Initiative zur Einrichtung eines Schwerpunktprogramms

Mountain Building Processes in Four-Dimensions (4D-MB)

Monviso (Cottian Alps, 3841 m)

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1. Summary

4D-MB is a multi- and interdisciplinary project that forms an integral part of the international *AlpArray* mission. *It will test the hypothesis that re-organizations of Earth's mantle during the collision of tectonic plates have both immediate and long-lasting effects on earthquake distribution, crustal motion and landscape evolution in mountain belts.* *4D-MB* challenges conventional wisdom by recognising that in the Alps (**Fig. 1**) links between Earth's surface and mantle can only be explained by integrating 3D imaging of the entire crust-mantle system with geologic observations and modeling to enable us to look both backwards and forwards in time, the 4th dimension. This integrated 4D approach is an emerging field with far-reaching scientific and socio-economic relevance. Proposals are invited for **four research themes** related to the central hypothesis:

Theme 1: Reorganizations of the lithosphere during mountain building will help determine the origin of switches in subduction polarity, particularly to understand how tears in lithospheric slabs nucleate and propagate in time and space. A detailed view of these deep structures with innovative geophysical methods will yield fresh insight into the structure and rheology of the lithosphere, especially as it relates to response of the surface to changes of lithospheric structure.

Theme 2: Surface response to changes in mountain structure on different time scales will shed new light on the debate over the competition of climate and tectonics during mountain building. We will test the controversial idea that time-integrated denudation and uplift rates partly reflect slab-tearing and -breakoff events.

Theme 3: Deformation of the crust and mantle during mountain building will resolve the question of whether deep structures manifest early stages of mountain-building (subduction, collision) or primarily preserve the imprint of later events (indentation, lateral escape). Determining this will constrain rates of structural change in the crust and mantle, and help us understand how subducted continental and oceanic lithosphere are preserved during exhumation to the surface.

Theme 4: Motion patterns & seismicity will identify the spatial and temporal patterns of faulting and seismicity to gain an overall motion picture from the present back in time. This theme is aimed at understanding whether present earthquakes and fault motion are related to the deep structure of the Alps or if another kinematic pattern is being established in response to a new tectonic regime.

These studies will take advantage of the Alps' unique exposure of different stages of orogenesis, from ongoing continental collision and indentation in the east to post-collisional rebound in the west. Focus will be on integrated geophysical-geological studies along swaths of closely spaced seismometers in the tectonically most active parts of the orogen (Eastern & Southern Alps) and across the Alps-Apennines orogenic fronts. 4D-MB will galvanize the Earth Sciences in the German and European communities, helping to bring them to the forefront of international geoscience.

2. State of the Art & Preliminary Work

This section reviews knowledge in the four main research themes outlined above. In addition, we review other mountain belts worldwide that have been targeted for advanced studies, highlighting their main similarities and differences with the Alps.

A. Reorganizations of the lithosphere – switches in subduction polarity

Mountain building is a transient process involving a host of interactive mechanisms operating at depth and on the surface on widely varied time scales. Transience is manifested in the rock record, as well as in the structure and motion history of an orogen. Switches in the directions of subduction are first-order examples of transience and two such switches have been proposed in the Alps: one at the transition of the Western Alps to the Apennines that occurred in Paleogene time (Vignarolli et al. 2008, Molli et al. 2010) and the other, controversially, at the transition of the Western to the Eastern Alps in the Miocene (Lippitsch et al. 2003, Kissling et al. 2006). The latter switch challenges the traditional notion of uniform-sense subduction in the Alps, even as it confirms previous knowledge of opposite Cenozoic thrusting directions in the Alps and northern Dinarides (Ustaszewski et al. 2008).

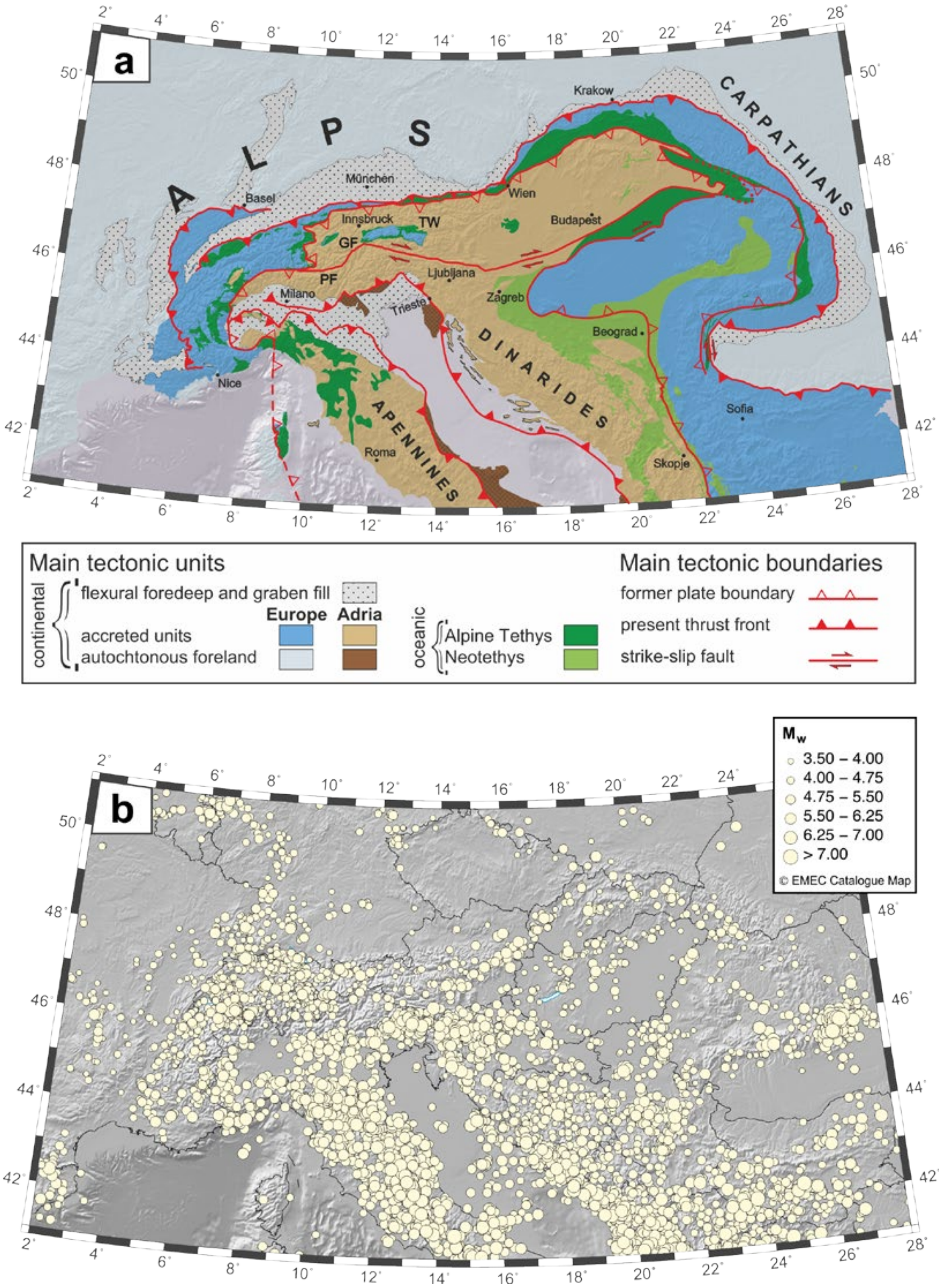

***Figure 1**: **(a)** Tectonic map of the Alpine chain and its forelands. The Alps result from the collision of two tectonic plates, Europe (blue) and Adria (brown). Red lines mark the main tectonic boundaries; PF - Periadriatic Fault, a major late-orogenic fault system offset by the Giudicarie Fault (GF). TW – Tauern Window. Map compiled from Schmid et al. (2008), Ustaszewski et al. (2008), Schmid & Slejko (2009) and Handy et al. (2010, 2015); **(b)** Earthquakes of magnitude M_w for the period 1000 to 2006 AD compiled from the EMEC catalogue.*

In the Western Alps, the predominantly northwest-vergent thrusting direction is consistent with southward subduction of the European plate beneath the Adriatic plate as interpreted from seismic images of the Moho and of the slab itself (**Fig. 2, sections AA' and DD'**, Zhao et al. 2015). In contrast, in the Eastern Alps (defined as the part of the Alps east of a north-south line defined by the Giudicarie Fault, **Fig. 1a**), the nappes in the vicinity of the Tauern tectonic window are folded and dissected by Miocene-age normal and strike-slip faults that accommodated orogen-parallel extension (Ratschbacher et al. 1991, Selverstone 2005, Scharf et al. 2013). There, the slab is steeply to moderately inclined to the north (**Fig. 2, section CC'**) and is separated from the European slab to the west by a conspicuous, if poorly defined, gap in positive P-wave velocity anomalies at ~11°E (**Fig. 2b**). In this gap, which coincides with the TRANSALP profile (**Fig. 2**), teleseismic tomography indicates that the slab is short (≤ 150 km) and dips vertically (**Fig. 2, section BB'**).

However, other seismic studies image a south-dipping European Moho (Lüschen et al. 2006, Bleibinhaus & Gebrande 2006) that extends 20-30 km south of the Periadriatic Fault System and underlies the Adriatic Moho (Kummerow et al. 2004, Brückl et al. 2007). Thus, the southward subduction geometry in the crustal sections appears to be inconsistent with the northward dip of the slab anomaly in this part of the Eastern Alps. Moreover, existing crustal models for the TRANSALP section do not agree regarding the inclination and depth of the Adriatic Moho (Kummerow et al. 2004, Lüschen et al. 2004, Ebbing et al. 2006, Bleibinhaus & Gebrande 2006, Diehl et al. 2009). The newest Moho map of this area based on combined controlled-source and receiver-function information indicates a Moho gap beneath part of the Eastern Alps (white area in **Fig. 4c**, Spada et al. 2013), one of the targets in this SPP (section V). Given these discrepancies, it is hardly surprising that interpretations of subcrustal structure in the Eastern Alps are contradictory. For example, both south-directed (Castellarin et al. 2006a, Lammerer et al. 2008) and north-directed (Schmid et al. 2004, Kissling et al. 2006) subduction has been proposed along the TRANSALP section. Controversy also persists over whether the slab anomaly beneath the Eastern Alps is part of the Adriatic or European plate (Mitterbauer et al. 2011, Handy et al. 2015). Whatever its origin, this anomaly is oriented obliquely to the crustal structure (Schmid et al. 2013), as well as to the orogen-parallel motion vector of the Eastern Alps towards the Pannonian Basin (Grenerczy et al. 2005). One of our challenges is therefore to determine whether decoupling occurs within the orogenic crust (Oldow et al. 1990) or along the crust-mantle boundary beneath the Eastern Alps.

Geodetic measurements indicate that the Adriatic plate is currently rotating counterclockwise and indenting the Eastern Alps at ~2 mm/yr (Vrabec et al. 2006, D'Agostino et al. 2008), whereas in the Western Alps near the rotational pole of Adria, the convergence rate is at or below GPS resolution (≤ 1mm/yr, Nocquet & Calais 2004, Tesauro et al. 2005). Thus, the Alps afford a unique opportunity to study different styles of mountain building along the Adria-Europe plate boundary, from ongoing indentation and orogen-parallel escape in the Eastern Alps (Scharf et al. 2013) to orogenic arcuation, post-collisional extension and isostatic uplift in the Central and Western Alps (Sue & Tricart 2003). *4D-MB* may shed light on why the Alpine slabs are largely aseismic, even in the eastern part of the Southern Alps where Adria-Europe convergence is still active.

B. <u>Surface response to changes in deep structure</u>

The complex structure of the Alps manifests a history of oblique plate convergence punctuated by two slab rupturing events: an Oligo-Miocene event in the Eastern and Central Alps (von Blanckenburg & Davies 1995) and a younger, possibly Plio-Pleistocene event in the Western Alps (**Fig. 2, section DD'**; Kissling et al. 2006, Fox et al. 2015). Both events appear to coincide with increased deposition rates in the foreland Molasse Basin (Sinclair 1997; Schlunegger & Willet 1999, Kuhlemann et al. 2002, Spiegel et al. 2000, 2002), but deposition lags behind tectonic uplift. The depositional record reflects the competing effects of tectonics, climatics, lithology and erosion (Kühni & Pfiffner 2001), as well as the selective preservation of younger sediments (Willenbring et al. 2010). Linking the latter of these breakoff events to the record of recent uplift and erosion in the Alps is problematic; whereas recent erosion rates in the Central and Western Alps determined by cosmogenic Be-10 from river sediment (Wittmann et al. 2007) are equal to or somewhat less than rock- and surface-uplift rates (0.2-1.1 mm/yr, Kahle et al. 2007), rock-uplift rates exceed erosion rates in the Eastern Alps (Norton et al. 2011). This has been used to argue that the Western Alps are at dynamic steady state in the absence of convergence (Bernet et al. 2001, Wittmann et al. 2007) and assuming isostatic compensation at the current Moho depth. Norton et al. (2011) further speculate that the predominance of erosion in the west may be due to the greater influence of geomorphic inheritance there (glaciation in response to Mio-Pliocene global cooling; Champagnac et al. 2007), whereas the relative importance of uplift in the east may reflect ongoing Adria-Europe convergence.

An enigmatic feature in this context is that topographic relief and average height do not strictly correlate with Moho depth; the Alpine crust is thickest (48-52 km) in a trough just north of and along the Periadriatic Fault (**Fig. 4c**), whereas the highest mountains and greatest topographic relief occur north and west of this trough, in the vicinity of the External Basement Massifs where the crust is only ~40 km thick. Thus, the Western Alps may not be in dynamic equilibrium after all. Possibly, the parity of rock uplift and erosion rates in anomalously high, isostatically overcompensated topography in the west is a transient response to slab break-off (Fox et al. 2015) and the isostatic compensation depth was instead situated at the lithosphere-asthenosphere boundary (LAB) above the purported slab break (**Fig. 2, section DD'**). Thus, slab tearing rather than climate change may have triggered exhumation of the External Basement Massifs some 4-6 Myr ago (Vernon et al. 2008, Glotzbach et al. 2011). Distinguishing between these scenarios will not only require clearer images of lithospheric structure in the Western Alps, but also better insight into the physics of surface-slab coupling as provided by lithospheric-scale numerical models (Lechmann et al. 2011, Li et al. 2014).

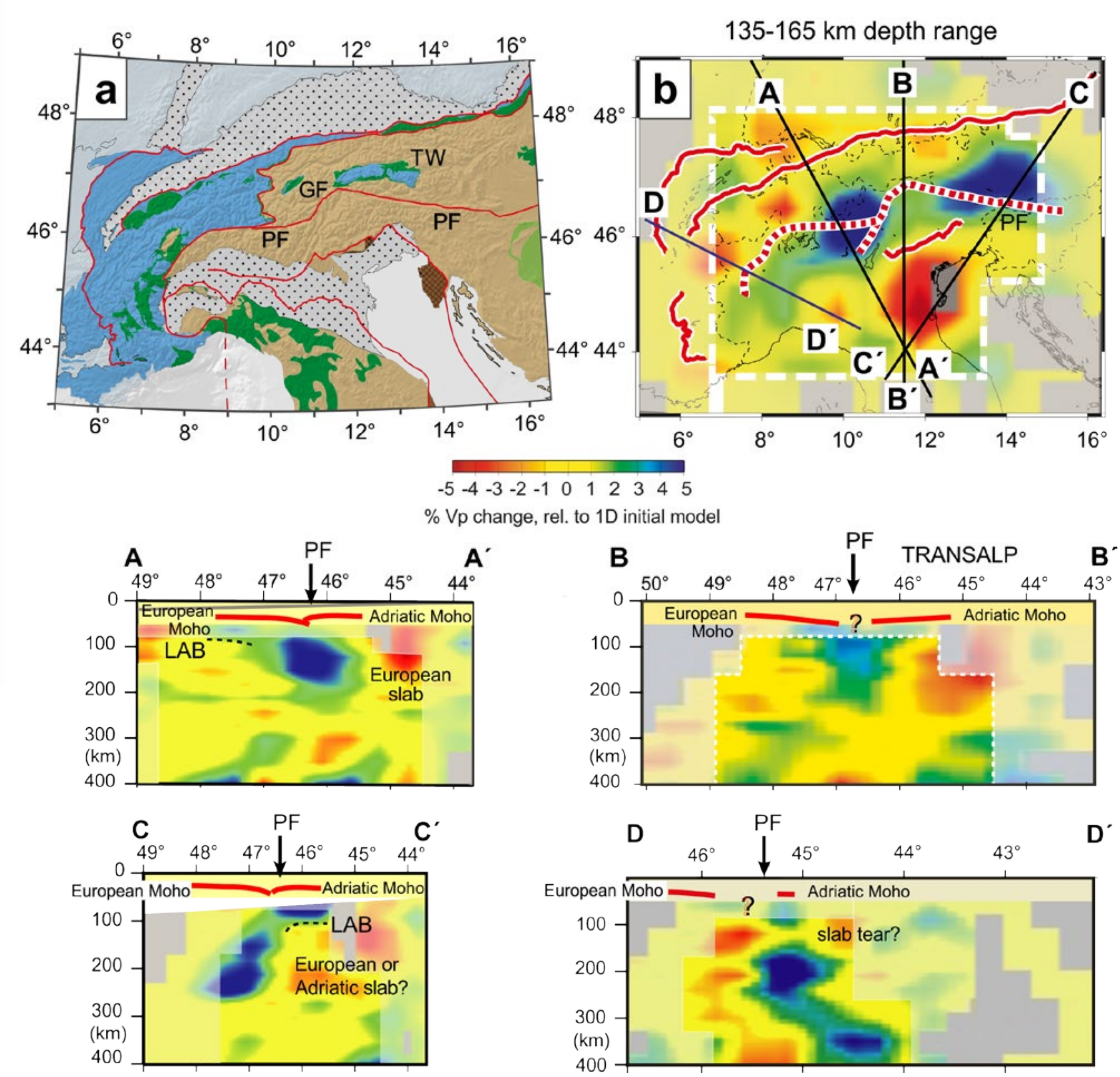

***Figure 2**: Mantle structure beneath the Alps imaged in seismic tomography: **(a)** Tectonic map as in Fig. 1a; **(b)** tomographic depth slice for the 135-165 km depth range showing positive V_P anomalies (blue) interpreted as subducted slabs of lithosphere. Black lines indicate traces of tomographic sections: **A-A'** section across south-dipping European slab beneath the Central Alps; **B-B'** section parallel to TRANSALP 1998-1999 active-source experiment and through the gap between positive slab anomalies of the Central and Eastern Alps; **C-C'** section across north-dipping slab beneath the Eastern Alps; **D-D'** section across Western Alps parallel to the ECORS-CROP active-source section showing possible tear of European slab. Red lines in sections indicate Moho, dotted black lines indicate estimated location of lithosphere-asthenosphere boundary (LAB). Tomography from Lippitsch et al. (2003, their fig. 13a) and Kissling et al. (2006, their figs. 13A, 14A-C). PF - Periadriatic Fault, TW – Tauern Window, GF – Giudicarie Fault*

C. Rock trajectories and deformation during mountain building – views from the outside in

Subducting lithosphere is hidden from direct observation, but surface exposures of rocks that experienced burial to high-pressure (HP) to ultra-high pressures (UHP, 2500-3000 MPa) beneath the Alps in Early Cenozoic time (Chopin et al. 1991, Berger and Bousquet 2008) are flight recorders of the path the rocks took as they descended within the subduction channel and then returned to the surface via the same channel. So far, it is unclear what parts of the subduction channel are sampled by exhumation, how HP rocks are exhumed within the channel (Agard et al. 2009) and whether this channel can be detected in geophysical images of the tops of slabs (Kopp et al. 2009, Friederich et al. 2014). Petrological and thermo-chronological studies in the Alps reveal that subduction affected not only oceanic lithosphere, but also the distal continental margins of Europe and even of the Adriatic upper plate (Babist et al. 2006, Bousquet et al. 2012a, b). A striking and testable result of recent plate kinematic reconstructions is that most lithosphere subducted since Late Cretaceous time resides in the slabs or the mantle transition zone (Hafkenscheid et al. 2006, Lombardi et al. 2009) and that almost half of that material is continental (Handy et al. 2010).

Plate reconstructions indicate that the Alpine subduction rate exceeded the Adria-Europe convergence rate (Piromallo & Faccenna 2004, Handy et al. 2010, 2015), but these rates are poorly constrained. Retrodeforming the Alps along the EGT section (**Fig. 4a**) yields a convergence rate of 1-2 cm/yr (Schmid et al. 1996) which is greater than the exhumation rates of subducted rocks in the Alps (≤ 1 cm/yr, Rubatto & Hermann 2006). Estimating subduction and exhumation rates of HP and UHP rocks depends on obtaining accurate ages of their mineral assemblages; this is a vexing problem due to the sluggish kinetics of mineral reactions in the 500-600°C temperature range of subduction (Berger & Bousquet 2008). Controversy persists regarding the age of Alpine subduction, for example, in the Tauern Window (**Fig. 1a**) where thermo-chronology yields conflicting Eocene (Ratchbacher et al. 2004, Kurz et al. 2008) and Oligocene (Nagel et al. 2013) ages of HP metamorphism near the planned swath D and profiles (**Fig. 3b**). Despite more than 50 years of thermo-chronology in the Alps, the database is not uniform and is notably thin in some key areas (e.g., Tauern Window, star 2 in **Fig. 4b**). *4D-MB* will implement in-situ thermo-chronology including the use of high-retentivity isotopic systems to obtain more robust assessments of the age, duration and rates of subduction and exhumation in the Alps.

The microfabric of exhumed HP rocks contains clues about the strain field and rheology of the subduction channel and, in the case of ultramafic rocks, of structural and seismic anisotropy of the mantle (Long & Silver 2008). Seismic anisotropy, especially the fast direction of polarized or split shear (SKS) waves, is diagnostic of flow in the asthenosphere. Recent studies of anisotropy of the Alpine-Mediterranean area (Jolivet et al. 2009, Barruol et al. 2011) reveal that while SKS-splitting directions emulate the arc of the Western Alps, they deviate by some 30° in a counterclockwise sense from the structural grain of the orogen. In the Eastern Alps, however, SKS-splitting directions are subparallel to post-20 Myr orogen-parallel crustal motion (TRANSALP section, Kummerow & Kind 2006) and oblique to the subduction direction of the Eastern Alpine slab. However, the depth interval sampled by the SKS waves is poorly defined and the physical causes of mantle anisotropy are still unclear (preferred orientation of crystallography and/or microcracks; Healy et al. 2009, Ullemayer et al. 2011). Fry et al. (2010) proposed a depth-dependent anisotropy model in which orogen-parallel fast S-wave directions are related to stacked crustal nappes, whereas fast directions in the crustal root and lithospheric mantle seem to be oriented perpendicular to the orogen, i.e., subparallel to the subduction direction. Linking SKS-splitting with asthenospheric flow is problematic given that these flow patterns change over time (Kaminski & Ribe 2002) and may leave multiple imprints (Endrun et al. 2011). This is likely in the Alps given its complex kinematic history. Interpreting seismic anisotropy reliably thus requires dense seismic networks (Rümpker et al. 2003, Ryberg et al. 2005) and numerical flow models to track variations in asthenospheric flow patterns through time. The 4D images acquired by *AlpArray* will go beyond existing models in which asthenospheric flow is assumed to be static over millions of years (Faccenna & Becker 2010).

D. Motion and seismicity through time

Seismicity in the Alpine region is characterized by diffuse, shallow seismicity that only partly reflects Adria-Europe convergence and does not necessarily follow geologically mapped faults. Whereas the domain of highest Adria-Europe convergence at the Alps-Dinarides junction indeed correlates with high rates of seismicity (**Fig. 1b**), destructive earthquakes have also affected areas where long-term convergence rates are below GPS resolution, for example, in the basement core of the Central Alps in the Simplon area, in the northwestern Alpine foreland near the great Basel earthquake of 1356 (Ustaszewski et al. 2007) or in the northern Dinarides (Ustaszewski et al. 2014). This suggests that factors other than convergence rate affect earthquake activity, for example, stress state, crustal rheology, fluid pressure, and the distribution, orientation and motion history of existing faults. Indeed, rifting and subduction engendered many major faults in the Alps that were reactivated during collision and indentation, and that remain active today, for example, the Giudicarie fold-and-thrust belt (GF in **Fig. 2a**; Castellarin et al. 2006b, Pomella et al. 2011). Understanding how inherited fault geometry and kinematics interact with today's stress field is important for assessing seismic hazard.

The junction of the Alps and northern Dinarides is the seismically most active region in the Alps and includes the epicenter of the 1976 M_w 6.5 Friuli earthquake that killed hundreds and left thousands injured and homeless. Yet, seismicity also affects the Alpine forelands, the Eastern Alps south and east of the Tauern Window (1348 Villach earthquake, Reinecker & Lenhardt 1999) and the northern Dinarides (1511 Idrija event, Kastelic et al. 2008). The present stress state in this area reflects ongoing anticlockwise rotation of the Adriatic plate with respect to Europe accommodated by a combination of south-directed thrusting in the eastern part of the Southern Alps (Schönborn 1999, Merlini et al. 2002) and dextral strike-slip faulting in the northern Dinarides (Kastelic et al. 2008). Yet the crustal structures that link the surface trace of these faults with lithospheric mantle slabs at depth remain unknown and are targets of *4D-MB* (section V).

Seismicity in the Alpine region has never been monitored homogeneously due to the uneven distribution of permanent stations and different procedures of national seismological services. A unified 3D model for the seismically active zones of the entire Alpine region is not available, and the locations and properties of active faults are poorly known. A thorough analysis of the local seismicity and related structures, as well as cross-border homogenization of location routines need to be undertaken to improve seismic hazard assessment for the region. In *4D-MB*, it will be important to distinguish active interseismic faults from aseismic faults in order to constrain the 3D stress field in the Alps. Existing probabilistic seismic hazard maps (GSHAP, SHARE, Faccioli 2013) only marginally account for site effects (amplification and extension of ground motion) especially at long periods in deep sedimentary basins (Bordoni et al. 2012), as well as secondary effects like liquefaction.

Exhumed faults in the Alps offer a rare opportunity to study faulting processes that are otherwise only accessible in rock-deformation experiments (Handy et al. 2007). For example, it has been proposed that the partly exhumed SEMP fault in the Eastern Alps which accommodated Miocene orogen-parallel motion exposes the frozen-in transition from frictional, seismic sliding on discrete fault surfaces to ductile, aseismic creep in shear zones (Frost et al. 2011). In *4D-MB*, the integration of microstructural and petrophysical studies with modeling of strain-dependent feedbacks between stress, strain-rate and microstructure promises to yield a better understanding of the factors that control seismicity.

E. Research in other mountain belts worldwide - How are the Alps different?

Several active mountain belts have been targeted by geophysical-geological campaigns in recent decades, most notably the **Andes** (Oncken et al. 2006, Kopp 2013), **Taiwan** at the Eurasia-Philippines Sea plate boundary in the Western Pacific (Byrne et al. 2011) and the **Himalayas** along the India-Eurasia plate boundary (Yin & Harrison 2000). Mountain building in the Mediterranean area, including the Alps, differs from the circum-Pacific orogens and Himalayas in being driven by the quasi-independent motion of small plates, mainly Adria and Iberia, between the larger European and African plates (Handy et al. 2010).

The **Taiwan** orogen is in a juvenile stage of mountain building (≤ 4-6.5 Myr, Yu & Chou 2001), with convergence and erosion rates an order of magnitude greater (cm/yr) than in the Alps (mm/yr). Such high activity erases older tectonic features (Kaus et al. 2008, 2009) and the youth of the Taiwan collision makes it difficult to track orogen-scale processes back in time. High-resolution geological mapping of Taiwan is not nearly as advanced as in the Alps. Because Taiwan is an island, acquiring geophysical data with a density comparable to that of *AlpArray* is only viable with a very expensive offshore geophysical campaign, which is unlikely to be funded in the foreseeable future.

The **Himalaya-Tibet** collisional zone is huge and, despite several multinational efforts, is still only covered by widely spaced 2D geological and geophysical transects (Zhao et al. 1993, Nabelek et al. 2009). These reveal a generally cylindrical structure (Zhang & Klemperer 2010) quite unlike the small-scale non-cylindrism of the Alps (Schmid et al. 2004). Although the Himalayas are a spectacular example of collision, plateau formation and frontal extrusion of lower crust (Kellett et al. 2010), pre-collisional processes related to subduction are not nearly as well exposed or studied as in the Alps. Due to Tibet's enormous size and high elevation, seismological coverage similar to that of *AlpArray* is not technically feasible in the foreseeable future. The Alps are unique in providing a century and a half of geological research, five decades of geophysical monitoring, and a long tradition of international scientific cooperation.

The Alps are an ideal natural laboratory for the ambitious experiments in *AlpArray* and *4D-MB.* They are unique in exposing small-scale plate interactions. Their size and location in the heart of Europe renders them more relevant and easier to access than mountain belts in Taiwan and the Himalayas.

3. Project-related publications by members of the program committee (all under 3.1)

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5. Merits of the proposal taking into account objectives of the programme

5.1 Originality of the research questions in terms of topic and/or methodology

Motivation: Mountains are focal points of unrest on our dynamic Earth. Current studies of mountain-building processes are largely two-dimensional (2D) in nature and have focussed on projecting surface structures to depth between colliding tectonic plates. *4D-MB* challenges conventional wisdom by recognising that in the Alps, one of the best studied (in 2D) orogens on Earth, links between surface geology and seismicity can only be explained by integrating 3D imaging of the entire crust-mantle system with geologic observations and modeling to enable us to look both backwards and forwards in time, the 4th dimension. This holistic approach to studying Earth's surface and interior through time is an emerging field with profound scientific and socio-economic relevance. Investigating mountain-building processes on all scales, and from the present back into the past, will improve our ability to assess earthquake hazard in the heart of Europe.

Relevance – Why the Alps? The Alps and their forelands are one of the most populated and industrialized parts of the world, and are a hotbed of tectonic and seismic activity (**Fig. 1a**). They stretch for 1200 km in a spectacular arc from Nice to Vienna and have rugged topography with over 100 peaks higher than 4000 m. Earthquakes have repeatedly struck parts of the Alps, most noticeably the Upper Rhine (Germany, France, Switzerland) and Friuli (Italy, Slovenia, Austria) areas, inflicting human casualties and costly damage to urban infrastructure (**Fig. 1b**). Investigating the underlying causes of this activity is of paramount social and economic relevance.

The Alps are also an excellent natural laboratory for studying mountain building. Moreover, they provide a window for studying processes in Earth's crust and mantle. For over a century, they have spawned revolutionary ideas in geodynamics, from subduction (Ampferer 1906) and mobilism (Argand 1911) to plate tectonics (Dewey & Bird 1970, Laubscher 1970), up to the current debate on feedbacks between climate, erosion and orogenesis (Schlunegger & Willett 1999, Rosenberg & Berger 2009). Two decades ago, the first generation of geophysical-geological transects revealed the role of lower crustal indentation in shaping the Alps' irregular structure and arcuate mountains (ECORS-CROP, Roure et al. 1990; NFP20, Pfiffner et al. 1997; TRANSALP Working Group 2006, Schmid et al. 2004). Since then, the geoscience community has been startled by seismic tomography showing slabs of subducted lithosphere inclined in different, possibly opposite directions beneath the Western and Eastern Alps (**Fig. 2**, Lippitsch et al. 2003, Mitterbauer et al. 2011). This slab geometry in general and the switch in subduction polarity in particular remain controversial, partly because the mantle structure there is still poorly resolved, but also because the implications of switches in subduction polarity are so novel and far-reaching for our understanding of orogenesis. This also holds true for assessing their surface effects and natural hazards.

Timeliness: The time is ripe for a new Earth Science initiative to quantify the processes responsible for mountain building. Our mission is to obtain a 4D view of the Alpine orogen in order to understand how mountains form. To do this, the SPP will make use of a unique opportunity, the international *AlpArray* experiment, which involves the deployment of an array of closely spaced broad-band seismometers over the entire Alpine orogen, its peripheral basins and forelands (**Fig. 3**). Never has an orogen been covered by such a dense network of seismic stations. New geophysical methods combined with unprecedented computer power will yield a new generation of high-resolution, 3D pictures of structures beneath the Alps. The evolution of these structures in time will be obtained by integrating these new pictures with age and motion studies of rocks at the surface, as well as by modeling the development of the imaged structures. From top to bottom, the Alps will become the most comprehensively studied mountain belt in the world.

Benefits: *4D-MB* will further our understanding of crust-mantle interaction in mountain belts and so improve our ability to assess earthquake hazard over the entire Alpine area. The acquisition and deployment of land-based seismometers (DSEBRA, Appendix V) and ocean-bottom seismometers (LOBSTER, Appendix VI) as the German components of *AlpArray* will augment existing seismological surveys and international projects (section 6). Both national and European commitments have been made to realize this ambitious initiative (see *AlpArray* Scientific Plan, Appendix III). The international *AlpArray* consortium involves 64 institutions in 17 countries. *4D-MB* thus fulfills a dual purpose in unifying German geosciences and forming a corner stone of the *AlpArray* consortium. In so doing, it will catapult the Earth Sciences in Germany to the vanguard of solid-earth geoscience. Like all great experiments, *AlpArray* and *4D-MB* have the potential to revolutionize concepts of mountain building, and thus to rewrite textbooks and enhance public awareness of how mountains form.

5.2 Delimitation of scope taking into account duration of a Priority Programme

5.2.1 Themes: The main goal of this SPP is to *understand how re-organizations of Earth's mantle during the collision of tectonic plates are related to processes that ultimately affect the Earth's surface in mountain belts.* This will be enabled by generating the first truly 4D image of a mountain belt. Imaging mountains in four dimensions is a radical departure from traditional 2D and current 3D approaches which rely on classical seismic profiling and geological section-balancing to reconstruct crustal evolution, in most cases without regard for the mantle. 4D imaging combines leading-edge seismic imaging technology (e.g., full waveform inversion applied to dense, wide-aperture station arrays) with state-of-the-art geodynamic modeling and geological constraints on motion history (kinematic and geodetic analyses) to trace changes of this complex structure back in time. The resulting 4D image is a model that allows us to explore in exquisite detail the physical processes that have given rise to mountains and that are still actively shaping them today. This includes the study of transient processes acting on the scale of an entire mountain range, which is vital for better assessments of natural hazard and resources in orogens worldwide. 4D imaging will revolutionize solid-earth science in much the same way that CAT scans improved diagnostic medicine.

4D-MB is oriented around **four research themes** in order to foster interaction of the different subdisciplines required to realize the scientific objectives agreed on at the DFG round-table discussion in Hofgeismar (5-6. June, 2013) and described below.

Theme 1: Large-scale reorganizations of the lithosphere will shed deciding light on debates over whether the Eastern Alps are the site of a switch in subduction polarity and whether the subducted lithospheric slab beneath the Western Alps is in the process of breaking off. This will involve applying and developing new techniques to image the Alps from the surface down to the mantle transitional zone, and beyond. Specifically, it will entail defining the shape and orientation of subducted slabs, as well as of the lithosphere beneath the Alpine forelands. A detailed view of these deep structures will improve our knowledge of the rheology of the lithosphere, particularly as it relates to coupling of the surface and mantle.

Theme 2: Surface response to changes in deep structure on different time scales addresses an ongoing controversy over the competing roles of climate and tectonics in mountain building. Specifically, we will test the hypothesis that recent denudation and uplift rates partly reflect long-term, deep-seated processes imaged by *AlpArray*, including slab-tearing and –breakoff. A related aspect of this theme is comparing the impacts of faulting and seismicity where there is active convergence (eastern Southern Alps) and orogen-parallel extension (Eastern Alps) with areas undergoing little or no convergence (Western Alps). A challenge will be to distinguish the geomorphic impact of glaciation and tectonically induced events.

Theme 3: Rock trajectories and deformation during mountain building will resolve the question of whether mantle and crustal structures manifest early stages of mountain-building (subduction, collision) or primarily preserve the imprint of later events (indentation, lateral escape) up to the present. This theme is concerned with the internal structure of faults, the processes underlying this structure and its relationship to seismic anisotropy. This also pertains to the rates of structural and chemical change, especially the way in which fragments of continental and oceanic lithosphere are subducted and preserved during their return to the surface.

Theme 4: Motion and seismicity from the present backwards in time is aimed at explaining the enigma of why the upper crust and foreland of the Alps are seismic, whereas the lower crust and mantle lithosphere, including slabs beneath the Alps, are largely aseismic. This will involve relating patterns of deformation and seismicity to the overall motion picture of the Alps since the onset of subduction and collision. Establishing connections between structures exposed at the surface and imaged in the lithosphere may help us to see whether current seismicity and fault motion are linked to the deep structure of the Alps or to a newer tectonic regime. These studies will also improve assessments of seismic hazard in the Alps.

4D-MB tests the idea that reorganizations of Earth's mantle have both immediate and long-lasting effects on earthquake distribution, crustal motion, and landscape evolution. Research will focus on the Alps, a proven testing ground for new ideas with revolutionary implications for mountain building on a global scale.

5.2.2 The *AlpArray* seismic network – a milestone in probing the deep structure of mountain belts

The scientific objectives outlined above can only be realized if the *AlpArray* seismic network is built; Germany is a key player in this international endeavor. This network is a state-of-the-art, multi-component instrument that will deliver the high-resolution 3D images which form the starting point for 4D modelling of the Alps and is a requisite for all four of the research themes outlined above.

The array comprises a network or ***backbone*** of 579 broad-band seismometers that will cover the Alps for 3 years, from the end of 2015 to the end of 2018 (white lines in **Fig. 3**, see Appendix III). The tomographic target volume of the backbone at the scale of the orogen extends from the surface down to the base of the Mantle Transition Zone (MTZ) at ~660 km depth. The backbone is broken down into 278 existing, permanent broad-band seismometers of the national networks, 268 mobile land-based seismometers from a multinational pool and 33 off-shore seismometers to be deployed temporarily in the Ligurian Sea (**Fig. 3b**). The German contribution to the backbone (**Fig. 3b**) includes 24 of the 33 ocean-bottom seismometers (OBS) in the Ligurian Sea (*LOBSTER*) and 68 land-based stations scraped together in a joint effort by 8 German universities (*UNIBRA*). The latter will be deployed in the central part of the Alps. From Autumn of 2017 onward, after acquisition of the 100 land-based stations of *DSEBRA*, the 68 university stations will be replaced and an additional 32 sites will be taken over from project partners (Fig. 3 of Appendix V).

The *AlpArray* backbone network will be augmented by several ***swaths*** of dense station deployments that will be deployed for 2 years across key areas of the orogen (**Fig. 3a**, see Appendix III). These are embedded in the *AlpArray* backbone and *DSEBRA*. Resolution generally decreases with depth due to defocussing effects, but increases with deployment time and decreased spacing between the stations; thus, the ~12 km spacing along the swaths will provide unprecedented 10-15 km resolution of structures down to ~200 km depth. Determining the conductivity structure of the crust and lithospheric mantle is desirable and will be prefaced by a feasibility study of magnotellurics (MT).

The German effort will concentrate on swaths C and D in order to complement previous campaigns (e.g., TRANSALP) across the gap in positive anomalies beneath the Central and Eastern Alps (**Figs. 3, 4**). This will help us to understand how active faults in the eastern part of the Southern Alps are linked to crustal and mantle structures that are accommodating ongoing Adria-Europe convergence. Combining dense, focused swaths with the *AlpArray* backbone network and *DSEBRA* will allow us to improve on the resolution of deep lithospheric images generated by *US Array*, the mobile seismological station network of the *Earthscope* project with 70 km backbone station spacing (Kerr 2013). This will be made possible by combining the new *AlpArray* data with leading-edge methods like full seismic wave-form inversion and seismic interferometry.

German stations of the backbone (*DSEBRA and LOBSTER*) – essential components of *AlpArray*

DSEBRA "Deutsches (German) Seismological Broadband Array" is a single array instrument of 100 broad-band, land-based stations and is dedicated to long-term, dense, large-aperture seismological field experiments, as described in detail in Appendix V. In this proposal (section VIII) we request funds to deploy and operate these mobile seismometers in order to fill large gaps in the permanent station network (**Fig. 3a**) in the middle of the *AlpArray* backbone (**Fig. 3b**). This part of the backbone will cover the central and eastern parts of the Alps, plus the Upper Rhine Graben and the Molasse Basin in southern Germany and Austria. The first mission of *DSEBRA* will therefore enable *AlpArray* to image slab geometries and properties, as well as deep structure in the vicinity of the Alps-Dinarides join (Themes 1, 3). This is where the Adriatic and European plates are actively converging, where surface effects are most pronounced (Theme 2) and where seismic hazard and risk are highest (Theme 4).

LOBSTER "Ligurian Ocean-Bottom Seismology & Tectonics Research" provides ship time to deploy OBS stations and to insure 24 broad-band OBSs from the German DEPAS pool. The proposal was granted by the DFG Senate Commission for Oceanography in January of 2014 and the commission has since confirmed the use of ship time and OBS rental in 2017 (Letter, Appendix VI). Data analysis and OBS insurance are not included in these proposals; therefore both points are part of the funding package requested in this SPP (therefore section VIII). The off-shore stations in the Ligurian Sea will provide crucial information on the 3D structure of the Alps-Apennines join by capturing surface and body waves emanating from earthquakes in the Pacific area and penetrating the Alpine slabs. Both DSEBRA and LOBSTER are keys for understanding how the surface and lithosphere are responding to changes in the polarity of subduction (Themes 1, 3).

Combining seismic array technology with innovative geophysical imaging methods in *4D-MB* is an emerging field that will revolutionize our view of mountain building. The new German stations of DSEBRA will bring Germany to the forefront of international geodynamic research.

5.3 Coherence of planned research activities

5.3.1 Project strategy, targeting & siting, overall scheduling

Strategy: To generate 4D models of mountain building in the Alps, *4D-MB* scientists will pursue the following activities in a coordinated fashion: (1) Acquire geophysical data with the *AlpArray* seismological network to produce a high-resolution, real-time 3D image of Earth's interior; (2) Obtain geological data to better constrain the direction and history of crustal motion, as well as the rates and amounts of denudation and uplift in key areas (numbered stars in **Fig. 4b**); (3) Integrate the real-time 3D image of the Alps' interior with the motion history of the crust and surface to reconstruct motion of the lithosphere in the Alps back in time; (4) Incorporate orogenic motion through time into thermo-mechanical models of the lithosphere to obtain 4D models of mountain building. 4D-modeling can then be used to test different modes of coupling between surface and Earth's interior. **Table 1** shows the schedule of these activities, including the deployment of the *AlpArray* seismic backbone and the swaths. A more detailed schedule for the deployment is included in Appendix V. This schedule must be maintained in order to ensure sufficient overlap in time with other national station deployments as required for a homogeneous seismic illumination of the Alps.

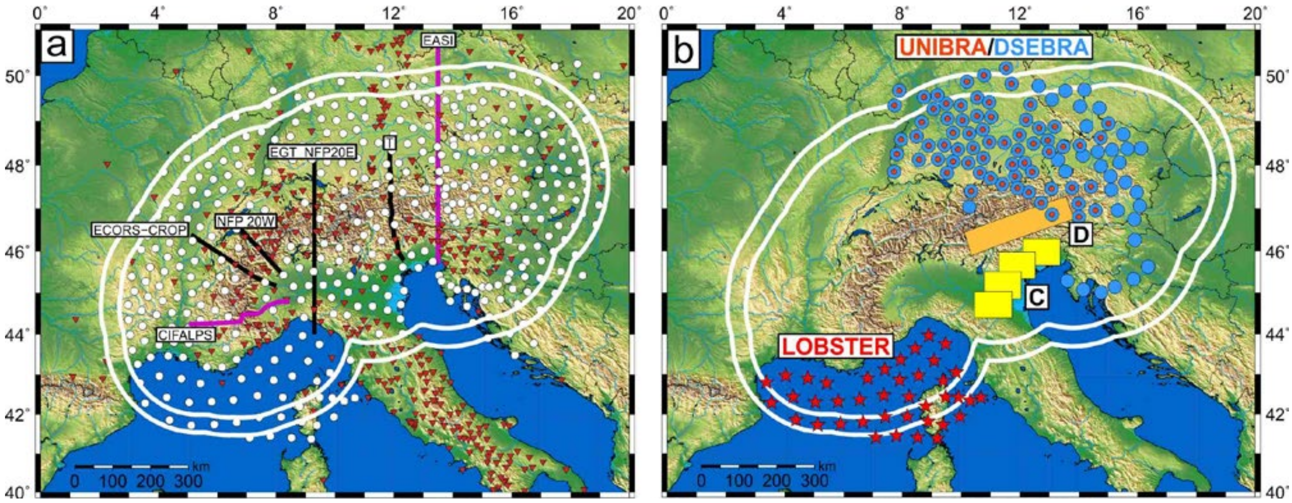

Figure 3: *The Alpine domain with seismological experiments:* ***(a)*** *White lines delimit the international backbone network with all 579 broad-band seismometers (red triangles – permanent national stations, white circles – AlpArray mobile stations). Purple lines - AlpArray passive seismic swaths with densified station configurations:* EASI *– Czech-Austria-Swiss swath,* CIFALPS *– China-Italy-France swath. Black lines – active seismic experiments of the 1980s and 90s, including T, the* TRANSALP *profile;* ***(b)*** *German seismometers in AlpArray backbone network: Red-blue circles –* UNIBRA *later replaced by* DSEBRA*; Blue circles -* DSEBRA*; Red stars –* LOBSTER*; Yellow boxes - mobile swath C; Orange rectangle - swath D with densified station networks.*

Timing & targeting of seismological investigations: All international parties in *AlpArray* have agreed to a strict deadline of autumn 2015 for deploying the broad-band seismometers, including the German parts of the backbone station network (UNIBRA, DSEBRA, LOBSTER). **Figure 3b** shows the location of German geophysical investigations and of all European partners (**Fig. 3a**). Whereas the backbone is designed to image seismicity, slab geometry and asthenospheric flow beneath the Alps and its forelands all the way down to the MTZ, the swaths will target the uppermost 200 km at the transition of the Eastern Alps to the Central and Southern Alps; this is where the purported switch in subduction polarity occurs (Themes 1, 3), where crustal and surface responses to this switch are expected to be most pronounced (Theme 2), and where ongoing Adria-Europe convergence is associated with active faulting and the greatest seismic hazard in the Alps (Theme 4). In short, this part of the Alps is an excellent place to study transient orogenic processes on all scales.

Siting of station swaths: **Swath C** is a mobile station array that will be deployed four times between the Northern Apennines (site of the 2012 Emilia earthquake) across the Po Plain to the Friuli area of the Southern Alps (site of the 1976 Friuli earthquake) in order to target active fault systems along these opposing orogenic fronts and their forelands. It will yield highly resolved seismic parameters (shear-wave velocity, attenuation) and allow us to quantify various site effects, most important, the amplification and extension of ground motion due to 2D and 3D effects, and secondary effects like liquefaction. **Swath D** is situated along the tip of the eastern Adriatic indenter and covers part of the Moho gap in the Eastern Alps (**Fig. 4c**) and the slab gap between Central and Eastern Alps (**Fig. 4d**). It complements the orogen-perpendicular EASI swath of Czech, Austrian and Swiss partners, as well as the TRANSALP section (**Fig. 4a**), thus providing optimal coverage of structures in the crust and upper mantle that may be related to a switch in subduction polarity and to orogen-parallel motion of the orogenic crust (Themes 1, 3). Swath D will image prominent crustal and lithospheric structures (e.g., Periadriatic Fault System) with unprecedented clarity down to the base of the crust and/or lithosphere, allowing surface structures to be linked with the deeper structures targeted by the backbone (Theme 4).

Location of geological investigations, integrating geology & geophysics: Structural geological, thermo-chronological, petrological and surface studies are planned in areas with thematic focus (stars in **Fig. 4b**): Active and exhumed fault systems (Stars 1, 2; Themes 3 and 4), exposures of the subduction channel (stars 3, 4; links Themes 1 and 3) and denudational studies above areas of possible slab polarity switching and tearing (stars 5, 6; links Themes 1 and 2). All of these studies will complement geophysical imaging, especially along the profiles and swaths (**Figs. 3, 4)** as outlined below. It is emphasized, however, that geological investigations must extend beyond the narrow confines of the swaths simply because surface structures suited for studying mountain-building processes do not everywhere coincide with the younger structures at depth or with the logistical constraints of station deployment.

Overall schedule: *4D-MB* will require 2 three-year funding periods starting in 2017 (**Table 1**). If the program is funded, a first round-table meeting will be organized immediately to update the goals and workshops will be organized on the research themes and activity fields. The 1st year of *4D-MB* will be devoted to deploying seismic stations, employing young scientists and acquainting them with the newest methods, data and research. Harmonization and coordination of available data as well establishment of infrastructure for management and data-handling will be another essential part of this 1st phase (below and section VI). During the 2nd and 3rd years, scientific work will be accompanied by annual round-table meetings to inform all *4D-MB* participants and international *AlpArray* partners of new results and to identify potential problems. Towards the end of the 2nd year, proposals for specific sessions at international congresses will be submitted. During the 3rd year, initial results will be published in a special volume of an international peer-reviewed journal. Already at this point, plans for the 2nd phase of *4D-MB* (2019-2022) will be discussed and goals will be adjusted to fit the newest needs and challenges, and to ensure coordinated submission of proposals.

5.4 Strategies for collaborating / networking across disciplines and locations

5.4.1 Networked activities & deliverables

Table 1 shows the work program divided into four activity fields geared to address the interdisciplinary research themes in section 5.2.1. These activities range from equipment deployment, data acquisition and processing, to analysis of structural, metamorphic and denudation patterns at the surface, and numerical modeling of geophysical and geological information. As the geophysical data from the backbone network and the swaths becomes available, their meaning for mountain-building processes and seismic hazard assessment will only be clear if placed in a robust geological framework that can be extended back in time. These activities must be coordinated to ensure that the geophysical images from the *AlpArray* experiment are interpreted consistently with geological information from the surface. The activities overlap in time during the 1st phase (2017-2020) of *4D-MB* and some must be intensified during the 2nd phase (2020-2023).

1st Phase: 2017-2020

Activity field 1: Deploy equipment and acquire geophysical data

Deployment of land-based (UNBRA/DSEBRA) and sea-floor (LOBSTER) seismometers contributing to the backbone array. The 68 mobile land stations provided by German universities (UNIBRA) will already be in place by late Autumn of 2015 and deliver data to EIDA nodes at GFZ-Potsdam, BGR-Hannover and LMU-Munich by January of 2016. The DSEBRA stations will be deployed in Autumn of 2017, replacing *UNIBRA* and taking over an additional 32 sites of *AlpArray* partners. DSEBRA will run simultaneously with the swaths to provide essential coverage of their surroundings (Appendix V). Data transmission to the EIDA nodes will continue smoothly. Data from the seafloor stations can only be retrieved after instrument recovery (~12 months after deployment). German ship time for deployment has been granted for Autumn of 2016 (Appendix VI). Hence, offshore data will be sent to EIDA by Autumn of 2017. Ship time for offshore deployment of broad-band OBS stations will be shared by Germany and France (LOBSTER; French cruises for deployment and maintenance after 6 months). IPGP (Paris) will commit its 9 OBS stations to *AlpArray*. To achieve a station spacing of < 60 km in the Ligurian Sea, LOBSTER will deploy 24 OBS from the DEPAS pool, bringing the OBS total to 33. Instrument costs for the IPGP and DEPAS pools will be shared by France and Germany, the latter through the funding package requested for *4D-MB* (section 9, Appendix VII). This shoreline-crossing approach will provide seamless subsurface images (Kopp et al. 2011).

Deployment of mobile broad-band seismometers in densified networks along swaths C and D: The moving array of swath C will comprise a network of 7 x 9 stations spaced some 12 km apart and covering an area of 100 x 70 km. Swath D will consist of a network of 6 x 26 similarly spaced stations over an area of 300 x 60 km deployed for two years. Deployment and operational costs for the swaths are part of the funding package in section 9 (Appendix VII).

Activity field 2: Determine seismic properties and model asthenospheric flow patterns

Real-time models of the orogen-wide distribution of seismic properties (velocities, attenuation and anisotropy) as well as seamless images of the LAB, the Moho and intracrustal detachment and melt horizons beneath the Alps and its forelands, especially near purported slab tears and switches in subduction polarity (Theme 1). Seismic data from swath D will be combined with results from the EASI swath (**Fig. 4a**) to provide unprecedented ~10 km resolution of lithospheric structures at the transition of the Central and Eastern Alps. The 3D models will be obtained from the inversion of travel times, amplitudes and full waveforms of teleseismic and local phases, 3D inversions of scattered and converted waves, together with high-resolution ambient noise and surface wave studies. The seismological images will be integrated with results from gravity studies to constrain the subsurface geometry of crustal-scale faults from the surface down, and with results of the MT studies pending a successful feasibility study..

Seismic anisotropy of the crust and mantle, and its origins (Theme 3): Seismic and laboratory investigations of seismic anisotropy will allow us to resolve how deformation is partitioned between the orogenic crust, the slabs and the surrounding mantle. When combined with geodynamic numerical modeling, this will give clues about the rheology of the mantle, especially at major mechanical and compositional interfaces (Moho, LAB). Seismic techniques applied to *AlpArray* data to constrain the 3D geometry of asthenospheric flow will include body- and surface-wave analysis, shear-wave splitting, polarization analyses, and the azimuthal dependence of receiver functions.

Thermo-mechanical models of the crust and mantle in the Alpine orogen and its forelands will be developed to understand the effects of slab configuration, slab breakoff and rheology on mantle flow patterns and crustal stresses as well as on vertical and horizontal surface motion patterns (Themes 2, 4). In addition, new geodynamic inverse modeling approaches will be developed which combine various geophysical datasets (seismicity, gravity, GPS velocity and possibly MT) with geodynamic models in order to constrain the rheology of the present-day Alpine lithosphere (Theme 3).

Activity field 3: *Geological studies of the kinematics, conditions and timing of orogenic processes*

Structural and thermo-chronological analyses of active and potentially active faults, particularly near swaths C and D (**Fig. 4b**): Targetable fault systems include thrusts (e.g., Sava-Fella system, star 1) and strike- and oblique-slip faults (e.g., the SEMP fault, star 2) that potentially show different degrees of coupling with the orogenic crust and mantle (Themes 1, 2, 3). Along swath C, comparing long-term “geologically” derived slip rates with short-term geodetically derived slip rates on active faults (star 1) will allow us to pinpoint locked faults and fault segments that have stored stress and are therefore likely to generate destructive earthquakes. Local seismicity datasets from the swaths will improve constraints on the geometry of active faults at depth. Synthesizing this data will help improve seismic hazard maps in the area (Theme 4).

Structural and geochronological investigations of fossil faults, including their geometry and microstructure, will yield insight into the rheology of strain localization, as well as constrain the duration of deformation (e.g., the Periadriatic Fault, **Fig. 4b**). This is essential for improving kinematic reconstructions of the Alps and yielding estimates of deformation rates (Theme 4).

Integrated petrophysical and thermo-chronological studies on HP and UHP metamorphic assemblages will enable the reconstruction of rock trajectories during subduction and exhumation as a guide to ongoing processes in subduction channels along the tops of slabs imaged by *AlpArray* (Theme 3). *Petrophysical measurements* will be conducted on exhumed rocks from former subduction zones to test for processes that contribute to seismic anisotropy of the crust. The Alps have a rich inventory of locations to study subduction and exhumation processes (e.g., stars 3 and 4 in **Fig. 4b,** Eclogite Zone and Glockner nappe in the Tauern Window, Dora Maira and Monviso areas in the Western Alps).

Measurement of denudation and uplift and their rates on different scales: Tracking erosion from individual seismic events paired with meteorological observations will yield insight into the efficiency of mass transfer from source areas to piedmont settings (Theme 2). Seismicity in the Alps will be compared with erosional estimates derived from hydrometric gauging as compiled by national agencies in the Alps. The long-term effects of slab breakoff at the surface (Themes 1 and 2) will be tested by measuring topographic metrics and rock-uplift and erosion rates in areas directly overlying the purported slab gaps and breaks (respectively, stars 5 and 6 in **Fig. 4b**) and comparing them with background rates (e.g., Norton et al. 2011). Uplift rates and time-integrated erosion rates will be obtained, respectively, from river loads, cosmogenic nuclides and thermo-chronology (Hovius & von Blanckenburg 2007).

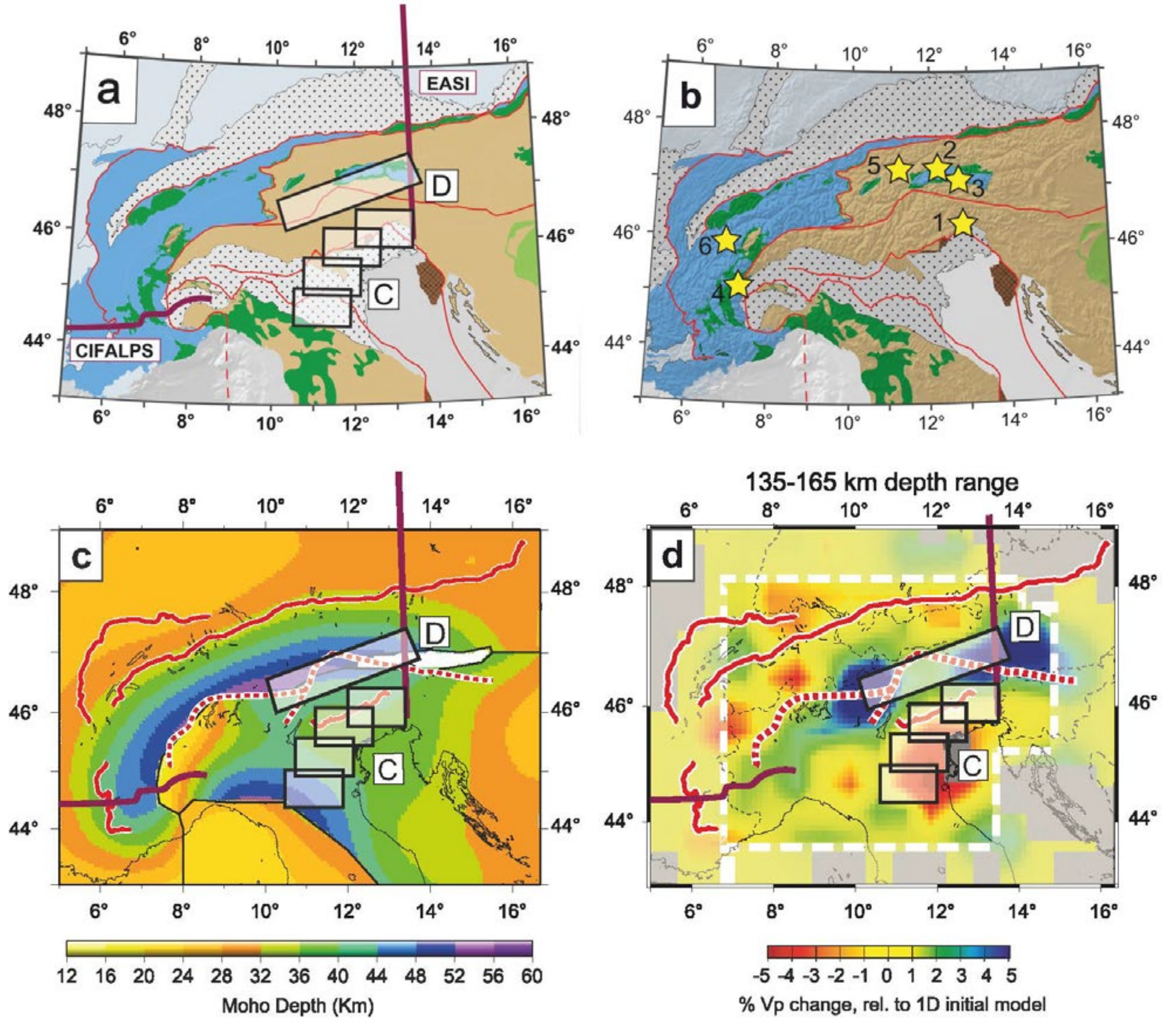

***Figure 4: (a)** Tectonic map of Alps as in Fig. 1 with new seismic experiments: C and D - German swaths in this study, EASI - Czech-Austria-Swiss swath, CIFALPS - China-Italy-France swath; **(b)** Tectonic map with numbered stars showing potential targets of geological investigation at the surface (see text); **(c)** Moho depth map (Spada et al. 2013) and **(d)** tomographic depth slice as in Fig. 2b (after Lippitsch et al. 2003) with new seismic profiles and swaths in the AlpArray experiment.*

Activity field 4: *Synthesis of geological and geophysical data; 4D-modeling*

Develop new lithospheric model of the Eastern Alps using a combination of new data from swath D and the EASI swath, reprocessed active-seismic data from the TRANSALP experiment (TRANSALP Working Group, 2006) and recent structural data at the surface (Schmid et al. 2013, Scharf et al. 2013). Reprocessing existing seismological data with new methods developed since the late 1990s will provide low-cost information that is a requisite for clarifying the subduction polarity and complex structure at the interface between Alpine orogenic crust and the Adriatic indenter. New structural geological data will be projected onto the TRANSALP section to obtain an integrated geological-geophysical section through the narrowest part of the Alps at 11°E, where shortening and orogenic indentation are greatest and where subduction polarity appears to switch (Theme 1).

Compile a kinematic age map of the entire Alps, including its foreland basins and parts of adjacent orogens (Apennines, Carpathians, Dinarides). The new map will complement existing geological maps of the Alps (Schmid et al. 2004, 2008, Bousquet et al. 2012b) which, however, do yet not contain any information on the kinematics or age of the main structures (e.g., large faults, slabs) that have accommodated Adria-Europe convergence since the onset of collision (Theme 4). This map will be published by the end of the 1st phase and will form the basis for paleotectonic maps of the Alpine collisional zone during the 2nd phase (below).

Derive 3D models of the current Alpine mountain belt consistent with all available geological and geophysical observations. This will include integrating terrestrial and satellite gravity data with the new seismological observations. To this end, we will create a unified gravity database for the Alps using terrestrial and GOCE satellite data and compile homogeneous motion datasets for velocities from the available GPS networks (GAIN, EUREF, FreDNet, section VII) to constrain surface motion (Theme 4). By combining models of seismic velocity with phase petrology, velocities can be converted to density, enabling us to test the sensitivity of the gravity field to different structural models of the orogenic root and slab geometry (Theme 1). Lithospheric stress fields will be estimated by combining this new 3D data with dynamic models.

Construct 4D thermo-mechanical models of Alpine mountain-building, beginning with the present configuration of tectonic plates in the Alpine-Mediterranean domain and reaching back to the onset of Tethyan rifting in Early Mesozoic time, possibly even to Late Paleozoic time when post-Variscan tectonics and magmatism cast the structural template on which the Alps were built. Parameterized 2D studies will be aimed at producing robust 4D forward models of Alpine-like mountain belts at 1-2 km of resolution and a million-year time scale. Thermo-mechanically consistent models for the Alpine evolution will be tested against available field and seismic data (Themes 1, 2, 3, 4).

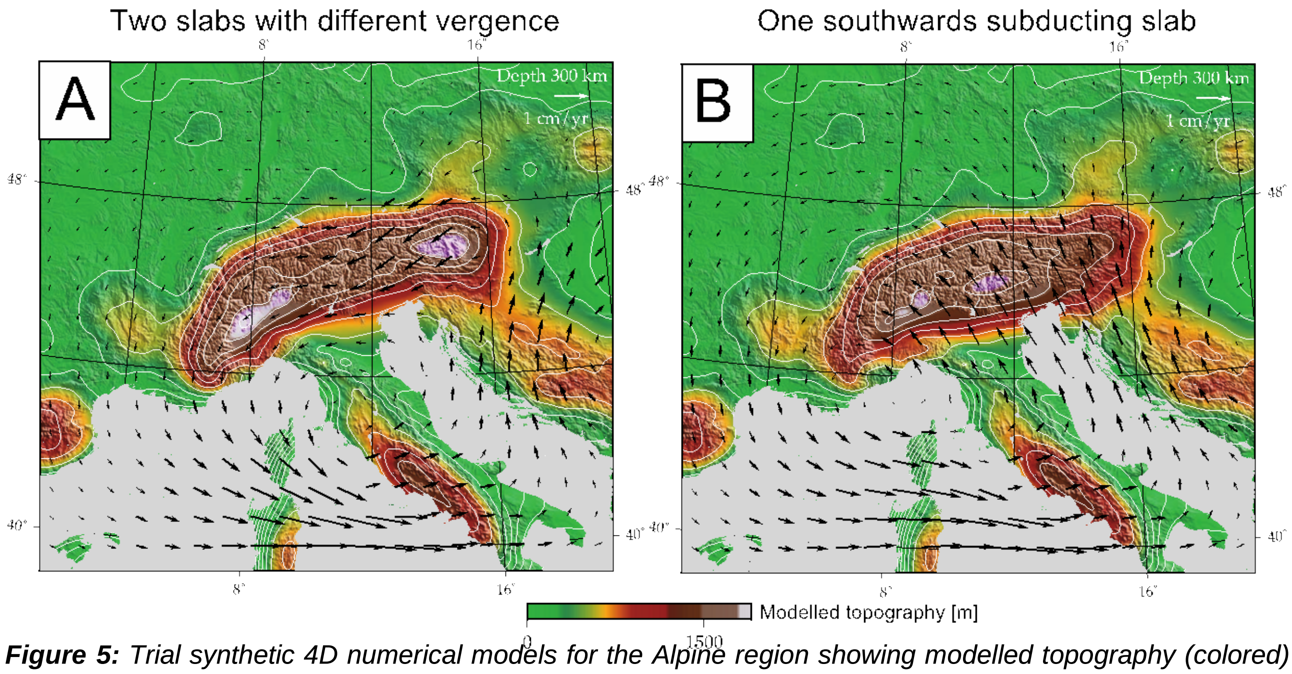

__Figure 5:__ Trial synthetic 4D numerical models for the Alpine region showing modelled topography (colored) and asthenospheric flow (arrows) for the present day at 300 km depth. The models differ only in assumed slab geometry (not shown): (a) Two-slab model with southward subduction in Western and Central Alps, and northward subduction in Eastern Alps; (b) Single-slab model with southward subduction beneath entire Alps. Note contrasting asthenospheric flow patterns and model topographies in the Alps due to differences in slab geometry. The flow patterns and slab geometries will be much better constrained with high-resolution data from the AlpArray experiment. Depth slices can be generated back in time by using numerical models like this to combine AlpArray data with kinematic, thermo-chronological, denudational and uplift data from surface studies, Images courtesy of Boris Kaus, a co-initiator of this proposal.

2nd Phase: 2020-2023

The following activities represent a logical continuation of the 1st phase, but with more emphasis on synthesizing geological and geophysical data to extend our understanding of Alpine mountain building back in time. The activities are sketched very generally and will obviously be specified during the final months of the 1st project phase.

Fine-tuning 3D geophysical models of Alpine substructure: The models from the 1st phase will be refined in the light of emerging methods and the full *AlpArray* data set. The focus can then be directed to inversions of the full data set including OBS and swath data, and integrating results from different groups to generate a 3D structural model of the present-day Alpine orogen. This is a necessary step for 4D-modeling.

Tectonic, petrological, and thermo-chronological investigations of Alpine structure*:* Structures mapped and analyzed during the 1st stage will be pursued across and along strike as necessary in order to determine the kinematics and age of deep structural images projected to the surface. This will involve inversion of thermo-chronological data to constrain the age and rates of deformation.

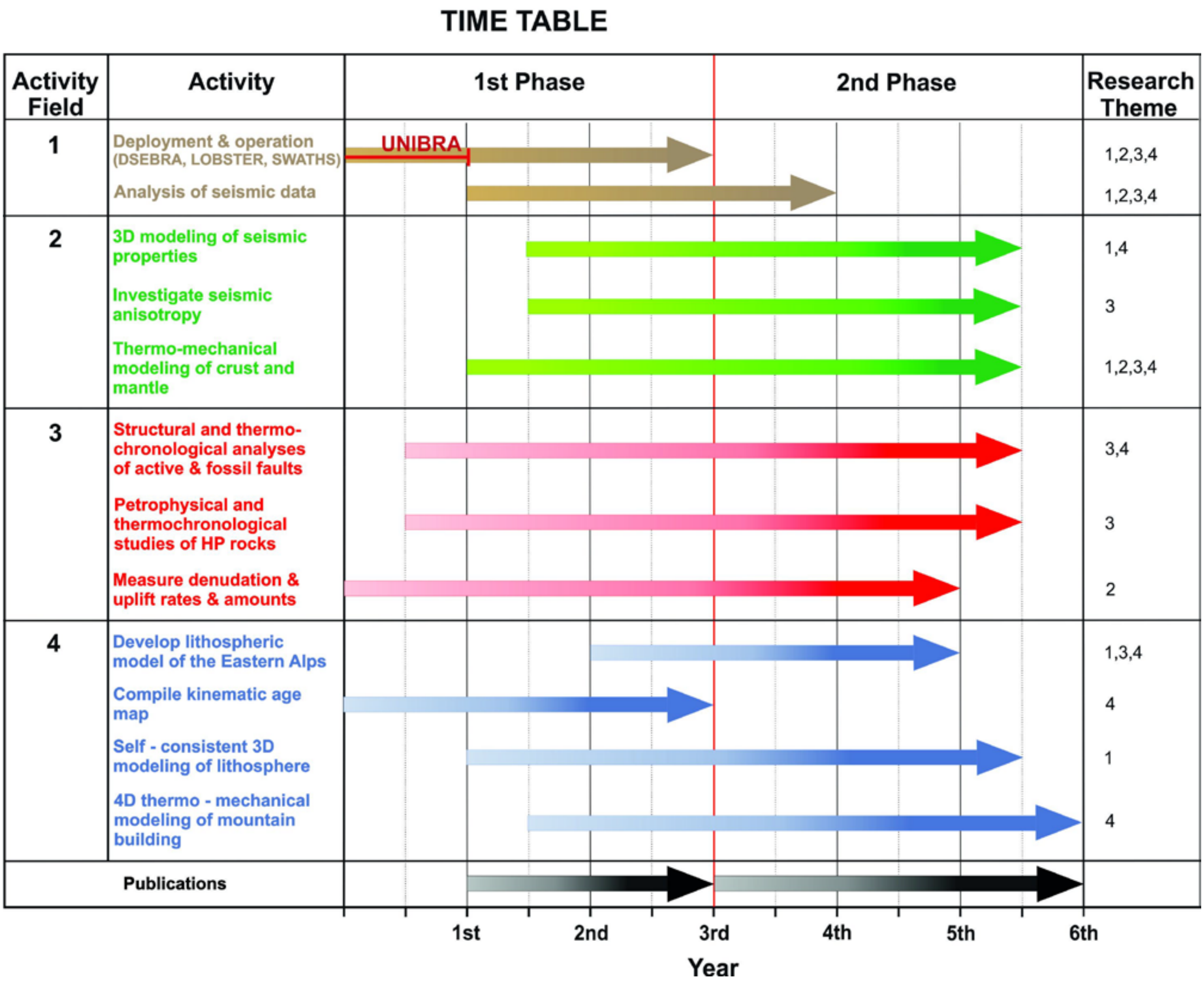

Table 1: Research activities and their themes for the 1st phase (2017-2020) and 2nd phase (2020-2023) of 4D-MB (see Appendix V and VI for activities related to seismometer deployment).

5.5 Early career support, promotion of female researchers, family friendly policies

5.5.1 Integrating young scientists

4D-MB will offer advanced educational opportunities for young scientists, especially at the PhD and post-doc levels. Of the many skills imparted, the following stand out: (1) Combining state-of-the-art expertise in specialized fields with multi- and interdisciplinary approaches to solve complex problems; (2) Learning to interact with other specialists in a solution-driven team environment; (3) Assuming responsibility and leadership in preparing joint results for presentation at international meetings and/or for publication in peer-reviewed journals. All *4D-MB* participants are experienced in teaching and coordinating research projects.

Interdisciplinary summer schools financed by *4D-MB (Appendix VII)* will assure immersion of young scientists in their fields of specialization, while offering insight into neighboring fields. This will satisfy increasing demand for scientists who think and act across disciplinary lines. Another distinguishing feature of *4D-MB* is the possibility it gives young geoscientists to combine land- and marine-based research, two aspects of the geological sciences that are often separated. Taken together, *4D-MB* will equip highly qualified Earth Scientists with the skills needed to play decisive roles in future geopolitical challenges.

5.5.2 Improving scientific career opportunities for women

The broad spectrum of disciplinary and interdisciplinary fields of the geosciences in *4D-MB* offers excellent opportunities for female scientists to network and enhance their scientific profiles. Forty percent of *4D-MB's* program committee are women, a greater proportion than currently found among the program's participants, but we want to increase that number. *4D-MB* will adopt a "cascade" policy for hiring qualified women scientists. Hiring will involve targeted advertisement in female scientist networks and gender-balanced interview commissions to assure a fair selection process. We will entice women to enter and stay in research with the following measures: (1) Flexible working hours and places; (2) Financing of child-care at facilities of host-institutions; (3) Extension of project duration for young children-rearing researchers; (4) Regular gatherings of female PhDs and postdocs with invited lectures by and meetings with female role models in higher echelons of academia; (5) Establishment of a mentoring program lead by established male and female scientists who will offer career counselling tailored for female scientists. To support measures (2) and (3), we request a sum of 20.000 € as part of the financial package (Appendix VII).

5.5.3 Outreach

At the outset of *4D-MB*, we will contact natural history museums in Germany to generate interest and financial support for a mobile exhibit and lecture series in the Alps. This will involve designing an interactive exhibit on the 4-D evolution of the Alps to showcase *4D-MB* and *AlpArray*. The exhibition will begin by introducing the general public to the Alps as a fascinating topographic and geologic anomaly that harbours diverse cultures. It will then display interactive models of the deep structure of the Alps, demonstrate the high-end technology used in imaging the Alpine subsurface, highlight the interdisciplinary approach used in reconstructing the history of mountain belts, and showcase the use of computers in numerical simulations, including animations of Alpine mountain-building. As in previous projects (e.g., DESERVE, Weber et al. 2009), a modest sum of money of *4D-MB* will be used to fund students from a film school for this endeavor and/or to provide seed money for television channels (Discovery Channel, ZDF Terra-X) to make a scientific documentary on the Geology of the Alps (20.000 € for outreach in Appendix VII).

5.6 Networking of planned research activities within international research system

4D-MB is intimately linked to the *AlpArray* mission, which is an international network by definition. Therefore, dialogue with members of participating institutions in this consortium –most of them outside of Germany- will be essential (members listed in Appendix III). As outlined above, several forums will be established, including colleagues from these institutions regularly to give talks and workshops, which will foster communication, especially for the benefit of young scientists in *4D-MB (section 5.5.1).*

5.6.1 Data ownership and handling

Geophysical data exchange is a requisite for many of the planned projects and will follow the guidelines in the *AlpArray* Science Plan and Technical Strategy signed by all participants of the *AlpArray* consortium (Appendix III, IV). *AlpArray* follows standards for integrating solid-earth science research infrastructure in Europe and is therefore a flagship project for EPOS, the European Plate Observing System. Data will be shared as it becomes available, with mutual agreements covering cases of overlapping interest (e.g., projects involving PhDs and post-docs). Data will then be made freely available to the community outside of the SPP three years from the time it is first prepared and available within the SPP. Data will be accessible through the following venues: (1) UNIBRA/DSEBRA backbone data – One EIDA node (European Integrated Data Archive) at the LMU-München, with long-term storage and accessibility in the archives of the GFZ (GEOFON) and BGR (GRSN); (2) LOBSTER backbone data – PANGEA (AWI) / GEOMAR archive; (3) Swath C – GEOFON archive (GFZ); (4) Swath D – GIPP archive / GEOFON archive (GFZ). The corresponding protocols and hard- and software are mostly in place. Personnel is needed for the handling and preparation of the data sets, as outlined in Appendix VII.

6. Differentiation from other on-going programmes on related topics

Several large projects and/or planned initiatives have potential for interaction with *4D-MB*:

CIFALPS "China-Italy-France Alps Seismic Survey" is a passive seismic experiment across the Western Alps (summer 2012 to April 2013) that has acquired and interpreted data along a single transect (**Fig. 4a**, Zhao et al. 2015). Like the swaths in *4D-MB*, the transect comprises closely spaced (5-10 km) stations, with several stations deployed off-section to complement the French permanent network. The results of this campaign are of first-order interest to participants of *4D-MB*, including geological colleagues working at the surface above the purported slab rupture in the Western Alps (Theme 2). The profiles and swaths in *AlpArray* do not overlap with the CIFALPS experiment. Several colleagues involved in CIFALPS are members of the *AlpArray* consortium.

Earthshape "Earth Surface Shaping by Biota" is a DFG Priority Program (SPP-1803) since 2014 to explore the role of biological processes in soil-production and topography-formation, specifically in the Andean (Chilean) coastal ranges. Although the focus is decidedly biotic and the Andes differ from the Alps both climatically and tectonically (and presumably also biotically), Earthshape adds a potentially useful dimension to future attempts to model the dynamics of surface processes in Theme 2. Two initiators of Earthshape are also members of *4D-MB* (T. Ehlers, F. von Blanckenburg), ensuring cross-fertilization between these very different projects.

EPOS "European Plate Observing System", 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 plan for the integration of existing national research infrastructures in seismology (http://www.epos-eu.org/). *AlpArray* and, with it *4D-MB*, are ideal projects for demonstrating the viability of the EPOS concept.

GAIN **"**Geodetic Alpine Integrated Network", is an international network of more than 35 permanent GPS stations that are part of the *ALPS-GPSQUAKENET* network to monitor surface hazards in the Alpine domain. The German component of this network, co-managed by the DGFI and TU-München, comprises stations along the northern perimeter of the Eastern Alps. Together with other networks (EUREF, FreDNet, etc.), there are more than 100 operational GPS stations in the Alpine region. Through co-operation with Prof. Dr. Florian Seitz, a participant in *4D-MB*, their geodetic data will be available and their expertise certainly integrated, especially in Themes 2 and 4.

GeoMol is an EU-funded project (2012-2015) to assess subsurface potential of the Alpine foreland (Molasse) basins for sustainable planning and use of natural resources. This project emphasizes 3D modeling of basin architecture as related to water management, geothermal energy, $C0_2$ sequestration and hydrocarbon exploration, but does not consider the structure of the Alps as a whole. GeoMol therefore pursues different goals than *4D-MB* or *AlpArray*. Nevertheless, the subsurface images of the foreland basins from *GeoMol* are of potential interest to all research themes and activities in *4D-MB* because sedimentary basins are important geo-archives for recording the history of motion and denudation (Themes 2, 4).

Geosystem – The Changing Earth (2014-2018) of the Helmholtz-Gemeinschaft will monitor coupled processes at the regional scale in the following locations: the North Anatolian transform plate boundary, the Central Asian plate collisional zone, the South African passive margin, the Dead Sea transform system and the Chilean convergent plate boundary. The central Asian and Chilean components are thematic complements to the *AlpArray* experiment (Theme 4), but do not contain any passive seismic experiments of comparable size and duration. Nevertheless, know-how from these observatories will be instrumental in the deployment and data-handling tasks of this SPP.

Oceans – From the Deep Sea to the Atmosphere (2014-2018) of the Helmholtz-Gemeinschaft will apply novel techniques to increase the resolution and coverage of the seafloor and ocean margins to aid our understanding of the dynamic processes in the ocean basins, particularly as they affect society. One of the focus themes will be crustal configuration and earthquake potential along the Eurasian-African plate boundary. This complements the research themes outlined in *4D-MB* and the *AlpArray* initiative, even though the latter are focused on continental collisional and the Alpine domain. The obvious synergies and links between these programs, e.g., in the quantification of tectonically active deformation zones and resulting potential hazards will certainly be exploited.

TOPO-Europe – This European research platform (2005-present) provides a network for multidisciplinary, international projects focussing on links between deep Earth geodynamics and surface or near-surface processes that contribute to Earth's topography. The network has included large geophysical experiments (TOPO-IBERIA, 2008-2012), European-funded training networks (TOPO-MOD, 2010-2013)(SUBITOP, 2016-2019) and a large (14.5M €) EUROCORE program (2009-2013). Many of the scientific objectives of *4D-MB* complement TOPO-Europe, and PIs from *4D-MB* and *AlpArray* have participated in past TOPO-Europe projects. We are in contact with members of the Topo-Europe leadership (e.g., Sean Willett, ETHZ, a participant in the Swiss component of *AlpArray*) and expect to take part in network activities, for example, by participating in annual TOPO-Europe conferences and workshops. This interaction will encourage multidisciplinary collaboration based on the results and activities of *4D-MB*.

ZIP – "Zooming in between *Plates* – *deciphering the nature of the plate interface in subduction zones*" is an EC post-graduate training program (2013-2017) devoted to earthquake-related processes along subduction zone megathrusts. The emphasis is on micro- to meso-scale processes (fluid-rock interaction, strain localization) in fossil subduction channels, a field with potential cross-fertilization with Theme 3 in this proposal. Members of *4D-MB* (M.R. Handy, T. John, T. Meier) are also active in ZIP, which will guarantee that ideas and results are exchanged on a regular basis.

7. Qualification of coordinator to manage a research network

Effective management requires organization, coordination and communication. Overall management will rest with Mark Handy (FU-Berlin) and Michael Weber (Potsdam, GFZ), both of whom have lead large, multi- and interdisciplinary research initiatives (Handy: Co-speaker of Berlin-Potsdam Excellence Cluster initiative in Earth Sciences; Weber: Head, Geophysics Dept., GFZ-Potsdam, coordination of DESERT, SAMPLE)

The SPP program committee will initially comprise the colleagues listed on the title page of this proposal, but its members will change as project needs evolve (Table 1). Each of the four research themes (section 5.2.1) will have its own interdisciplinary working group comprising members of the projects in these themes and coordinated by the following colleagues from the list of participants (section 8):

Theme 1: W. Friederich (Bochum), J. Ritter (KIT)
Theme 2: C. Spiegel (Bremen)
Theme 3: M. Scheck-Wenderoth (Aachen, GFZ)
Theme 4: K. Reicherter (Aachen)

These colleagues will shoulder the main responsibility of fostering communication and information in *4D-MB*, as well as of maintaining contact with *AlpArray* partners in other countries. Coordination will involve group activities at several levels:

- ☐ Research theme meetings, managed by the theme coordinators above;
- ☐ Round-table meetings where all members of *4D-MB* can present their newest results, discuss goals, and where invited speakers can give lectures on topics relevant to *4D-MB*;
- ☐ Topical workshops arranged as the need arises in the activity fields; and
- ☐ Special sessions at meetings, where the fruits of *4D-MB* will be presented to the international community.

The following activities require specialized expertise and will be coordinated by the following colleagues in close contact with the *AlpArray* coordinating bodies

UNIBRA / DSEBRA (land-based backbone stations): Wolfgang Friederich (Bochum)

LOBSTER (offshore backbone stations): Heidrun Kopp (Kiel, GEOMAR)

Swath C Stefano Parolai (Potsdam, GFZ)

Swath D Michael Weber (Potsdam, GFZ)

To ensure communication across disciplinary lines and between many locations in Germany, Europe and indeed over the world, the following administrative measures are needed:

Staff support in the form of 6 full-time scientific positions: (1) an experienced scientist to coordinate round-table meetings and workshops, to organize a *4D-MB* graduate school, to draft and update scientific progress reports, to maintain the *4D-MB* website and to manage outreach activities; (2) a central data specialist/manager to harmonize, screen and archive the incoming geophysical data into the central data bank, as well as to train users of this databank. The data manager will also coordinate search and retrieval services for *4D-MB*; (3) four instrument specialists to ensure smooth operation of the backbone (UNIBRA, DSEBRA, LOBSTER) and swath stations. The internationally agreed-upon terms of data archivation in *AlpArray* are laid out in a Memorandum of Understanding in the *AlpArray* Technical Strategy (Appendix IV).

Web-based video conferencing system will employ established open-source systems for video-conferencing (e.g., Google-hangout®). The SPP participants come from over 25 locations in Germany and *AlpArray* participants from 64 locations in Europe, so an effective network system is needed to link them with each other and with partners in N. America. Modern web-based communication and standardized data access will thus be an essential means of exchange and coordination.

8. List of potential applicants

The following list includes colleagues who attended the round-table meeting in Hofgeismar, Germany on June 5-6, 2013 and/or who submitted research summaries. Full lists of all national and international colleagues are included, respectively, in the *AlpArray* Science Plan and the UNIBRA, DSEBRA and LOBSTER sections of the Appendix (III, V and VI).

1	Prof. Dr. J. Behrmann, U. Kiel, GEOMAR	30	Dr. T. Plenefisch, BGR
2	Prof. Dr. R. Bousquet, U. Kiel	31	Prof. Dr. K. Reicherter, RWTH-Aachen
3	Prof. Dr. T. Ehlers, U. Tübingen	32	PD Dr. J. Ritter, KIT
4	Prof. Dr. A. Friedrich, LMU-München	33	Apl. Prof. Dr. O. Ritter, GFZ, Potsdam
5	Prof. Dr. W. Friederich, U. Bochum	34	Prof. Dr. G. Rümpker, U. Frankfurt
6	Prof. Dr. N. Froitzheim, U. Bonn	35	Dr. J. Pleuger, FU Berlin
7	Prof. Dr. C. Glotzbach, U. Hannover	36	Prof. M. Scheck-Wenderoth, RWTH-Aachen, GFZ
8	Dr. I. Sasgen, GFZ	37	Dr. A. Schmidt, U. Leipzig
9	Prof. Dr. A. Hampel, U. Hannover	38	Prof. Dr. H. Schmeling, U. Frankfurt
10	Prof. Dr. M.R. Handy, FU-Berlin	39	Prof. Dr. H. Schuh, GFZ, Potsdam
11	Prof. Dr. R. Hetzel, U. Münster	40	Dr. C. Sens-Schönfelder, GFZ, Potsdam
12	Prof. Dr. M. Hinderer, TU-Darmstadt	41	Prof. Dr. F. Seitz, TU-München
13	Prof. Dr. F. Holtz, U. Hannover	42	Dr. L. De Siena, U. Münster
14	Prof. Dr. N. Hovius, U. Potsdam, GFZ	43	Prof. Dr. K. Sigloch, U. Oxford
15	Prof. Dr. T. John, FU-Berlin	44	Prof. Dr. S. Sobolev, U. Potsdam, GFZ
16	Prof. Dr. B. Kaus, U. Mainz	45	Prof. Dr. C. Spiegel, U. Bremen
17	Prof. Dr. J. Kley, U. Göttingen	46	Dr. M. Stipp, GEOMAR, Kiel
18	Dr. B. Knapmeyer-Endrun, U. Potsdam	47	Dr. F. Sodoudi, TU-Berlin
19	Prof. Dr. H. Kopp, U. Kiel, GEOMAR	48	Dr. D. Tanner, LIAG, Hannover
20	Prof. Dr. M. Korn, U. Leipzig	49	Prof. Dr. C. Thomas, U. Münster
21	Prof. Dr. M. Krautblatter, TU-München	50	Prof. Dr. F. Tilmann, FU-Berlin, GFZ
22	Prof. Dr. C. Krawczyk., LIAG, Hannover	51	Prof. Dr. K. Ustaszewski, U. Jena
23	Prof. Dr. F. Krüger, U. Potsdam	52	Prof. Dr. F. v. Blanckenburg, FU-Berlin, GFZ
24	Dr. J. Kummerow, FU-Berlin	53	Dr. J. Wassermann, LMU-München
25	Prof. Dr. T. Meier, U. Kiel	54	Prof. Dr. M. Weber, U. Potsdam, GFZ
26	Prof. Dr. A. Mulch, Univ. Frankfurt & Senckenberg Museum, Frankfurt	55	Dr. U. Weckmann, GFZ-Potsdam
27	PD Dr. S. Parolai, GFZ, Potsdam	56	Dr. A. Wölfler, U. Hannover
28	Dr. M. Pilz, GFZ, Potsdam	57	PD Dr. A. Zeh, U. Frankfurt

9. Justification of requested annual funding amount for 1st funding period (2017-2020)

To realize *4D-MB*, we envisage two phases of funding of three years each: 2017-2020 and 2020-2023. The estimated amount of required funding is based on evaluation of 23 research summaries which were compiled at the DFG round-table meeting in Hofgeismar, Germany (5-6. June 2013).

The funding requested for the 1st phase (2017-2020) is **7.462.192 €**, of which **2.053.292 € €** is for deployment of geophysical equipment data acquisition and coordination (backbone stations, swaths and marine OBS insurance/deployment) and **581.300 €** for project coordination, outreach and career opportunities for young researchers and female scientists. A full **4.827.900 €** is for funding research projects (see detailed budget for the 1st phase in VII). The 100 stations making up the German part of the *AlpArray* backbone (DSEBRA) will be funded separately by the DFG-Großgerätefonds and therefore do not appear in the budget here. The cost of purchasing these stations is listed separately in Appendix VII.

Most of the funding for research projects will go to projects employing students and young scientists, with a total of 18 PhDs and 5 Post-Docs (including travel, field and laboratory expenses, expendables) in the 1st phase. Some of them will start after 2017, because data must be acquired and processed before it can be interpreted (**Table 1**). Proposals from university departments make up 85% of all proposals; only 15% come from research institutes (GFZ, GEOMAR, LIAG, AWI). These institutes will provide their support and infrastructure including the geophysical instrument pool (GIPP), data archives (GIPP + GEOFON), and their analytical and laboratory facilities.