flow variations.

Appendix B – Vault types

PASSCAL seismic vaults

Introduction link:
http://www.passcal.nmt.edu/content/instrumentation/field-procedures/seismic-vaults

Broadband vault construction link:
http://www.passcal.nmt.edu/content/instrumentation/field-procedures/seismic-vaults/broadband-vault-construction

A possible solution based on the CIFALPS experiment

Characteristics:

- fast, easy and discrete installation;
- reasonable cost (<200€);
- can be constructed either inside or outside buildings.

Requirements:

- good thermal insulation of the sensor (for low noise at long periods data on the vertical component);
- a horizontal slab.

Approximate costs:

Equipment	**Typical cost €**
A pipe (polyvinyl chloride or HDPE) with a screwed / lockable cap, watertight if outside. (Diameter up to 45 cm and at least 10 cm wider than sensor diameter; height between 40 and 100 cm.)	100
A pre-fabricated (wood) formwork for building a slab (about 50 cm x 50 cm x 20 cm)	10
Fast dry mortar / cement (50 kg or 25 kg) to construct the slab	25-50
1 panel of mineral wool insulation	5
1 panel of hemp insulation	10
Aluminium insulation	10
Rubber seal to protect incoming cabling	10
TOTAL	**170-195**

Examples:

		
HDPE pipe with a rubber seal	Polyvinyl chloride pipe with a rubber seal	Wood formwork

Pipe size:

- Broadband sensor STS-2 or T120PA: $\emptyset ext$ = 400mm
- Wide band sensor CMG-40T: $\emptyset ext$ = 315mm

For outside, soft soil sites (note: hard rock sites preferred for AlpArray):

- dig a hole (about 1m deep) and fully burry the vault (note: site must be above the water-level);
- drain the slab (drain pipe);
- build a 50 kg slab (25 kg is enough for inside sites).

Construction steps:

1. Construction of the slab with pipe inserted in the wet mortar	2. Internal thermal insulation (hemp wool + mineral wool) all around the sensor.	
		

3. External insulation	
	

Final result	
	
Outside	Inside