11th SAGA Biennial Technical Meeting and Exhibition
Swaziland, 16 - 18 September 2009, pages 515 - 520

History of stress at Vaalputs, Namaqualand, South Africa: evidence for a Mid-Cretaceous “Wegener-type Orogeny” in western southern Africa

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ABSTRACT

The paper reviews more than 20 years of structural, stratigraphic and seismic monitoring studies focused on the Vaalputs radioactive waste disposal site, 100 km SSE of Springbok, in Namaqualand. Our finds, supported by the recordings of two 3-components seismometers, show that the frequency of seismic events in this region may be slowly increasing over time, that the predicted M_{max} is ~5.8, and that deformation is governed by a NNW-SSE oriented horizontal σ_1, typical of an Andersonian strike-slip regime ($\sigma_1 > \sigma_v > \sigma_3$).

The history and dynamics of this large scale ($\geq$ 2x 10^6 Km^2) stress field, known as the Wegener stress anomaly, appears to be complex. The palaeostress record suggests that a stress field comparable to the current one became established after the opening of the Atlantic, perhaps at ~102 Ma and waned at about ~72 Ma, when it was replaced by a markedly different Andersonian thrust regime ($\sigma_1 > \sigma_2 > \sigma_v$) oriented NNE-SSW. It is uncertain when the current Wegener stress field was re-established, but some evidence points to a pre-Quaternary event.

Our finds at Vaalputs are consistent with published accounts of mid-Cretaceous, NW-SE oriented crustal shortening through reverse faulting, thrusting, and folding in Namibia and also in the offshore Bredasdorp Basin. This tectonic activity locally resulted in mountain building such as the Groot and Klein Karas Mts. of southern Namibia. As such, this tectonic style is difficult to reconcile with the extensional regime of a classic (passive) “Atlantic-type” continental margin, and calls for a new approach to the way the Kalahari epeirogeny of southern Africa is perceived.

Key words: Vaalputs, epeirogeny, intraplate seismicity, tectonic stress

INTRODUCTION

The stress field of the lithosphere is a fundamental tectonic and physical parameter that drives plates, shatters continents, and raises mountains and is responsible for most seismic calamities. As such, the study of stress across the globe has received much attention in the past 20 years, and is now one of the core competences of the German GFZ, tasked with the production and updating of the World Stress Map.

In this study we focus on the stress and its changing patterns of strength and orientation through time at Vaalputs, in Namaqualand, an area of sporadic, low to medium intensity intraplate seismicity. This site, where low and intermediate level radioactive waste is disposed in mid-Cenozoic sediments, is also located at a valuable geographic position to study the post-drift structural-stratigraphic evolution of a well investigated segment of the southern African plateau, a up to the present time.

Here we report how the epeirogenic processes that resulted in the present high elevations along the Great Escarpment facing the SE Atlantic Ocean are far more complex than currently envisages. Post-drift (<132 Ma) uplift episodes occurred at different places at different times, being accompanied by repeated rotations of the stress field between two preferred orientations (NNW-SSE; and NNE-SSW), by strike slip/reverse faulting, folding, thrusting and, at least at certain places, by the rise of small mountain ranges. Finally, our data support earlier findings that the seismicity of Namaqualand and Western Karoo are induced by an unusually high horizontal, NNW-oriented stresses field [Andreoli et al., 1996, 2007; Viola et al., 2005; Bird et al., 2006] of difficult interpretation.

METHOD AND RESULTS

Our study of the history of stress in the Vaalputs area, at the boundary between the heavily dissected Namaqualand escarpment belt and the ~1000 m Bushmanland Plateau, combines long term monitoring of the local seismicity with a multidisciplinary study of the local/regional geology (Andreoli et al., 1986, 1996, 2006m 2007; Brandt et al., 2003, 2005; Viola et al., 2005). Studies of pedogenic and landscape evolution (Kounov et al., 2007, 2008, 2009), and the acquisition of in situ stress data available from mines and prospects are also pursued. The latter include **direct determinations of σ_v, σ_2, σ_3** from mines (e.g. the SIMRAC report) and offshore **borehole breakouts** log data (O. Heidbach, unpublished data). Still in the Vaalputs area, structural measurements of the joints and faults that dissect the Cretaceous Cover, including the ~68 Ma melilitite pipes of the Gamoep clusters (Phillips et al., 2000), are currently being analysed to further constrain some key episodes in the **palaeostress history** of Namaqualand. Related issues of Meso- and Cenozoic landscape stability are further addressed through **stratigraphic drilling**, **trench mapping, soil testing, and remote sensing.** Finally, the Post-Karoo **tectonic fabric of Namibia** received special consideration for its commonalities with that of Namaqualand

Seismic Monitoring

The recording of the seismic data in the Vaalputs property of NECSA started in 1989 with the installation of a 1 Hz Triaxial Event Location Systems (TELS) on granite gneiss of the Namaqualand Metamorphic Complex. A second, 4.5 Hz TELS instrument was installed on clay-bearing arenaceous sediments of the Vaalputs formation. The distance of epicenters is instrumentally limited to 150 km.

Up to April 2009 the Vaalputs database comprises 457 events of Richter magnitudes up to 5.3 (Fig. 1; M_{max}= 5.8 ± 0.4; Scheepers and Andreoli, 2004). Some epicenters cluster along a NNW trending fault 10 km west of Vaalputs, while others cluster at Gamoep, a small farming community ~30 km NW of Vaalputs (Scheepers and Andreoli, op. cit.). The majority of the epicenters, including the most intense event of 06 04 2001 (M5.3), are scattered across the Bushmanland Plateau, particularly ~60 km NE of Vaalputs. Finally, a significant number of events plot in the proximity of Springbok, a formerly mining town. Given the excessive distance (ca. 70 - 80 km) of these epicenters from the Vaalputs instruments, it is generally difficult to establish if the events are natural or mining induced.

An interesting feature of our seismic data set is that the b value (a measure of the relative frequency of the occurrence of earthquakes of different sizes**)** is invariably <1, suggestive of a compressive, thrusting regime (Schorlemmer et al., 2005). Lastly, in the 20-years period of recording, the seismic events have shown a tendency to cluster in time swarms, such as those of 1996 and 2001, and have become more frequent by about 1996 and 2001. It is worth to note that these years were also marked by striking increases in the cumulative global Seismic Momentum (Fig. 1).

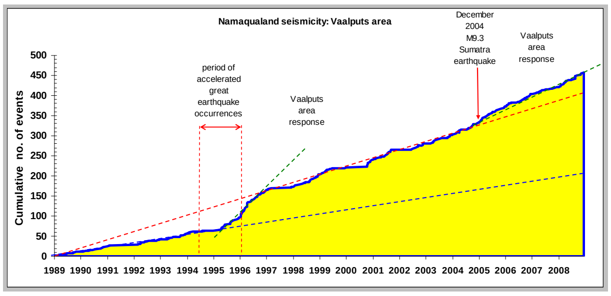

Fig. 1. Cumulative number of seismic events recorded between 1989 and April 2009 by the Vaalputs station. Indicated dates of increases in the cumulative global Seismic Momentum are after G. Ekström (*http://earthquake.usgs.gov.regional/neic*).

Stress Measurements

Recent compilations of stress data for southern Africa, and our new borehole breakout data from the offshore Bredasdorp basin, indicate that Vaalputs falls within a broad region of southwestern Africa (surface area: ≥ 2x 10^6 km^2) where S_{Hmax} is predominantly oriented NW/NNW – SE/SSE. This stress orientation, found with some minor variations as far as S Angola and the Walvis Ridge down to the Bredasdorp basin, offshore the Southern Cape, is highly discordant from that which might be predicted from the NNE vergence of drift of the African plate (cf. Zoback et al., 1989; Zoback, 1992; Bird et al., 2006). Because of this, the region indicated above has been referred to in the literature as the Wegener stress anomaly/field (Andreoli et al., 1996; Viola et al., 2005; Bird et al., 2006). The Wegener field is also anomalous because the continental margin of the SE Atlantic should be of the passive type in terms of plate tectonics, yet it is characterized by an overall Andersonian strike slip fault stress regime (Viola et al., 2005). The strength of the Wegener stress field appears variable, decreasing southward from a maximum in parts of NW Namibia (thrust fault regime) through Namaqualand and Bushmanland (strike-slip fault regime) to a minimum in the Witwatersrand basin (normal faulting regime; Viola et al., op. cit.). Likewise, the orientation varies from NNW-SSE in Namaqualand, W Namibia, and the adjacent SE Atlantic offshore, to NW/WNW-SE/SSE in the southern Cape, the Bredasdorp basin and in the Witwatersrand (cf. Bird et al., 2006, and references therein).

Palaeostress orientations

To study if and how the crustal stress field has changed in the past over the Vaalputs area, detailed field and remote sensing investigations are being conducted at a local and regional scale searching for brittle structures in all the main members of the Namaqualand-Bushmanland stratigraphy.

Holocene. At the Vaalputs waste disposal site, pedogenically consolidated red sands of reworked Aeolian origin yield TL ages not older than ~10 ka. This sand unit, rarely thicker than 1 m, is draped over hardpan, Pleistocene deposits described below. The red sand layer appears structurally undisturbed in the trenches, yet aerial photography and satellite imagery show that it is cut by a number of NNW-SSE trending linear features, particularly across the Santab pan area, ca. 14 km E of Vaalputs (Brandt et al., 2005).

Pleistocene. Palaeosoils and duricrusts, dated at 70 ka, 300 ka and older (U-Th disequilibrium ages), are extensively developed down to depths of 3 to 6 meters. This likely polygenetic soil horizon, which has formed on top of the deep weathering profile of Vaalputs Formation greywacke, manifests a great variety of poorly understood, complex structures and textures. The latter include soil cracking, shattering, breccias, and laterally extensive, shallow dipping to sub-horizontal fractures. These are interconnected, polished, often striated and in trenches B (1, 2) and B (1, 4) they dip up to ~25±5° toward ~NW or ~SE. It is significant that the set of parallel, NW-dipping fractures in trench B (1,4) is sub-parallel to a thrust-looking, SE-verging striated fracture with a 0.5 m duplex in the adjacent trench B (0, 1).

Neogene. The Vaalputs formation grades less disturbed between the depth of 6 (average depth of base of a gritty, olive green greywacke layer) and 8 m (bottom of trenches). However, there are features that require explanation., namely the undulating nature of the contact between the abovementioned layer and the underlying pebbly, beige greywacke (cf. Brandt et al., 2005), c) the 15° dip of a thin siltstone/clay layer at the base of the Vaalputs beds. In vie of the uncertainties (age, origin, lack of exposure), no palaeostress orientation was derived from this set of strata.

Cretaceous. Some 10 km west of the trenches, at the foot of the Namaqualand Highlands, the Vaalputs area preserves mesas of silicified, kaolinitized Namaqua basement with rare remnants of its Cretaceous sedimentary cover of sandstone and conglomerate (Brandt et al., 2003, 2005). These saprolites probably evolved over a lengthy period of time, during the 99-65 Ma, Late Cretaceous greenhouse climatic episode (de Wit, 1999; Brandt et al., 2005 and references therein; Davies et al., 2009). Our new field observations show that the type and depth of the chemical weathering correlate with jointing and structure of the basement. The Vaalputs site also hosts a swarm of melilitite pipes dated at ~ 67 Ma (cf. Jelsma et al., 2004; Phillips et al., 2000). Both types of rocks are cut by a large number of normal, strike-slip and thrust faults, characterized by well developed polished surfaces (fault mirrors) and slickensides which were extensively measured. Preliminary results of the palaeostress calculations show that several stages of brittle deformation have affected these rocks. Some of the estimated stress tensors, especially the most prominent compressional NW-SE and NE-SW, are similar to those observed in the Karoo sediments and Namaqualand gneisses.

Permian-Trias. Field and remote sensing observations of prominent (calcretized) lineaments and borehole data (G Schreuder, pers. comm.) indicate that the Mbizane Form. (Dwyka Group) and the Prince Albert Form. (Ecca Group) east of Vaalputs are extensively jointed and/or faulted (see above; e.g. ca. 19° 25' E - 29° 50' S). In particular, thin lineaments of calcrete patches in Dwyka sediments are clearly recognizable on Google Earth imagery of the Bushmanland Plateau, 37 km NE of Vaalputs (location: 30° 02' S – 18° 57' E). These lineaments correspond to faults, locally groundwater-bearing, in the underlying basement gneisses (Necsa, unpublished aeromagnetic data).

Namaquan Basement. Patterns of brittle deformation observed in the ~1000 Ma granites and gneisses of the Namaqua Natal belt mimic patterns of conjugate joints orientations observed in the cover rocks (see above). In addition, Google Earth images of Bushmanland reveal that a prominent cluster of seismic events (up to M5.3) corresponds to an area of intensely faulted gneisses and granulites ~60 km NE of Vaalputs (location: ca. 19° E – 29° 51'.S; orientations: NNW-SSE and NNE-SSW).

DISCUSSION

The data presented show that the crust of Namaqualand crust and adjacent areas (western Karoo, southern Namibia) is straining under the grip of a NNW-SSE oriented, strike-slip stress field, named the Wegener stress anomaly, active since at least the early Pleistocene beginning of the Quaternary (Viola et al., 2005; Andreoli et al., 1996). An expression of this strain is the recurrent seismic activity measured by the two recording instruments installed at Vaalputs. More in general, we conclude that the Wegener stress field governs the sporadic seismicity of much of the SE Atlantic seaboard (both onshore and offshore) from the southern Cape up to southern Angola (Viola et al., 2005; Mangololo and Hutchins, 2008; Bird et al., 2006).

This coast-parallel lithospheric stress may be caused, at first sight, by the incipient propagation of the East African Rift into the subcontinent (Hartnady, 2002; Bird et al., 2006). However, the finite element modelling by the latter authors could not reproduce the observed **strike slip** regime that extends from the interior plateaus of western southern Africa through the continental shelf to the ocean floor near the Walvis ridge (Viola et al., 2006; Ben-Avraham et al., 2002; Bird et al., 2006). Likewise, none of the current models which describe the post-drift epeirogenic history of the African subcontinent (cf. Burke, 1996, Partridge and Maud, 2000; De Wit, 2007) may account for the stress and tectonic history of the SE Atlantic seaboard (and adjacent shelf basins) as summarized in Table 1. Likewise for the Vaalputs area, the model proposed by Brandt et al. (2005) cannot explain the Wegener stress anomaly. Instead, it may only produce sets of W-dipping normal (less frequently reverse) faults marking the eastward migration of the escarpment bulge (Gilchrist et al., 1994).

CONCLUSIONS

The data summarized in this (cf. Table 1) and previous publications (cf. Andreoli et al., 1996, 2007; Viola et al., 2005; Bird et al., 2006) show that the history of stress field at Vaalputs reflects events taking place at a much larger scale across the south-western margin of the African subcontinent and its offshore. In addition, the anomalous stress is not confined to the crust because at ~90 Ma it affected the region of the diamondiferous Group-II kimberlites in the deep keel of the Kaapvaal Craton, perhaps even the lower mantle (Tachibana et al, 2006). All the data we report on also point to one simple conclusion, that the geological process known as the Kalahari epeirogeny, described in the literature as essentially passive and of subcontinental scale (cf. Burke, 1996; de Wit, 2007), needs to be reviewed. Similarly, the concept of an extensional, Atlantic-type passive margin as modelled by Gilchrist et al. (1994) and Brandt et al. (1995) is quite inadequate to explain the events in Table 1.

In our new scenario, different segment of the southeast Atlantic seaboard were uplifted at different time, even as independent blocks separated by faults. Among the latter, some are subvertical (Raab et al, 2002), others are high angle reverse (Geol. Surv. Namibia, 1977), others again are thrusts (Miller, 2008; van der Merwe and Fouché, 1992). Associated folding of Karoo rocks is also recognized across the South African border, up to the Klein and Groot Karas Mts. (Geol. Surv. Namibia, 1977, 1982, 1997; I Stengel, unpublished data). Conversely, the data in Table 1 suggest that the episodes of NNE-SSW oriented tectonic stress at ~ 120 Ma and at ~63±7 Ma were perhaps more robust than expected by comparison with other "passive" segments of the Atlantic margins, a fact that calls for further attention.

Finally, the Groot and Klein Karas Mts. (maximum height: ~2200m) and the more eroded Waterberg-Otjohorongo structure of Namibia may represent examples of tectonic uplifts neither produced by colliding plates, nor by rift-related extension (e.g. the Ruwenzori Mt.) nor buoyancy (epeirogeny *sensu stricto*). Instead, they reflect the crustal response to intraplate horizontal compressive stresses of yet undetermined, distant/deep? origin. The term "Wegener-type" Orogeny is here proposed for such crustal responses.

Table 1. Tectonic palaeostress and selected events in western southern Africa.

Ma	S_{Hmax}	*Comments*	*Ref*
~135±2	?	**S Atlantic**: rift-drift transition. **Africa**: stationary relative to Europe; change of plate direction	1,2
~133	NW-SE	**S Cape –Bredasdorp basin:** folding, NW-verging ***T***	2
~132	≈S_{Hmin}	**Namibia**: Circular, Etendeka-age intrusions point to low horizontal stress (σ_v» σ_2≈ σ_3).	3
~125 ±7	?	**Subcontinent:** 1st major uplift /exhumation **of** Kalahari epeirogeny:	4
~120	NE-SW	**KV Craton**: peak of Group 2 – K.	4-6
<132- >67	WNW-ESE	**N Namibia:** crustal shortening (Waterberg & Otjohorongo *T*). **S Namibia**: crustal shortening (Karas Mts. to Orange Riv.), (***T***).	3, 7
~103±3	NE- SW	**S Cape: - Bredasdorp Basin:** SW-verging thrust fault, folding post Mid-Albian 14At1unconformity	2
~102±13	WNW-ESE	**Namaqualand**: reactivation of WNW faults (***N***?).	1
~96±9	?	**SW Indian Oc.n Agulhas Plateau:** volcaniszm (LIP?)	4
~90	WNW-ESE	**KV. Craton**: peak of Group I- K	4, 6
~86±9	?	**Subcontinent:** 2nd major uplift /exhumation of Kalahari epeirogeny	4
Late? Cretaceous - >67	Under evaluation	**Namaqualand:** crustal compression /extension: faulting of Cretaceous saprolite.	*
72	WNW-ESE	**E Namaqua belt**: Nouzees –group 1-K.	6
~70	?	**Namibia**: Vertical reactivation of Waterberg fault: S side up.	8
~68.5±1.5	NNE/N-SSW/S	**Namaqualand**: Gamoep –Vaalputs: M-K swarm; **Namibia**: Gideon K.	6
<67	Under evaluation	**Namaqualand**: crustal compression /extension; faulting of Cretaceous saprolite and M/K pipes.	*
~65±10	-	**Africa:** stationary re. Europe	4
~63	W/WNW-E/ESE	**S Cape**: M, Spiegelrivier.	6
58±2	E-W?	**S Cape – Bredasdorp Basin:** Alphard Banks, trachyte plugs	13, 14
Early Cenozoic	?	**S Cape - Bredasdorp Basin:** 1k m uplift of the Agulhas Arch truncates 800 m of early Cenozoic sediments	9
54	?	**Namaqualand**: M, Garies.	6
52	NNE-SSW	**Central Namibia**: Ph, Rehoboth.	6
46	W-E?	**SW Namibia**: Klinghardtberge.	6
Quaternary	NNW-SSE	**N Namibia**: reverse faults in calcrete (W of Omaruru) (***T***). **S Namibia**: Hebron – Dreylingen Fault system (***N***+***SS***).	10
Quat.ry	NNW-SSE	**Namaqualand**: Santab pan (E of Vaalputs) **-** Santab Fault swarm (***N****?*)	11
Present	NNW-SSE	**Namaqualand**: Springbok & Aggeneys mines; offshore mud volcanoes (*SS*).	10, 12

KV. Craton: Kaapvaal Craton; M: melilitite; K: kimberlite; Ph, phonolite; (*N*), (SS), and (*N*): normal, strike slip and thrust/reverse faults (Andersonian) stress regimes; 1, Kounov et al., 2009; 2, van der Merwe and Fouché, 1992; 3, Miller, 2008; 4, de Wit, 2007; 5, Barnett and Lorig, 2007; 6, Jelsma et al., 2004; 7, Geol. Surv. Namibia, 1977, 1982, 1997, 1999a, b; 8, Raab et al., 2002; 9, D. Broad, pers. Communication, 2009; 10, Viola et al., 2005; 11, Brandt et al., 2005; 12, P. (Pottie) Potgieter, personal communication); *, unpublished data by A. Kounov and G. Viola.

ACKNOWLEDGMENTS

We thank the NECSA staff at the Vaalputs facility for their contribution in maintaining the seismometers and the logistical support, the NECSA Management for supporting financially this research, and I Saunders (Council for Geoscience) for sharing the seismological information. We also thank the Geological Survey of Norway for financial support to GV, and D Broad and V Storm (Petroleum Agency) for providing a set of calliper log data from the Bredasdorp basin and valuable discussions. We thank T (Spike) McCarthy, M Cloete, F Ellis, J Lamprecht and the many other colleagues and friends that have contributed to this long term investigation with invaluable help, comments and discussions. S Woodborne provided TL and U-Th disequilibrium ages of sand and calcrete on contract from NECSA.

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