Surface wavefield tomography of the Alpine region to constrain slab geometries, lithospheric deformation and asthenospheric flow

PIs: Thomas Meier[1], Wolfgang Friederich[2], Jörg Ebbing[1]; PhDs: Marcel Tesch[1], Manuel Ditz[2], Collaborator: Amr El-Sharkawy[1]
1- University Kiel, 2- Ruhr-Universität Bochum

The Alpine orogeny allows to study the full complexity of mountain building despite of its relatively small dimensions compared e.g. to the Himalayan orogeny. A variety of processes like pronounced slab fragmentation, changes in subduction polarity, slab break-off, and strong crustal deformation are shaping mountain building in the Alps. Tomographic imaging of the Alpine deep structure is essential to understand the driving forces of plate collision and deformation. AlpArray provides the unique opportunity to analyze wavefields of seismic phases in a strongly heterogeneous region and to obtain high-resolution images of the Alpine crust and upper mantle.

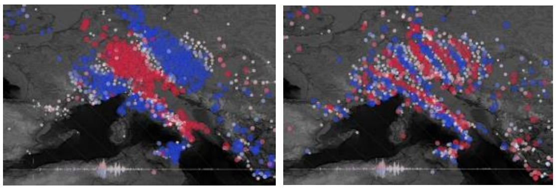

Fig. 1. Snapshots of P- (left) and Rayleigh- (right) wavefields observed with AlpArray for an event in southern Chile on 12/25/2016 (Tesch et al., in prep.).

Fig. 1 shows wavefields for a P- and Rayleigh wave, respectively (Tesch et al., in prep.). Both, the extraordinary new options AlpArray is providing as well as the complexity of the seismic wavefields become obvious. Especially the surface wavefields are srongly deformed. Body as well as surface wave tomography will be based on quantitative analyses of wavefields observed by AlpArray. This requires substantial methodical developments. We developed automated software tools for the measurement of the phase and amplitude wavefields based on cross correlation with a synthetic reference wavefield (Tesch et al., in prep.). They have been successfully tested on synthetic wavefields. Applications to real data show that especially at shorter periods, the wavefields are even more complicated than expected (Fig. 2). The Rayleigh wave phase and amplitude are strongly influenced by the structure beneath the array but also by structure outside and show strong phase shifts in areas of increased amplitudes (Alps, Sicily) or decreased amplitudes (central Apennines). These observations will form the basis for Helmholtz tomography that accounts for phase and amplitude perturbations in the wave-fields in order to obtain high-resolution phase velocity maps for the area.

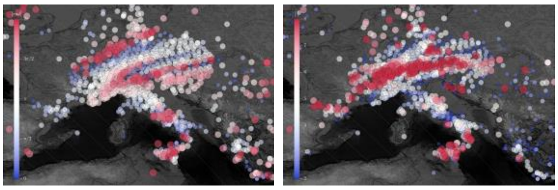

Fig. 2. Properties of surface wave fields in the Alpine area (Tesch et al., in prep.). Perturbation of the observed phase (left) and amplitude (right) at 25 s period with respect to a spherically symmetric Earth model for an event in southern Chile on 12/25/2016.

Fig. 3 shows examples of anisotropic phase velocity maps at 30 s and 100 s period obtained by automated phase velocity measurements (El-Sharkawy, 2019, El-Sharkawy et al., in prep.). Low Rayleigh wave phase velocities at 30 s in the Alpine region (Fig. 3, left) indicate the crustal root and the fast directions point to orogen parallel flow in the eastern Alpine domain whereas in the western Alps azimuthal anisotropy is more inclined to the present shape of the Alpine arc. At 100 s period (Fig. 3, right), high velocities are found in the central Alps likely related to the Eurasian slab. Low velocities in the western Alps support the shallow slab brake-off model (Lippitsch et al., 2003). Azimuthal anisotropy hints at asthenospheric flow from the region of the western Alps towards the Ligurian Sea and through the slab gaps beneath the Central Apennines and the northern Dinarides towards the Pannonian Basin.

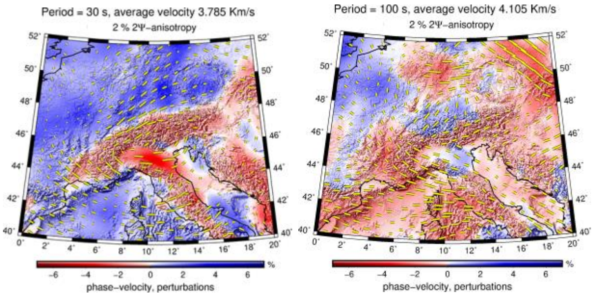

Fig. 3. Azimuthally anisotropic Rayleigh wave phase velocity maps for the Alpine region at 30 s (left) and 100 s (right) period (El-Sharkawy, 2019; El-Sharkawy et al., in prep.). Colors indicate the isotropic perturbations to an average phase velocity. Yellow

bars show the fast direction of Rayleigh wave propagation.

Automated measurements of surface wave phase velocities using earthquake data were combined with ambient noise measurements (Kästle et al., 2016) and contributed to a shear-wave velocity model for the broader Alpine area down to about 200 km depth (Kästle et al., 2018). An efficient stochastic inversion algorithm for surface wave measurements has been developed using a particle swarm optimization technique (El-Sharkawy, 2019, El-Sharkawy et al., in prep.). Its application led to a three-dimensional isotropic shear-wave velocity model for the Alpine area (Fig. 4; El-Sharkawy, 2019; El-Sharkawy et al., in prep.).

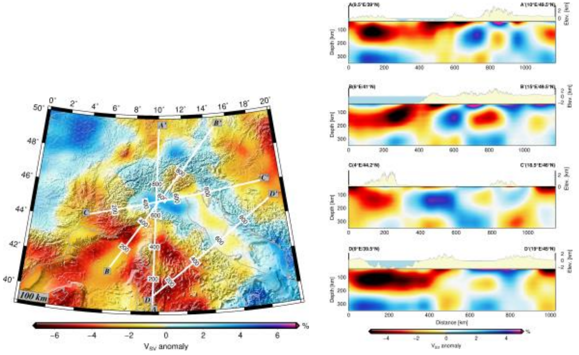

Fig. 4. Vertical cross sections through the shear-wave velocity model (right) obtained by inversion of Rayleigh-wave phase velocities (El-Sharkawy, 2019). The location of the profiles in indicated on the horizontal cross section at 100 km depth (left).

Surface wave tomography is well suited to image the shear-wave velocity structure down to about 300 km depth. At 100 km depth, a continuous high velocity belt is found from the central Alps towards the eastern Alps and the Dinarides indicating slabs with a rather complicated structure especially in the eastern Alps (Fig. 4). Low velocities beneath the western Alps point to slab brake-off. Remarkable are further high velocities beneath the northern Apennines and the Po Basin due to the retreating northern Apenninic Slab. The almost north-south oriented cross section AA' shows the south dipping central Alpine as well as the northern Apennine slabs. Cross section BB' indicates the complicated structure in the eastern Alps. Neither a northward dipping Adriatic Slab (Lippitsch et al., 2003) nor a subducting Eurasian Slab (Mitterbauer et al., 2011) have been imaged clearly so far. It is likely, that both the Adriatic and the Eurasian Slabs contribute to the high velocity anomaly beneath the eastern Alps. The region of the eastern Alps and their forelands requires additional attention in the second phase of the SPP. Cross section CC' indicates a shallow slab break-off in the western Alps (Lippitsch et al., 2003) as well as the proximity of the Eurasian eastward subducting lithosphere with the retreating northern Apennine slab. The Apenninic Slab is steeply dipping beneath the Po-Basin. Cross section DD' shows the slab gap beneath the central Apennines as well as the slab in the southern Dinarides. This asymmetric structure could potentially contribute to the anti-clockwise rotation of Adria.

These hypotheses on the slab geometries developed from surface wave tomography became the basis for numerical modelling by the group in Mainz. They will be further tested against the gravity field in cooperation with the modelling group at GFZ. In the course of the project, this initial model will be continuously updated using surface wavefield measurements from AlpArray data. Furthermore, surface wave propagation in this updated model will be modelled by a newly developed hybrid forward modelling technique in order to test the validity of the 3D shear-wave velocity model using AlpArray data.

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