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Special issue

Seismic anisotropy and shear-wave splitting: achievements and perspectives

Foreword

This special issue of Annals of Geophysics "Seismic anisotropy and shear-wave splitting: Achievements and perspectives" originates from a session (S10) of the 37th General assembly of the European Seismological commission ESC 2021 Conference which was planned to take place on 21 September 2021, in Corfu Greece, but due to the Covid19 pandemic was Virtual.

The main theme of the session and of this special issue was the crucial role of seismic anisotropy in investigating the Earth's interior from the upper crust to the inner core. Shear-wave splitting, one of the most effective ways to study seismic anisotropy, can identify the properties and the geodynamics of the upper mantle, and identify the presence of fluid-saturated microcracks, oriented according to the stress regime, in the upper crust. Azimuthal anisotropy and radial anisotropy can be assessed from earthquake or ambient noise recordings to detect the seismic layered features and to rebuild the 3D seismic structure.

The session was organised in three parts, each with an invited presentation: the first part was focused on anisotropy in the crust, starting with an interesting introduction by Prof. Martha Savage, titled "Seismic anisotropy on volcanoes and geothermal areas". The second part included seismic anisotropy studies using receiver functions techniques and seismic tomography, in the framework of which the invited talk was given by Prof. Jeffrey Park with the title "The expression of Seismic Anisotropy in Ps an Sp Converted waves". The third part was about shear-wave splitting analysis at Mantle scale, with Prof. Stephen Gao giving an invited talk with the title "On the interpretation of teleseismic shear wave splitting measurements. Lesson learned in North America, Africa and Australia". The session was an occasion, even if only in virtual mode, to have a fruitful exchange of information and ideas between seismologists working on seismic anisotropy to understand the Earth's interior, structure and processes. The session hosted 3 Invited presentations, 14 Oral presentations and 8 Posters.

The main purpose of the papers collected in this special issue, "Seismic anisotropy and shear-wave splitting: Achievements and perspectives" is to stimulate collaboration between the seismologists who assess seismic anisotropy with various techniques in very different environments and at different scales, to improve the database of shear-wave splitting available to the scientific community and to provide useful and reliable information to young scientists who start working on seismic anisotropy.

The 12 articles included in this special issue can be divided into three groups. The first group, 3 contributions, is methodological and provides important and useful criteria about the selection of data and constraints of different techniques for studying seismic anisotropy. The second group, 5 contributions, includes studies related to the presence, the causes and the temporal evolution of seismic anisotropy in the Crust. The third group, 4 contributions, deals with the presence of seismic anisotropy in the Lithosphere or in the Mantle and its significance. Below, there is a brief review of the contents and authors of each work.

Seismic anisotropy techniques

The paper “Crustal Anisotropy from the Birefringence of P-to-S Converted Waves: Bias Associated with P-Wave Anisotropy” by Park et al. [2023] focuses on the anisotropic parameters and wave-propagation effects that help distinguish Ps amplitude variations from thin anisotropic layers and Ps splitting that accumulates throughout the crust. It is proposed that the standard minimum-transverse method for estimating shear-wave splitting can be applied to the radial and transverse Receiver Functions (RF) and that simple crustal models that include only shear anisotropy are estimated well by RF birefringence, whereas the Ps amplitude variation induced by compressional anisotropy leads to misleading estimates of birefringence. Synthetic seismograms for a total of 36 anisotropic crustal models are computed to examine the effects on Ps birefringence of S or P anisotropy and the depth range of anisotropy. It is revealed that large variations in Ps birefringence estimates with back-azimuth occur theoretically in the presence of P-wave anisotropy, which normally accompanies S-wave anisotropy.

The paper “Testing observables for teleseismic shear-wave splitting inversions: ambiguities of intensities, parameters, and waveforms” by Rümpker et al. [2023] assesses the capabilities of different observables for the inversion of core-refracted shear waves (XKS phases) to uniquely resolve the anisotropic structure of the upper mantle. A “brute-force” inversion approach is employed by sampling the complete model space and by directly comparing full waveforms and waveform proxies. Canonical models of anisotropic structure in the upper mantle are considered and the study focuses on accessing the suitability of apparent splitting parameters, splitting intensity, and full waveforms for the inversions to infer the model parameters. The results show that it is not possible to fully resolve the anisotropic parameters of a model, but inversions of both waveforms and apparent splitting parameters lead to similar models that exhibit systematic variations of anisotropic parameters. It is concluded that XKS-splitting inversions and related tomographic schemes are not sufficient to fully resolve the heterogeneous anisotropic structures of the upper mantle and that combinations with alternative methods are required.

The paper “On the effects of wrongly aligned seismogram components for shear wave splitting analysis" [2022] by Fröhlich et al. is investigating the problem of mixing wrongly aligned recording components. This may result in misleading and wrong data representations, including the particle motions in both the ZNE and the ray (LQT) coordinate systems and waveforms in the LQT coordinate system. The authors consider that the main pitfall is that start and end times of the single traces in general differ due to data storage details. This effect is regarded to distort under certain conditions splitting signals or to simulate non-existing ones. To overcome this problem, the users have to make sure that the traces are temporally aligned relative to each other in a correct way, either based on a reference time or by cutting the traces to their shared time window.

Seismic anisotropy in the Crust

The paper “Shear-wave splitting perspectives from the intense aftershock sequence of Damasi – Tyrnavos” by Kaviris [2023] performs an upper crust seismic anisotropy study in Thessaly (Greece), at the Damasi – Tyrnavos area that hosted a $M_w = 6.3$ earthquake on 3 March 2021, followed by a rich seismic sequence. A complex upper crust anisotropic regime was identified. Fast shear-wave polarization directions at stations to the north and to the east area strike WNW-ESE to NW-SE, consistent with the Anisotropic Poro-Elasticity (APE) model and the strike of the local active fault planes. However, stations at the central part exhibited different anisotropy directions. In addition, the highest normalized time-delay values were obtained at the northern stations, possibly related to the migration of seismicity to the north during the initial stage of the sequence.

The paper “Shear-wave splitting patterns in Perachora (Eastern Gulf of Corinth, Greece)” by Spingos et al. [2023] is an upper crust seismic anisotropy study at the Perachora peninsula, Central Greece, that hosted a seismic swarm in 2020, with the strongest event having a magnitude of 3.7. A complex state of anisotropy was identified, with NE-SW polarization directions prevailing before the swarm, while a dominant WNW-ESE orientation was present during the swarm. Furthermore, variations of normalized time-delays were observed during the seismic crisis. Taking into account these results and the fluid diffusion during the swarm, shear-wave splitting in the upper crust of the Eastern Gulf of Corinth was considered mainly driven by pressure gradients.

The paper ”Seismic anisotropy in the upper crust around the north segment of Xiaojiang faults in the SE margin of Tibetan Plateau” by Wu et al. [2023] aims to better understand the relation among crustal deformation, fault characteristics and regional stress. To achieve this goal, the authors employ near-field seismic waveform data from a dense temporary seismic array around the north segment of the Xiaojiang fault zone (XJFZ) to study the crustal anisotropy and to analyse the detailed spatial characteristics in the upper crust, as well as the crustal deformation implications. A total of 875 effective records were obtained at 50 stations. Based on the spatial distribution of the polarization of the fast shear-wave (PFS), the study area is divided into two zones. The PFS in the north (N) zone is scattered, with the dominant direction being consistent with the regional maximum principal compressive stress. In the south (S) zone, the dominant PFS directions at most stations are nearly N-S, consistent with the strike of the Xiaojiang fault.

The paper "S wave Splitting in Central Apennines (Italy): anisotropic parameters in the crust during seismic sequences" by Pastori et al. [2023] performs a review of the main anisotropic findings obtained in the last two decades along the Central Apennines. The authors improved the database with results for the Montereale area, covering spatio-temporal gaps between two of the main seismic sequences in Central Italy (L'aquila 2009 and Amatrice-Norcia-Visso 2016. The collected results reveal a general NW-SE fast shear wave direction, consistent with the orientation of the extensional active Quaternary and inherited compressive fault systems, focal mechanisms and local stress field. The results can be interpreted either with the Extensive-Dilatancy Anisotropy (EDA) model, where the anisotropic pattern is related to the local stress variation, or with the Structural-Induced Anisotropy (SIA) model, where the anisotropic pattern is related to the major structural features and most of the variability is visible only in space. The discrimination between stress and structural anisotropy is quite complex in a region where the directions of the extensional regime and the strike of major faults coincide.

The paper "Seismic Anisotropy in the upper crust beneath the Sanjiang lateral collision zone in the southeastern margin of the Tibetan Plateau revealed by S wave splitting from a temporary array" by Li et al. [2023] employs local seismic data to obtain the essential properties of upper crustal seismic anisotropy. The dominant polarization of the fast shear-wave is found to strike NNW. The study area is divided into three subzones according to the dominant polarization direction, which gradually varies from NNW, NS to NNE from the west subzone to the east one. The largest time delay is found at the east side of the western boundary of the Sichuan-Yunnan rhombus block. In addition, the authors identified an area of strong anisotropy stretching along the western segment of the Lijiang-Xiaojinhe fault. It is concluded that the crustal structure may be strongly controlled by the fault and block boundary strike.

Seismic anisotropy in the Lithosphere and Mantle

The paper "Azimuthal anisotropy of receiver functions in the central south china block and its tectonic implications" by Shi et al. [2023] employs seismic data to obtain the crustal structure and the anisotropic parameters using receiver functions. The authors further analyse the lithospheric deformation and composition in the central South China block, where strong lateral heterogeneity in crustal structures was revealed. Another result of the study is that the crustal thickness reduces from northwest to southeast, with significant differences across the boundary of the sub-blocks. In addition, the average crustal Vp/Vs ratio gradually increases from west to east, leading to high values in the coastal region, which suggests that the subduction of the Pacific plate has possibly caused the underplating of magma or the upwelling of upper mantle material. The crustal azimuthal anisotropy of the orogen is considered to be related to the extension and deformation of the lithosphere.

The paper "Rayleigh phase velocity and azimuthal anisotropy from ambient noise data in the Sanjiang lateral collision zone in the SE margin of the Tibetan plateau" by Tian et al. [2023] employs the direct surface wave tomography method to obtain the 3D S-wave velocity for periods 2 s to 40 s and azimuthal anisotropy in the study area. The authors perform a forward calculation of the phase velocity and azimuthal anisotropy. The fast velocity directions are found to mainly align with N-S, while at periods 10 - 35 s they rotate clockwise from north to south. The phase velocity and azimuthal anisotropy obtained by forward calculation are mainly discussed, and the phase velocity results, obtained by the one-step method, are compared with those obtained by the conventional method. The intensity of anisotropy in the low-velocity zone is considered stronger than that in the high-velocity zone.

The paper "Peeking inside the mantle structure beneath the Italian region through SKS shear wave splitting anisotropy: a review" by Pondrelli et al. [2023] reviews the results of more than 11.000 core phase measurements by international projects and published papers. The work focuses on retrieving the anisotropic structure beneath Italy, promoting advances in the knowledge of geological and geodynamic settings. The aim is to better understand the complex and active geodynamic evolution of the active and remnant subduction systems characterising this region and the associated Apennines, Alps and Dinaric belts, together with the Adriatic and Tyrrhenian basins. Measurements of core refracted phases are used as a measure of mantle deformation and interpreted into geodynamic models. Images of anisotropy identify well-developed mantle flows around the sinking European and Adriatic slabs, recognised by tomographic studies. Slab retreat and related mantle flow are interpreted as the main driving mechanism of the Central Mediterranean geodynamics.

The paper "Upper Mantle Anisotropy beneath Northern Algeria from Shear-Wave Splitting" by Radi et al. [2023] conducts a Lithosphere and Mantle deformation study. Seismic anisotropy is investigated using the SKS shear-waves splitting method using recordings of broadband seismic stations installed in central and north-western Algeria. The results show that seismic anisotropy can be described by two main orientations. The ENE-WSW follows the general trend of the Saharan Atlas, particularly in the central and western parts, and the ESE-WNW one follows the Hodna Mountains in south-eastern Algeria. The obtained results are compared to velocity directions estimated from GPS measurements, implying that anisotropy fast axes are nearly perpendicular to the convergence direction between the African and Eurasia plates.

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The Guest Editors and the Authors are grateful to the Editors of Annals of Geophysics for the opportunity to publish the special issue "Seismic anisotropy and shear-wave splitting: Achievements and perspectives" and to the reviewers, whose contribution has been fundamental to improve the quality of the articles.

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