Relation of crustal and upper mantle deformation beneath Sunda-Banda Island Arc inferred from shear-wave splitting analysis

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Abstract. We study the possible correlation of deformation in the crust and upper mantle beneath Sunda-Banda Island Arc using shear wave splitting analysis. The study area is very complex and located in the region where there is a transition in tectonic setting from subduction to collision. In this study, we measure the upper mantle splitting parameters from local events recorded at 6 broadband stations. The fast directions of the upper mantle splitting results are then compared with the orientation of fast waves previously obtained in the crust. Thus, this complex tectonic setting is expected to provide correlation of deformation pattern in the crust and upper mantle derived from the splitting results. The results show that the upper mantle fast orientations are generally parallel to the crustal splitting pattern. This finding suggests that this pattern could be caused the preferential alignment of anisotropic mineral inside the medium vertically localized in thin channel underneath the volcanic islands, or fracture zone fabrics related to the change of tectonic regime from subduction to collision, which involves high stresses and strains in the plate boundary.

1. Introduction
The Sunda-Banda Island arc is situated in the boundary where there is a change in tectonic setting from subduction of Indo-Australian oceanic lithosphere along the Sunda arc in the west to collision of Indo-Australia continental lithosphere along the Banda arc in the east. The current subduction rate in the Sunda arc is estimated to be around 70 mm/yr, and decreases to around 15 mm/yr along the Banda arc [1, 2]. The change of the tectonic regimes in this region may provide variation in structure and morphology, indicating that this region is highly deformed [e.g. 3, 4]. Furthermore, the study area consists of some volcanic islands forming the magmatic arc aligned in west-east direction, including the island of Sumbawa and Flores. The two islands are separated by the discontinuity line of volcanism suggesting that there may be a major tectonic discontinuity called as Sumba fracture separating the Sunda arc and Banda arc [5]. Thus, the geodynamic process of this area is influenced by several tectonic activities including subduction, collision and volcanism.
The complex tectonic of this transition zone has been of wide interest to earth scientists to understand the dynamic processes and deformation mechanism in this area. For example, Syuhada et al. [6] investigated the influence of the interaction between two tectonic regimes to the crustal characteristic around the region using receiver function analysis. They revealed that the crust in the study area is commonly characterized by high Vp/Vs related to the local geologic materials and structures such as the presence of fracture zone and partial melt due to magmatic activities in the upper mantle. In addition, crustal anisotropic study using shear wave splitting analysis conducted in this area [7] also observed different deformation patterns in the subduction and collision domains due to the influence of the two tectonic settings, indicating that this area is highly dynamic. In the continental domain of the study area, Syuhada et al. [7] found crustal anisotropic polarizations is not solely parallel to strain direction, suggesting that anisotropy is not only controlled by stress or strain field, but also caused by the contribution of structural fabrics related to the aligned macroscopic fractures or anisotropic minerals. In order to obtain better knowledge about the dynamic process in this area, we extend our research in investigating the geodynamic process in the upper mantle by using shear wave splitting analysis.

Figure 1. Tectonic setting of study area showing the seismic stations used in this study (the inverted red triangles). The red arrows represents the subduction rate of the Indo-Australian plate and the Australian continental plate relative to the Eurasian plate. The black circles represent the epicenters of the events used in this research.

Shear wave splitting (seismic anisotropy) is a phenomenon in which the shear wave propagating through an anisotropic medium will be split into two quasi shear waves with different directions and velocities, namely the fast and slow shear waves. Shear wave splitting analysis measures the fast direction $\phi$ and the delay time $\delta t$ between the fast and slow arrivals. In the crust, anisotropy is controlled by micro-cracks oriented parallel to the stress field direction [8], geological features related to the active faults [9] or horizontal layering [10] and preferential alignment of anisotropic minerals [11]. In the mantle, anisotropy is mainly caused by lattice preferred orientation (LPO) of olivine related to the recent mantle flow or fossilized mantle deformation derived from past tectonic events. If we know the connection between tectonic process, strain and stress and seismic anisotropy in the mantle and crust, the shear wave splitting analysis may provide information about sources, mechanism
and geodynamic process in the Earth [12, 13, 14]. Therefore, in this study, we report shear wave splitting measurements using data sets from Sunda-Banda island arc, and explore the relation of anisotropic causes in the upper mantle and crust that may be associated with subduction and collision-related processes such as melt production, stress deformation and magmatic flow.

2. Data and method

This research uses waveforms from local earthquakes recorded by 6 broadband GEOFON-IA stations between 2009 and 2015 (figure 1). The depth range of earthquake between 40 km and 120 km is then chosen to assure that the waveforms sample the upper mantle. This selection is based on the previous seismology study about the crustal thickness [e.g. 3, 6] and the lithosphere thickness in this area [15]. In addition, we are also restricted our analysis to waveforms from the events with epicentral distance less than 300 km. This restriction is selected to ensure that the rays have incident angles less than 35° to avoid the complicated waveforms due to phase conversion near the free surface. Finally, we then use the relocated event catalogue [16] to find the selected events that meet the above constraint.

Figure 2. Example of shear wave splitting measurement for station EDFI. The left top panel shows the filtered three component seismograms. The right top panel depicts uncorrected and corrected fast and slow components of the split waves. The four digrams in the left bottom panel displays uncorrected and corrected splitting waveforms including their particle motion. The right bottom panel is the contour diagram providing the best measurement (blue cross).
Upon selection of the best record for splitting measurement, the seismograms containing clear S arrival are manually picked. Shear wave splitting measurement is then carried out using MFAST package [17]. This program is based on the Silver and Chan Method [18], which determines the splitting parameters using eigen-value minimization, and cluster analysis [19], which search the most stable solution of splitting parameters over a given set of time windows. The MFAST method employs 14 band pass filters to seek the best filter based on the product of signal-to-noise ratio (SNR) - bandwith. The F-test is applied for the selected time window to calculate the uncertainties of the measurement with the 95% confidence level for the optimum values of the splitting parameters. The measurement results are then categorized using a grading scheme from A to D representing good and bad results. This ranking system is chosen based on SNR, uncertainty and the stability of the time window [17]. In this report, we only use high-quality shear wave splitting measurements with grade of at least “B” for further analysis (figure 2). As splitting parameters such as phi have a bimodal distribution causing 180° ambiguity, thus the directional statistics described by Mardia [20] are then implemented to calculate the mean value and the error analysis.

3. Result and discussion

For the selected seismograms examine at 6 of GEOFON-IA stations, we obtain 274 high quality shear wave splitting measurements. The results of shear wave splitting analyses are shown by table 1 and figure 3. All seismic stations used in this research show mean time lags between 0.19 and 0.26 s, and fast orientations oriented roughly NW-SE (standard deviation 42°-58°) or perpendicular to the plate motion direction. Here, the absolute plate motion directions are derived from CGPS 2004 [21]. Considering that our splitting measurements sample the upper mantle structure in this area, thus, it is also important comparing our results to the previous mantle anisotropic studies conducted around the study area [22, 23]. The fast directions of our analyses are generally comparable to those anisotropic studies conducted by using teleseismic and depth local events to measure seismic anisotropy in the mantle and slab in this area [22, 23]. They found complicated pattern of seismic anisotropy around this area, which can be interpreted as fossilized anisotropy from past tectonic deformations related the change of tectonic setting from subduction to collision. In the crustal scale, interestingly, our results are also consistent to the average fast polarizations in the crust obtained from the previous crustal anisotropic study for seismic stations located in and near collision domain [7] (figure 1 and figure 3). The pattern of these fast directions observed in the crust and mantle indicate that there might be correlation between anisotropic causes in the crust and upper mantle.

| Table 1. Mean and standard deviation of splitting parameters obtained from N number of measurements |
|---------------------------------|----------------|----------------|
| Station | N  | $\phi$ (°) | $\delta t$ (s) |
| BMNI   | 7  | 0±43         | 0.22±0.11      |
| DBNI   | 107 | -53±58       | 0.20±0.11      |
| EDFI   | 35  | -18±52        | 0.19±0.16      |
| LBF1   | 67  | -18±42        | 0.26±0.16      |
| LRTI   | 3   | -49±50        | 0.25±0.14      |
| MMRI   | 55  | 87±45         | 0.26±0.18      |
Figure 3. Comparison of fast directions obtained for this study and other anisotropic studies. The top panel shows rose diagrams of fast direction measured from this study. The mid panel displays rose diagrams of fast direction derived from the crustal anisotropic study [7]. The red and blue lines in the rose diagrams of top and bottom panels represent the mean and standard deviation of fast direction, respectively. The bottom panel show the splitting results obtained from other mantle anisotropic studies [22, 23]. The blue, brown and green bars in this panel mark fast polarisations measured from SKS, source-side S and local S, respectively, and the direction of absolute plate motion derived from CGPS 2004 model [21] is marked by the black arrow lines.

It is widely accepted that seismic anisotropy in the upper mantle is mainly caused by lattice preferred orientation of anisotropic minerals (e.g. olivine) in the convective flow [24], thus, it will provide the fast direction of S-wave parallel to absolute plate motion. However, some studies also show that the fast orientation of S-wave tends to align perpendicular to the plate motion under the influence of stress, temperature, pressure and water content [25, 26, 27]. The laboratory results show that in the condition of high pressure and low temperature with high water content, the crustal of anisotropic materials tends to align 90° from the convection flow direction [25]. Long and van der Hilst in [28] also observed the fast polarisation of splitting waves oriented perpendicular to the mantle flow direction due to increasing water content forming olivine fabric with the fast axis oriented perpendicular to the mantle flow. Therefore, the long subduction process occurred since 45 m.y. ago in
the Sunda-Banda arc may provide cold enough temperature in the subducted slab to support the high pressure condition. In addition, the presence of volcanic arc in this study area may indicate the presence of localized high water content in the mantle as suggested by Karato in [29] allowing the development of olivine fabric with the fast axis orthogonal to the shear direction. Another plausible mechanism is anisotropy related to the fossilized anisotropy recorded from past tectonic events as suggested by other studies [22, 23]. The study area is located in the boundary zone of the two tectonic settings and has been modified by multiple tectonic events, and thus complicated pattern of splitting pattern is expected

However, the question that arises is why the splitting patterns obtained from this study are consistent to that measured from crustal anisotropy study? The splitting patterns observed in the continental subduction and subsequent collision are expected to reveal the vertically coherent deformation in the crust and upper mantle. This coherence deformation has been observed in many collision setting [e.g. 30, 31]. In this case, the direction of the surface strain rate will be consistent to the direction of the shear strain in the mantle. If the main crustal anisotropic mechanism in the region is caused by the influence of stress induced anisotropy, then the crustal fast directions will be parallel to the maximum compressional strain [e.g. 32, 33]. As a consequence, if the mantle and crust deform coherently, the measured anisotropy direction in the mantle should match the anisotropy direction observed in the crust.

In this area, the previous crustal anisotropic study [7] shows that the crustal fast directions near the boundary of the transition zone are not consistently parallel to the axis of maximum horizontal compressional strain rate. They interpret this condition could be due to the presence of fluid-filled fractures beneath this region. At deeper part of the crust, the presence of fluid will maintain the fracture to open under high pressure causing the fast direction perpendicular to the principal strain axis. Therefore, the consistent fast directions observed in the crust and upper mantle of the study area could be related to the preferred alignment of magma filled pockets/dikes causing anisotropy perpendicular to the direction of subduction as suggested by Fischer et al. in [34]. We thus suggest that this partial melt may be localized in vertical thin channel underneath the volcanoes. This idea is based on the fact derived from the recent receiver function study [6] that the crust in the study region is characterized by low velocity zones and high Vp/Vs indicating the presence of partial melting. The parallelism of the fast axis direction obtained in the crust and upper mantle also could be related to the trend of shallow geological feature. This splitting pattern is generally consistent to strike of strike-slip and reverse faulting derived from focal mechanism study [35, 36] suggesting that this parallelism is associated to the fracture zone due to strain partitioning as result of the arc-continent collision [37]. We observe that our results have fast polarisations with high standard deviation indicating the presence of complex or multi layers of anisotropic structure beneath the region. Thus, this complex anisotropic structure may have significant contribution to the strong parallelism of fast directions measured in the crust and upper mantle. This complicated anisotropic structure can be identified by observing a \(\pi/2\) periodicity of splitting parameters at long periods as a function of the initial polarization [38]. Therefore, further research is necessary to test this idea by involving larger dataset both from local and teleseismic events.

4. Conclusions
From the result of this study, we may conclude that the striking parallelism between crustal and upper mantle anisotropic direction in this region is primary due to the preferential alignment of anisotropic mineral inside the medium. Alternatively, this parallelism is caused by fracture zone fabrics forming due to past tectonic activities such as strain partitioning as consequence of the arc-continent collision. Another plausible cause is due to the presence of complex or multi layers anisotropic structure, although this idea needs further investigations to obtain more evident.
Acknowledgments
We acknowledge Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) and GFZ Potsdam for their seismogram data used in this study.

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