# A palaeoseismic trench investigation of early Holocene neotectonic faulting along the Kango Fault, southern Cape Fold Belt, South Africa– part II: earthquake parameters

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**Abstract**

The location and estimated magnitude of a recent surface rupturing earthquake along the eastern part of the Kango Fault traversing the southern Cape Fold Belt, South Africa, is reported here, as well as the minimum recurrence interval and maximum slip rate. These palaeoseismic data are derived from analysis of the mapped logs of an 82 m long, 5 m deep trench excavated across the fault, supported by 12 optically stimulated luminescence (OSL) dates.

The tectonic event that formed the observed 2.0 ± 0.06 m free-standing fault scarp at the trench site had a moment magnitude estimated between 6.97 ± 0.01 M and 7.18 ± 0.01 M. According to the recently established Environmental Scale of Intensity, the rupture was devastating (ESI $I_o$ = XI). It would have been accompanied by strong ground shaking felt across most of South Africa by the ancestors of the indigenous people groups who experienced the well-known 6.3 M Ceres-Tulbagh event of 29 September 1969 (currently South Africa's largest and most damaging earthquake). This latter strike-slip event occurred along the western end of the same Ceres-Kango-Baviaanskloof-Coega (CKBC) fault system, but was not accompanied by significant surface deformation. In contrast, the Kango 'Toorwater' earthquake reported here displaced the land surface vertically, by over 2 m in places. While the fault scarp extends laterally for at least 84 km, from near the town of De Rust, east of Oudtshoorn, towards the start of the Baviaanskloof in the Eastern Cape, it is unlikely the entire surface rupture length originated during only the most recent event.

The palaeoseismic data reported here have contributed to a seismic source characterization model used to update the existing seismotectonic model for South Africa, first established in the mid-1990's, and revised at various intervals since. The presence of a potentially active, capable, seismogenic structure within a low-seismicity intraplate stable cratonic region suggests that the current 5.3 to 6.3 M $m_{max}$ for the south and south eastern Cape must be reviewed, should these data be included in a revised Probabilistic Sesimic Hazard Assessment (PSHA) for critical structures in the region.

## Introduction

A brief description of the Kango Fault and its regional setting in the southern Cape Fold Belt is provided in Goedhart and Booth (2016 - Part I, this volume).

Regional seismotectonic models were established for southern Africa in the mid-90's (Andreoli et al., 1993, 1995, 1996; Partridge, 1995; Hartnady, 1996a; du Plessis, 1996a,b). These have been reviewed several times and updated (Brandt, 2008; Singh et al., 2009; 2011; Bommer et al., 2014). The seismotectonic province developed for the southern Cape region has specifically included the Kango and Worcester faults as potential seismogenic structures. However, prior to 2000 there was little palaeoseismic information available for this region, other than a rough estimate of potential magnitude (~8.7 M) based on a desk-top assessment of possible erosion rates (e.g. Partridge, 1995).

The main purpose of this paper is to provide palaeo-earthquake parameters for use in a revised PSHA of the region, and to collate potential tectonic drivers that have been proposed for the observed fault reactivation in the Cape Fold Belt, thought to be part of a stable cratonic region (SCR).

## Results

### *Earthquake parameters*

The required format for presenting palaeoseismic data has evolved with time (Bonilla, 1970; 1982; Atwood, 1987; Bonilla and Lienkaemper, 1991; McCalpin, 1996; Hanson et al., 1999; Grant and Gould, 2004). Data are increasingly used to augment seismic catalogues to extend the earthquake record back in time to provide a more robust assessment of seismic hazard in a region (Kijko and Sellevoll, 1992; Kijko, et al., 2004; McCalpin, 2009). The inclusion of uncertainty in the reported palaeo-earthquake data is essential, as poorly constrained data may simply increase the hazard rather than assist in refining it.

### *Location*

The trench site is located at Latitude 33°28'08.7”S, Longitude 22°50'53.0”E some 18 km east of De Rust, a small town 35 km east of Oudtshoorn (Figure 1).

The linear fault scarp, across which the trench was excavated, extends eastwards for more than 84 km towards the Baviaanskloof. Uncertainty in the lateral die-out points suggests the surface rupture length (SRL) is about 94 km (Goedhart and Booth, 2009; Goedhart, 2012; 2013). The applicability of the vertical offset at the trench site to the entire strike length of the fault scarp is quantified and discussed in Midzi and Goedhart (2009). Although it was not expected that the maximum 94 km scarp length ruptured in a single earthquake as the Most Recent Event (MRE), subdivision (Goedhart, 2006) has only recently been confirmed by identification of additional rupture events closer to De Rust in the west, and near the entrance of the Baviaanskloof in the east (Hanson et al., 2012, 2014).

### *Magnitude*

Palaeoseismic investigations commonly estimate earthquake magnitude from some measure of the surface rupture length and vertical offset or fault displacement, and compare these parameters to international datasets where the same features, among others, were measured from modern ruptures of known magnitude. As for the range of attenuation equations relating earthquake magnitude with expected ground motion at a particular site some distance away from the epicentre or focus, there are many regression relations to estimate the magnitude of a surface rupture. Each of these advocate measuring certain aspects of a palaeo-earthquake to reduce uncertainty or variance, and thereby improve the accuracy of the estimated magnitude. A number of other measurements may also be factored in, but these require additional data not obtained in this investigation, for example: seismic moment, shear rigidity, or rupture width down the dip of the fault. Due to the natural 'saw tooth' variation in surface displacement along a fault scarp (McCalpin, 1996, 2009), one risk in estimating earthquake magnitude and particularly $m_{max}$ from a single point along the rupture (e.g. in a trench or at an outcrop), is that the measured site is statistically unlikely to reflect either the true maximum displacement (MD) or the average displacement (AD). Both these parameters form the basis of empirical relations equating vertical offset to earthquake magnitude (e.g. Wells and Coppersmith, 1994). Due to the site selection process followed in this study, the probability that the actual vertical offset measured in the trench (Goedhart and Booth, 2016 - Part 1, Figure 15, section I, p.561) is comparable to the AD along the fault scarp is greater than it representing the MD along the rupture.

A comprehensive review of the Wells and Coppersmith (1994) AD and MD method of calculating palaeo-magnitude from trenched ruptures is provided in McCalpin (1996, Ch.9.2.1.3, p.447-453; see also McCalpin, 2009, p.11-20, notably Ch.9.2.1.4). Since the MD is really an outlier in the range of variable displacement along a rupture trace, MD relations are not really used as much in trench investigations as the AD method. This is because most trench sites are not commonly excavated at the position of maximum displacement along the fault scarp; thus using the MD relation would underestimate the palaeo-magnitude. While we advocate the use of the actual displacement measured in the trench as approximating the AD, we also include the MD relation below to illustrate the point that it underestimates the palaeo-magnitude.

### *Average displacement method*

An empirical equation initially formulated by Wells and Coppersmith (1994) was used to estimate the moment magnitude of the MRE at the trench site. Although there are valid criticisms of the underlying datasets used to derive the regression relations (McCalpin, 2009), and alternative point-data and scalar methods proposed (Hemphill-Haley and Weldon, 1999; Wesnousky, 2008; Leonard, 2010; Stirling and Goded, 2012;

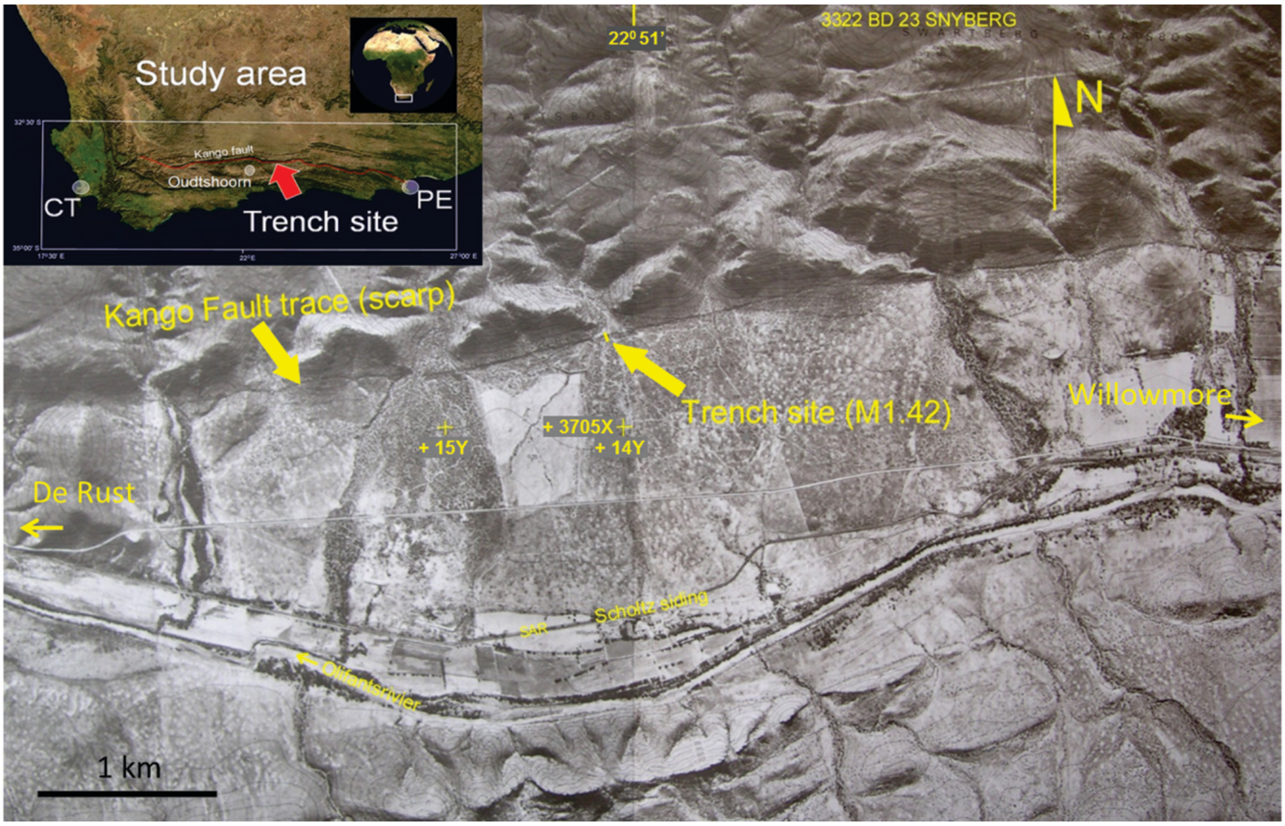


***Figure 1.*** *Location of the trench site (M1.42) across the Kango Fault trace. The fault scarp is clearly depicted by the dark line (untouched!) extending from west to east across the centre of the aerial photographs. Insert shows the location of the trench site in the southern Cape, near the town of Oudtshoorn, which lies approximately half way between Cape Town (CT) and Port Elizabeth (PE).*

Stirling et al., 2013), several of the initial relations developed for various tectonic settings have remained popular in the palaeoseismic literature (Hanks and Bakun, 2008; McCalpin, 2009).

The AD relation used here was derived from a regression line obtained from 56 historical earthquakes in the US, plotted on a log-normal diagram relating moment magnitude to average displacement. This relation is:

$$M=6.93+0.82*\log(AD) \qquad (1)$$

*Where: M is the moment magnitude ($M_w$ ), and AD is the average displacement.*

Using the 2.0 ± 0.06 m actual displacement measured at the trench site as a proxy for the AD, the above relation suggests an earthquake of moment magnitude 7.18 ± 0.01 M caused the surface rupture.

Since the CKBC fault system, of which the Kango Fault is one segment, has recorded strike-slip motion at its western end in the Ceres area (van Wyk and Kent, 1974, Krüger and Scherbaum, 2014; Smit, et al., 2015), this initial estimate using the relation that includes all fault types in the underlying dataset is conservative as it does not minimize risk. Rather, it provides a possible ceiling for $m_{max}$ that should incorporate variance in slip vectors that might in future be found along the curvi-linear fault trace, for example on large bends, or at sharp inflections where conservation of volume during tectonic deformation is not easily maintained (Gibbs, 1984).

If the Wells and Coppersmith (1994) dataset is trimmed to their subset of only 12 normal faults, the coefficient and standard error of 6.78 and 0.65 may be exchanged for the values above. In this case, the moment magnitude for the MRE at the trench site is slightly lower, approximately 6.97 ± 0.01 M.

At this early stage of investigation, however, the initial more conservative estimate of palaeo-magnitude is preferred. The inclusion of a MD method below is to illustrate the effect of a different displacement relation using the same measure of vertical offset in the trench.

#### *Maximum displacement method*

If assuming the trench exposure defines the maximum characteristic earthquake for the Kango Fault, the original empirical equation initially formulated by Wells and Coppersmith (1994) may be imported and applied to the CFB. This relation was derived from a regression line obtained from 80 historical earthquakes in the US, plotted on a log-normal diagram relating moment magnitude to maximum displacement. This plot is reproduced and discussed in McCalpin (1996, Figure 9.3, p.448; 2009, Figure 9.3, p.11), together with the relation:

$$M = 6.69+0.74*log(MD) \qquad (2)$$

*Where: M is the moment magnitude ($M_w$ ), and MD is the maximum displacement.*

Using the 2.0 ± 0.06 m actual displacement measured at the trench site, the above relation suggests a palaeo-earthquake of moment magnitude 6.91 M caused the surface rupture. Using the data scatter in the Wells and Coppersmith's plot to constrain error, the expected maximum to minimum range for $m_{max}$ is about ~7.05 M to ~6.80 M, a difference of 0.25 M, suggesting the moment magnitude for the MRE is 6.91 ± 0.13 M. Alternatively, based on the retro-deformation error, the displacement range is 2.06 m – 1.94 m, corresponding to a range in $m_{max}$ between 6.92 M – 6.90 M. This result is a moment magnitude of about 6.91 ± 0.01 M. As may be expected, this is less than that obtained from the preferred AD relation above.

Of the 80 events included in the Wells and Coppersmith (1994) dataset, only 16 were from normal faults. When only this subset is considered, the coefficients in equation 2 reduce to 6.61 and 0.71 respectively. The final $m_{max}$ is then lower at 6.82 ± 0.01 M, as may be expected if removing all strike-slip and compressive environments, leaving only pure extensional tectonics. The relations for various other fault types (strike-slip, reverse) and their standard error are listed in McCalpin (1996, Table 9.3, p.452; 2009, p.14). For the purpose of comparing the final MD magnitude to that from the AD method above, we report only equation 2 as the inclusion of more than just normal faulting is again conservative in terms of final risk.

***Date of the MRE***

Considering the OSL-sample positions and dates provided in Goedhart and Booth (2016 - Part 1, Figure 14, p.559), the earthquake that ruptured the Little Karoo land surface in the vicinity of the trench occurred between about 13 to 8.5 ka (12,206 ± 723 and 8,878 ± 452 years ago). This is the most conservative widest age-range to bracket the event, using the oldest date from the younger set of footwall samples (i.e. sample B17-S1A) and the date of the hanging-wall sample E26-S1A near the top of the graben-fill sands. Since this includes the time taken to fill the graben with sand, a more probable date for the MRE is between 12 ka to 10 ka (12,206 ± 723 and 10,327 ± 755 years ago), derived from the dates of samples B17-S1A and F27-S1A above the toe of the colluvial wedge. This age range is illustrated by the red bar in Figure 2A crossing the 11.7 ka Pleistocene / Holocene boundary (ICS, 2009).

In contrast to these sample ages, Figure 2B indicates the age and range of the lower-lying samples, from stratigraphic unit 1b located just above the floor of the trench. A disconformity between this unit and the overlying unit 2a is clearly apparent when comparing ages of footwall samples G22-S1A and F15-S1A (Goedhart and Booth, 2016 - Part 1, Figure 14, p.559). The erosional contact between stratigraphic units 1b and 2a reflects a hiatus of some 105 ka. This gap in deposition is an order of magnitude longer than the depositional period for all sediments accumulated above the disconformity and probably reflects a regional hiatus or erosional event.

From Figure 2A, it is evident that various other bracketing combinations are possible. This is due to the statistically similar ages (no significant difference) of samples F27-S1A above the toe of the colluvial wedge, E25-S1A above the proximal colluvial wedge, and F15-S1A in the lower footwall. The latter sample's age appears well-constrained with low data scatter (Jacobs, 2006), but the age is stratigraphically inverted with respect to the less well constrained older sample B17-S1A higher up on the trench wall (Goedhart, 2006). The similar dates suggest the MRE possibly occurred around 10,327 ± 755 to 10,620 ± 509, and maybe even 10,167 ± 507 years ago. These are all just within the beginning of the Holocene Period (Figure 2A). The simplest option is to use the 10,327 ± 755 year age for sample F27-S1A, located at the toe of the co-seismic colluvial wedge, as the constraining date for the MRE.

***Minimum recurrence interval***

According to the detailed description of the trench stratigraphy, soil horizons and structure, the geometry of the interpreted trench log (Goedhart and Booth, 2016 - Part 1, this volume), and the returned OSL sample dates, it appears that the fault scarp at the trench site is the result of one surface-rupturing earthquake, the Most Recent Event (MRE). There are no cross-faulted faults, obviously reactivated fault strands, or new secondary faults that further offset the trench stratigraphy; features that might otherwise indicate a second, younger, surface rupturing event. Mapped fault strands, including the antithetic faults forming the southern boundary of both the 32 m wide main graben and 8 m wide sub-graben, all terminate before or at the same stratigraphic level, namely below the top of the calcified 'white gravel' of trench unit 2g and its thin but patchy cover of calcified sand (unit 2h), interpreted as the former land surface or event horizon (Goedhart and Booth, 2016 - Part 1, Figure 15, Section J, p.561). If any aftershocks occurred, they were apparently not large enough to cause additional rupture at the same site. Post-MRE surface-rupture events found elsewhere along the Kango Fault (e.g. Hanson et al., 2012, 2014) do not appear to have reactivated this de-stressed part of the fault. Although the ruptured Kango Fault segment is currently aseismic, pre-historic seismicity may have caused strong ground shaking sufficient to generate soft-sediment deformation at saturated spring deposits further east along the fault trace (e.g. site M1.129b, Goedhart, 2005).

The recurrence interval is the time span between any two palaeo-earthquakes. Since the penultimate event (PE) has not yet been unearthed at the trench site, the time period between the oldest bed in the floor of the trench and the age of the MRE still provides some indication of the minimum recurrence interval. This period is between the weighted mean age of the three samples from trench unit 1b near the floor of the trench (Goedhart and Booth, 2016 - Part 1, Figure 14; 117.130 ± 4.72 ka, p.559), and the age of the MRE, obtained from the first sample above the event horizon (Goedhart and Booth, 2016 - Part 1, Figure 14; 10.327 ± 0.755 ka, p.559). These two dates provide a minimum recurrence interval of 106.803 ± 5.475 ka.

It should be noted that this number, which suggests a minimum characteristic 'return time' for a similar surface-rupture

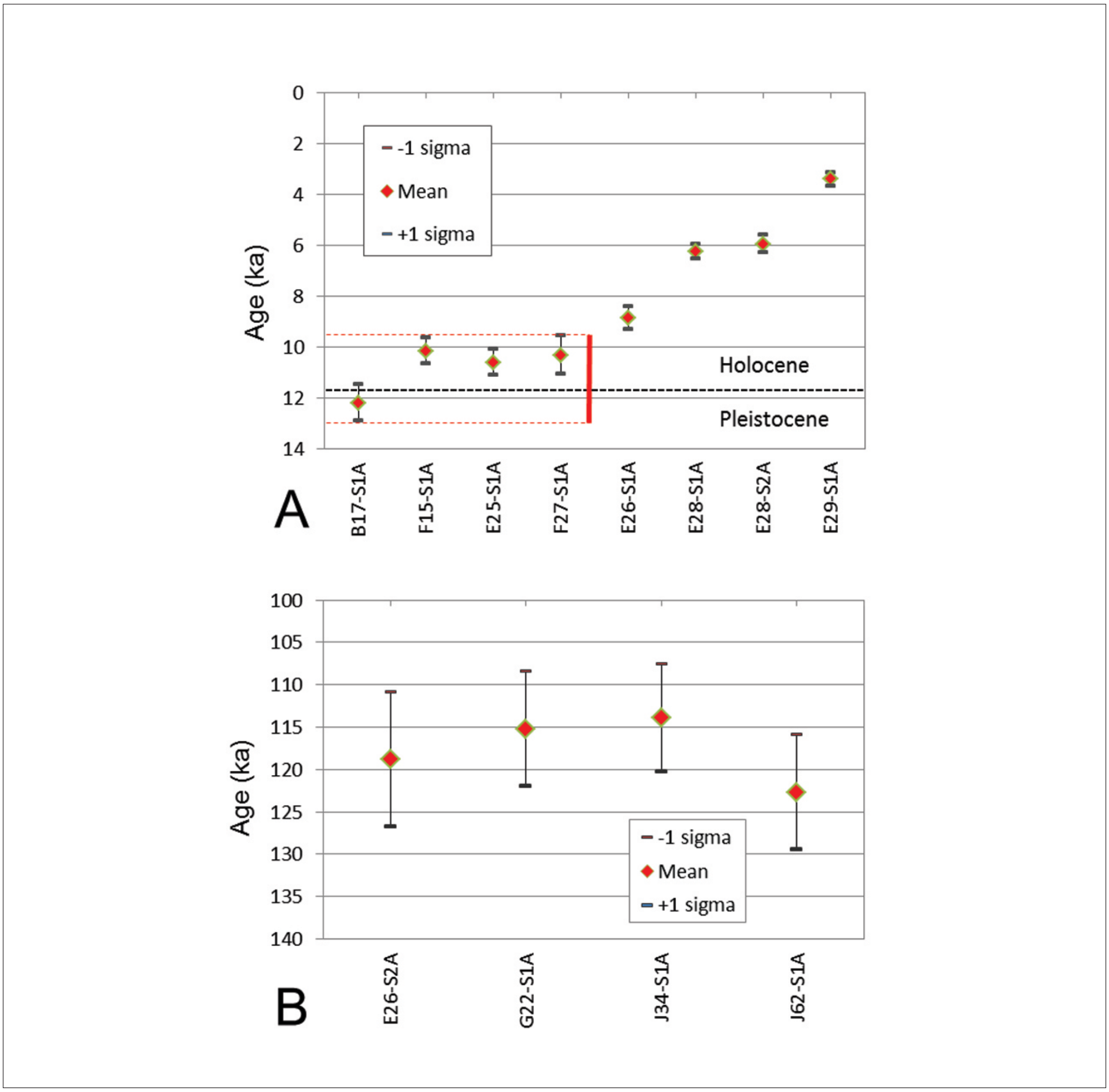


***Figure 2.*** *Age and analytical error of OSL samples from key stratigraphic units depicted in Goedhart and Booth, 2016 - Part 1, Figure 13 (this volume). (**A**) Sample ages above the basal disconformity exposed in the trench between stratigraphic horizons 1b and 2a. The most probable age range for the MRE is indicated by the vertical red line crossing the 11.7 ka Pleistocene/Holocene boundary. (**B**) Dates from below the basal disconformity. Note the change in vertical scale.*

along the Kango Fault, is probably in the order of ~100 ka. This does not mean that because ~10 ka has passed since the MRE at the start of the Holocene, we should only expect another, similar, event 90,000 years from now. It means we can expect the return of a similar magnitude event at an annual probability of 1/100,000. This is a one-hundred thousandth of a chance of a similar magnitude rupture occurring sometime this year, or next year, or even in the next 50 years, i.e. low risk. This is in good agreement with estimates of recurrence intervals for similar magnitude events in stable continental regions elsewhere (100 to 150 ka). Had the PE been located below the trench, and dated, the recurrence interval would be lengthened, providing an even lower annual probability of a similar magnitude event. The slip rate would also be reduced, as described below.

It should further be noted that the presence of large non-surface rupturing earthquakes is not included in the above assessment. Field reconnaissance along the Kango Fault and other similar faults (e.g. Goedhart, 2005; Goedhart et al., 2009) provides evidence of strong ground shaking in places, i.e. mesoscale soft-sediment deformation. The date derived from a small trench in such disturbed sediment, directly on the trace of the Kango Fault, differs from the date of the MRE rupture

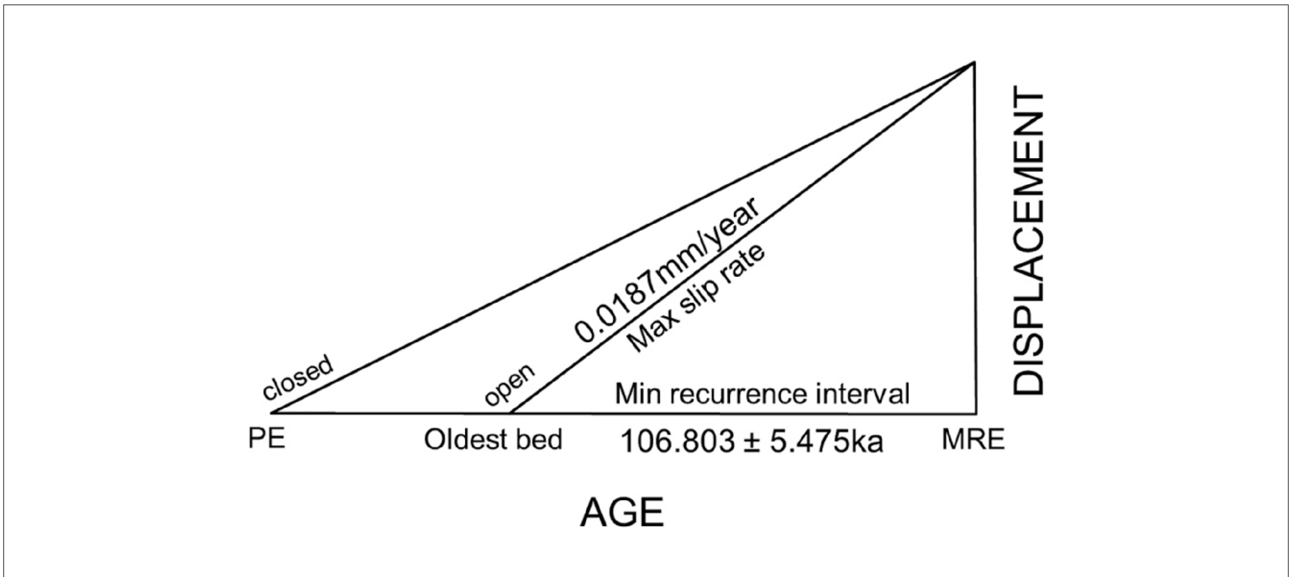


***Figure 3.*** *Summary of the minimum recurrence interval and maximum slip rate for the Kango Fault at the trench site, using the displacement and age of the most recent event (MRE) and the age of the oldest bed exposed in the floor of the trench. Had the penultimate event (PE) been exposed (i.e. below the floor of the trench) and the seismic cycle closed, a longer recurrence interval and lower slip rate is expected.*

reported here (i.e. younger, Late Holocene). This suggests that there has been some serious ground shaking in the vicinity of the Kango Fault, quite recently, but without direct surface rupture. These and other characteristic features need to be located elsewhere (e.g. de Beer, 2005a, b; 2012), and evaluated prior to inclusion in Quaternary neotectonic maps (Anderson and Miller, 1979; Allen, 1986; Wheeler, 2002; Bezerra et al., 2005). Knowledge of the age and distribution of soft sediment deformation is necessary prior to including them in seismic hazard assessment.

### *Maximum slip rate*

Since the penultimate event (PE) was not exposed in the trench, the PE – MRE seismic cycle was not closed. As a result, only the maximum slip rate can be determined. This is calculated by dividing the net fault displacement measured at the trench (Goedhart and Booth, 2016 - Part 1, Figure 15, section I, p.561) by the minimum recurrence interval above, measured between the oldest bed and the MRE.

With a single net displacement of 2.0 ± 0.06 m at the trench and a minimum recurrence interval of 106.803 ± 5.475 ka, considering only the means suggests the average maximum slip rate at the trench site is 0.0187 mm/year (Figure 3).

Including the error range, this can also be reported as 18.7 ± 1.5 mm per 1000 years. Alternatively, the maximum fault slip is about the height of a tall person over a period of 100,000 years (1.87m/100 ka). This low maximum slip rate is consistent with fault slip rates from intra-plate stable continental regions elsewhere (Crone et al., 1987, 1997a,b; Machette et al., 1992; Masana, 1996; McCalpin, 1996, Ch.9.3, p.456-467; Masana et al., 2001; Mazzotti, 2007). Such faults are characterized by large events (>5.0 M) with long recurrence intervals, typically between 100,000 to 150,000 years, rather than numerous on-going tremors from recurrent small slips. This is because intra-plate faults are stick-slip by nature, rather than sliding continuously or experiencing many small slips.

### Discussion

A magnitude of about 8.7 M was previously proposed for the reactivated Kango-Baviaanskloof Fault (Partridge, 1995). This considerably higher 'back-of-the-envelope' desktop estimate was based on a rough approximation of the potential scarp erosion rate. Partridge (*op cit.*) did not have the benefit of a palaeoseismic trench, nor a good estimate of the surface rupture length. The new palaeo-magnitudes reported above, based only on the actual displacement observed in the trench, are still very conservative. They are also based only on the original Wells and Coppersmith (1994) relations, rather than derivatives or variants that each aim to reduce some component of error in the final magnitude estimate.

Future palaeoseismic research along the Kango Fault and other faults in the CFB may well reduce the preferred AD magnitude estimate reported in this study, rather than increase it. Should the number of events along the fault trace increase, which is very likely as there are several possible segment boundaries (Goedhart, 2012), or more than one event be found at any particular site (in which case the magnitude of individual ruptures would be reduced by dividing the net vertical offset equally or unequally by the number of events), the increased slip rate may well elevate the seismic hazard rather than reduce it. This is particularly the case if the reactivation is within a current seismic cluster, as concluded by Hanson et al. (2012, 2014). Until such time, however, a conservative approach is suggested as $m_{max}$ may be included directly in attenuation studies to test engineering design of nearby critical facilities (e.g. Atkinson, 2007; Kijko et al., 2005). These evaluations should probably be regarded as preliminary screening tests for estimating the possible maximum peak ground acceleration (PGA) at any particular site. Final PSHA for critical facilities are increasingly relying on multi-variable inputs, each with defined error that are ranked and weighted on select branches of a logic tree (McCalpin, 2009). The purpose of the logic tree is to identify and order the full range of parameters required to conduct a PSHA and, most importantly, capture and quantify the uncertainty associated with each of the parameters. The end result is a single probability distribution that contains the full range of epistemic uncertainty in the hazard (Bommer and Scherbaum, 2008). In terms of forecasting potential future earthquakes of various magnitudes in a region, or at a particular locality, the logic tree formalism is simply a tool to constrain the overall earthquake probability by breaking up the analysis of the uncertainty into its separate components. Although the general procedure to list, sequentially order and weight individual parameters for each branch of the logic tree is now standardized, the identification of input parameters may vary between seismotectonic regions and even individual faults. The selection of parameters, and particularly their loading or assigned weights, is a matter of debate (Castaños and Lomnitz, 2002; Budnitz et al., 2005; Bommer and Scherbaum, 2008). The number of branches, their sequence and weighting, is best accomplished through careful selection by a panel of objective experts rather than one individual (Bommer and Coppersmith, 2010; Coppersmith et al., 2010, 2012; Bommer et al., 2013, 2014).

**Uncertainty in the estimated palaeo-magnitude**

The most accurate measure of actual displacement on a fault plane is best approximated by the instrumentally derived seismic moment release distribution. This is not available for palaeoseismic events and has therefore to be estimated by comparison with measured surface effects of modern earthquakes. McCalpin (1996, Figure 9.4, p.450; 2009, p.13) puts the simple magnitude estimate reported here into perspective by illustrating the relationship of geological surface data to the actual subsurface slip distribution in the area around the foci on a deep subsurface fault plane. There are clearly many sources of uncertainty between measured surface data and the actual slip distribution and seismic moment at depth. Regression relations simplify the relationship by including all variability in a single measure of palaeomagnitude.

While the applicability of the results from this single trench investigation to the remaining fault length has been quantified (Midzi and Goedhart, 2009), it is clear additional work is still required to better characterise the fault scarp and determine its rupture history. Whereas much has been done in this respect (Bierman et al., 2014; Hanson et al., 2012, 2014), with investigations also moving to other parts of the Cape Fold Belt, neotectonic data are only beginning to be incorporated into the existing seismotectonic models for the region.

McCalpin (2009, Ch.9.2.1.4, p.15-20) suggests an alternative method of estimating the AD for a rupture, using a number of displacement points measured along the fault scarp. This ensures a greater degree of accuracy as it encompasses the natural variance in degree of surface deformation along fault strike. This method is similar to that proposed by Hemphill-Haley and Weldon (1999). Their use of scarp height data instead of net-slip in a trench assumes the scarps are a good reflection of displacement by each tectonic event. This is not always the case due to scarp erosion, and this may lead to an underestimate of $m_{max}$. However, by assigning an affected length to each scarp height position, the resulting weighted displacement method suggested by McCalpin (*op. cit.*) more closely approximates the integral of displacement along the entire surface rupture than the arithmetic mean displacement. Since the original Wells and Coppersmith (1994) dataset did not include uncertainties in measurement of surface rupture length, displacement or magnitude, their relations are from ordinary least-squares regressions. Had variance been included, for example by giving more weight to better-defined points to provide a weighted least squares regression, there should be less variance within the final result. This should better approximate the effect of the seismic moment, and thus earthquake magnitude. Various other spatial manipulations of rupture data are possible, with scaling relations between them becoming increasingly apparent (Papazachos, et al., 2004; Leonard, 2010; Stirling et al., 2013). By including uncertainty in palaeoseismic measurements, a range in estimates for the probable palaeomagnitude is obtained rather than just one estimated result. This range can then be included and weighted on various branches of a logic tree in a revised PSHA of the region (e.g. Hanson, et al., 2014; Bommer, et al., 2014).

**Uncertainty in the recurrence interval and slip rate**

The very slow overall rate of extensional subsidence described above is supported by cosmogenic nuclide dating of alluvium and high-level terraces cut into the foothills and flanks of the adjacent Swartberge, which show low erosion rates for the eastern Little Karoo region (Bierman et al., 2014). Similar very slowly eroding hard rocks on high-level land surfaces are also apparent in the Western Cape, suggesting tectonic stability across much of the Cape Fold Belt (Scharf et al., 2011; 2013). In such a resistant and apparently stable environment, the long-term neotectonic slip rate for the Kango Fault may be determined by dating the lowermost down-faulted alluvium where it rests on the underlying bedrock and dividing the bedrock displacement by this age (Goedhart and De Klerk, 2011; Goedhart et al., 2011; Goedhart, 2011, Hanson et al., 2012, 2014). Additional work elsewhere along the Kango Fault has unearthed another two pre-historic earthquakes since the Late Pleistocene, indicating there were at least three surface-rupturing events along the eastern Kango Fault since ~25 ka (Hanson et al., 2012, 2014). Their proximity and timing suggests they are part of an earthquake cluster superimposed on the long-term slip rate for the fault. In SCR's, such clusters are commonly separated by long periods of tectonic quiescence typically lasting more than a hundred thousand years. The presence of an earthquake cluster at the eastern end of the Kango Fault suggests it may still be in a state of heightened stress.

To put the Kango Fault 'Toorwater' rupture[#1] described here into perspective, its estimated magnitude and surface effects can be compared to catalogues of other surface-rupturing events worldwide, for example through use of the recently developed Environmental Scale of Intensity.

## ESI and GEM catalogues

Since the original Wells and Coppersmith (1994) relations were developed from faults in the USA, many of which were from strike-slip environments as this was the area of interest at that time, large datasets of earthquake surface effects are being compiled from all tectonic environments, worldwide. An example is the recently established International Quaternary Association (INQUA) Environmental Scale of Intensity catalogue (ESI, 2007; Guerrieri and Vittori, 2007), which is also known as the Environmental Earthquake Effects (EEE) catalogue. This scale was ratified in 2007 by INQUA, having been developed by their Terrestrial Processes (TERPRO) sub-commission on Palaeoseismology and Active Tectonics (A. Michetti, pers. comm., 2007). The intent is that the scale is used globally to classify and compare the environmental effects of earthquakes of known magnitudes. It can then be used to evaluate the intensity and/or magnitude of surface rupture and other tectonic deformation in areas that are currently seismically inactive, or where seismic records are absent. For example, in terms of the ESI scale, the most recent event (MRE) along the Kango Fault was 'devastating' ($I_o$ = XI)[#2].

Another good example is the Global Earthquake Model (GEM) faulted earth program for active faults and seismic sources (Berryman et al., 2009). Geospatial and other open-source tools are being developed to assist risk management decision-making, aimed at risk mitigation and improving societal disaster resilience. Making risk decisions on behalf of communities, however, requires a sound understanding of the public's perception of risk[#3].

Although the ground-surface effects of large palaeo-earthquakes along the Kango Fault may have been severe, due to their rarity and age near the start of the Holocene, earthquakes do not feature in the local folklore of South Africa (Albini, 2012; Albini et al., 2014). Indeed, if it were not for the records compiled by Van Wyk and Kent (1974), or De Klerk and Read (1988), there is little surviving human recollection of earthquakes prior to, and even including, the 6.3 M Ceres-Tulbagh 'quake of 29 September 1969. While there was little to no permanent surface deformation associated with this strike-slip event, surface deformation features along the Kango Fault are described in detail in Goedhart (2005) and Goedhart et al. (2009), with the more spectacular outcrops presented for SSHAC evaluation and Geoheritage purposes (Goedhart, 2012, 2013).

## Seismotectonic models

This investigation has confirmed and quantified the initial tectonic assessment of Toerien (1979) and Hill (1988) used by Andreoli et al. (1993, 1995, 1996), Partridge (1995), Hartnady (1996a) and du Plessis (1996a,b) in the compilation of the first seismotectonic models of the southern African region. This information impacted revisions of the models (Brandt, 2008; Singh et al., 2009) as well as updates (Singh et al., 2011; Hartnady, 2012; Bommer et al., 2014). However, the new palaeoseismic data suggest it may be necessary to revise and update $m_{max}$ for the southern Cape Fold Belt (Kjiko and Graham, 1998, 1999; Kjiko, 2004; Wheeler, 2009, see also Hebden and Stein, 2007), as used in one of the more recent Probabilistic Seismic Hazard maps for South Africa (Kjiko et al., 2003). In this assessment, the Western Cape is expected to experience the highest magnitudes of around 6.3 to 6.7 M, from strike-slip movement. In contrast, the Eastern Cape is limited to magnitudes of 5.6 to 6.3 M, from mainly extensional events. This is slightly more than the maximum 5.5 $M_b$ (4.9 $M_w$) 1968 instrumentally-recorded earthquake for the Eastern Cape (Fernandez and Toerien, 1986; Hartnady, 1996a; du Plessis, 1996a; Brandt et al., 2005; Midzi et al., 2013). It seems that the hazard for the southern to south-eastern Cape should now be upgraded, to include a rare ~7.0 $M_w$ event. However, it is likely that the addition of a long-recurrence large-magnitude earthquake hardly affects the calculated ground motion of a distant site. This is because the addition of a low recurrence linear source to an existing seismic source zone already populated with enough historic 2 to 5 M seismicity 'just doesn't add much of an increment of hazard' (J. McCalpin, pers. comm., 2009). In contrast, the effect of a large long-recurrence earthquake is much greater if there is little historic data in the seismic source zone (SSZ) in which the high magnitude event is recorded.

Definition of seismic source zones along the larger linear fault sources within the broad seismotectonic model for the CFB region has been attempted (Goedhart, 2007; Goedhart and Saunders, 2009; Goedhart, 2012). Although these proposed zones have a variety of boundaries (e.g. soft, leaky, etc.), they have not been recognized as unique hazard sources in the newly-established Seismic Source Characterization (SSC) model

[#1] The name given to the event (Goedhart, 2013) derives from the Towerwater hot spring located at its northernmost extent, approximately midway along the ruptured Kango Fault trace (T = 44ºC, 11 l/s; Meyer, 2002). At an elevation of 813 m above sea level, it is the highest hot spring in the Cape Fold Belt region, with meteoric water circulating to depths of at least 2000 m below the ruptured surface (Harris and Diamond, 2002). The deep circulation suggests regional tension rather than compression across the southern Cape Fold Belt.

[#2] By definition: 'Surface faulting extends from several tens of km up to more than one hundred km, accompanied by slips reaching several metres. Gravity graben, elongated depressions and pressure ridges develop. Drainage lines can be seriously offset. Tectonic subsidence or uplift of the ground surface with maximum values in the order of numerous metres may occur.' (Guerrieri and Vittori, 2007).

[#3] The public's perception of risk (which ultimately bankrolls all hazard investigations) is low when probable loss of life, due to a potentially hazardous activity, has a high degree of personal voluntary control, and the effects are immediate, i.e. crossing a busy street. Risk is perceived high when there is a lack of personal control, and the activity has a delayed or unknown hazardous effect (Hunter, 2001, with data from the Union of Concerned Scientists and National Radiation Commission, USA). Giving over control for perceived high risk activities therefore requires a high level of trust, based on education.

for the Cape Fold Belt (Coppersmith et al., 2012). This is due mainly to the low level of historic and instrumentally recorded seismicity in the CFB region and the poor epicentral location for most pre-2000 events. It was simpler to regard the entire southern CFB region as a single SSZ or seismotectonic province (Bommer et al., 2014). While the 4.8 ± 0.5 M 1969 Heidelberg event, located along the Kango Fault west of Oudtshoorn, is reported as the maximum recorded earthquake in their new Extended Continental Crust SSZ (also reported as 5.2 ML, or Intensity VI, in Brandt et al., 2005, p.29), $m_{max}$ values distributed between 6.0 ~ 7.9 M were also included, weighted with a low probability of recurrence on the logic tree used in the revised PSHA of the region. The wide 95th percentile spread in the magnitude used in their assessment, about a mean of ~7.3 M, is due mainly to the uncertainty associated with the palaeoseismic data, both for the reported magnitude and dates.

Despite the absence of additional fracturing in the sandy graben fill and repeated small floods overtopping the scarp in the fan head area, if the monolithic debris facies of the interpreted flood unit 4c (Goedhart and Booth, 2016 – Part 1, Figure 15, section E, p.561) is re-interpreted as a second, younger, tectonic colluvial wedge, it would reflect the MRE. The MRE identified in this study at around 10 ka would then be the PE. This would imply a closed seismic cycle and a recurrence interval of about only 4,362 years. The resultant higher probability of recurrence at any particular time (~1 / 4,300 per annum) equates to a much higher potential seismic hazard for the Little Karoo even if the overall long term slip rate for the fault remains low. For example, a similar aged MRE is reported a short distance west, towards De Rust, with the suggestion that the Kango Fault may currently be in an elevated state of stress and experiencing a cluster of seismic activity (Hanson et al., 2014). While it is possible that the Kango Fault ruptured as a characteristic earthquake with little migration of segment boundaries (McCalpin 2009), potential segment boundaries along the fault have only just begun to be investigated (Goedhart, 2012; Hanson et al., 2012).

A cluster pattern of short recurrence intervals separated by long periods of quiescence is still typical of SCR regions (Stein and Mazzotti, 2007; McCalpin, 2009). Increasingly, palaeoseismic investigations seem to indicate that over the long term, stable continental regions may be 'not so stable' (K. Coppersmith, pers. comm., 2012). The question now raised is whether the repeated orogenic deformation events within the Atlantic-type rifted margin along the southern boundary of the African plate (Hälbich, 1992) have weakened it sufficiently to cause it to respond somewhat differently to the more stable cratonic interior. In addition, while it appears extensional stress is dominant in the southeastern Cape ($S_V > S_{Hmax}$), and that this could possibly be changing to compression (Logue et al., 2011, 2012), what has driven the observed neotectonic reactivation of the Kango Fault?

**Potential tectonic drivers**

Earthquakes in intraplate stable continental regions are a puzzle, particularly as they may be related to far field stresses that are initially not well understood in a specific area of investigation (Masana, 1996; Crone et al., 1997a, b; Stein, 2007). For example, the higher PGA expected in the Western Cape (Kjiko et al., 2003) is thought to be related to Atlantic Ridge Push forces (ARP), where horizontal stresses exceed vertical stresses ($S_{Hmax} > S_V$; De Beer, 2002). However, Logue et al., (2012) point out this may not be as simple as it appears. Even so, the 29 September 1969 Ceres-Tulbagh earthquake in the Western Cape, which was strike-slip dominated (Van Wyk and Kent, 1974) with a subsurface rupture velocity of about 3 km/s (Krüger and Scherbaum, 2014), is an example of this sudden release of accumulated stress. Micro-seismic activity between Ceres and Tulbagh, recorded over a 5 km wide zone to a depth of 15 km, suggests ongoing reactivation of pre-existing structural elements in the deeper underlying basement (Smit et al., 2015).

Unlike the Ceres event, the Kango Fault rupture had significant surface deformation, approximating those of the 7.0 $M_w$ 60 km long extensional Machaze rupture of 23 February 2006, in the Manica Province of nearby Mozambique (Clark and Bommer, 2006; Saunders, 2006; Cichowicz, 2006; Pule and Saunders, 2009; Saunders et al., 2010). While this latter event is widely accepted as being due to the southward propagating East African Rift from Malawi through a diffuse wide plate boundary zone extending into the Mpumalanga province of South Africa (Fairhead and Girdler, 1969; Hartnady, 1990; 1996a, b) and south-southeast into the offshore (Stamps, et al., 2008), the neotectonic stress field further south in the intraplate region of the southeastern Cape Fold Belt is still largely unknown and remains enigmatic. However, there are several hypotheses for the origin and direction of stress in this region, including:

- Uplift of the interior coastal zone along the Cape Isostatic Anomaly (Hales and Gough, 1960, 1961; De Beer, 1983; Pitts et al., 1992; Faurie et al., 1993, p.14). This potential source of stress is receiving renewed attention (Goedhart and Saunders, 2009; Goedhart and Combrinck, 2011, Goedhart et al., 2011), despite the absence of an obvious root to the Cape Fold Belt (Lindeque et al., 2007; 2011). This is because a low-density source may occur in the mid-crustal level rather than at its base (Goedhart et al., 2011; Goedhart, 2011). If the anomaly was already compensated in the Western Cape (Hales and Gough, 1960), the remnant in the Eastern Cape has an analogy in northern Spain (Gunnel et al., 2008).
- Continued relaxation of Permo-Triassic orogenic compressive stress (Hill, 1988).
- Reactivation of the Agulhas Falkland Fracture Zone (Ben Avraham, 1995), and
- Far-field stress along the Ceres-Prince Edward Fabric, related to the Trans-Indian Fracture Zone (Andreoli et al., 1996; Bird et al., 2006, Andreoli and Viola, 2007).

There are few ways to test any one of these hypotheses, even with long-term geodetics (Stein, 2007). In the Cape Fold Belt, if vertical tectonic uplift is in the region of 0.187 mm/year (or 18.7 mm/100 years), geodetic verification may entail a data accumulation phase of many decades. While 'it may seem slow in relation to horizontal plate motions of the order of 10 mm/year, tectonic uplift that averages 0.1 to 0.3 mm/year is actually quite a respectable figure for vertical displacements' (Hartnady and Partridge, 1995; Hartnady, 2012).

## Stress modelling

Stress modelling of the eastern end of the Kango Fault and into the linked Baviaanskloof Fault, by finite element analysis, has not yet been attempted. Although direly needed, doing so is somewhat speculative, as it requires a major assumption regarding the local state of stress in the crust. While there are some recent crustal-scale models in place (e.g. Bird et al., 2006), there are currently too few seismically-derived focal plane solutions available for the region to constrain the modelled stress direction. The very recent (8th October, 2016) 3.4 M earthquake that was accurately located in the Swartberge northwest of Oudsthoorn (I. Saunders, CGS, pers. comm., 2016) occurs 10 to 15 km north of the Kango Fault trace, and some 40- to 45 km west-northwest of the trench investigation reported here. The focal plane solution, the only one in the south-eastern CFB, and south-eastern part of the country, revealed slightly oblique left-lateral slip on one of the numerous north-northwest to south-southeast striking high-angle joints and small transfer faults in this part of the Swartberge. Although there were some smaller aftershocks in the same area, and similar events in 2005 and 2010 about 17 km to 38 km further west, additional and larger events are required to confirm that the observed first motion is a regional trend. Small slips on footwall transfer faults could be local responses to regional extension, as documented in this study and that of Hanson et al., 2012, 2014). It is concluded that a stress modelling investigation might best start with pure dip-slip, as indicated by the trench exposure and other various outcrops along strike. A variable percentage of strike-slip movement can be included, particularly if extending the model towards the Western Cape (Goedhart, 2012; Bommer et al., 2014), or where accommodating large-scale sinuosity or abrupt changes in direction of the fault trace (Gibbs, 1984).

## Summary and conclusions

The palaeoseismic trench excavated across the Kango Fault scarp, on the 'Scholtz' farm, east of De Rust and Oudtshoorn has revealed:

- The moment magnitude of the rupture was between 6.97 ± 0.01 M and 7.18 ± 0.01 M. This was derived from the 2.0 ± 0.06 m vertical offset of the event horizon preserved within the trench stratigraphy using the traditional empirical relations developed for capable seismogenic structures (Wells and Coppersmith, 1994). For comparison, the Ceres-Tulbagh earthquake of 29 September 1969 registered 6.3 M on the logarithmic Richter scale. The Kango Fault rupture may therefore have been almost an order of magnitude more powerful than South Africa's highest instrumentally recorded earthquake.
- In the exposure provided by the trench, the minimum recurrence interval between successive surface-rupturing earthquakes is 106.8 ± 5.5 ka. The annual probability of recurrence is therefore about 1/106,000, which is low, supporting the conclusion that even with capable seismogenic structures, tthe Cape Fold Belt is best modeled as part of an intraplate Stable Continental Region.
- Maximum slip rate for the Kango Fault is 0.0187 mm/year (or 1.87 m/1000 years). A former penultimate event is most likely buried below the northern end of the trench, or may lie buried south of the trench (Goedhart and de Klerk, 2011; Goedhart et al., 2011; Goedhart, 2011). Closing the seismic cycle by locating the PE beneath the trench would very likely increase the recurrence interval and reduce the slip rate.
- This study has demonstrated that palaeoseismic investigation is able to extend the earthquake record for South Africa back in time beyond the current instrumental and historic catalogue by several tens to hundreds of thousands of years. This is particularly useful in a stable continental region (SCR) like South Africa where current levels of seismicity are low, focal depths are fixed, and direct association of historical poorly-constrained epicentres with fault surface traces are not easily made (Theron, 1972, 1974; De Beer, 2002; Goedhart and Saunders, 2009; Goedhart, 2012).
- The Kango Fault trench results have several regional implications, the most important being confirmation that the rationale underpinning the initial seismotectonic models established for South Africa was correct (Andreoli et al., 1993, 1995, 1996; Partridge, 1995; Hartnady, 1996a; du Plessis, 1996a, b; see also Brandt, 2008; Singh et al., 2009). However, it may be necessary to revise and update $m_{max}$ for the south eastern Cape Fold Belt (Kjiko and Graham, 1998, 1999; Kjiko, 2004; Wheeler, 2009), used in one of the more recent Probabilistic Seismic Hazard maps for South Africa (Kjiko et al., 2003). The process followed for a recent revision of seismic hazard in the southern Cape Fold Belt is provided in Coppersmith et al., (2012), and Bommer et al. (2014).

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http://www.eskom.co.za/Whatweredoing/SSHAC_ProjectResults/Pages/DataPublications.aspx.

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