Doctoral dissertation summary

Seismotectonics of Botswana: New insights from seismic velocity and anisotropy structure of the upper lithosphere

ボツワナの地震テクトニクス：リソスフェア上部における地震波速度と異方性の構造にもとづく新しい考察

Submitted to the Department of Geophysics
Division of Earth and Planetary Sciences
Graduate School of Science
Kyoto University

MPUANG Admore Phindani

2023 年 10 月

1. Introduction

The April 2017 Mw 6.5 earthquake of central Botswana, an intraplate region, was a potential disaster that raised worrying questions on disaster preparedness in the region. While understanding intraplate earthquakes such as this, remains an elusive challenge, detailed knowledge of the seismic velocity structure, tectonics and geodynamics of the region is important in understanding the potential dangers and implementing disaster mitigation strategies. Botswana, whose location straddles the southern edge and northwestern part of Congo craton and Kalahari craton, respectively, has seen limited seismological studies compared to other parts of the world. However, as a result of recent improvements in seismic station coverage, it is now known that the crust beneath the Okavango rift Zone (ORZ) is thinner than the surrounding regions (e.g. Leseane et al., 2015; Yu et al., 2015b; Fadel et al., 2018), and that this thinner crust extends into central Botswana (Fadel et al., 2018; 2020). It is within this region that two main zones of seismicity are observed, and despite a reported low velocity anomaly linking the two zones (Fadel et al., 2020), their relationship in terms of tectonics and geodynamics remains unknown. In this thesis, this relationship is explored by investigating the velocity and anisotropy structure of the crust and uppermost mantle, which are important indicators for crustal modification processes and regional stress state, leading to clues on the associated seismotectonics in the region. The investigations are divided into three sub-studies focusing on (i) intracrustal shear wave velocity (Vs) structure, (ii) dipping and anisotropic shallow structures and (iii) azimuthal anisotropy of the crust and uppermost mantle.

2. Data and Methodology

All the sub-studies in this thesis used seismic data obtained from broadband stations located across Botswana; 21 stations from the Network of Autonomously Recording Seismographs – Botswana (NARS – BW network) (Utrecht University, 2019), 17 from the Seismic Arrays for African Rift Initiation (SAFARI) network (Gao et al., 2013) and an additional station from the Global Seismological Network (GSN). The receiver functions method was employed for studying intracrustal Vs structure, assuming flat homogenous isotropic layers. The same method was also applied in the second sub-study assuming the presence of dipping interfaces and anisotropic layer in the shallow crust. The ambient noise method was used to determine azimuthal anisotropy and phase velocity variations in the crust and uppermost mantle.

2.1. Receiver function analysis

The receiver functions method is a well-established technique for determining the velocity structure of the crust beneath a seismic station. The most common approach makes use of the structural response to incident teleseimic P waves, which is isolated by deconvolution from other contributing factors in a 3-components seismogram (Langston, 1979). While several techniques exist for carrying out the deconvolution, the extended-time multitaper technique (Helffrich, 2006; Shibutani et al., 2008), which has an advantage of minimizing spectral leakage and spectral holes, was used in this thesis. Deconvolution reveals P to S converted phases at interfaces beneath a recording station, such that, in homogenous isotropic layers with horizontal interfaces, these converted phases and their multiples are observable on the radial component only. In this thesis, radial receiver functions computed with corner frequency ~ 1Hz were used for investigating intracrustal Vs structure. The radial receiver functions at a single station were stacked in back-azimuth and slowness bins, followed by an inversion for 1D Vs-depth models using the genetic algorithm inversion technique (Shibutani et al., 1996; Sambridge & Drijkoningen, 1992).

2.2. Harmonic decomposition analysis

The transverse component of receiver functions contains converted phases in the presence of dipping interfaces and anisotropic layers. In addition, the amplitude and delay time of P to S converted phases display a systematic back-azimuthal variation in the presence of dipping interfaces and anisotropic layers (e.g. Langston, 1977, 1979; Owens & Crosson, 1988; Ammon, 1991; Cassidy, 1992; Savage, 1998; Park & Levin, 2016), with a $\pi/2$ phase shift between the radial and transverse receiver functions (Maupin & Park, 2007). By stacking the radial and transverse receiver functions with a $\pi/2$ phase shift, the effects of dipping interfaces and anisotropy can be enhanced, while stacking with a $(-\pi/2)$ phase shift diminishes those effects (Shiomi & Park, 2008; Bianchi et al., 2010). This stacking technique, termed harmonic decomposition (Bianchi et al., 2010), has been widely adopted in receiver function studies and is used in this thesis for the investigation of dipping and anisotropic structures in the shallow crust, using receiver functions calculated with corner frequency ~ 2 Hz. To characterize the dipping and anisotropic structures at stations located within the mobile belts in the proximity of the Kalahari craton displaying shallow Ps converted phases, the “Dip/Anisotropy” panel, obtained by stacking radial and transverse components with a $\pi/2$ phase shift, was subjected to inversion using a modified genetic algorithm. The modifications resulted in an increased exploitation of better fitting models and an increased exploration of model space, which led to an overall improvement in the optimization process and a better statistical representation of the best fitting model parameters.

2.3. Ambient noise analysis

The ambient noise method, which uses surface waves propagating at different periods, has become a powerful tool to investigate the depth variation of anisotropy in the crust and uppermost mantle. For uniformly distributed noise sources around a recording station pair, phase velocities can be estimated by comparing the properties of the stacked cross-correlation of noise recordings with those of a zeroth order Bessel function of the first kind (Aki, 1957; Kästle et al., 2016). In this study, we follow a similar procedure to that of Kästle et al. (2022) in which only the vertical seismogram component is considered, which isolates the Rayleigh wave, and phase velocities are estimated by fitting the zero crossings of the real part of the cross-correlation spectrum to the zero crossings of the zeroth order Bessel function using a smooth picking procedure. Eikonal tomography (Lin et al., 2009) was then applied to produce maps of isotropic phase velocities and estimate anisotropic parameters; % anisotropy and fast direction of propagation. Eikonal tomography was applied to phase velocity measurements and results were analyzed for periods between 15s and 50s with peak depth sensitivity within depths of 10km to 80 km.

3. Intracrustal structures

Resulting Vs models were analyzed by dividing the crust into 4 layers of sediment, upper, middle and lower crust based on reported Vs ranges and composition of common crustal lithologies (e.g. Wedepohl 1995; Christensen & Mooney 1995; Christensen 1996). This analysis revealed important features that can enhance our knowledge of tectonics and geodynamics of Botswana. The thin crust beneath the ORZ (average 33.7 km) is confirmed, extending to central Botswana where there is a transition from thinner to thicker crust across the epicentral location of the 2017 Mw 6.5 earthquake. The thin crust region is collocated with and follows a similar trend as a lower Vs region in the middle crust, along a Paleoproterozoic suture zone between the Kalahari and Congo cratons with thrust and shear zones (Key & Ayres, 2000). Furthermore, reported hypocenters of the April 2017 Mw 6.5 earthquake and its aftershocks (of magnitude greater than 4) at depths between 20 and 30 km (Paulssen et al., 2022) lie well within the depth range of the low Vs region in the middle crust and the upper part of the lower crust. Where there are no depth constraints, the epicentral distribution of the natural seismicity of Botswana (Paulssen et al., 2022) lie above this low Vs region, suggesting a connection between the suture zone, low middle crust Vs, thin crust and observed seismicity.

4. Dipping and anisotropic shallow structures

Analysis of a strong shallow Ps conversions observed in the mobile belts in the proximity of the Kalahari craton, with receiver functions of higher frequencies (~2Hz) and considering dipping interfaces and anisotropy in the inversion of harmonic components, enabled the delineation of the shallow structures. In the Kaapvaal craton, near the border region with the Limpopo belt, steeply dipping interfaces are located at depths ~4km beneath the station NE212 and NE220, with dipping angles ~50° that are common in the region (Kolawole et al., 2017; Mulabisana et al., 2021; Paulssen et al., 2022). The trends of the steeply dipping interfaces are consistent with the orientations of two main branches of the Zoetfontein fault zone: the approximately E-W branch at the location of NE212 and the WSW-ENE trending branch at the location of NE220. The Zoetfontein fault zone is a crustal lineament (Hutchins & Reeves, 1980; Pretorius, 1984; Ranganai et al., 2002) that formed during major orogenic episodes in the lower Proterozoic Era (Smith, 1984). The proximity to the stations NE212 and NE220 as well as the consistency of interface orientation suggests that the dipping interfaces beneath the stations may be part of the Zoetfontein fault zone. Elsewhere, the complex deformation history of the Limpopo belt is confirmed by local shallow structure variations, near surface anisotropic amphiboles as well as strong near surface heterogeneities.

5. Azimuthal anisotropy of the crust and uppermost mantle

The distribution of isotropic phase velocity indicates the presence of a lower velocity region that extends from the Okavango rift zone in northern Botswana to SE Botswana, with a similar trend as the thinner crust region and the lower Vs region in the middle crust. This feature is most extensive in the periods 30s – 35s, suggesting a middle-to-lower crustal origin. Anisotropy fast directions on the other hand show a depth dependence. Upper crustal anisotropic fast directions (periods 15s and 20s) align with focal mechanism solutions and geological features (NE-SW in the ORZ and NW-SE in SE Botswana), and such anisotropy can be explained by aligned cracks (Crampin, 1994) that have developed in response to present-day tectonic stresses in the crust near the seismogenic regions.

Anisotropy fast directions start to change at periods (25s – 35s). The rotation of fast directions to WNW-ESE, especially observed across the ORZ at periods longer than 35s, is consistent with a general NW movement of the southern portion of the Congo craton relative to northern part of the Nubian subplate reported by Altamimi et al. (2012); Saria et al. (2013) and thus can be explained by associated shear stresses that result in preferentially orientated amphiboles and olivine crystals in the lower crust and uppermost mantle (e.g. Crampin et al., 1984; Barruol & Kern, 1996; Barberini et al., 2007; Tatham et al., 2008). However, the rotation of fast directions between the seismogenic regions at periods 40s – 50s to almost N-S and E-W directions suggests a more complex mechanism, that can possibly be explained by intraplate relative motion between the Kalahari and Congo craton. This intraplate relative motion is supported by a reported 0.5 – 2 mm/year clockwise rotation of the southern Africa block relative to the rest of the Nubian plate (Malservisi et al., 2013).

6. Discussions

The results of the investigations from the three sub-studies when combined with additional constraints from previous studies, provide interesting new insights on the seismotectonics of the region between the Kalahari and Congo cratons. The coincidence of a thinner crust region with a lower Vs in the middle crust, a lower isotropic phase velocity region in the middle to lower crust within a Paleoproterozoic suture zone (Key & Ayres, 2000) with steeply dipping thrust and shear zones, suggests that the lower velocities are due to the extensive deformation in this region compared to the surrounding undisturbed cratons. This is further supported by a reported low Vs region at 30 – 50 km depth beneath the location of the April 2017 M6.5 earthquake.

Anisotropy results in the upper crust, with fast directions that align with focal mechanism solutions and the trends of geological features, suggest that the accumulation of tectonic stresses in the upper crust along ancient zones of weaknesses plays a role in the observed seismicity in this region. The slow and gradual buildup of stresses along the weak-zones from the tectonic forces related to the relative motion of the southern Africa block (Malservisi et al., 2013) would result in stress accumulation, which explains the observed seismicity.

To explain how stresses accumulate at weak zones, we propose a geodynamic model based on our anisotropy observations and results from previous studies. Deep roots of the Congo and Kalahari cratons, which extend to depths beyond 250 km (James et al., 2001; Muller et al., 2009; Khoza et al., 2013a; Ortiz et al., 2019; Fadel et al., 2020) likely deflect mantle flow due to temperature and density contrasts (e.g. Paul et al., 2023). The associated preferential alignment of olivine crystals gives rise to anisotropy at uppermost mantle depths with fast directions parallel to the (deflected) mantle flow (e.g. Verma, 1960; Backus, 1965; McKenzie, 1979; Ribe, 1989; Montagner, 1994; Hirth & Kohlstedt, 2004). Since mantle flow drives plate motions and deformation (Turcotte & Oxburgh, 1967), differential shear tractions that develop at the base of the cratonic roots can be transmitted to the crust (e.g. O'Neill et al., 2010), resulting in the differential intraplate relative motion between the Congo and Kalahari cratons and stress accumulation and deformation along the pre-existing weak zones, where seismicity is observed. There is indeed a need for detailed imaging or modelling of such a deflected flow to prove this hypothesis as the mechanism behind the movement of the southern Africa block (Malservisi et al., 2013). Measurements of fast directions at depths coinciding with the expected mantle deflection (about ~250km depth of the cratonic roots) are expected to provide a clearer picture concerning this hypothesis. Furthermore, a complete seismic catalogue with accurately determined focal depths will also be useful to further localize the discussions of seismotectonics in the region.

7. Conclusion

New insights on the relationship between geodynamics, tectonics, and seismicity in the region between the Congo and Kalahari cratons were obtained by multiple studies on the structure of the upper lithosphere beneath Botswana. The main conclusion of this dissertation is that seismicity observed between the Congo and Kalahari cratons in Botswana is a result of the accumulation of tectonic stresses, driven by intraplate relative motion and deformation likely due to deflected mantle flow by the deep roots of the Congo and Kalahari cratons. These conclusions represent a significant step towards understanding the present-day tectonics and geodynamics of the southern African region, as well as the generation of intraplate seismicity in the region.