Chapter 1

Seismological Implication to the Tectonic Evolution of the Lützow-Holm Bay Region (East Antarctica)

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Additional information is available at the end of the chapter

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Abstract

Passive source studies using teleseismic events demonstrated heterogeneous structure in the Lützow-Holm Bay (LHB) region, East Antarctica. Depth variations of upper mantle discontinuities (410 and 660 km) were derived from long-period receiver functions by local array stations. Shallow depths in topography of upper mantle discontinuity were cleared beneath the continental ice sheet back azimuth. These results reflect a paleo-upwelling of the mantle plume associated with Gondwana breakup. Lithospheric mantle anisotropy derived by shear waves' (SKS) splitting anticipated a relationship between "fossil" anisotropy and the past tectonics in NE-SW orientation. Origin of mantle anisotropy was assumed to be caused by supercontinent assembly rather than present asthenospheric flow parallel with absolute plate motion. The deep seismic surveys by active sources, moreover, were carried out over continental ice sheet and provided clear information on crust-mantle boundary, together with inner lithospheric mantle reflections. The extracted lithospheric cross-sectional images by seismic reflection analyses implied tectonic influence of compressive stress during Pan-African age.

Keywords: upper mantle structure, Lützow-Holm Bay region, East Antarctica, Gondwana supercontinent, tectonic evolution

1. Introduction

East Antarctic continent consists of several geological terrains as resultant of amalgamation and breakup of Rodinia and Gondwana [1, 2]. In wide areas of Western Enderby Land-Eastern Dronning Maud Land, inside the East Antarctica, several geological complexes are adjacent to each other from East to West: the Napier (Archaean), the Rayner (late Proterozoic), the Lützow-Holm (early Paleozoic), and the Yamato-Belgica (early Paleozoic) (**Figure 1**) [3–5]. Combined with other Gondwana component continents such as Africa, India, and Australia,

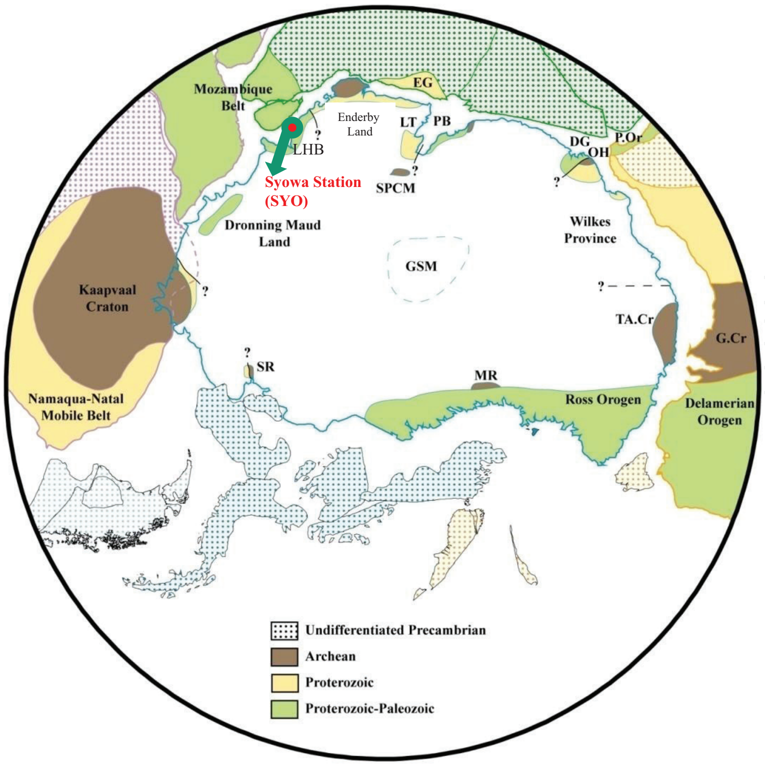

Figure 1. Gondwana reconstruction at 480 Ma, centered on East Antarctica (modified after [5]) showing the geologic ages of major exposed coastal outcrops [2]. The areas corresponding "undifferentiated Precambrian" terrains belonging to each continental blocks of Gondwanaland (Australia, Africa, South America, and Antarctica) are distinguished by different colors (yellow dot, green dot, brown dot, and light-blue dot), respectively. Abbreviations are as follows: SYO, Syowa Station; LHB, Lützow-Holm Bay; SR, Shackleton range; SPCM, Southern Prince Charles Mountains; LT, Lambert Terrane; EG, Eastern Ghats; PB, Prydz Bay; DG, Denman Glacier; OH, Obruchev Hills; P. Or, Pinjarra Orogeny; TA. Cr, Terre Adélie Craton; G. Cr, Gawler Craton; MR, Miller Range; GSM, Gamburtsev Subglacial Mountains.

the crust and lithospheric mantle architecture with relevant tectonic history of East Antarctica provide evidence of amalgamation and separation of the past supercontinents [6, 7]. The Lützow-Holm Bay (LHB) region, where the Japanese Syowa Station (SYO, 69S, 39E) is located, has been experiencing regional metamorphic events in early Paleozoic [8]. The metamorphic grade increases from amphibolite facies in eastern LHB to granulite facies in the western. During the Pan-African metamorphism, LHB was deformed under compression stress perpendicular to the thermal axis [9].

Seismological evidence with respect to the structure and tectonics of the upper mantle beneath LHB has been derived in the last few decades by both the computer modeling and field observations by the Japanese Antarctic Research Expedition (JARE). Teleseismic data detected at seismic stations in LHB have sufficient signal-to-noise quality for various kinds of analyses so as to clarify local seismicity, heterogeneities of the lithospheric structure, as well as deep interiors of the Earth [10–13]. Several studies had aimed at deriving static structure, tectonics, and dynamics within the crust and mantle depths, associated with geological evolution of the region [14, 15]. In this chapter, by taking into account the tectonic evolution around the Lützow-Holm Bay (LHB) region, passive and active seismic source studies were reviewed in order to provide comprehensive understanding in formation of the upper mantle structure and dynamics beneath LHB, associated with evolving process of supercontinents in southern hemisphere during the Earth history.

2. Seismic investigations of the upper mantle

Seismological investigations in LHB demonstrated sufficient images of the structure and dynamics in the upper mantle underneath the Antarctic continent. The investigations by using passive seismic sources such as teleseismic events occurring over the globe had demonstrated strong heterogeneity existing in the upper mantle depths. Depth variations of the upper mantle discontinuities (410 and 660 km depths, respectively) were derived from long-period receiver function analysis (0.2 Hz low-pass filtered), which indicated shallow depths in the 660 km seismic discontinuity beneath continental back azimuths in LHB (**Figure 2**) [16]. The depth distributions of P-S conversion points were also revealed in particular for the 660 km discontinuity. The shallow depths in topography for the 660 km discontinuity were identified beneath the continental azimuths over the ice sheet. These results could provide an evidence of upwelling flow associated with mantle plume in terms of Gondwana breakup

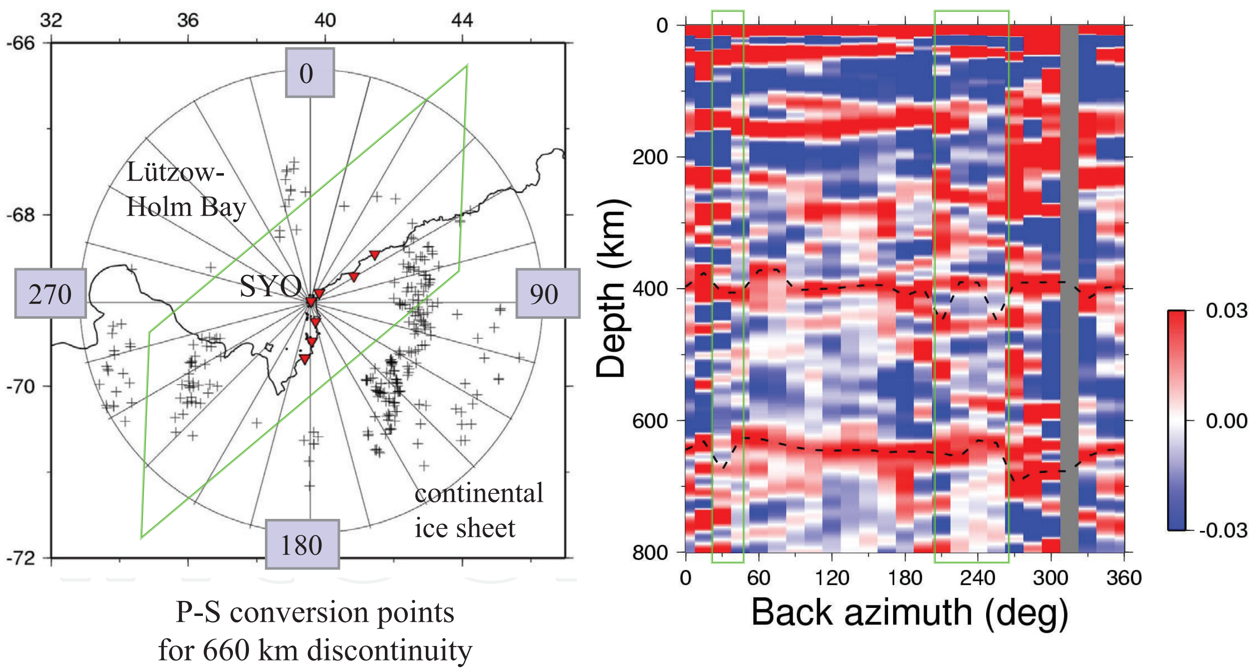

Figure 2. Back azimuth distribution of the depth variation in the upper mantle seismic discontinuities by receiver function analyses of broadband seismic data in LHB (modified after [16]). (Left) Location of the strong heterogeneous azimuths in LHB. The area for strong depth variations in upper mantle discontinuities is represented by the light-green open squares, which are almost parallel with the coastal line. Symbolic notation for the P-S conversion points at the mantle discontinuities around 660 km in depth. (Right) Color images represent the smoothed amplitudes of the long-period receiver functions. Two dashed lines are traced for the maximum amplitudes of both 410 km and 660 km depth discontinuities, respectively. Two back azimuth groups for strong depth variations in the upper mantle discontinuities are circled by the light-green open squares.

process. Moreover, strong heterogeneities were observed in both 410 km and 660 km discontinuities in back azimuths of 20–50° and 200–260°, respectively. These back azimuths are almost parallel to the coast line and are assumed to have a relationship with the breakup of Gondwana supercontinent.

Shear wave splitting analysis by using SKS waves [17], in addition, indicated clear association between "fossil" anisotropies relating to the past tectonics, which appeared to be in present lithospheric mantle structure beneath LHB. A two-layered structure model was assumed for upper mantle anisotropy; upper was supposed to be the "lithosphere," and lower corresponded to the "asthenosphere," respectively. By using the data from local seismic network in LHB, azimuthal variations of the shear wave splitting parameters were obtained (**Figure 3**). The fast polarization directions of the SKS waves were compared with those directions by an absolute plate motion, which are reflecting more recent mantle flow process of the Antarctic Plate (**Figure 3**) [18]. Since the fast polarization directions in lower layer were generally parallel to the directions of the absolute plate motion, the lower layer's anisotropy might reflect the asthenospheric anomalies due to horizontal mantle flow along the plate motion. On the other hand, the fast polarization directions of upper layers did not coincide with the absolute plate motion direction. It was supposed that anisotropic structure could be involved in the past tectonics; the origin of anisotropy was considered as "frozen" within the lithosphere. The Gondwana assembly in early Paleozoic age might be the major aspect in forming the present anisotropy [2].

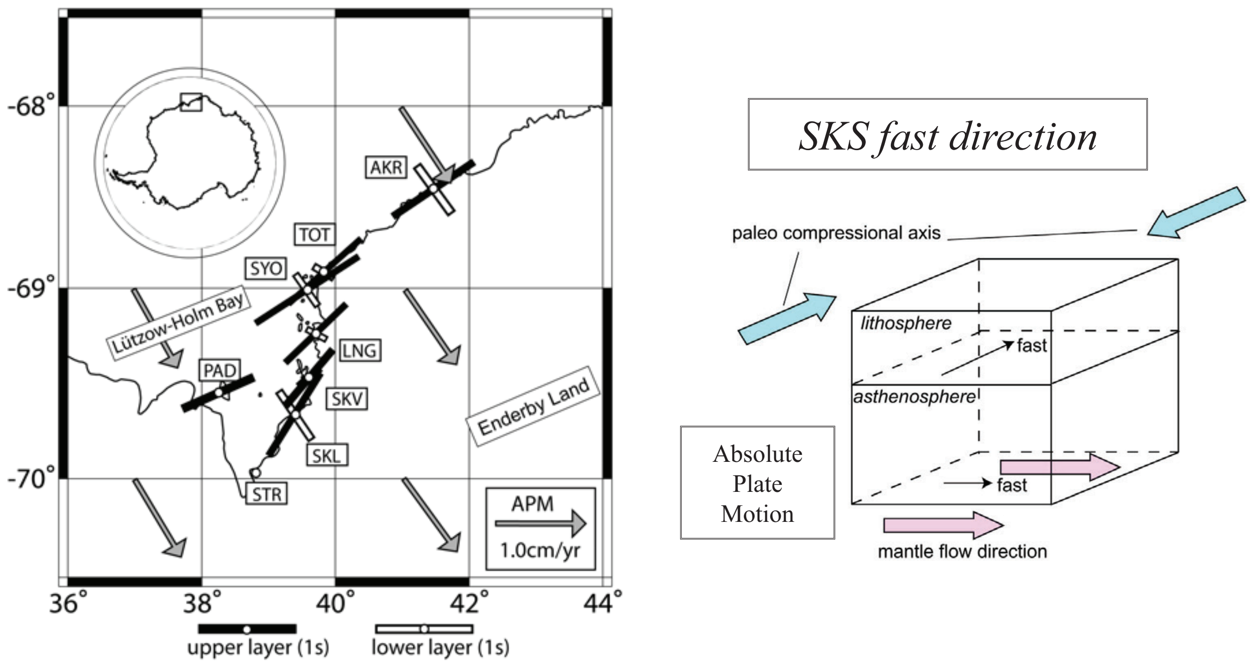

Figure 3. (Left) Upper mantle anisotropy in LHB derived from SKS splitting (modified after [17]). At the stations of AKR, LNG, SKL, SYO, and TOT, the lower layer anisotropy is supposed to be caused by recent asthenospheric flow. For almost all other stations, the direction of anisotropy in the upper layer (corresponds to the "lithosphere") is parallel to NE-SW convergence during the Pan-African age. (Right) Schematic illustration of a two-layered model of seismic anisotropy within the lithosphere and asthenosphere.

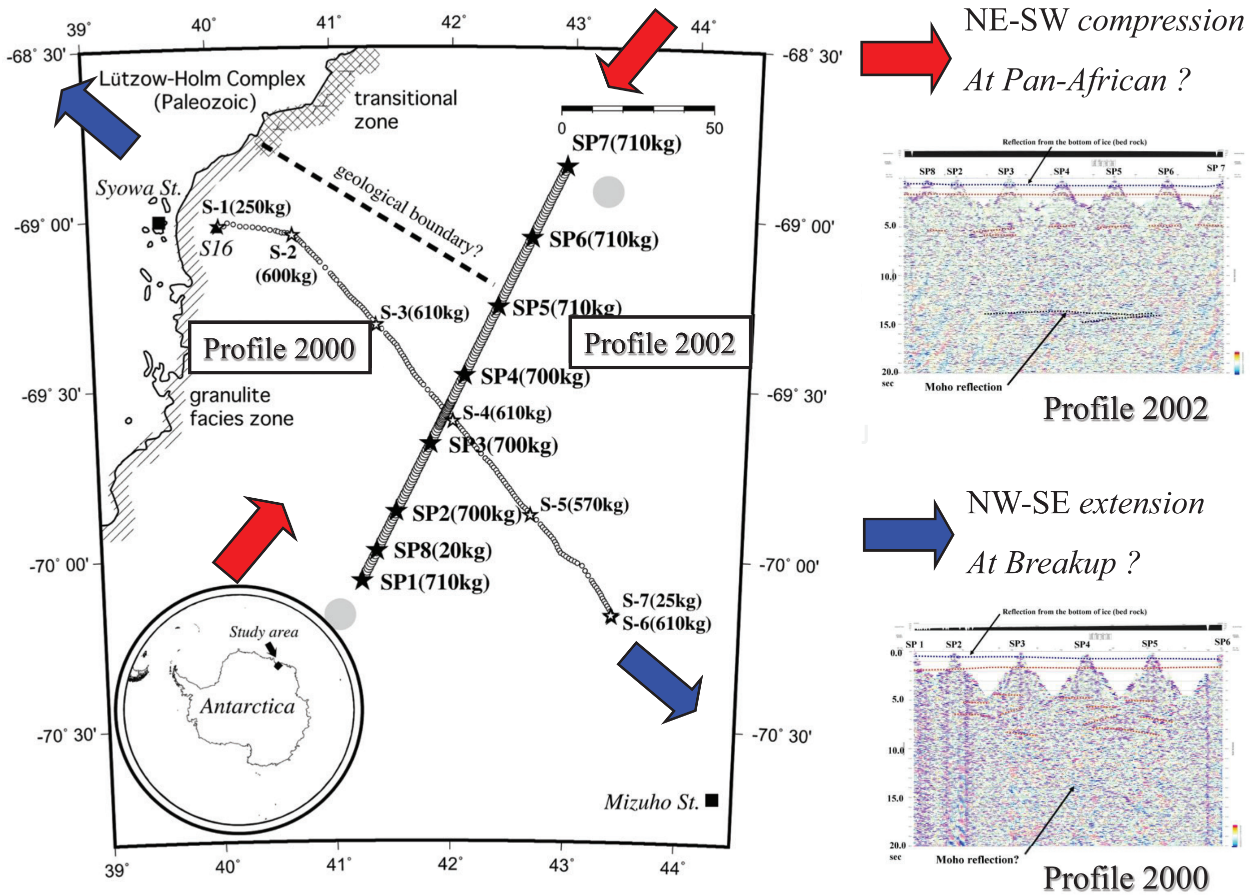

Figure 4. (Left) Map showing the location of deep seismic surveys conducted in LHB (modified after [19]). Solid and open stars indicate the shot locations in 2002 and 2000, respectively. Large and small circles represent the geophone stations on ice sheet for both the active seismic source operations. The size of each shot given is the weight of dynamite used. (Right) Tectonic interpretations of the seismic reflection cross sections. The CDP stack section with offset limited to traces within 120 km for the 2002 profile (upper) and to near traces for the 2000 profile (lower), respectively. Several seismic reflections in the crust and the Moho discontinuity are identified by broken lines and solid arrows. Moreover, reflections from the bottom of the ice sheet are traced by the broken line in the shallow layer of the topmost crust.

Furthermore, active seismic source investigations (wide-angle reflection/refraction and near vertical reflection studies) imaged striking lithospheric mantle reflection patterns involving regional tectonics during Pan-African and the next following extension regime at the continental margins of the breaking-upped supercontinent (**Figure 4**) [14, 19]. By these evidences, tectonic evolution model of LHB was estimated in order to explain the heterogeneities in the present upper mantle. For the 2000 active source profile on continental ice sheet in LHB, a single coverage of common depth point (CDP) with only nearer traces was identified in the lower-right panel of **Figure 4**. On the contrary, the CDP stack section with offsets less than 120 km was depicted for the 2002 active source profile. A laminated seismic velocity layer in the lower crustal depths, moreover, was modeled by comparing synthetic receiver functions with those of observed ones in short-period frequencies (0.1–1.0 Hz) [20]. The repetitive crust-mantle transition zone derived by 2002 profile suggested an influence of compression stress in NE-SW orientation during the Pan-African, which might occurred at the last stage of formation of a great mobile belt between East and West Gondwana [1]. Successive breakup of the supercontinent in mid-Mesozoic could explain the formation of stretched reflection structure above the Moho discontinuity as imaged by the 2000 active source profile.

These seismic reflection cross sections were assumed to reflect multi-genetic origins, including igneous intrusions, lithologic/metamorphic layering, mylonite zones, shear zones, seismic anisotropy, and fluid layers [21, 22]. In spite of the multi-genetic origin, metamorphic layering could be principal candidates in the case of LHB. A strong reflectivity in the deeper crust-upper mantle might be expected by layered sequences of mafic and felsic rocks [23]. Moreover, such the reflectivity might be originated when the mafic rocks had been interlayered by a combination of the upper amphibolite and lower granulite facies metapelites [24]. In any continental terrains on the Earth, the primary causes for reflectivity might be enhanced by ductile stretching during a late tectonic extensional process [25]. The reflecting layers near the Moho, moreover, were predominantly identified at the crustal thinning tectonic regimes. In these regards, reflectivity in the lower crust and lithospheric mantle beneath LHB might be enhanced under extensional conditions by the last breakup of Gondwana.

3. Estimation of tectonic evolution

On the basis of the seismological evidence mentioned above, a regional tectonic model of LHB was estimated so as to explain formation process of the present upper mantle structure. A history of evolution, including major tectonic events in LHB, was summarized in **Figure 5**(**a, b**). Dedicated geological studies revealed regional metamorphism of the area during the Pan-African age [1, 2]. Metamorphic grade increased progressively from amphibolite facies in the NE to granulite facies in the SW of LHB. The maximum thermal axis runs through the southern LHB with a NNW-SSE striking direction [26]. From geological evidence, the LHB experienced deformation of compression stress oriented perpendicular to the thermal axis, almost parallel to the coast, during the last stage of deformation process within a mobile belt between East and West Gondwana [1, 2]. The high-amplitude magnetic anomalies occurring in LHB compared to those in surrounding terrains [27] indicated that the LHB might be located in one of the major suture zones of the Pan-African mobile belt. These major suture zones appeared to continue from LHB to the Shackleton Range of West Antarctica [1, 28].

Lower crust and upper mantle beneath LHB were characterized to have lateral as well as vertical variations as revealed by seismological studies mentioned in this paper. The gently inland dipping Moho discontinuity (38–42 km) beneath the 2000 deep seismic profile was inverted by travel time analysis from refraction and wide-angle reflection surveys [29]. The present structure was characterized to hold the past regional tectonics, in particular metamorphic activities during the Pan-African. Inferred thrust duplicated (similar to the wedge-shaped) lower crust-upper mantle transition structures interpreted on the 2002 seismic profile (**Figure 4**) [19] implied compressive stress regime along the profile oriented in NE-SW direction during the Pan-African events. In spite of these geophysical and lithologic information, LHB was assumed to be formed under convergence, perpendicular to the thermal axis, during the collision between supra terrains of the Gondwana at the last stage of supercontinent formation [15, 30]. When the LHB underwent NE-SW compression, related paleo-mantle flow

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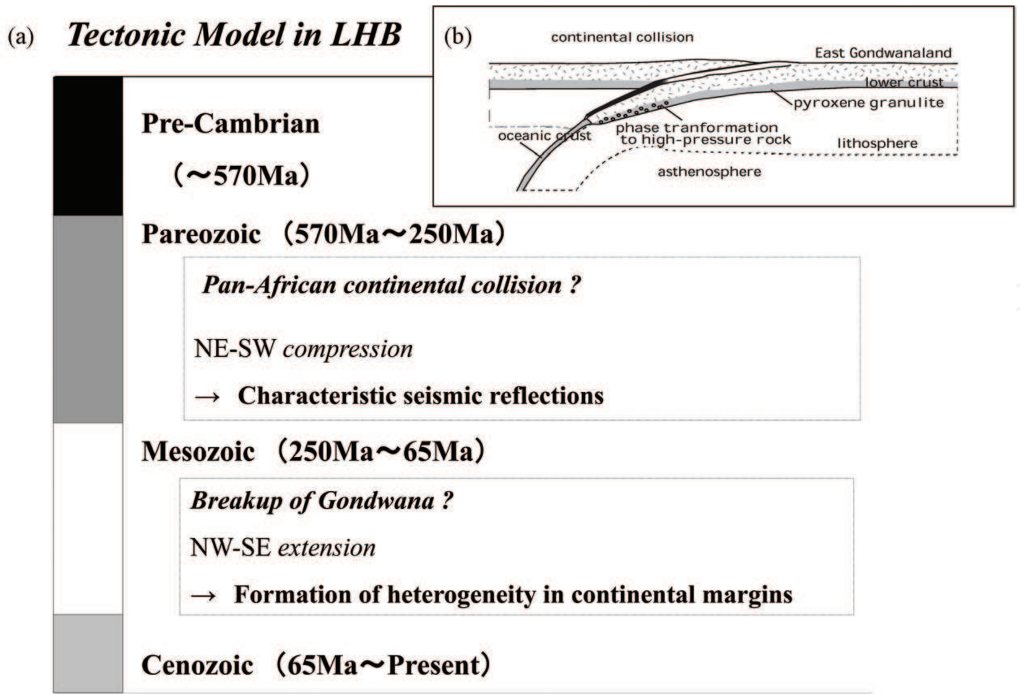

Figure 5. (a) Tectonic evolution model in LHB estimated by several seismological studies. Pan-African orogeny and mid-Mesozoic breakup could be the major two events affecting to form the present upper mantle structure. (b) Illustration of the collision tectonics around LHB at Pan-African orogeny in Eastern Dronning Maud Land-Western Enderby Land (modified after [30]). East Gondwana block includes the Archaean Napier Complex in the middle part of Enderby Land.

along the direction might produce well-defined seismic anisotropy associated with a thermal axis of the progressive metamorphism. Since the direction of paleo-compression was consistent with resultant fast polarization by SKS splitting [17], anisotropy in the upper layer in **Figure 3** could be explained by "lithospheric" deformation during the formation of LHB. **Figure 5b** illustrates the tectonic evolution of Pan-African orogeny in Eastern Dronning Maud Land-Western Enderby Land (modified after [30]). The tectonic evolution process is supposed to be divided into three stages: (1) collision of East Gondwana (Archaean Napier Complex), (2) LHB exhumation by wedge uplift of basement of underlying the Napier Complex, and (3) LHB exposure due to surface erosion, respectively.

At the breakup between Antarctica and Australia-India in 150 Ma [31], LHB experienced extensional stress, which caused thinning at the continental margins of Antarctic continent. The flat-lying reflectors above the crust-mantle boundary identified in the 2000 seismic profile (**Figure 4**) suggested the presence of an extensional stress regime in NW-SE direction resulting from the breakup. The seismic reflective layers at the crust-mantle boundary and lithospheric mantle might have been enhanced by extensional conditions during the final stages of the breakup. The LHB experienced regional high-grade metamorphism during the Pan-African age [32]; the metamorphic grade increased progressively from the north to the south, and the maximum thermal axis lied in the southernmost part of LHB [9]. The "fossil" anisotropy in the lithospheric mantle could be deformed by the past regional tectonics. A majority of the fast polarization directions in the upper layer, which corresponded to the "lithosphere," were orientated in a NE-SW direction (**Figure 3**). This direction was consistent with that of the paleo-compression stress during Pan-African and the conversion stage between East and West Gondwana terrains at the age. In these concerns, it was proposed that the mantle anisotropy had been originated by lithologic orientation of the mantle minerals during amalgamation process of Gondwana rather than the current asthenospheric flow which parallel to the absolute plate motion.

The lattice-preferred orientation (LPO) induced mechanical anisotropy developed along the direction of preexisting lithospheric structure during continental rifting [33]. The origin of anisotropy beneath Western Dronning Maud Land was pointed out as the ancient lithospheric structure modified by rifting processes during breakup [34]. Since the spreading direction off the Enderby Land was NW-SE initial stage of breakup [35], a strike of the rift was generally parallel to the continental margin of LHB. The fast polarization directions of the upper layer (“lithosphere”) in the SKS analysis were roughly parallel to the continental margin. In this regard, it was plausible that the breakup process affected the formation of anisotropy in the lithosphere. The preexisting lithospheric structure might also influence the formation of anisotropy in the succeeding breakup process.

4. Summary

Passive seismic source investigations using teleseismic data revealed heterogeneous structure in LHB. Depth variations of the upper mantle discontinuities (both for 410 and 660 km) were derived by long-period receiver functions by using local array network at the area. Shallow depths in topography of upper mantle discontinuity were identified at the continental back azimuth beneath the ice sheet. The evidence reflected the effect by paleo-upwelling flow associating the mantle plume with regard to the Gondwana breakup. Lithospheric mantle anisotropy derived by the SKS splitting was supposed to be formed by “fossil” anisotropy caused by the past tectonics in NE-SW orientation. The origin of the mantle anisotropy was assumed by the LPO involving the process of supercontinent assembly rather than present asthenospheric flow which parallel with the absolute plate motion on the Earth’s surface. In addition, several results from deep seismic surveys by using active seismic sources which were carried out on the continental ice sheet provided clear information on crust-mantle boundary, in addition to the inner lithospheric mantle seismic reflections. After processing of deep seismic reflections, the extracted lithospheric cross section implied tectonic influence of compressive stress during Pan-African age.

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