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Making and Breaking of a Continent: Following the Scent of Geodynamic Imprints on the African Continent Using Electromagnetics

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Abstract The African continent inherits a long history of continental accretion and breakup. The stage of "making" a continent goes back to the Archean, when the first continental masses formed cratons which mostly remained stable ever since. Subsequent collision of weaker continental masses was followed by several extension and compression episodes that resulted in the formation of super-continents. After the assemblage of Gondwana, a period of predominantly "breaking" , i.e., the breakup of super-continents, took over. The modern-day African continent exhibits different types of margins; continental rifting occurs side by side with recent collision. Since the late 1960s, magnetotelluric (MT) experiments have played an important role in studies of the electrical conductivity structure of Africa. The early results significantly shaped the MT community's understanding of continental-scale conductivity belts and basic characteristics of cratons and mobile belts on both crustal and lithospheric mantle scales for some decades. Modern MT studies in Africa have generally supported earlier results with high resistivities observed on cratons and low resistivities observed across mobile belts. Advances in instrumentation, data processing and interpretation resulted in higher-resolution images of the lithosphere, which in consequence induce an improved understanding of tectonic processes and geological prerequisites for the occurrence of natural resources. The high electrical conductivity of mobile belts and their relation to reactivated fault and detachment zones were often interpreted to characterize mobile belts as tectonic weak zones, which can accommodate stress and constitute zones along which continents can break. Recent breaking of the African continent can be studied on land across the East African rift; however, the lack of amphibian MT experiments across today's margins does not allow for good resolution of remnants of continental breakup processes. Naturally, the regions and the focus of the MT studies in Africa are diverse, but they all contribute to the story of making and breaking a continent.

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1 Introduction

The concept of making and breaking of continents is described by the so-called Wilson cycle (e.g., Wilson 1966; Dewey and Burke 1974). Starting this cycle with the rifting process, a continental rift develops, such that the crust stretches, faults and subsides. This process is followed by seafloor spreading, forming a new ocean basin. As the ocean widens, it is flanked by sedimented passive margins. Once subduction of oceanic lithosphere begins on one of the margins, the ocean basin closes and continental mountain building starts. During orogeny, the ocean basin vanishes, and the crust thickens and leaves a suture zone behind, which completes the mountain-building process. Later, processes such as erosion, post-orogenic and post-collisional extension or the existence of a mantle plume may thin the crust again, thereby creating the prerequisites for subsequent continental rifting.

Originally, the Wilson cycle offered an explanation for the movement of continental plates and the lack of oceanic lithosphere older than 180 Ma. Clearly, the concept is also wedded to the question: Since when in Earth's history we might refer to land masses as continents, or in other words, when did plate tectonics come into play? However, an explanation on the formation of continental, in particular old, cratonic lithosphere is not offered.

In the Hadean, formation of the Earth from dust and gas took place. Based on investigations of zircons of this age, the Earth's surface is believed to have consisted of oceans of liquid rock, boiling sulfur, impact craters and volcanoes. The young Earth also experienced heavy bombardment of rocks and asteroids from space (e.g., Valley et al. 2002). In consequence, continents—as we know them today—did not exist in Hadean times. However, analyses of the approximately 4 billion-year-old Acasta Gneiss suggest that the first continents and oceans have developed before the Archean (Stern and Bleeker 1998). "Continental" crust formed on the Hadean Earth was eventually recycled into a partially molten "magma" ocean, counteracting the longevity of the continent.

The Archean is the period during which the present continents successively took shape. Most present continents have nuclei at their cores that formed between 3 and 2.5 billion years ago during the Archean. Subduction-related amalgamation of lithospheric fragments and the addition of new mantle-derived material are considered as key processes for the present-day evolution of continents. The existence and in particular the onset of early Archean (>3.0 Ga), present-day style plate tectonics (e.g., de Wit 1998; Kato and Nakamura 2003; Furnes et al. 2007) remains controversial (e.g., Foley et al. 2003; Hamilton 1998; Van Kranendonk et al. 2007), in spite of many studies addressing this topic. Alternative models include plume-dominated processes and crustal delamination, during which vertical motions controlled the Archean dynamics. This controversy of Archean plate tectonics was heavily debated in the late 1990s (e.g., de Wit 1998; Hamilton 1998). However, both factions agree on the existence of continents during that time.

The African continent—like all continents—inherits a long evolution history of continental accretion and breakup following in principle the concept of the Wilson cycle. However, on the African continent, the tectonic remnants are well preserved over an enormous time span starting in the Archean, making Africa an ideal natural laboratory for studies of geodynamic processes of different ages. The stage of "making" a continent goes back to the time when the first continental masses formed larger fragments within a relatively narrow window of time in the Archean. Ever since many of these continental nuclei have for the most part remained stable. The formation of cratons is followed by continental collision, which typically happened in the late Precambrian and early Paleozoic when much "weaker" land masses, the so-called mobile belts, collided and were wrapped around cratons, possibly acting as crumple zones to add to the stability of cratons (Lenardic et al. 2000). The term "mobile belt" describes elongated continental masses that collided in the Precambrian and Proterozoic and underwent intensive structural deformation during orogeny. Reasons for the weakness of mobile belts compared with stable cratonic regions are still discussed. Ziegler and Cloetingh (2004) believe that the strength of mobile belt lithosphere depends largely on its composition, thermal regime, the presence of fluids and also the existence of deep-reaching faults. In an alternative explanation, Vauchez et al. (1998) argue that mechanical anisotropy might be responsible for a weakened lithospheric mantle below mobile belts. Hyndman et al. (2005) describe mobile belts as being comparatively hot and therefore weak enough to be deformed by forces transmitted from plate boundaries.

After several episodes of extension and compression, continental fragments formed the first super-continents in the Proterozoic (Begg et al. 2009; Bleeker 2003, and references therein), followed by the formation of the most recent super-continent, Gondwana in the Paleozoic. After the assemblage of Gondwana, a period of predominantly "breaking" followed. The modern-day African continent exhibits different types of margins, volcanic and non-volcanic, and rifted and sheared margins. Processes of rifting still continue today, e.g., in the East African rift zone; however, it occurs side by side with recent collision, e.g., in the Mediterranean.

This huge variety of tectonic processes and provinces coupled with the occurrence of natural resources in Africa have always attracted geoscientists. The magnetotelluric (MT) method complements other geophysical methods, such as seismics, magnetics and gravity, in imaging imprints of processes occurring in continental dynamics. While seismics is sensitive to elastic properties of rocks, MT provides images of electrical conductivity or, its inverse, electrical resistivity. This parameter is particularly sensitive to electrically conductive phases in rocks, such as fluids, melt, ores, graphite and sulfide, or temperature. For a detailed description of the MT method, I refer to textbooks (e.g., Berdichevsky and Dmitriev 2008, and references therein) and the case studies discussed in this review. These papers usually describe (1) the MT data processing, (2) its interpretation using 2D/3D forward or inverse modeling to obtain images of the subsurface conductivity distribution and (3) the resolution and robustness of obtained conductivity anomalies. In order to create a conductivity anomaly observable with MT, the conductive phases must be interconnected over large distances. This implies that the occurrence of conductive phases is often linked to tectonic processes and features, e.g., fault zones providing pathways for fluids, lubricating the system and adding to its mobility (e.g., Ritter et al. 2005). Even if the fluids have escaped over time, the mineral phases left behind often retain high conductivities and maintain the mobility of the system. Apart from fluids, graphite and sulfide play an important role in continent–continent collisions. Carbon-bearing sediments deposited at the bottom of ocean basins can be transported to deeper crustal levels during subduction processes. At pressure–temperature conditions at depth typically greater than 50 km and in shear zones, carbon can be metamorphosed to graphite. This means that conductive phases can have a significant impact on the strength of the material and can provide imprints of tectonic processes in a similar way as radiopaque material does in medical science.

Since the late 1960s, MT experiments have played an important role in studies of the lithospheric structure beneath the African cratons and surrounding mobile belts. In southern Africa, the group of van Zijl, de Beer and Gough started with numerous geoelectric and electromagnetic measurements to study known geophysical anomalies, terrane boundaries and regions of economical interest. Their results significantly shaped the MT community's understanding of continental-scale conductivity belts for some decades. The first West African MT studies in the 1980s focused on the West African Craton. Although experimental layout, data quality and interpretation methods were not ideal, first differences between cratons and surrounding belts were observed in terms of their deep electrical conductivity structure. Results were compared between different cratons in North America and Africa to unravel a common architecture of these tectonic units. With new insights into electrical conductivity mechanisms, e.g., the role of graphite, mineralization and fluids in shear zones, the focus of MT experiments and data interpretation moved more toward understanding remnants of tectonic processes, either recent with the involvement of fluids and magma or fossil with retained imprints due to graphite and mineralization along shear planes. Modern MT studies in southern Africa, across different mobile belts and cratons, have confirmed the early MT results in general; however, due to their higher resolution and larger profile coverage, the new results lead to an improved understanding of tectonic processes and geological prerequisites and conditions for the occurrence of natural resources. Moreover, images of mobile belts revealed many electrical conductivity anomalies, which were attributed to known and previously unknown shear and detachment zones. The general high electrical conductivity of mobile belts and the existence of reactivated fault and detachment zones in the crust were often interpreted to characterize mobile belts as tectonic weak zones (e.g., Haak and Hutton 1986). These weak zones seem to be important for the stabilization of continents due to their ability to accommodate stress, but, on the other hand, because of their structural weakness, they constitute zones along which continents can break.

Recent breaking of the African continent is studied by various groups across the East African Rift, which is a first-class natural laboratory for ongoing rifting processes. The African continent would also provide ideal conditions for a comparison of fossil rift zones, e.g., the West and Central African Rift, with recent ones. Unfortunately, this task has not been tackled yet. Similarly challenging are studies across existing margins, which are also related to large rifting processes. The lack of amphibian MT experiments across today's margins of Africa does not allow for good resolution of remnants of continental breakup processes. First amphibian experiments are on their way and will add an important aspect to the understanding of continental breakup.

In this paper, I will summarize the geological and geophysical, in particular electromagnetic (EM), studies that have taken place on the African continent during the last 50 years. Naturally, the regions and the focus of the studies are diverse, but they all contribute to the story of making and breaking a continent.

There are many African activities and publications that are not included in this review mainly because their work does not have an geodynamic or tectonic focus. Several papers deal with the equatorial electrojet, whose EM field strongly affects MT data of stations close to the equator (e.g., Doumouya et al. 1998; Ogunade 1995). Sedimentary basins with their aquifers are of great importance for the African continent: Several shallow MT experiments were conducted throughout the continent (e.g., Brasse and Rath 1997; Mekkawi et al. 2007) just as detailed studies of active shallow fault zones that pose a risk for nearby towns and settlements (e.g., Mekkawi et al. 2005; Mekkawi 2007).

A substantial amount of MT data have been collected for geothermal energy exploration throughout the East African rift in Tanzania and Ethiopia (e.g., Kalberkamp 2010).

2 Evolution of the African Continent

This section summarizes the complex tectonic evolution and basement geology of Africa to provide a background for the case and regional studies described below.

Since the late Proterozoic, Africa has been a center of continental accretion. From this time, several super-continents including Laurentia, Gondwana and Pangaea were born. Since the Cretaceous, breakup has formed the African continent into its modern-day shape (Fig. 1). Today, Africa is surrounded on three sides by divergent plate boundaries. Despite some compression on its northern edge, it is essentially stationary (Begg et al. 2009); however, along the East African Rift Zone, the African continent is beginning to break apart (e.g., Rosendahl 1989). Based on geophysical results and geodynamic modeling, the existence of a major mantle upwelling, the so-called African Superswell, was inferred (e.g., Nyblade and Robinson 1994; Lithgow-Bertelloni and Silver 1998, and references therein) to be responsible for a sustained uplift of central Africa.

The lithospheric architecture of the African continent as shown in Fig. 1a consists of several Archean cratons and smaller cratonic fragments, which are stitched together and flanked by younger fold belts. Its evolution through time since the late Archean is shown in Fig. 1b–g.

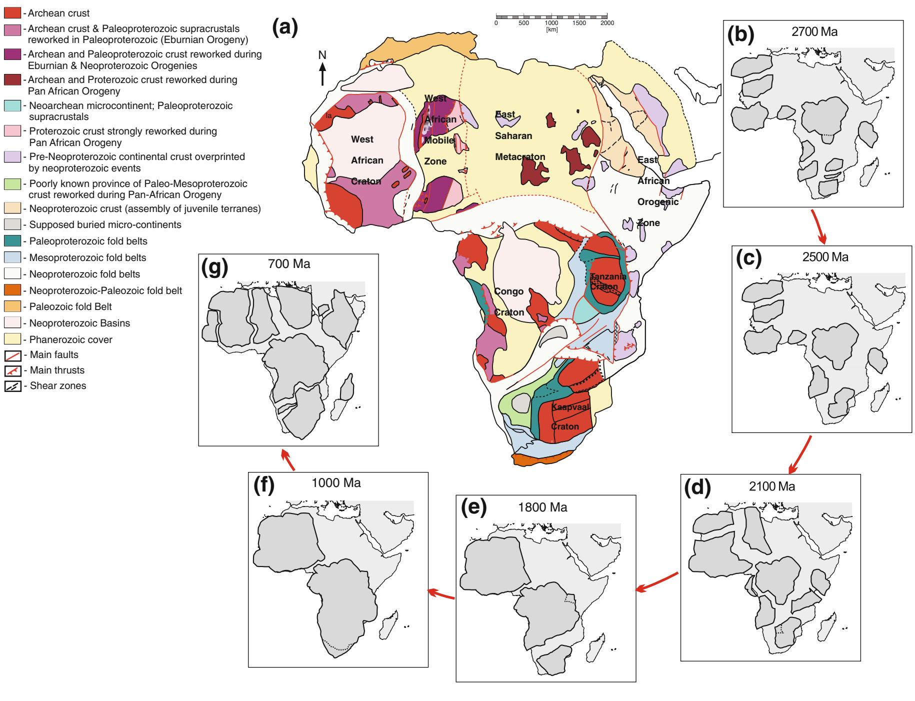

Fig. 1 **a** Geological map of present-day Africa outlining major tectonic units, modified after Begg et al. (2009). **b–g** Sketch showing the tectonic assembly of Africa for different periods, also modified after Begg et al. (2009). A detailed description can be found in the text

In the late Archean (2,700–2,500 Ma, Fig. 1b, c), cratons (in darker gray) were widely separated. Some of the cratonic nuclei were already large enough to survive subsequent modification. Later in the Proterozoic (2,100 –1,800 Ma, Fig. 1d, e), collision of cratons and cratonic fragments occurred to form larger cratons, which are the West African, the Congo and the Kalahari Cratons. Mesoproterozoic orogenic activity is limited to the margins of the Congo and Kalahari Cratons and the Mozambique micro-continent. In the late Proterozoic (1,000 Ma, Fig. 1f), convergence between the Kalahari and Congo Cratons can be observed. A series of mobile and fold belts (e.g., Gordonia and Namaqua-Natal) as well as some island arcs accreted successively around the Kalahari Craton. The last sketch (700 Ma, Fig. 1g) illustrates both the onset of a series of rifting processes from approximately 800 Ma on and the Pan-African orogeny as one of the major convergence events. Thereby, several of the African cratons were separated, but approximately 150 Ma later, the northern African cratons amalgamated and the Kalahari and the Congo Cratons converged forming the Damara orogen (Prave 1996). These compressional and extensional events clearly show that the cratonic margins and the intracratonic domain boundaries have played an important role in the tectonic evolution of Africa. These boundaries have localized successive cycles of extension, rifting and renewed accretion.

The tectonic evolution of Africa since the late Paleozoic has been dominated by rifting processes. During Permian-Triassic extensional events—before the actual breakup of Gondwana—several rift basins had been generated. Originally, only the sedimentary deposits of southern Africa were termed "Karoo Basin". Subsequently, this term has been applied to numerous extensional basins containing continental sedimentary sections of similar ages that are scattered over several thousand kilometers of the African continent (Catuneanu et al. 2005). However, only younger extensional systems were clearly related to the breakup of Gondwana. They consist of onshore extensions of tectonic events that ruptured the super-continent and generated passive margins around Africa (Lambiase 1989).

The geology of the present-day African continent (Fig. 1a) reveals a basic fabric consisting of several major Archean cratons and smaller cratonic fragments, stitched together and flanked by younger fold-and-thrust belts. Many of the tectonic units were reworked and overprinted several times throughout Africa's evolution. Large parts of the basement rocks in Africa are covered today by basins and young Phanerozoic sediments.

3 Pioneering EM Work in Africa

Since the late 1960s, pioneering geo-electric and MT experiments concentrated on three focal areas in Africa: southern Africa, western Africa and the East African Rift zone. Results were already compiled in review papers by Hutton (1976), Haak and Hutton (1986) and Hjelt (1988). In this review, I will briefly mention highlights of this work as some fundamental ideas developed during this time, which significantly shaped the MT community's understanding of continental-scale conductivity belts and tectonic characteristics of cratons and mobile belts for some decades.

Probably, the most prominent group doing EM research in Africa focused on tectonic structures in southern Africa. van Zijl (1977b) compiled the results of deep geo-electric soundings and magnetometer array experiments from almost a decade into a keynote publication. In the paper, the author described marked differences between mobile belts and cratonic areas in terms of their crustal electrical conductivities and developed a schematic resistivity model of the crust (Fig. 2a). While the mobile belts were assumed to

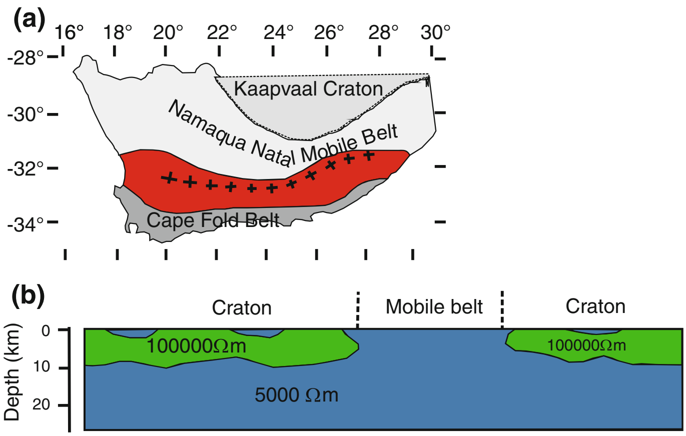

Fig. 2 Summarizing some of the early geo-electric and magnetic results that led to the postulation of the Southern Cape Conductive Belt (SCCB) and a generalized description of the characteristic properties of mobile belts and cratons. **a** Map showing prominent tectonic units in southern Africa together with location of the maximum of the Beattie Magnetic Anomaly (BMA (*line* of *crosses*), Beattie 1909) and the SCCB (*red color*) as derived from magnetometer array measurements modified after de Beer and Gough (1980). **b** Proposed fundamental properties of cratons and mobile belts as derived from both deep geo-electric and magnetometer array measurements modified after van Zijl (1977a)

be rather homogeneous in their resistivity distribution (5,000 Ωm) down to approximately 30 km depth, the cratons were interpreted to consist of an extremely resistive upper layer of ~100,000 Ωm in the upper 5–10 km (Fig. 2b). van Zijl (1977a) suggested that mobile belts may be reworked cratons.

Apart from a tectonic interpretation of the southern African deep geo-electric soundings (e.g., Meyer and de Beer 1987), several methodological approaches and developments such as one-dimensional (1D) inversion (Petrick et al. 1977) were tested.

In addition to deep geo-electric experiments, magnetometer array studies were conducted over extensive regions (de Beer et al. 1982b). de Beer et al. (1976) revealed a zone of concentrated induced currents at lithospheric depth crossing Namibia, Botswana and Zimbabwe based on a reversal in the vertical magnetic field at periods of ~1,000–10,000 s. The inferred east–west trending zone of high electrical conductivity was found to be approximately 100 km wide in Namibia and widening toward western Zimbabwe to 250 km. Based on the half-width of the normalized anomalous magnetic fields and the induction vectors, the conductor was inferred to be at crustal depth following the Zambezi rift, the Okavango Delta into the Damara Belt in Namibia. However, the interpretation based on the anomaly's half-width seems to be in contrast to interpretations based on the period range of the observed anomaly, which would relate the anomaly to mantle depth. Therefore, de Beer et al. (1975) interpreted the origin of the high-conductivity belt to be caused by either high temperatures in the upper mantle or a fracture zone filled with fluids or graphite in the lithosphere, or a combination of both. The authors speculated on a correlation of the high conductivities with a line of weakness within the continent (e.g., Fyfe and Leonardos Jun 1973). de Beer et al. (1975) suggested that the high-conductivity belt is associated with the continuation of the East African Rift system into the central/southern part of Africa.

A similar magnetometer array study was conducted in South Africa in 1971 by de Beer and Gough (1980) following several ultra-long Schlumberger soundings throughout the country (e.g., van Zijl 1969). The electric and in particular the magnetic results revealed a crustal zone of high conductivities crossing the southern tip of Africa in an east–west direction. This high-conductivity zone was named "Southern Cape Conductive Belt" (SCCB, see Fig. 2a). Because of its spatial relation to the static magnetic anomaly—the Beattie Magnetic Anomaly (BMA, see Fig. 2a) (Beattie 1909)—a common source in terms of a serpentinized paleo-oceanic sliver of ~100 km width and ~30 km depth was proposed. This interpretation survived for several decades (e.g., Paton and Underhill 2004; Pitts et al. 1992; Harvey et al. 2001; Eglington, 2006) although some colleagues also suggested an alternative cause of the high electrical conductivity based on the existence of mineralized fault and shear zones (Corner 1989). However, the idea of a SCCB also made its way into geology as several geological and tectonic cross sections through the Namaqua-Natal Mobile Belt (NNMB) and the adjacent Cape Fold Belt (CFB) included the SCCB as a tectonic unit (e.g., Turner 1999). The famous conductivity anomaly was finally reinterpreted on the basis of modern high-resolution MT data from 2004 (Weckmann et al. 2007a, b; See also Sect. 4).

A second large group of scientists mainly from Great Britain focused on studying the Kenya Rift as part of the East African Rift Zone. Beamish (1977) reported on geomagnetic deep sounding results of a magnetometer array study from 1972 and 1971 (Banks and Ottey 1974). By calculating vertical magnetic as well as interstation transfer functions, they delineated two prominent electrical conductivity features related to the Kenya Rift: The first feature was rather shallow coinciding with the rift axis, while the second was located east of the rift at mantle depths. Banks and Beamish (1979) interpreted these high-conductivity anomalies with the help of other geophysical data as zones of melting in the crust and upper mantle. For the anomaly related to the central rift, they estimated an average melt concentration of 5–10% to explain the observed resistivities of 10 Ωm. In addition, Rooney and Hutton (1976) reported on first MT measurements in and around the Kenya Rift valley. In contrast to Banks and Beamish (1979), they suggest that a combination of high temperatures and water saturation caused the conductivity anomaly directly in the rift valley rather than partial melts. However, they also suggest further EM work to map a possible continuity of the crustal zone of high conductivity from the East African Rift to southwest Africa as assumed by de Beer et al. (1975).

A third focus of experimental work was on mobile belts and cratons in West Africa. While magnetometer arrays and deep geo-electric soundings were applied in southern and eastern Africa, EM activities in West Africa focused on the MT method. Ritz (1984) described in his paper results of 23 MT sites along an approximately 600-km-long profile in Senegal (West Africa). This experiment focused on several tectonic zones and their associated boundaries: the West African Craton, the West African Mobile belt and the Senegal sedimentary basin. In studying the structure of the Senegal sedimentary basin, Ritz (1984) expected to gain new insight into processes related to the opening of the South Atlantic and the differences between mobile belts and cratons. The two-dimensional (2D) forward models showed a conductivity contrast between the basin and the mobile belt mainly in the crust, while the underlying mantle seemed to have the same electrical conductivity properties. However, a marked difference in lithospheric mantle depth was observed between the mobile belt and the craton. While Ritz (1984) used on the order of 20 MT sites, Oni and Alabi (1972) in Nigeria concluded that 3 MT sites were insufficient to obtain reliable models of the subsurface and subsequent tectonic interpretation. Nevertheless, Oni and Agunloye (1976) already developed a 3D forward model in an attempt to explain the results of their three MT sites in Nigeria.

Based on several MT experiments between 1974 and 1977 in Niger and Burkina Faso (former Upper Volta), Ritz (1983) investigated the lithospheric conductivity structure beneath the West African Craton and the Central African Mobile Belt. Contrary to the conceptual conductivity image by van Zijl (1977a) (see Fig. 2b), he suggested the resistive cratonic material to continue downward to approximately 130 km depth, while beneath the mobile belt, low resistivities were observed at lower crustal depths. A compelling explanation for apparently different properties of cratons in southern Africa, Australia and West Africa could not be provided at that time.

Tectonic units characterized by different resistivities were already taken up by Hutton (1976). She suggested that instead of searching for conductivity profiles being characteristic of a particular tectonic type or age of tectonic activity, existing studies should be extended to come up with an improved and maybe unique interpretation. Thereby, she clearly argued for an improved and extended database by doing more experiments rather than coming up with revised interpretations of existing data. Ten years later, Haak and Hutton (1986) reinterpreted some of the observations of the 1970s. They suggested that different tectonic processes like rifting or continental collision can produce the same type of electrical conductivity anomaly in terms of elongated conductors. On the contrary, Hjelt (1988) pointed out that, since the results are based on single profiles only, the database seemed to be not appropriate to establish characteristic properties of different tectonic units throughout the African continent.

4 Making a Continent: Case Studies

Several MT studies on different aspects of continental collision—the making of a continent—have taken place in southern Africa. However, as already pointed out, the story of making a continent does not only involve compressional events. Instead, we always look at cycles of compression and extension, which in the end resulted in the formation of supercontinents. Of similar importance for Africa's current shape are also oblique collisions and shearing processes. Figure 3 illustrates the different major tectonic units in southern Africa together with the location of MT experiments, which are discussed in detail below. Often, the remoteness of some areas and/or the political situation of some countries has prohibited an ideal site coverage for regional studies.

In the late 1990s, Bailey et al. (2000a, b) investigated shallow basins in the Zimbabwe valley. The Zambezi Valley basins are thought to be part of a series of Karoo basins in south central Africa, which have evolved during the first-order cycle of super-continent assembly and breakup of Pangaea. The "main" Karoo basin is located in South Africa; however, the term was extrapolated to other parts of Gondwana to describe the sedimentary fill of basins of similar age (Catuneanu et al. 2005). van Zijl (1977a) already described the Karoo sedimentary basin in South Africa as consisting of several distinct conductive layers, which cover large parts of the southern African continent. A decade later, Losecke et al. (1988) detected some highly conductive layers in the Lower Zambezi Valley and in the Zambezi Mobile Belt, for which the authors suggested a link to the conductive structures of the Damara Belt (e.g., de Beer et al. 1982b, 1976, 1975). These early MT measurements were supplemented by a first audio-magnetotelluric profile farther west through the Mana Pools Basin (Whaler and Zengeni 1993). Due to the higher frequencies recorded in this experiment, some very shallow features within the sedimentary basin could be resolved. However, resolution of deeper structures could only be obtained by a follow-up experiment some years later extending the frequency range to approximately 1 mHz

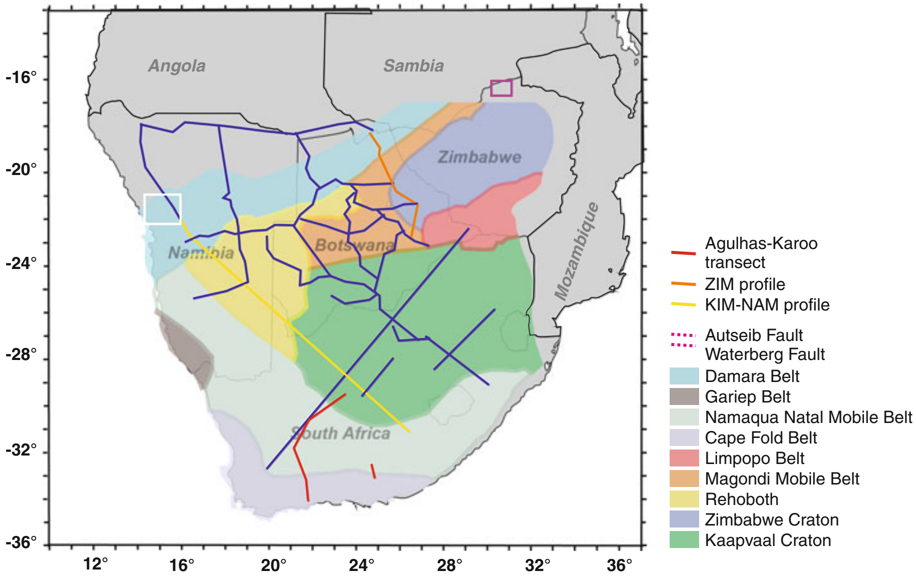

Fig. 3 Regional-scale map of southern Africa showing major tectonic units discussed in the text. Black lines indicate MT profiles of the SAMTEX project (Evans et al. 2011; Jones et al. 2009; Muller et al. 2009; Miensopust et al. 2011) throughout Namibia, Botswana and South Africa. Red lines show high-resolution MT profiles of the *Inkaba yeAfrica* project (de Wit and Horsfield 2006; Weckmann et al. 2007a, b) A *yellow rectangle outlines* the region of MT experiments in the Lower Zambezi valley basins by Bailey et al. (2000a, b); Whaler and Zengeni (1993) and Losecke et al. (1988). A *white rectangle* shows the area in which a regional MT experiment (200 km) and a local MT experiment (20 *km x* 20 *km*) were conducted by Ritter et al. (2003b) and Weckmann et al. (2003b)

(Bailey et al. 2000b). Two-dimensional inversion and forward models reveal a zone of high electrical conductivity in the Upper Karoo. A deeper conductivity anomaly is probably present; however, the inversion seems to be unable to resolve these two structures as separate features. While the cratonic region to the south shows high resistivities as expected, the resistivities below the seismically defined basement seem to be quite low. Bailey et al. (2000b) suggested that the Mana Pools basin is a half-graben in contrast to the Lower Zambezi basin, which was interpreted as a pull-apart basin (Bailey et al. 2000a). The craton to the south of the Mana Pools basin exhibits anomalous, comparatively high conductivities, while the typical cratonic high resistivities are observed for the same craton south of the Lower Zambezi basin and also for the craton to the north of the Mana Pools basin. Based on these observations, Bailey et al concluded that the cratons are not affected by processes such as basin formation which take place in the adjacent mobile belts.

One of the largest MT experiments in Africa is the South African MagnetoTelluric Experiment (SAMTEX) project, being conducted by a consortium of several university partners, geological surveys and industry from five countries. The experiment is designed to gain insight into the electrical conductivity structure of the crust and lithospheric mantle beneath the southern African cratons and their neighboring terranes. Within the first phase of the project, the site coverage was mainly following the layout of the South African Seismic experiment (SASE; Carlson et al. 1997), which covered a corridor of a couple of hundred kilometers from the Western Cape in the southwest to Zimbabwe in the northeast.

The complete SAMTEX MT database comprises data from more than 730 sites spread over an area of one million square kilometers, involving South Africa, Namibia and

Botswana. The experiments were conducted in four main phases between 2003 and 2008. The main target of these experiments was the lithospheric mantle. Therefore, the experimental design consisted of several long profiles adding up to an areal site distribution over southern Africa with a typical site spacing of approximately 20 km for the broad-band instrument recordings in a period range of 0.003–5,000 s. An extension toward longer periods was accomplished by long-period MT (LMT) recordings (<10,000 s) with a spacing of $\sim$60 km. This setup allows a "high-resolution" mapping (Jones et al. 2009) for the subcontinental lithospheric mantle (SCLM), but crustal structures might be inadequately resolved due to spatial aliasing. However, this data set provides excellent opportunities to characterize large regions by mapping the electrical conductivity. Mapping electrical conductivities over large volumes can be accomplished with different approaches: 3D forward modeling and/or inversion or the application of imaging methods (e.g., Weckmann et al. 2003a; Caldwell et al. 2004). 3D inversion of such an extensive area is time consuming and computationally expensive. Imaging methods are faster but restricted to imaging pseudo-depths as regional maps can only be created for a specific period as a proxy for penetration depth. Weckmann et al. (2003a) used a transformation of the impedance tensors from MT experiments in the Damara Belt into current ellipses (see Fig. 5a).[1] Thereby, the MT response of the subsurface is transformed into an equivalent anisotropic Earth model. The results are displayed as ellipses, whose orientation (major axis) reflects the direction of preferred current flow. The ellipticity is a measure of the strength of a nearby conductivity contrast. With this approach, Weckmann et al. (2003a) were able to resolve the internal structure of one of the major faults within the Damara Belt (Namibia). Jones et al. (2009) used an alternative approach in order to image large tectonic units rather than internal details of more confined tectonic features. The authors calculated Niblett–Bostick (e.g., Niblett and Sayn-Wittgenstein 1960; Bostick 1977) maximum resistivities and Niblett–Bostick depths for creating maps of the conductivity distribution (Fig. 5b). Such an approach was already used in the 1970s to compute 1D resistivity curves to characterize tectonic units (van Zijl 1977b). The maximum resistivity maps seem to give robust information on large-scale regional features, such as craton boundaries, but oversimplify and average complex features. Comparison with maps of seismic velocities shows a good correlation in the lithospheric mantle beneath southern African cratons. Not only the seismic velocities below the Bushveld Complex were reduced by the large igneous intrusion but also the electrical resistivity seems to be significantly lower when compared to the rest of the craton. The Bushveld Complex is a large layered igneous intrusion within the crust, which has been tilted and eroded and now outcrops around what appears to be the edge of a large basin. Several authors discussed whether the Bushveld Complex has mantle or crustal origin (Richardson and Shirey 2008). Correlation of information from kimberlites with maps of the Niblett–Bostick maximum resistivity suggests a spatial relation between diamondiferous kimberlite fields and the edges of the cratons where larger gradients in electrical resistivity are observed. The areas with larger gradients are indicative of shallower lithospheric mantle roots compared to the center of the craton, suggesting that either kimberlite magmas are unable to penetrate extremely thick cratonic roots or the initiation of kimberlitic eruptive magmas takes place at shallower depths.

Hamilton et al. (2006) concentrated on the comparison of electrical anisotropy in the MT data with seismic shear-wave splitting results from the SASE experiment (Silver 1996). So-called SKS shear-wave splitting studies are sensitive to zones of seismic anisotropy along the waves' pathways (Silver et al. 2004). Seismic anisotropy in the upper

[1] The experiment is described in detail below.

mantle is predominantly interpreted to arise from the preferred orientation of anisotropic minerals as a result of mantle deformation caused by past and present geological processes (Silver 1996). So far it seems that there is no direct link between seismic and electric anisotropy. Hamilton et al. (2006) observed typical characteristics of electrical anisotropy in the long-period SAMTEX MT data (e.g., phase splitting); however, the electrical results for the upper lithospheric mantle do not seem to correlate well with the shear-wave splitting results. Instead, the electrical responses associated with upper mantle depths are likely caused by large-scale, regional geological structures.

Muller et al. (2009) focused on a 1,400-km-long profile, consisting of 69 broad-band and 10 LMT sites across the western part of the Kaapvaal Craton, the Rehoboth Terrane and the Ghanzi-Chobe/Damara Belt (KIM-NAM; see Fig. 3). Two-dimensional inversion models (Fig. 4a) of the MT data revealed lateral variations in the electrical resistivity distribution of the lithospheric mantle. The Rehoboth terrane, which has been interpreted as an Archean craton, shows a marked difference to the Kaapvaal Craton. The model in Fig. 6 gives evidence for low resistivities of the deep lithospheric mantle beneath the Rehoboth terrane; the typical resistive deep roots of cratons are not found. The Ghanzi-Chobe/Damara Belt seems to exhibit the most conductive lithospheric mantle along the profile. Based on the assumption that electrical resistivity of major mantle minerals (olivine, pyroxene and garnet) is highly sensitive to temperature (Jones et al. 2009), Muller et al. (2009) deduced the parameter of lithospheric thickness from the obtained resistivity section. Therefore, average resistivity profiles with depth are computed for a footprint of approximately 200 km to characterize particular tectonic units. A comparison of electrical resistivity versus depth profiles for the eastern and western Kimberly block of the Kaapvaal Craton as well as for the Rehoboth terrane and the Ghanzi-Chobe/Damara Belt shows clear differences in the bulk resistivity distribution. As the electrical resistivity of mantle minerals decreases significantly with increasing temperature (e.g., Constable 2006, and references therein), a lower bulk resistivity is indicative of a hotter geotherm, which is associated with a thinner lithosphere. Muller et al. (2009) compared the geotherms derived from the electrical resistivity profiles with geotherms recorded in xenoliths from kimberlite pipes, which represent thermal conditions during eruption.

Miensopust et al. (2011) show 2D inversion results of a second profile (ZIM) of the SAMTEX data set (Figs. 3, 4b). This 600-km-long profile consists of 31 broad-band MT sites and crosses the Magondi Mobile Belt and the Ghanzi-Chobe Belt as well as some marginal parts of the Zimbabwe Craton. Similar to the KIM-NAM profile discussed by Muller et al. (2009), the Zimbabwe Craton is associated with a resistive lithospheric mantle, indicating the coolest geotherm and thus the thickest lithosphere. Thinner lithosphere interpreted on the basis of lower electrical resistivities is found below the mobile belts. However, the Ghanzi-Chobe Belt appears to exhibit higher resistivities in the crust and lithospheric mantle than the KIM-NAM profile farther west.

In the same region through the Damara Belt in Namibia (see Fig. 3), high-resolution MT measurements were conducted by Ritter et al. (2003b) and Weckmann et al. (2003b) to study characteristics of the remnants of the continental collision in the Early Cambrian. Within two different experiments, the regional structure of the Damara Belt with its high-conductivity belt (de Beer et al. 1982b; van Zijl and de Beer 1983) was investigated, and a high-resolution study of one of the major fault zones, the Waterberg Fault/Omaruru Lineament (WF/OL), was conducted. MT data were collected on both regional (200 km) and local (20 km) scales, with the majority of the 110 sites focused on the local profiles, where site spacings ranged from 500 to 2,000 m. The regional-scale MT model provides insight into the deep structure of the Damara Belt (Ritter et al. 2003b). A generally resistive upper

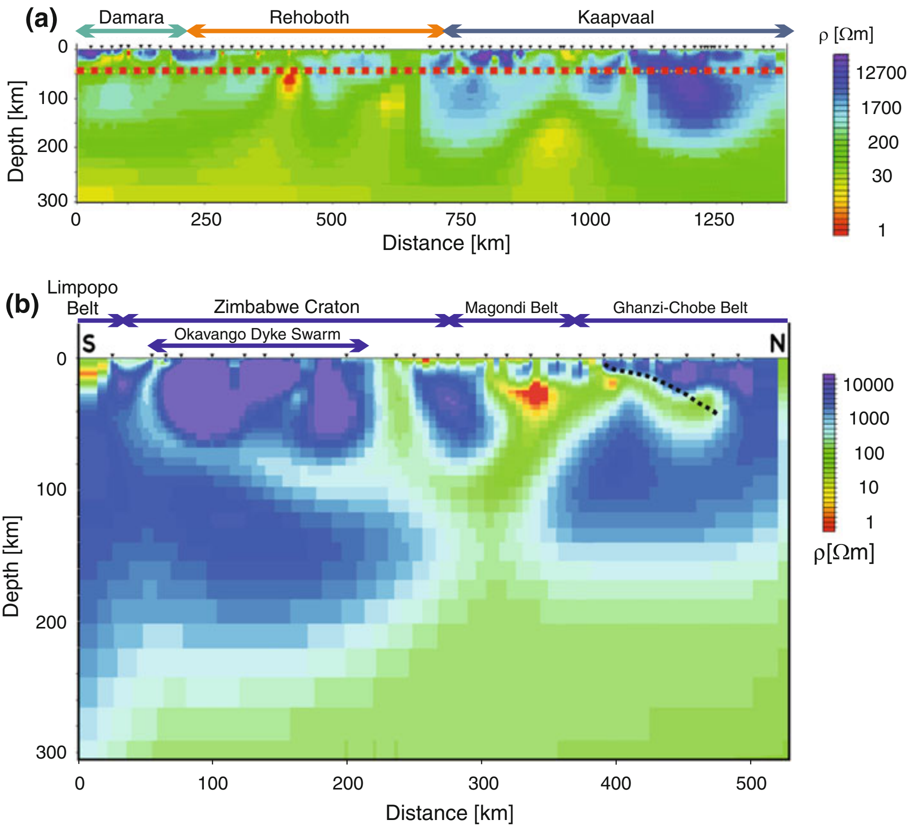

Fig. 4 Two-dimensional electrical resistivity models for **a** the KIM-NAM and **b** ZIM profiles derived from 2D inversion modified after Muller et al. (2009) and Miensopust et al. (2011). Zones of low electrical resistivity are shown in *red*, zones of high resistivity (or low conductivity) in *blue colors*. The surface extent of the respective geological units is indicated by *arrows* above the resistivity sections. Both profiles run in southeast–northwest direction, but they are separated by more than 500 km. In both models, the cratonic terranes exhibit resistive and thus cool and thick lithospheric root, while the mobile belts seem to be much more conductive correlating with hotter and thinner lithosphere. The *red dashed line* along the KIM-NAM profile in **a** shows crustal thickness. The *black dashed line* in figure **b** indicates the northward-dipping boundary between the resistive Ghanzi-Chobe Belt to the north and the Magondi Belt to the south

crust tends to increased conductivities for the lower crust. The upper crust is furthermore pierced by two subvertical conductors, whose locations coincide with the surface expression of two of the major faults of the Damara Belt, the Autseib Fault (AuF) and the Waterberg Fault/Omaruru Lineament (WF/OL), suggesting that they represent the continuation of these shear zones at depth. Both structures appear to terminate at the lower crustal conductor, the top of which is interpreted as a lower crustal detachment. The geometry of the conductive structures could reflect a regional shear system in which upper crustal listric faults pass into a detachment zone in the middle crust. The high electrical conductivity is interpreted in terms of graphite (or other forms of mineralization) enrichment along the shear planes. The regional-scale shear system that likely makes up a zone of crustal weakness may have originated in Pre-Damara times and had probably experienced several episodes of crustal reactivation before the intrusion of basaltic dike

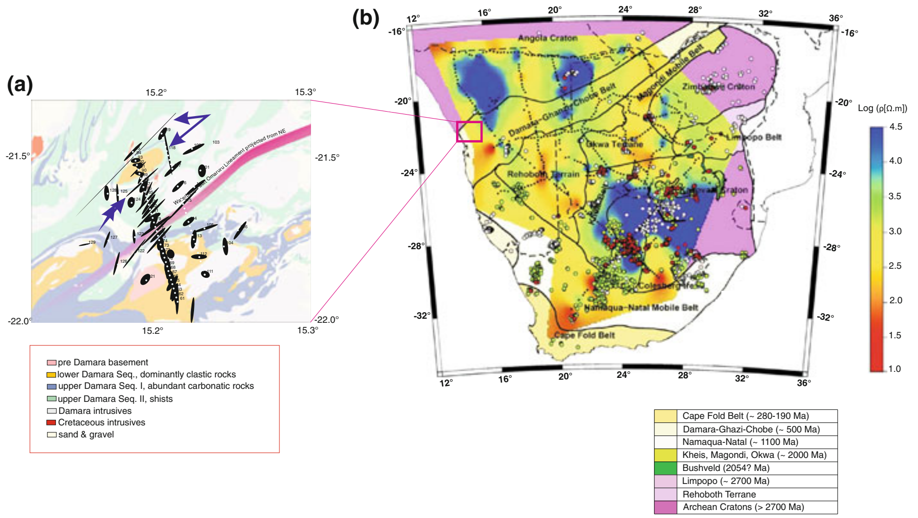

Fig. 5 **a** Using current ellipses to image structural details of the MT data set across the Waterberg Fault / Omaruru Lineament (WF/OL) in Namibia (Weckmann et al. 2003a). The length of an ellipse defines a measure of a nearby conductivity contrast, while the orientation shows the direction of preferred current flow. Parallel and elongated ellipses north of the WF/OL can only be explained by a 10-km-wide fault zone showing internal electrical anisotropy parallel to the fault. Extremely elongated ellipses (marked with a *blue arrow*) image a shallow, very conductive ring structure of graphite-bearing marbles. **b** Application of an imaging method to the SAMTEX data set (Jones et al. 2009). This approach is based on the maximum resistivity values for a depth of 200 km using the Niblett–Bostick transformation (e.g., Niblett and Sayn-Wittgenstein 1960; Bostick 1977). *Colored circles* on top show kimberlite locations (*red* ≙ diamondiferous, green ≙ non-diamondiferous and *white* ≙ not defined or unknown. *Black dots* indicate site locations. Zones of high resistivity (*blue*) correlate with cratonic mantle lithosphere. The occurrence of diamondiferous kimberlites seem to be mostly confined to the craton boundaries

swarms during the Cretaceous rifting and magmatism associated with the opening of the South Atlantic.

The local MT study (Weckmann et al. 2003b) consisted of two dense profiles crossing the WF/OL with additional off-profile sites to provide areal coverage of the lineament zone. The MT data show strong 3D effects that originate from a more complicated Earth structure than the 2D lineament structure observed at the surface would suggest. Based on a novel imaging method (Weckmann et al. 2003a; see also Fig. 5a), these effects can be attributed to a 10-km-wide and at least 14-km-deep zone of anisotropic conductivity in the shallow crust with a strike direction parallel to the WF/OL. In general, fluids cannot be ruled out as a cause of the observed crustal conductivity; however, there is no supporting field evidence for hydrothermal alteration along the faults. In contrast, graphite-bearing marbles are widespread in the area and suggest that shearing could create an interconnected graphite network on kilometer length scales. Metamorphic facies indicate that the area surrounding the WF/OL was once at mid-crustal depths. Considering that the upper crust has been eroded, this implies that the fault zone penetrated throughout the entire crust. Fossil shear zones, which exhibit their lower crustal, former ductile levels at the Earth's surface today, can be regarded as proxies for the deep roots of active shear zones. In a recent, active environment, deeper levels of faults are often difficult to image in detail because of the shielding effect in the presence of upper crustal high conductivities.

Another continental-scale conductivity belt found in Africa is the Southern Cape Conductive Belt (SCCB; de Beer et al. 1982a). This anomaly was interpreted to be a remnant of a continental collision resulting in an approximately 100-km-wide and 30-km-deep reaching zone of serpentinized paleo-oceanic crust (e.g., Pitts et al. 1992). This important conductivity anomaly was revisited in the framework of the *Inkaba yeAfrica* project (de Wit and Horsfield 2006) with modern and high-resolution MT measurements. The MT profile follows an onshore/offshore geoscientific traverse from the Agulhas plateau through the Cape Fold Belt (CFB), the Namaqua Natal Mobile Belt (NNMB) onto the Kaapvaal Craton. As the focus of the MT experiments (see Fig. 3) is crustal and upper mantle structures, a dense site spacing of 2–3 km was used for the broad-band MT recordings (0.001–1,000 s), which were supplemented by LMT recordings (<50,000 s) every 10 km.

To study the SCCB in detail, 73 sites along a 140-km-long section of the Agulhas-Karoo profile (Fig. 6, profile kilometer 120–260) in the west [cf. profile location in Fig. 3; (Weckmann et al. 2007b)] and 33 sites along the 70-km-long line 350 km farther east [cf. profile location in Fig. 3; (Weckmann et al. 2007b)] were deployed. Two-dimensional conductivity models (Fig. 6) at a scale of the entire crust exhibit several distinct zones of high conductivity: (1) Beneath the surface trace of the axis of the BMA, a high-conductivity anomaly at 5–10 km depth is observed (c1 in Fig. 6); the shorter eastern profile also exhibits a narrow zone of high conductivity, here reaching to mid-crustal levels (c2 in Fig. 6). This observation suggests that the conductivity anomaly is a contiguous feature in the east–west direction. To test whether the BMA and the spatially related narrow zone of high conductivity can have a common source, 2D magnetic modeling studies have been applied (Weckmann et al. 2007a). They revealed that a possible source of the BMA must have a width of at least 50–100 km, incompatible with the observed high-conductivity anomaly beneath the maximum of the BMA. Therefore, Weckmann et al. (2007b) interpreted the subvertical conductors in terms of a crustal scale fault zone. Such a fault zone could be a feature embedded within the Beattie magnetic anomaly, but it cannot explain the much wider SCCB (de Beer et al. 1982a). Weckmann et al. (2007b) observe generally high "background" conductivity of $\sim 30\ \Omega$m (green colors beneath labels NNMB in Fig. 6) for the entire NNMB and the CFB. These relatively high electrical conductivity values are unexpected for metamorphic basement rocks (e.g., Telford et al. 1990). However, it is possible that the SCCB deduced from sparse magnetometer array measurements is an integrated result of the generally conductive NNMB and the conductivity anomalies within. (2) A second prominent anomaly is a shallow subhorizontal band of high conductivity (c3 in Fig. 6), which can be linked to the 50- to 70-m-thick pyritic-carbonaceous Whitehill formation in the Karoo sedimentary basin. This marker horizon is intersected in several deep boreholes and can be traced throughout the Karoo basin (Branch et al. 2007). Catuneanu et al. (2005) reported on very similar stratigraphy throughout the family of Karoo basins in Africa, which suggests that a similar formation could explain the observed shallow high-conductivity layer in the Lower Zambezi Valley Basin and the Mana Pools Basin.

South of the NNMB, the Cape Fold Belt was accreted during Permo-Triassic times and experienced several cycles of extension and compression, resulting in an inversion tectonic setting with extreme rock deformation. Although it is widely acknowledged that the CFB plays an important role for the reconstruction of Gondwana, there is still an active debate on its tectonic evolution. The 2D inversion result of the CFB (Fig. 6, profile kilometers 0–100) shows good correlation with surface geology (Weckmann et al. 2011). The MT model images deep and resistive roots of the CFB mountain ranges (r1 and r2 in Fig. 6), which are incompatible with a major crustal detachment zone and thick-skinned tectonics. The Kango Fault, which runs south of the resistive Kango formation (r3 in Fig. 6), seems

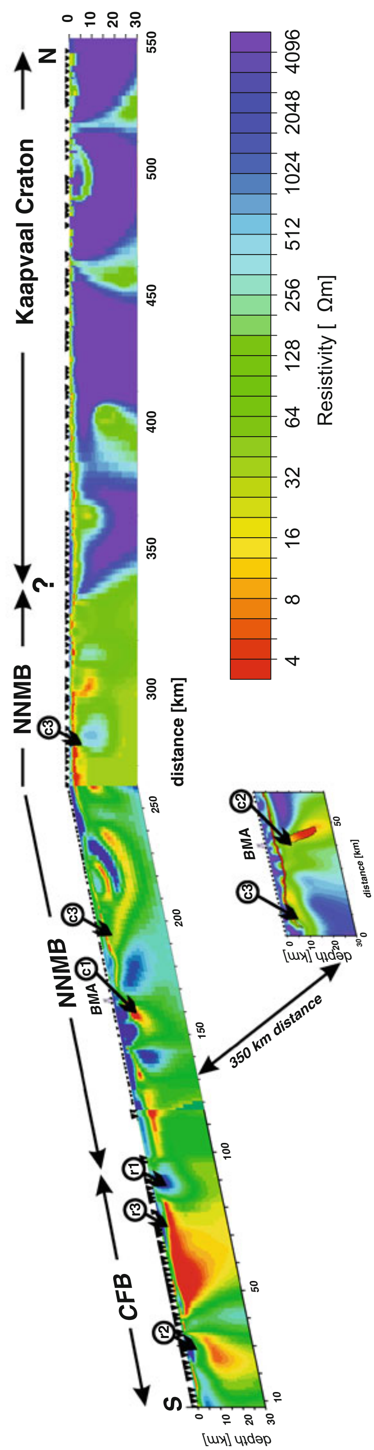

Fig. 6 Compilation of 2D inversion results of several MT experiments (Weckmann et al. 2007a, b, 2011, 2008), for reference see also Fig. 3 crossing different tectonic units of the Cape Fold Belt (CFB), Namaqua-Natal Mobile Belt (NNMB) and into the Kaapvaal Craton. Zones of low resistivity are shown in *red*, zones of high resistivity (or low conductivity) in *blue colors*. *Black triangles* indicate the locations of MT sites. The model is cut at a depth of 30 km, focusing on crustal features. A detailed discussion of prominent conductivity anomalies, labeled with c1–c3 and r1–r3, is provided in the text

to be a rather shallow ($\sim$2 km) feature. In fact, the shallow dip of the Kango fault and the Kango inlier, as a major tectonic building block of the CFB, suggests predominantly thin-skinned tectonics.

The northern section of the Agulhas-Karoo transect (cf. Fig. 6; profile kilometer 260–550) crosses the boundary between the NNMB and the Kaapvaal Craton (Weckmann et al. 2008). This part of the profile is almost coincident with the first SAMTEX line (Evans et al. 2011; see also Fig. 3); however, the focus of this experiment was on resolving structural details of the boundary between the Kaapvaal Craton and the younger mobile belt. As mentioned before, the NNMB exhibits low electrical resistivities of approximately 30 Ωm, while the cratonic rocks show resistivities >5,000 Ωm (blue colors beneath label Kaapvaal Craton in Fig. 6). Interestingly, the geologically inferred craton boundary is located farther northeast when compared with the onset of high resistivity material. While direct surface observations of the boundary are impossible due to the thick sedimentary cover of the Karoo basin, geochemical analysis of xenoliths from this area (Kobussen et al. 2008) supports a modified boundary location.

Processes of continental collision can be studied at the northern edge of the African continent. The Atlas mountain chains developed from the inversion of a Jurassic rift or transtensional basins as a consequence of continental convergence between Africa and Europe during the Cenozoic. The Atlas System of Morocco is an intracontinental mountain belt extending for more than 2,000 km along the northwest African plate with a predominant northeast–southwest trend. In the late 1980s and early 1990s, MT measurements were conducted through the Atlas Mountains by Schwarz et al. (1992). They presented stitched 1D inversions and maps of induction vectors to deduce several crustal zones of high conductivities located at the middle crustal levels. These zones with a listric shape were interpreted as remnants of inversion tectonic processes. In the last few years, this region has aroused geophysicists' interests again. The multilateral PICASSO project, which focuses on southern Spain and Morocco, aims to test hypotheses for material recycling from the surface back into the mantle. In the area, conflicting models suggested that the region is either a relict subduction system or a zone of mantle delamination. In the framework of this project, onshore/offshore seismic and MT data were collected in 2007 (e.g., Evans et al. 2010; Kiyan et al. 2010). At the crustal scale, first results reveal a middle to lower crustal conductive layer stretching from the Middle Atlas southward toward the High Moulouya basin. The most resistive (and therefore potentially thickest) lithosphere was found beneath the Central High Atlas.

5 Breaking a Continent: Case Studies

The convergence between the African and Eurasian plate which forms the Atlas system in the west had also consequences farther east as it led to fragmentation of the African plate and the formation of the Arabian plate (cf. Fig. 7). Along the eastern edge of the African plate, the Dead Sea transform (DST) accommodates the differential motion between Africa and Arabia by left-lateral slip. This fault zone extends over 1,000 km from the Red Sea rift to the collision zone in eastern Turkey. Since 2000, several MT experiments investigated the DST in a simple transform fault setting and in a pull-apart basin (Dead Sea) setting (Ritter et al. 2003a; Meqbel et al. 2008). 2D and 3D inversion results from the Dead Sea Basin reveal the lateral boundaries as abrupt changes from moderately low (20 Ωm) to high (>1,000 Ωm) resistivity at depths of 3 and 4 km under the eastern and western segments of the profile, respectively (Fig. 8a). The locations of the boundaries coincide

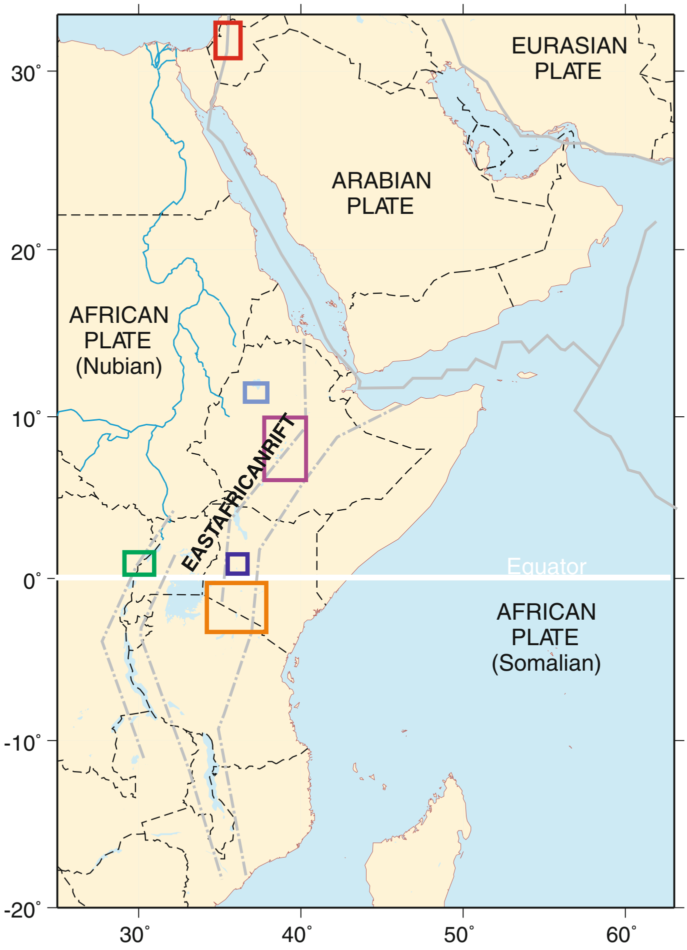

Fig. 7 Tectonic setting of the eastern African plate. Rectangles indicate the location of recent MT studies discussed in detail in the text. *Red* DESERT and DESIRE projects across the Dead Sea Transform (Ritter et al. 2003a; Meqbel et al. 2008, see also Fig. 9). *Dark blue* Baringo Rift basin, Kenya (Hautot et al. 2000). *Light blue* Mesozoic basin structure beneath the Lake Tana area, Ethiopia (Hautot et al. 2006). *Green* Western Branch of the East African Rift, Uganda (Häuserer and Junge 2011, Riftlink). *Lilac* Ethiopia Afar Geoscientific Lithospheric Experiment, Ethiopia (Whaler and Hautot 2006, EAGLE). *Orange* KRISP-94 project, Kenya (Simpson et al. 1997; Sakkas et al. 2002)

with the surface traces of the eastern and western border faults (EBF and WBF in Fig. 8a). The border faults appear to prevent cross-fault fluid flow of the Dead Sea brines (Meqbel et al. 2008). Farther south, between the Dead Sea and the Red Sea, where pure transform setting dominates, resistivity images of the DST show a conductive half layer in 2–5 km depth being terminated by the fault trace (Ritter et al. 2003a; Fig. 8b). This feature is interpreted as an indirect image of the shallow DST, which prevents cross-fault fluid flow. In contrast to other continental-scale transform faults, a distinct fault zone conductor, associated with the damage zone of the fault, is not expressed at the DST (e.g., Ritter et al. 2005; Becken et al. 2008).

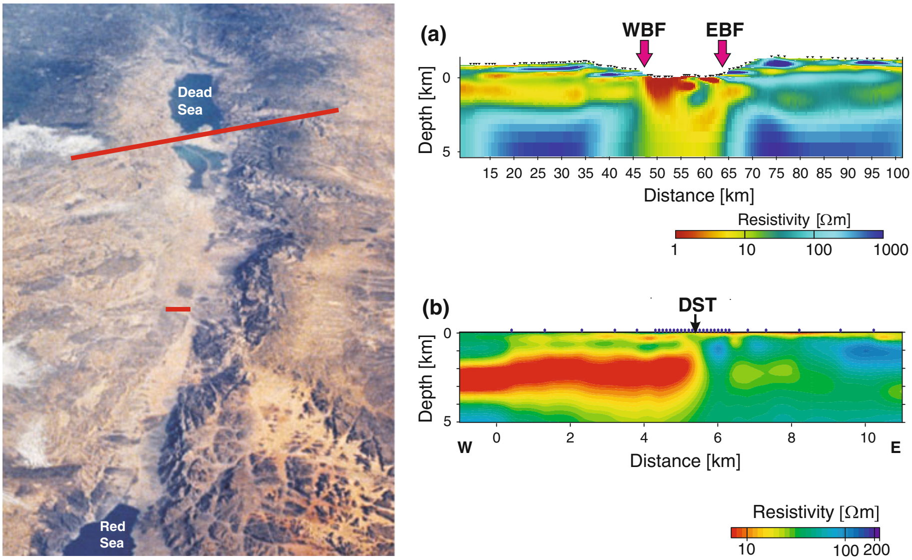

Fig. 8 The locations of the two profiles crossing the Dead Sea Transform are indicated on top of an aerial picture (left side). **a** 2D inversion result of the main profile of the DESIRE data set (Meqbel et al. 2008). In the upper 5 km, several shallow conductivity anomalies can be observed, which correlate well with sedimentary sequences known from existing boreholes. Beneath the Dead Sea (conductive Dead Sea brines imaged in *dark red colors*), in the center of the profile a vertical zone of higher conductivities is observed, flanked by higher resistivities (*blue colors*) beneath the eastern and western shoulders. The *vertical boundary* of this anomaly coincides with the location of the Eastern and Western boundary faults of the DST (EBF and WBF, respectively). **b** 2D inversion result of the inner part of the DESERT profile (Ritter et al. 2003a). The most prominent feature is the conductive half layer in 2–3.5 km depth, which is interpreted as the image of brines in a sedimentary layer. In this simple transform fault setting, the shallow DST appears to be a barrier for cross-fault fluid flow

The African plate is also separating along the East African rift system, where the Somalia plate to the east is formed. This process has been studied since the early 1970s with EM methods. The focus of most of these experiments has been to identify sources and possible pathways for magma.

Simpson et al. (1997) report on the KRISP-94 experiment in southern Kenya, where broad-band MT data (0.01–10,000 s) were collected along a profile across the Kenya Rift, a branch of the East African Rift system. Although the rift structure would suggest a regional 2D setting, the observed induction vectors hint at a much more complex subsurface. For longer periods ($\sim$1,000 s), they exhibit deep conductivity features with an oblique strike direction to the rift. Some years later, Simpson (2000) interpreted the data set and in particular the induction vectors using a 3D forward model (Fig. 9a). The model is divided into three depth regions: (1) the near-surface expression of the conductive sedimentary infill of the north–south striking rift, with the western half of the graben being more conductive than the eastern half, (2) an upper mantle being more conductive west of the rift and (3) dominant and deeply penetrating, northwest–southeast striking conductive lineaments, which are required to dissect both flanks of the rift and the rift itself. Simpson (2000) interpreted these structures as being related to the suture zone between the Mozambique Mobile Belt and the Nyanza Cratonic Segment and to the rifting process itself. Since the Quaternary, rotation of the stress field resulted in reactivation of the

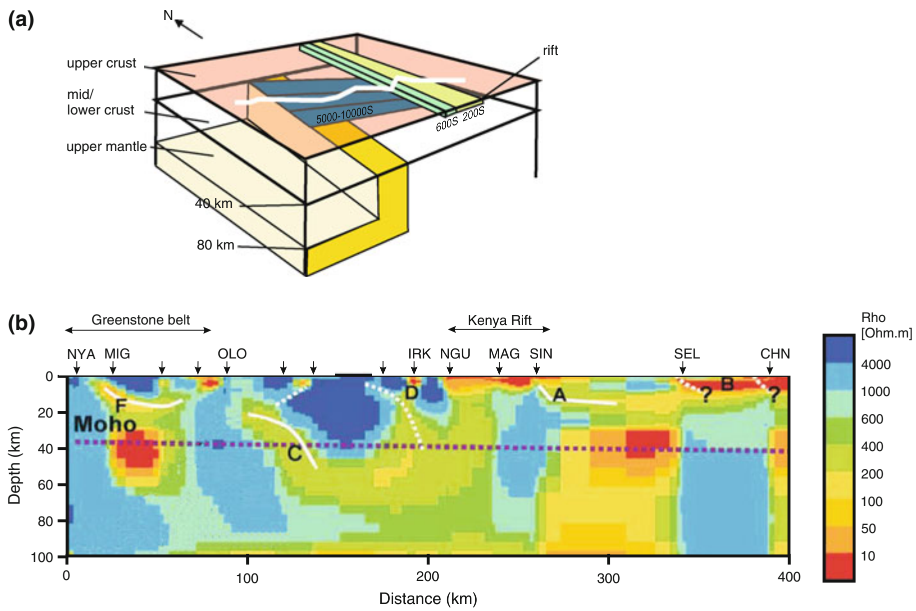

Fig. 9 **a** Forward 3D model to explain the KRISP-94 MT data modified after Simpson (2000). The *white line* indicates the MT profile. The model consists of 3 distinct depth levels: (1) a shallow (<5 km) level consisting of the rift related eastern and western half-graben anomalies, (2) the mid /lower crustal northwest–southeast trending conductive structures and (3) an upper mantle zone of enhanced conductivities west of the rift. **b** Two-dimensional MT model of the same data set modified after Meju and Sakkas (2007). Zones of low resistivity are shown in *red*, zones of high resistivity (or low conductivity) in *blue colors*. The *violet dotted line* indicates the seismic Moho. A more detailed discussion can be found in the text

existing, northwest–southeast trending faults. These pre-existing structures in the sheared Mozambique Mobile Belt have controlled the development of rifting and fracture propagation at the upper crustal scale. Meju and Sakkas (2007) reanalyzed the KRISP-94 data set and proposed a 2D interpretation, after thorough strike and dimensionality analysis and subsequent down-weighting data with 3D effects. The 2D inversion model shows a very heterogeneous lower crust and upper mantle, but some features are comparable with the 3D forward model. In the upper layers, a rift-parallel conductivity anomaly occurs, which seems to be associated with the rift sediments. Although quite different in shape, Meju and Sakkas (2007) found an upper mantle high-conductivity zone on the western side of the rift. Conductive blocks east of the rift valley were interpreted as the location of the suture zone between the craton and the Mozambique Mobile belt (Fig. 8b).

Hautot et al. (2000) studied the Baringo-Bogoria Basin in Kenya, which lies within the eastern branch of the East African Rift. Other geophysical observations have inferred basement structures such as several structural blocks and deep-reaching lineaments that originated possibly during the evolution of the Kenya Rift. In particular, northwest-trending basement structures corresponding to ductile-brittle shear zones were active in the Late Proterozoic. These shear zones may have controlled the position of large transfer zones that segment the rift into several blocks and the distribution of large axial volcanoes to the south and north of the basin. As the subsurface including these complex structures was expected to be 3D, an MT survey with an areal site coverage was carried out in an area of 15 × 25 km^2. Three-dimensional modeling of the MT data revealed a thick resistive layer in 1.5–5 km depth that was related to a mid-Miocene plateau-type flood phonolite. Phonolite occurrences are typically associated with intracontinental volcanism, melting above mantle plumes covered by thick continental crust, or low degree partial melting of granitic material in collisional orogenic belts. This resistive layer overlies a conductive body, the top of which is interpreted as the sedimentary infill of a basin developed during the initial phase of rifting. The recognition of a deeply buried Paleogene basin beneath the Baringo axial rift zone suggests a much wider initial rift setting compared to existing models (Mugisha et al. 1997, and references therein).

On the western side of the Lake Victoria, Häuserer and Junge (2011) conducted two MT experiments across the western branch of the East African Rift. The aim of the project was to image and understand tectonic processes of the rift-flank uplift and origin of the Rwenzori Mountains in Uganda. Within the *Riftlink* project, 23 long-period MT sites were deployed in 2007 and 2008, which recorded EM data in a period range of 10–10,000 s. Forward 3D anisotropic models revealed higher conductivities for the Rift sediments compared to the Rwenzori Mountain. Furthermore, the existence of electrical anisotropy at 20–50 km depth with the high conducting direction perpendicular to the Rift axis was proposed in the rift valley.

Within the framework of the multidisciplinary EAGLE project (Maguire et al. 2003), Whaler and Hautot (2006) investigated the transition from continental rifting to sea floor spreading in the northern main Ethiopian rift. This process is linked with progressive episodes of lithospheric stretching, heating and magmatism. However, the actual process of continental breakup is still poorly understood. Eighteen MT sites were occupied across the northern main Ethiopian Rift. This profile was coincident with a seismic and gravity line. A two-dimensional model of the MT data shows shallow structure generally correlating with geologically mapped Quaternary to Jurassic rocks. A shallow conducting lens-shaped structure at less than 1 km depth beneath the Boset volcano may represent a magma body. A second, slightly deeper and more conductive body in the lower crust beneath the northern plateau is tentatively interpreted as a zone of partial melt.

Farther north of the EAGLE experiment, the marine sequence of the Blue Nile basin may be underlain by rift basins that could be an extension of the NW–SE trending Karoo rift system of the Ogaden Basin (Hautot et al. 2006). The northwestern Plateau of Ethiopia is almost entirely covered with extensive Tertiary continental flood basalts that mask the underlying formations. To unravel deeper structures, Hautot et al. (2006) deployed 27 broad-band MT sites south of Lake Tana in Ethiopia. Two-dimensional modeling of the data reveals a 1.5- to 2-km-thick conductive sedimentary series beneath 0- to 250-m-thick resistive continental flood basalts. The deepening of the basement over a 30- to 40-km section suggests that the form of the basin is a half-graben. Resistive features in the model are interpreted as volcanic materials that intruded the rift basin sediments through normal faults.

6 Discussion and Conclusions

In this paper, several case studies have been discussed to illustrate how the electrical conductivity distribution of the African subsurface has helped to characterize and constrain structure, geometry and physical, thermal and compositional states of tectonic units as well as imaging remnants of tectonic processes.

The early EM work of the late 1960s and 1970s resulted in many fundamental ideas about the architecture of continents and large-scale tectonic units. While the first publications focused on characteristics of cratons and mobile belts in terms of their electrical conductivity, in later years, interest shifted more toward understanding processes and their imprints. In this respect, the existence of continental-scale homogeneous conductivity belts was proposed. Not only on the African continent but also in North America and Eastern Europe, elongated zones of high electrical conductivity were found by magnetic variation studies (Haak and Hutton 1986). These conductivity structures were interpreted as indications of mechanical weakness of mobile belts. During that time, terms like "pre-existing tectonic structures" or "weak zones" were discussed in the geological literature and were taken over by the EM community. Possible causes for weak zones, discussed in the literature, were composition, thermal regime, presence of fluids, existence of deep-reaching faults or mechanical anisotropy (e.g., Hyndman et al. 2005; Vauchez et al. 1998; Ziegler and Cloetingh 2004). The elongated conductive zones were interpreted to mark pre-existing zones of weakness in the lithosphere, possibly a highly faulted/sheared and thinned part of the crust. Since then, discussions centered on how weak zones are formed and what property or material in these zones can give rise to the observed low resistivities. The observation that a conductivity anomaly is maintained along a zone of fossil weakness means that physical properties modified by tectonic processes within mobile belts are retained over very long time spans.

Another interpretation for weak zones in the lithosphere has been suggested by, for example, Burke et al. (1977) in terms of a suture zone containing oceanic lithosphere wedged between continental lithospheric slabs. Based on laboratory measurements of serpentinized rocks from the Indian Ocean ridge, Stesky and Brace (1973) concluded that serpentinite was generally conductive. However, Drury and Hyndman (1979) pointed out that the primary cause for high conductivities might be the presence of fluids, released in chemical reactions during serpentinitization. This would suggest that fossil mobile belts, which normally consist of highly metamorphosed rocks, would bear little resemblance to the material used for the laboratory measurements. Rock measurements by Bruhn et al. (2004) characterized serpentinite as moderately resistive rocks. However, in a fossil environment, graphitization (or other types of mineralization) seems to play an important role. Based on results from the KTB (Kontinentale Tiefbohrung; ELEKTB Group 1997), graphite, once created, seems to be stable over very long time spans. Thus, fault and shear zones may remain conductive long after tectonic activity has ceased. In addition, graphite lowers shear friction, enhances the mobility of faults and hence possibly supports the formation of zones of weakness. Alternative interpretations for North America and Europe suggest that the elongated conductive belts are formed from buried carbon (and sulfide)-bearing meta-sedimentary rocks, which formed when ocean bottom sediments were transported into deeper crustal levels (e.g., Korja et al. 2002; Boerner et al. 1996). Even if candidates for the source of induction anomalies have shifted over time from serpentinite to graphite or other forms of mineralizations, the interpretation in terms of lithospheric weak zones is still relevant. The role of these pre-existing structures for subsequent tectonic reactivation is still considered to be important.

Modern, high-resolution MT experiments, in combination with very substantial advances in data processing and inversion methods, can resolve structural heterogeneities within these "conductivity belts" and image shape and properties of tectonic units in much greater detail. With additional geophysical, geological and petrophysical information, these new resistivity images allow for far-reaching interpretation and for testing of different scenarios and models for continental evolution and breakup. These new interpretations have significantly improved and sometimes revised our understanding of tectonic units and the underlying processes. MT investigations of fossil regimes offer a unique opportunity for a comparison with active regimes of continental collision and the related structures. In fossil regimes, we can benefit from erosion and exhumation, which uncovers former deep levels of the crust. It is easier to study the former ductile part of a deep fault zone if the target is nowadays close to the surface. The information gained can be compared with active regimes where shallow conductivity anomalies often obscure our view on the lower crust.

A number of MT studies from various regions of the African continent report on electrical anisotropy (e.g., Simpson 2000; Hamilton et al. 2006; Weckmann et al. 2011, 2003b; Häuserer and Junge 2011). However, crustal anisotropy was only found in Namibia (Weckmann et al. 2003b) and South Africa (Weckmann et al. 2008, 2011). More often, electrical anisotropy is associated with the upper mantle (Simpson 2000; Häuserer and Junge 2011). Nevertheless, electrical anisotropy could be more generally associated with continental collision and breakup, in particular if anisotropy is a possible candidate for the weakness of mobile belts.

Many aspects of geodynamic research in Africa and a number of important questions remain unanswered. Many interesting targets remain unexplored for various reasons.

An entire continent such as Africa provides very dissimilar natural laboratories to study processes of continental collision and breakup on different time scales, and many pieces for an overall evolutionary puzzle are still missing. This is not a new insight; however, Rosemary Hutton remarked in her review from 1976 that "induction studies should be initiated in other parts of Africa". Quite often, pragmatic reasons prevent us from investigating a representative target area for certain tectonic processes or times: difficult and dangerous access to very remote regions, harsh terrain and climate, the political situation in some African countries and a lack of African cooperation partners. Besides identifying new geodynamic targets, more focused investigations should also be kept in mind. Only by focusing on a specific target, e.g., the San Andreas Fault in California, with a multitude of geoscientific methods, can we gain significantly in our understanding of composition and evolution of deep structures and related tectonic processes. As long as the MT experiments are not included in larger integrated geoscientific projects and follow the principle of indiscriminate all-round distribution, in-depth and revolutionary insights will be long in coming. These advances must be linked with an improved comprehension of conductivity mechanisms. Depending on the tectonic setting, we refer to different causes for the observed conductivity anomalies: in fossil regimes, candidates are graphite, sulfide, ores or minerals, while in active regimes, the role of fluids and/or the occurrence of (partial) melt is discussed. Currently, we still do not know why many of the billion-year-old mobile belts show unexpectedly high electrical conductivities, e.g., the Namaqua Natal Mobile Belt (Weckmann et al. 2007a). Here, many more appropriate rock samples and laboratory measurements are necessary.

Rosemary Hutton (1976) raised another issue: "Surveys should be undertaken with preferably an array of instruments". Future MT experiments will shift even more from measurements along profiles toward areal coverage of sites. However, we need sophisticated experimental layouts to avoid gaining some 3D coverage at the expense of high-resolution images.

Only over the last couple of years, the margins of Africa came into focus. Africa comprises passive, sheared and rifted margins, a setting that can provide unique insights into the processes of continental breakup of super-continents. Combined onshore/offshore MT experiments are very important in this respect. Some of this amphibian experiments were recently conducted in the Mediterranean (e.g., Evans et al. 2010) to investigate the compressional setting at the northern edge of the African continent and are envisaged for the Walvis Ridge in northern Namibia to study the opening of the South Atlantic.

In summary, more international involvement and interest in the diverse geodynamic targets in Africa would be desirable. Thereby, a close cooperation with national groups in Africa is very important in view of capacity building. Encouraging examples can be observed in Ethiopia, where an international MT project has been continued by the Geological Survey of Ethiopia and where scientists have bought MT equipment for their own research. *Inkaba yeAfrica* has triggered an unprecedented capacity building program in South Africa, in which more than 100 students are now trained in geosciences. Nationally and internationally operating companies also use MT measurements successfully for the investigation into natural resources: In Kenya, for example, MT data have been collected data for geothermal exploration and in the oil and gas industry intends to use MT in South Africa to evaluate unconventional gas resources. In addition, several case studies in Africa have shown that MT data are valuable for exploration of natural resources, e.g., for diamond exploration. However, smaller countries, research institutes and universities could benefit greatly from Pan-African collaborations to join manpower, instruments and software to successfully run larger MT projects on their own. Obviously, such collaborations are also necessary because tectonic features do not stop at political borders.

Finally, I would like to encourage all EM colleagues to become scientifically involved on the African continent and also to consider African journals for publications. Even if the impact factors may be lower, many of our colleagues read the few journals they can access very thoroughly and with great interest. Obviously, it is of utmost important to us to share new results with our African colleagues.

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