Superplume versus far-field stress as geodynamic controls on Witwatersrand sedimentation and Ventersdorp Large Igneous Province (LIP):

Insights from south-retreating and northward-advancing orogens of 3.1-2.5Ga Kalahari Supercontinent

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Supercratons Valbarra and/or Zimgarn inconsistent with unifying 3.1-2.5Ga Kalahari supercontinent and 2.75Ga vs 2.0Ga start of Limpopo belt orogenesis

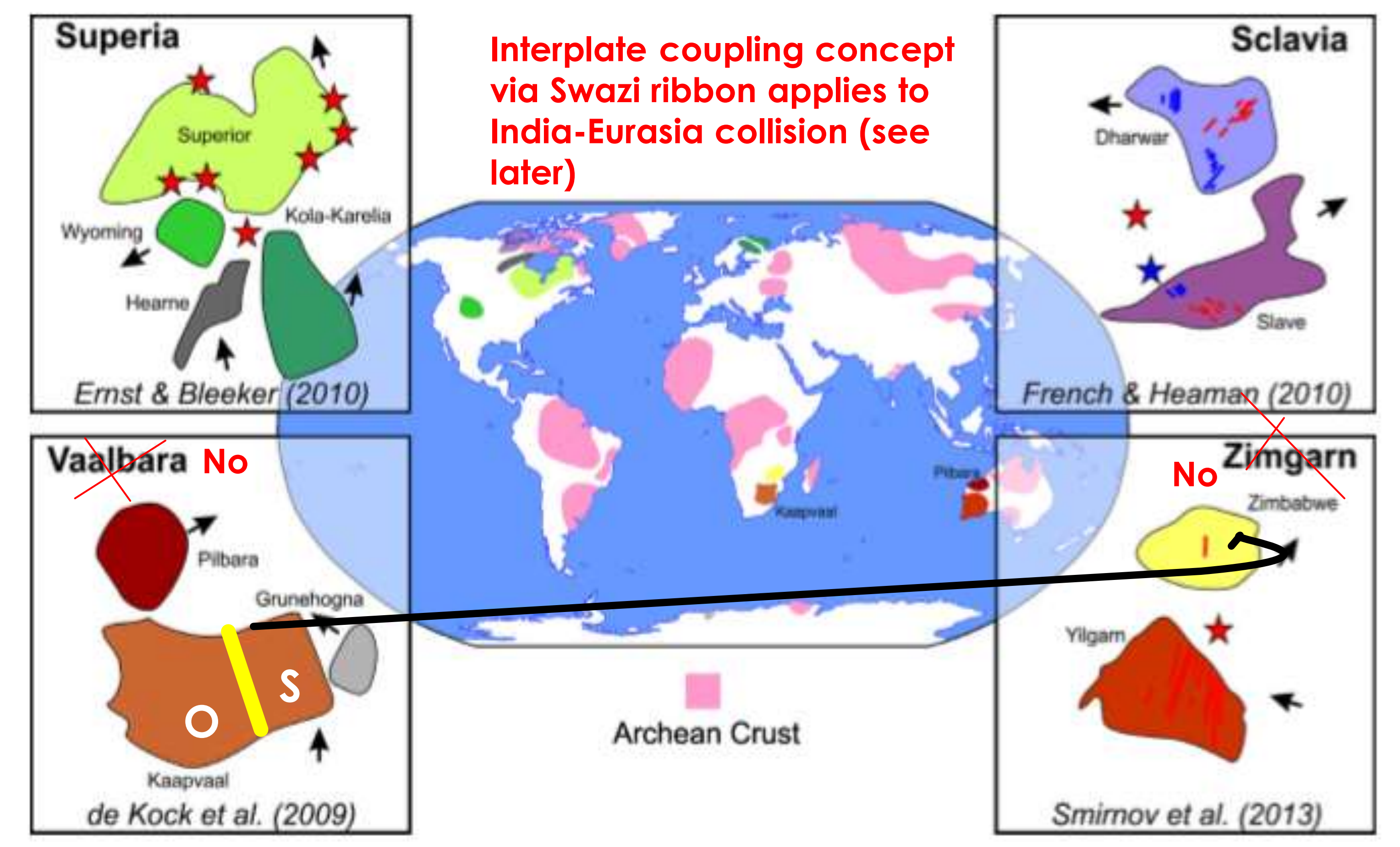
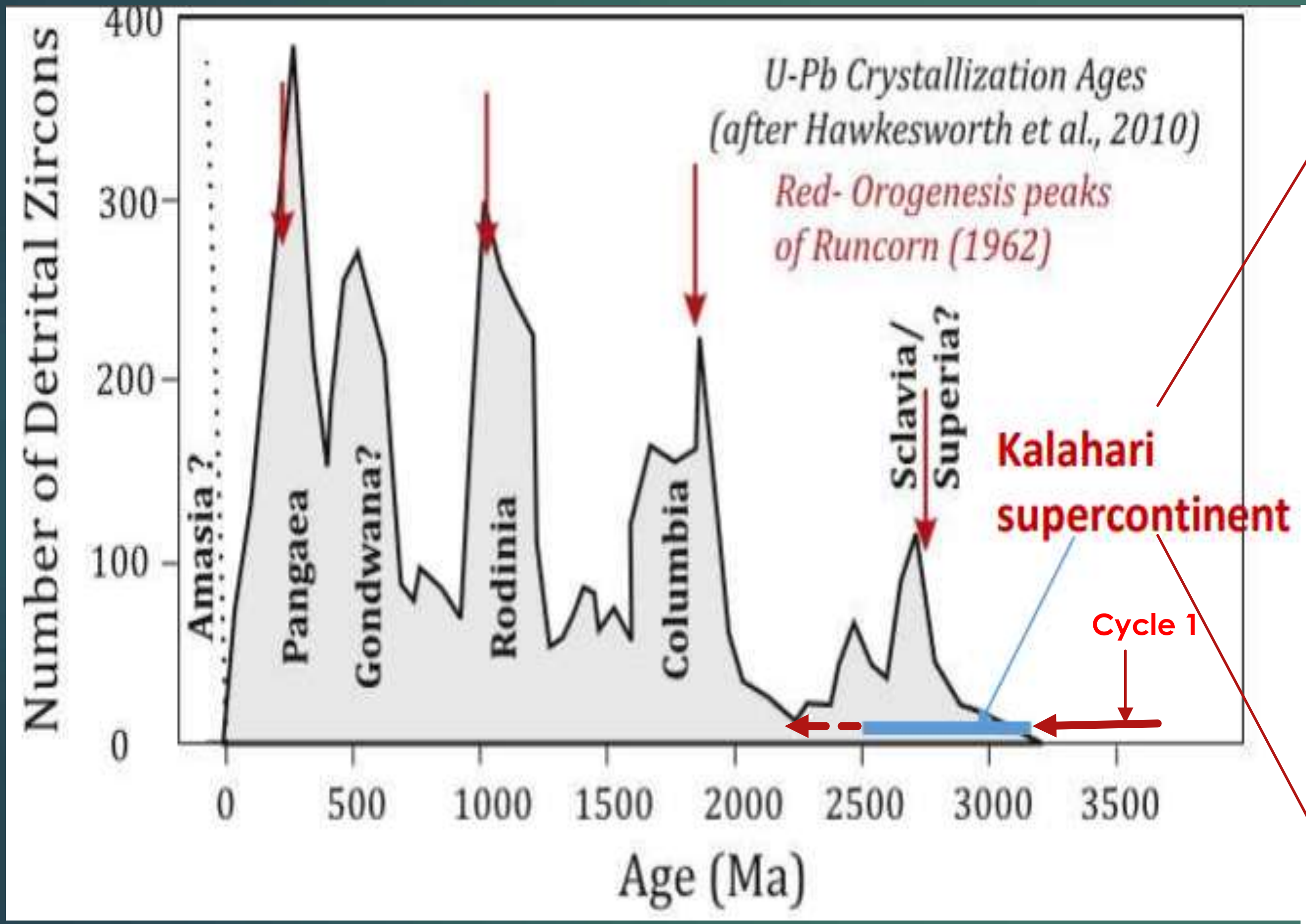
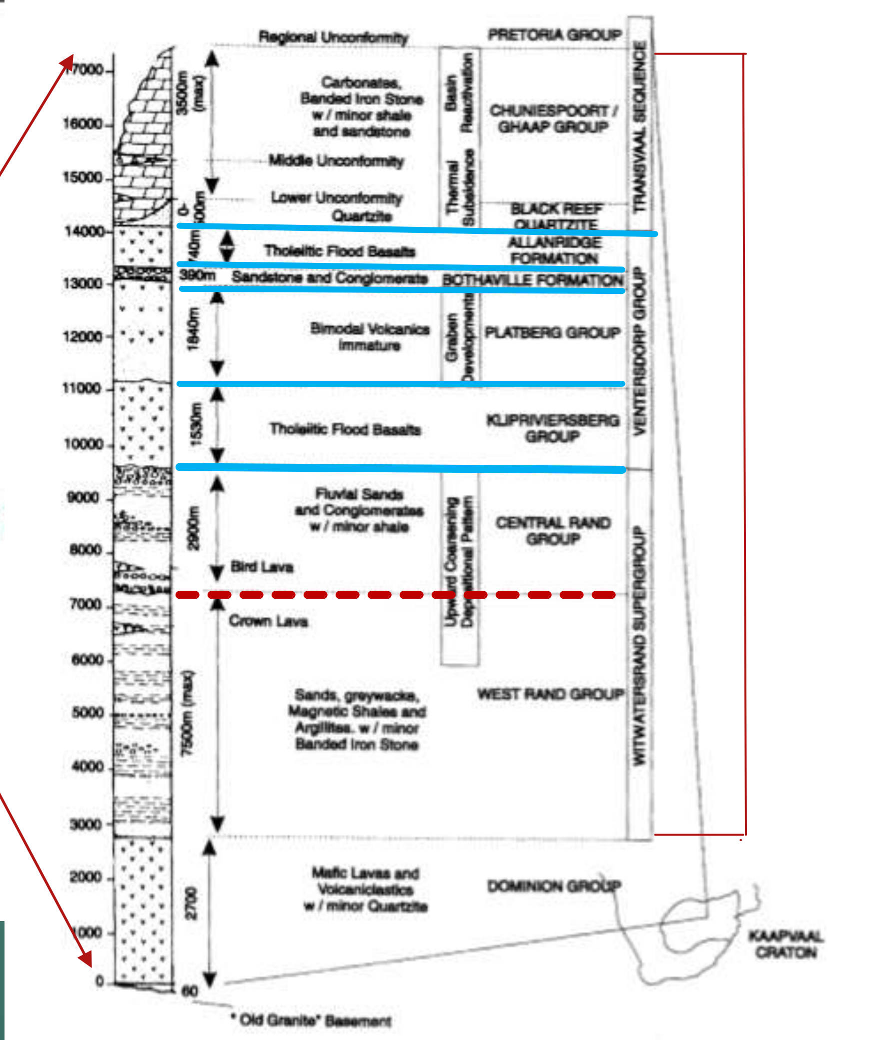


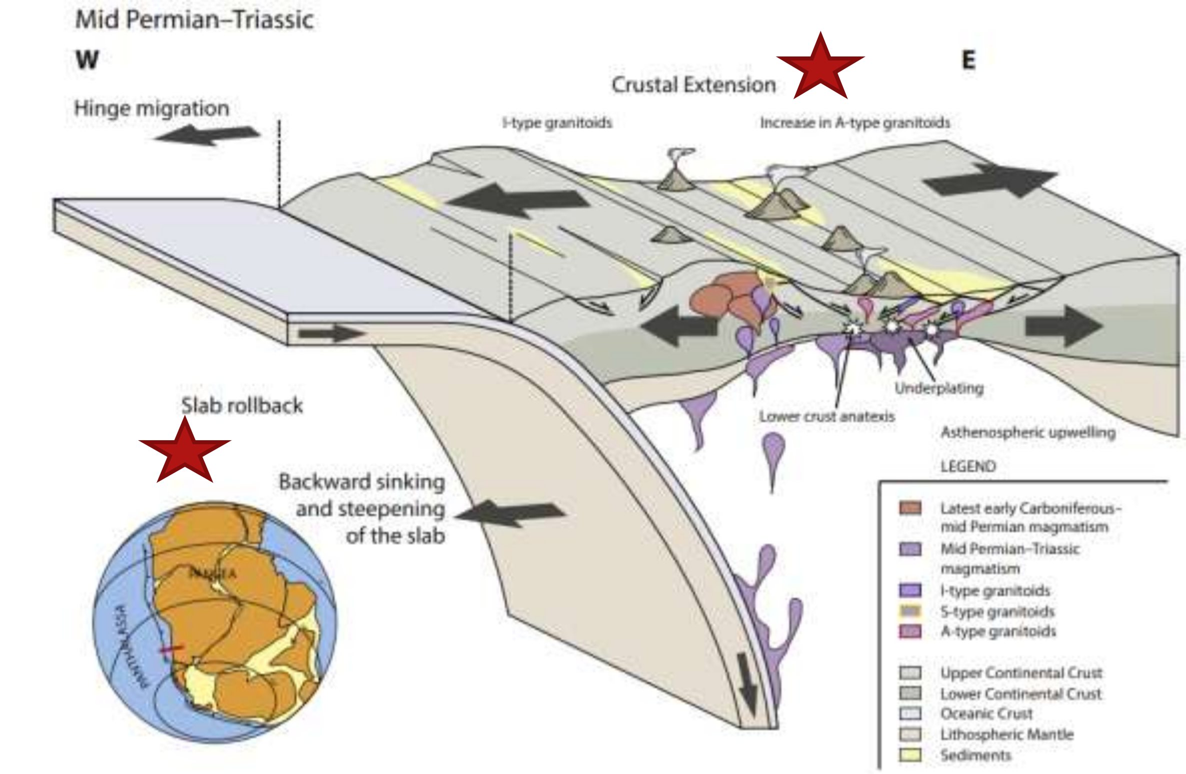
Figure: 1. Distribution of preserved Archean crust globally, with the various supercratonic configurations proposed at left and right. These supercraton configurations include Superia after Ernst and Bleeker (2010), Vaalbara after de Kock et al. (2009), Sclavia after French and Heaman (2010) and Zimgarn after Smirnov et al. (2013). The current outline of the cratons that make up these supercratons are shown. This includes the proposed cratonic configurations along with the present-day truth north directions in each craton with defining magmatism from coeval dyke swarms and sill provinces also shown.

3.1-2.5Ga Kalahari Supercontinent spans intraplate chronostratigraphy & onset of modern plate tectonics at 3.0Ga (Accretionary to collisional; e.g. de Wit et al 1992)

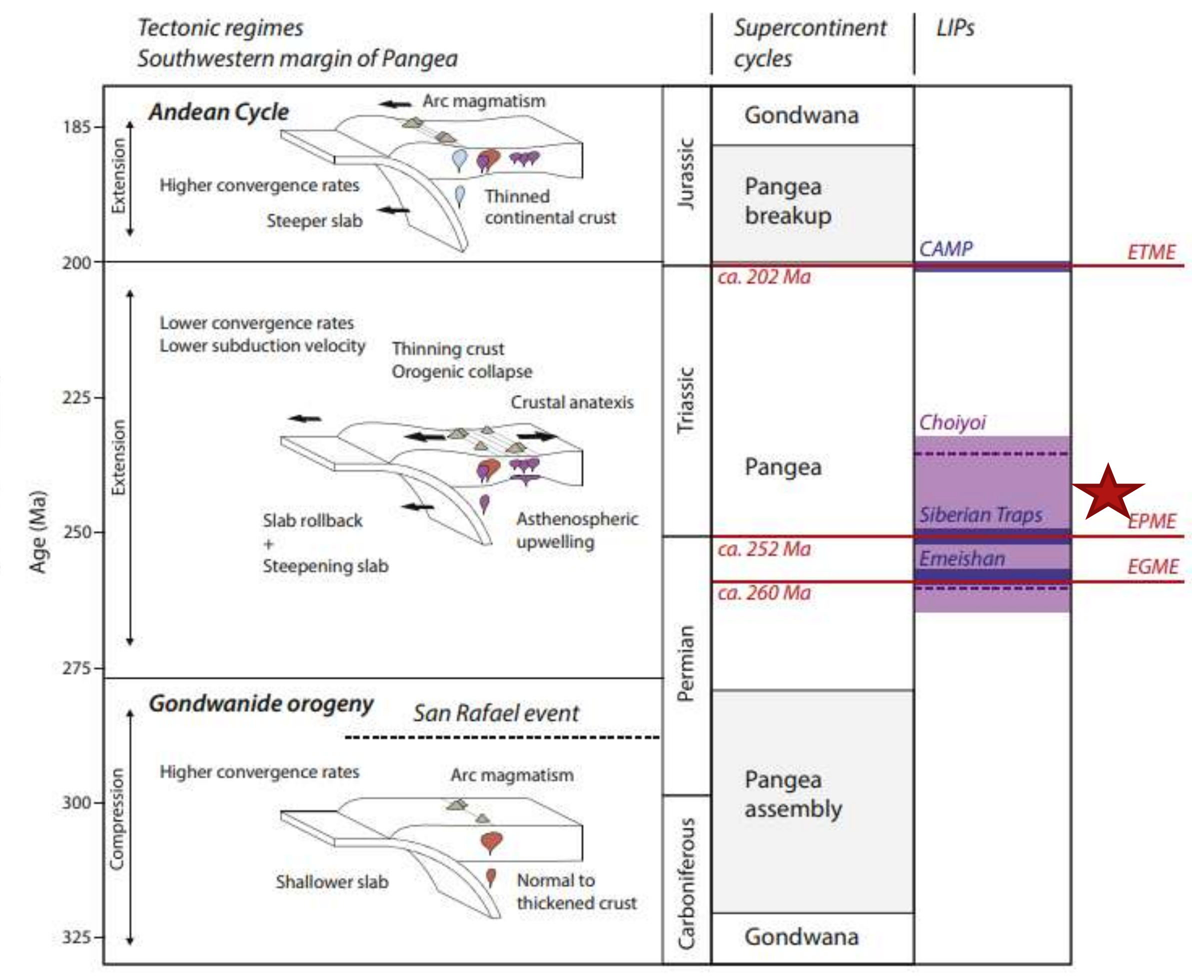




Pangea supercontinent includes Large Igneous Provinces LIPs



From de Rey et al., 2019



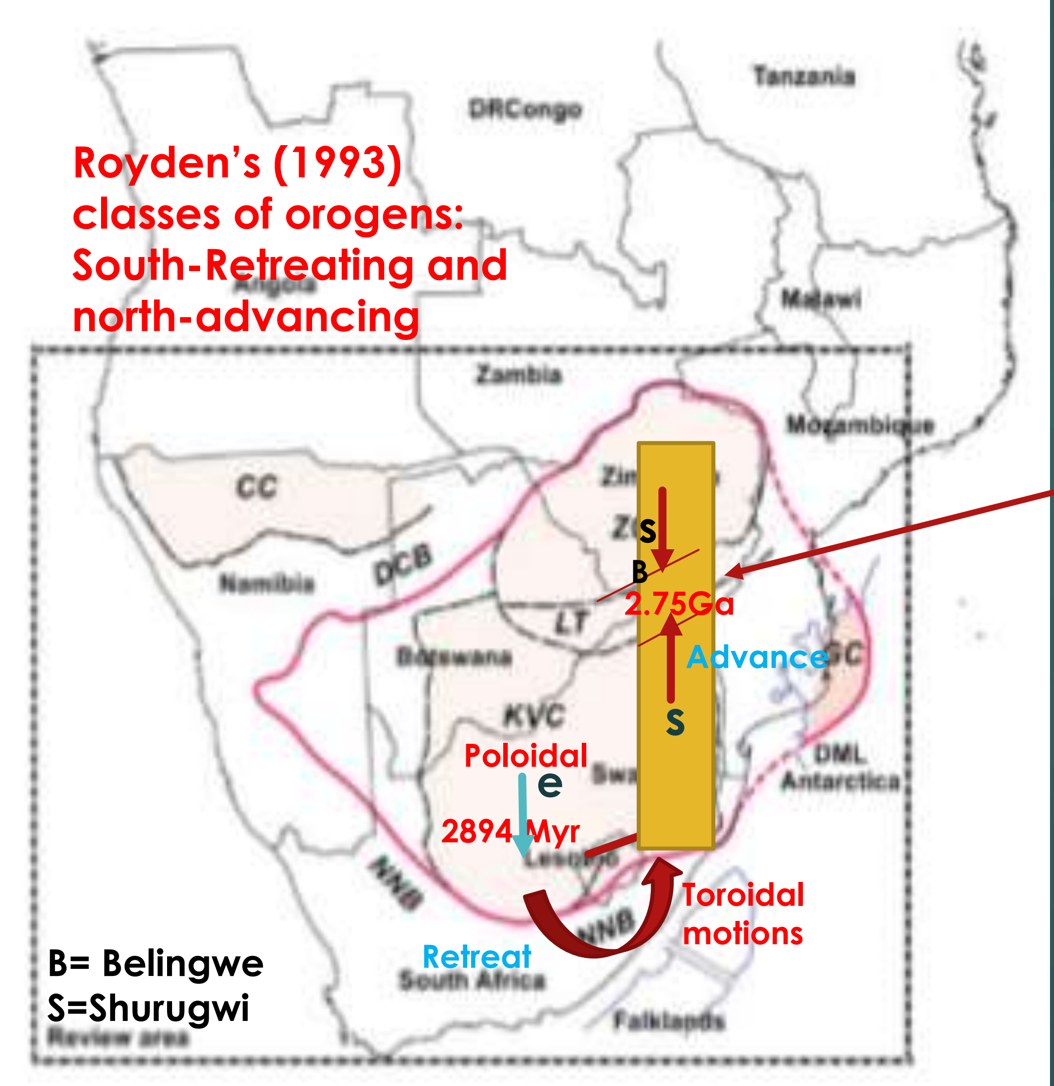
From de Rey et al. 2019

Unifying 3.1-2.5Ga oroclinal Kalahari Supercontinent: interplate coupling via stiff 3.6-3.2Ga protocratonic domains

How does a larger Kaapvaal craton indent a smaller Zimbabwe craton?

Secondary Swazi (2.9Ga) and Tokwe (2.75Ga) ribbons as crustal beams transmitting compressive stresses across Limpopo orogen from 2.75Ga

Indentation is microplate (e,g, India, Adria, Arabia-type) behaviour: Swazi ribbon evolved as rigid hinterland indenter

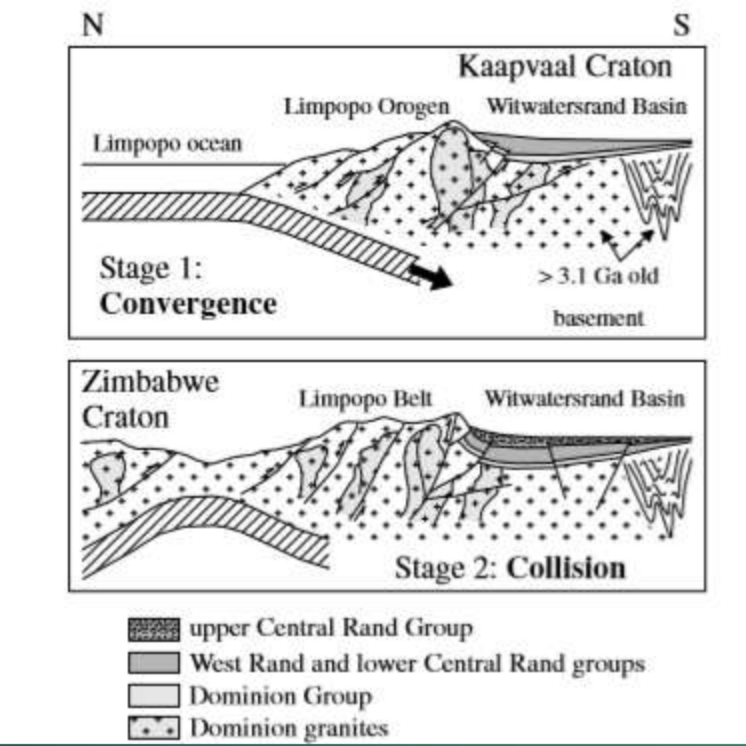


Note orogen boundary obliquity to North-advance

Plate behaviour is controlled by strong plates and weak plate interface (Toussaint et al. 2004); e.g. 3.6Ga AGC and MNK leading margin plus thermally-weakened Tokwe S margin

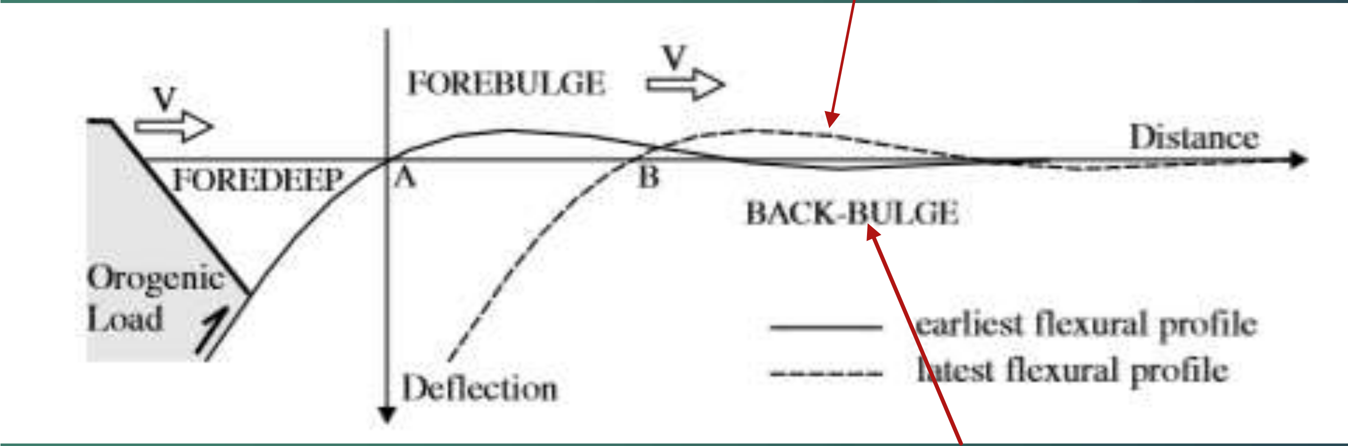
Previous north-south compressive models for Witwatersrand foreland system: revision as north-south extensional basins in south-retreating orogen

Flexural model of 2001



Flexural profile

Pongola basin as backbulge



NE-directed oblique convergence key orogenic loading by Kimberley arc

But Mozaan Group, up to 1.8km thick: exceeds >back-bulge accommodation (Catuneanu, 2001)

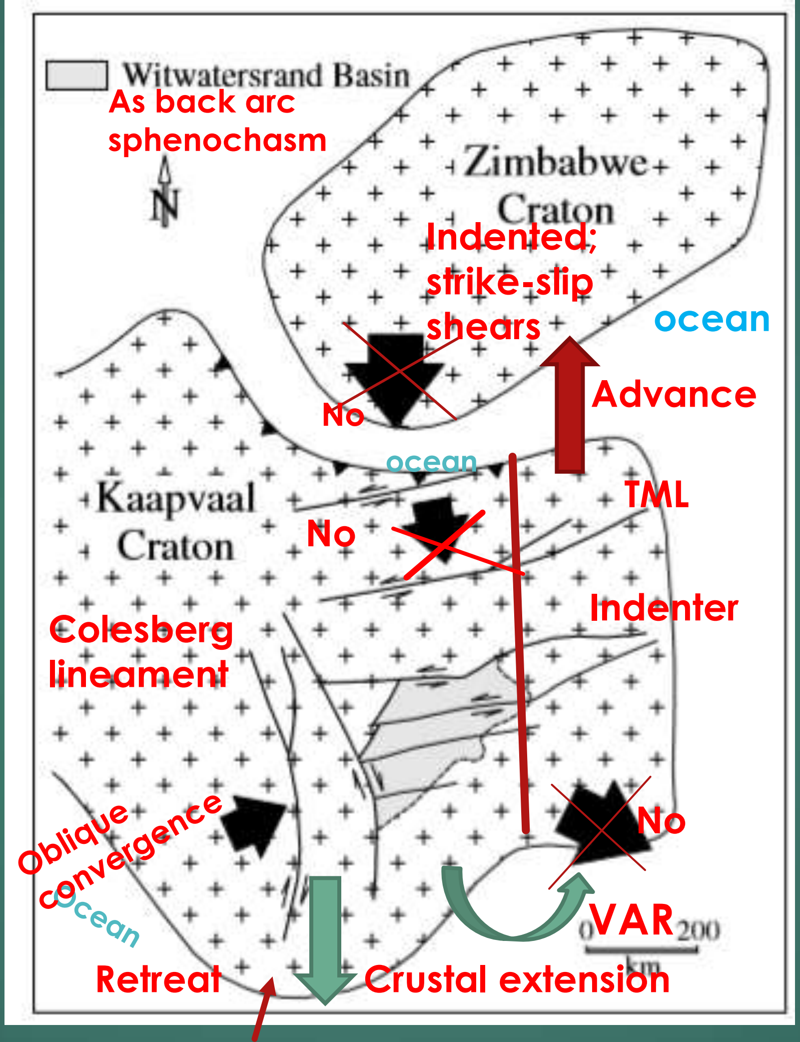
Catuneanu, 2001; Eriksson et al. 2008; Robb & Meyer, 1995

Mesoarchean Swazi indenter shape, size and rheology & south-retreating orogen (=regressive hinge migration)

Cautionary tale for geochron.

Time-integrated evolution from Retreat to Advancing orogen & Persistence of convergence

Pongola basin not backbulge basin of foreland Witwatersrand foredeep basin



Ocean-continent convergent margin in rollback

To indent a smaller Zimbabwe craton, the larger Kaapvaal craton evolved a microplate Swazi ribbon that acted as lower plate

Note >2/3 Kaapvaal craton is upper plate and 1/3 becomes lower plate Swazi ribbon for Limpopo ocean subduction and continental subduction

Why bother about rifts or Archean Kalahari supercontinent cycle hypothesis?

- Rifts and Passive Margins; Structural Architecture. Thermal Regimes, and Petroleum Systems by Michael Nemcock, 2016, 607pages CUP.
- Current exploration thrust on post-Archean basins for oil and gas-CBM in Zimbabwe: max depth of crustal basins is 17km!
- Extensional tectonic regimes understated yet key to new mineral systems search including VMS, porphyry-related Molybdenum, Lithium pegmatites, emplacement of batholithic Chilimanzi suite of Zimbabwe craton
- World single-largest gold depocentre >45,000 tonnes gold produced by 1996 from Witwatersrand basin yet regional tectonic controls remain enigmatic despite over a century of mining (Dankert & Hein, 2010; Msanzi et al., 2013)
- Rifts and the “Belingwe model” at the heart of intriguing debate on origin, composition and organisation of Bulawayan Supergroup in Eastern and Western Succession of Prof Wilson (1979) or classic rift-related bimodal volcanism
- Trend to examine rifting in plate tectonic terms (Merle, 2011)
- Pangea supercontinent includes LIPs, rollback subduction like in Kalahari supercontinent

Coping with large tectonic system in time-space

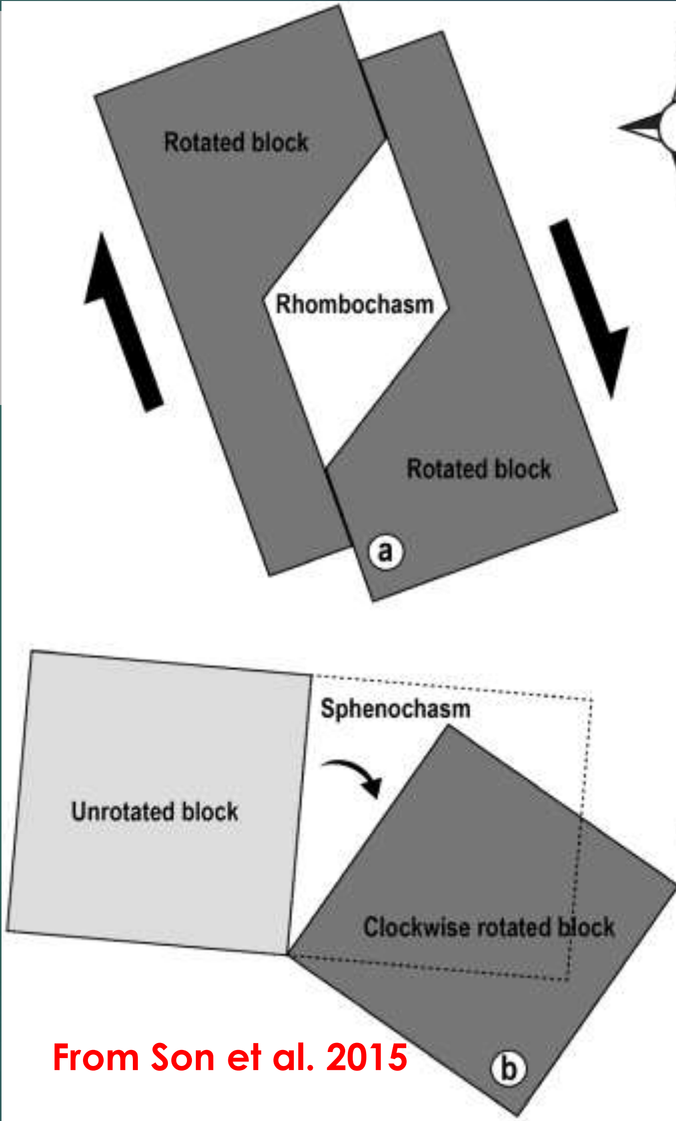
Carey Oroclines (mobilistic) & Sphenochasms in Kaapvaal craton

S. Warren Carey, 1962: "Scale of Geotectonic Phenomena", Jour. Geol. Soc., India

"**Our thinking in tectonics and structural geology is done with models.**" The importance of gravity increases with the size of tectonic features.

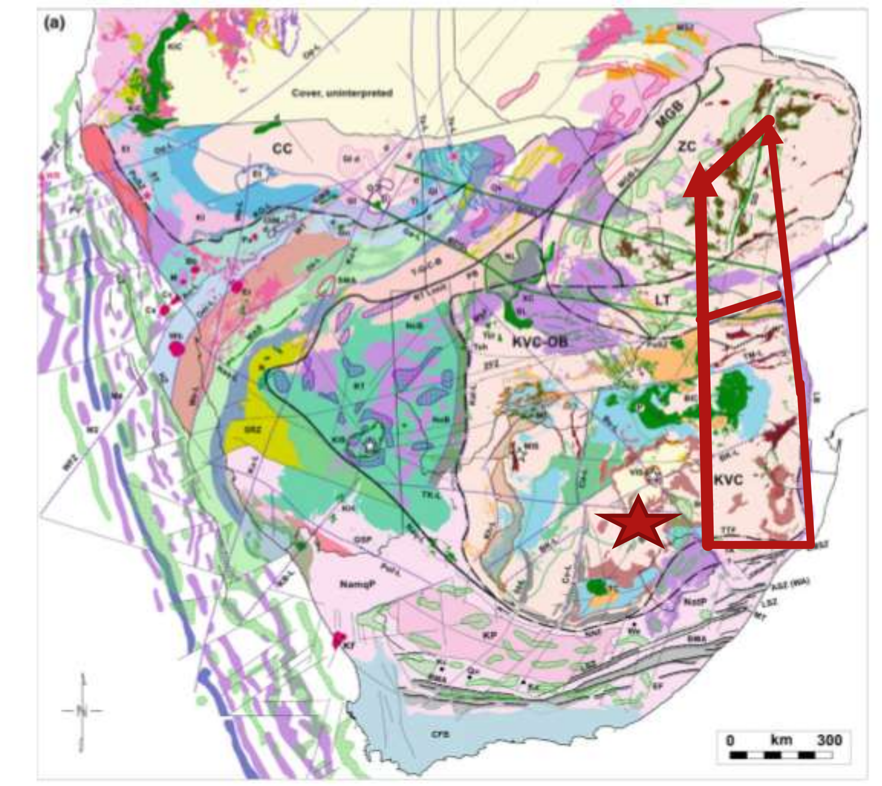
Requires:

- Global tectonics approach (some good textbooks in Structure and Tectonics)
- Episodicity of Dominion to Transvaal Supergroups: a Kalahari supercontinent cycle test!
- Accretionary protoKaapvaal and Tokwe host-continents and cratonic foreland
- Retreating, Advancing (Royden **1993**) or Neutral subduction zones in Archean
- Protocratonic lithosphere-dominated collision-indentation
- Natural examples versus numerical and analogue modelling results on indentation
- Geological-geophysical-geochronological compilations: 2D, 3D and 4D concepts

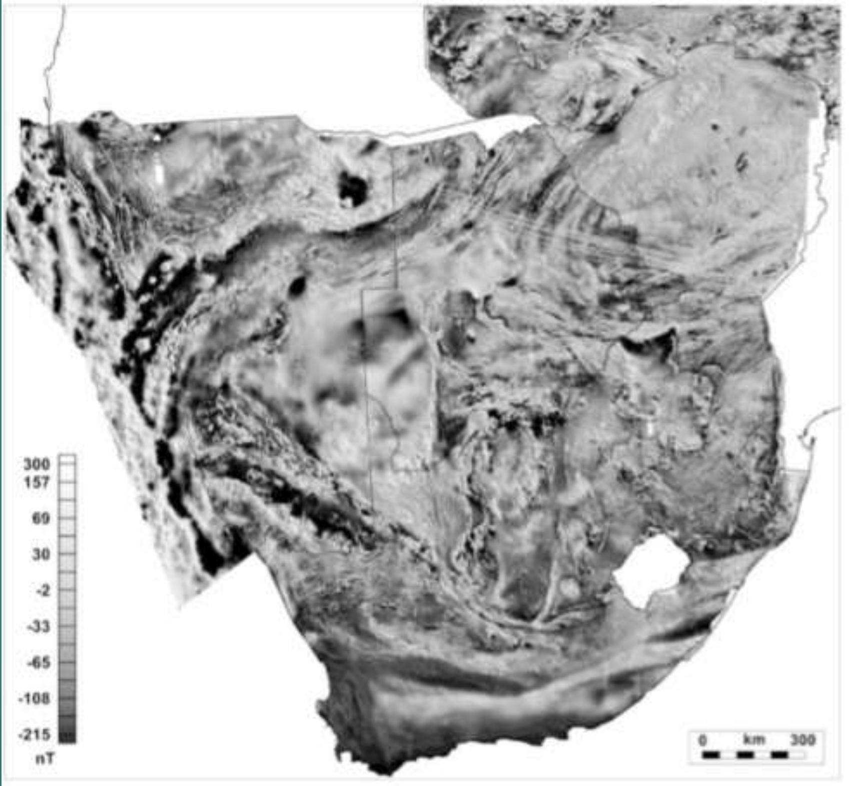


From Son et al. 2015

Regional tectonic axes and boundaries evolution in Kalahari supercontinent. Note inter-plate coupling dominated by ancient protocratonic domains post 2.8Ga



Regional SADC aeromagnetics map



Compilations by Corner, 2018

End-member models of Bulawayan Supergroup LIP of Zimbabwe craton (in passing outline)

Model 1 (?Active rifting)

- Vertical accretion by sedimentary and volcanic deposition in a broadly continuous sequence (e.g. Bickle et al., 1994; Blenkinsop et al., 1993; Hunter et al., 1998; Prendergast 2004; Wilson et al., 1995; Bolhar et al. 2003; Prendergast and Wingate, 2007
- Bulawayan LIP of Reliance-Zeederbergs span 2.75-2.68Ga (Prendergast and Wingate, 2012): c 70Myr & diachronous span
- Special nature of Archean basin sedimentation & plume magmatism

Model 2 (model-driven mobilistic)

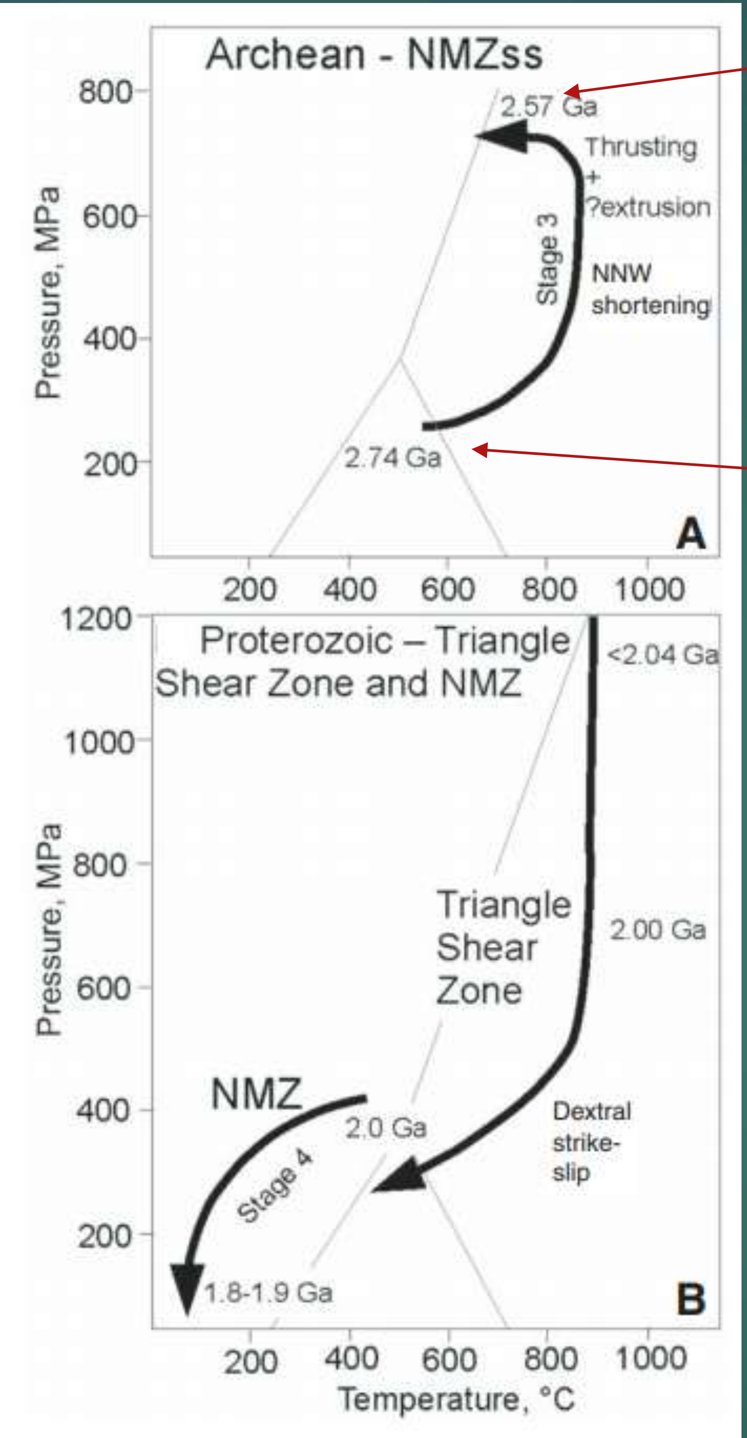
- Lateral accretion by early, craton-scale thrust-stacking of diverse continental and oceanic rocks, back arcs (e.g. Hofmann and Kusky, 2004; Jelsma and Dirks, 2002; Kusky 1998) between 2.67-2.62Ga

- ❑ weak foreland definitions &
- ❑ no indentation-escapes
- ❑ Model lacks external kinematic and plate boundary conditions or TABA systems
- ❑ Model does not involve Limpopo subduction-collision as a boundary condition
- ❑ Model regards strike-slip (Treloar and Blenkinsop, 1995) & NLTZ as late, c2.62Ga

In the above, no attempt made to separate 'Belingwe model' active from passive rifting, or hybrid model.

Pressure-temperature-time paths and NNW shortening tectonics (my Swazi indenter) of Archean and Proterozoic events in Northern Marginal Zone (from Kamber & Biino, 1995) in Blenkinsop, 2011.

- The 2.75-2.74Ga age is U-Pb age for Mashaba-Ultramafic Complex and related komatiitic flows (Prendergast and Wingate, 2012)
- The 2.74Ga are recorded in felsic gneisses in the footwall of the North Limpopo Thrust Zone (Rollinson & Whitehouse, 2011) : **Andean arc of NMZ with back arcs on Tokwe**
- 2.74Ga age of Rooiwater Complex in Murchison belt, MNK

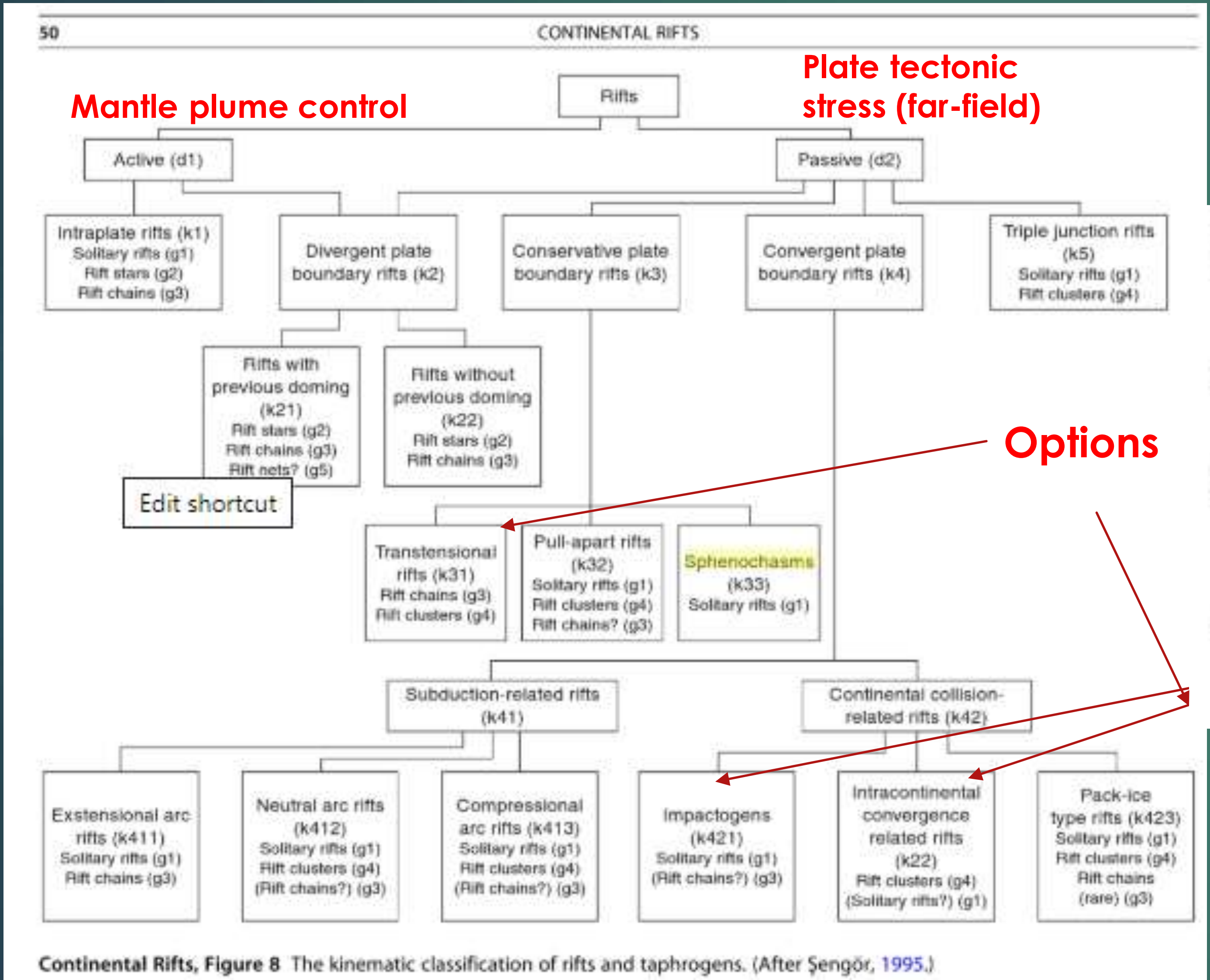


2575Ma Great Dyke as stitching intrusion to Kalahari supercontinent amalgamation

What is the meaning of 2.74Ga early start age in relation to Bulawayan Supergroup LIP (Prendergast & Wingate: 2.75-2.68Ga on the Zimbabwe craton?)

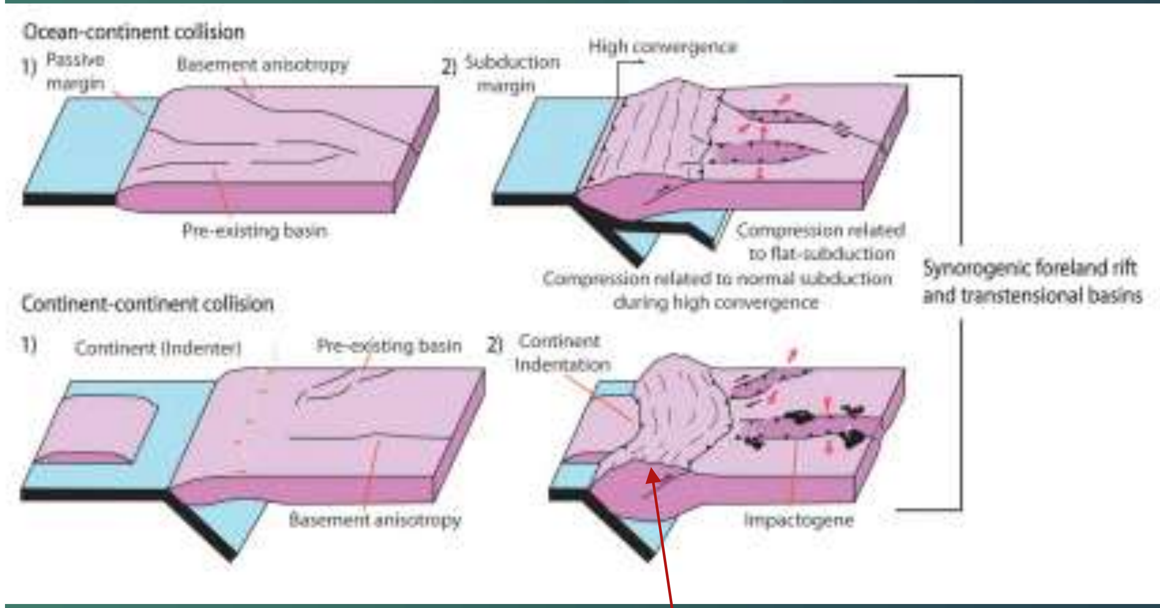
Yet increasingly, researchers (see Soderlund et al., 2014) are proposing a Proterozoic collision between Zimbabwe and Kaapvaal cratons

The 'continental Belingwe rift' on west margin of Tokwe protocraton plate requires appropriate kinematic classification in context of older start of Limpopo subduction-collision tectonics



Continental Rifts, Figure 8 The kinematic classification of rifts and taphrogens. (After Şengör, 1995.)

E.g. Orogenic-induced foreland rifting/transtension or reactivation of ancient NNE tectonic grain of Tokwe



OPE stretching lineations with plunge culminations SSW-NNE

From Giani et al., 2015

Active versus passive rifting

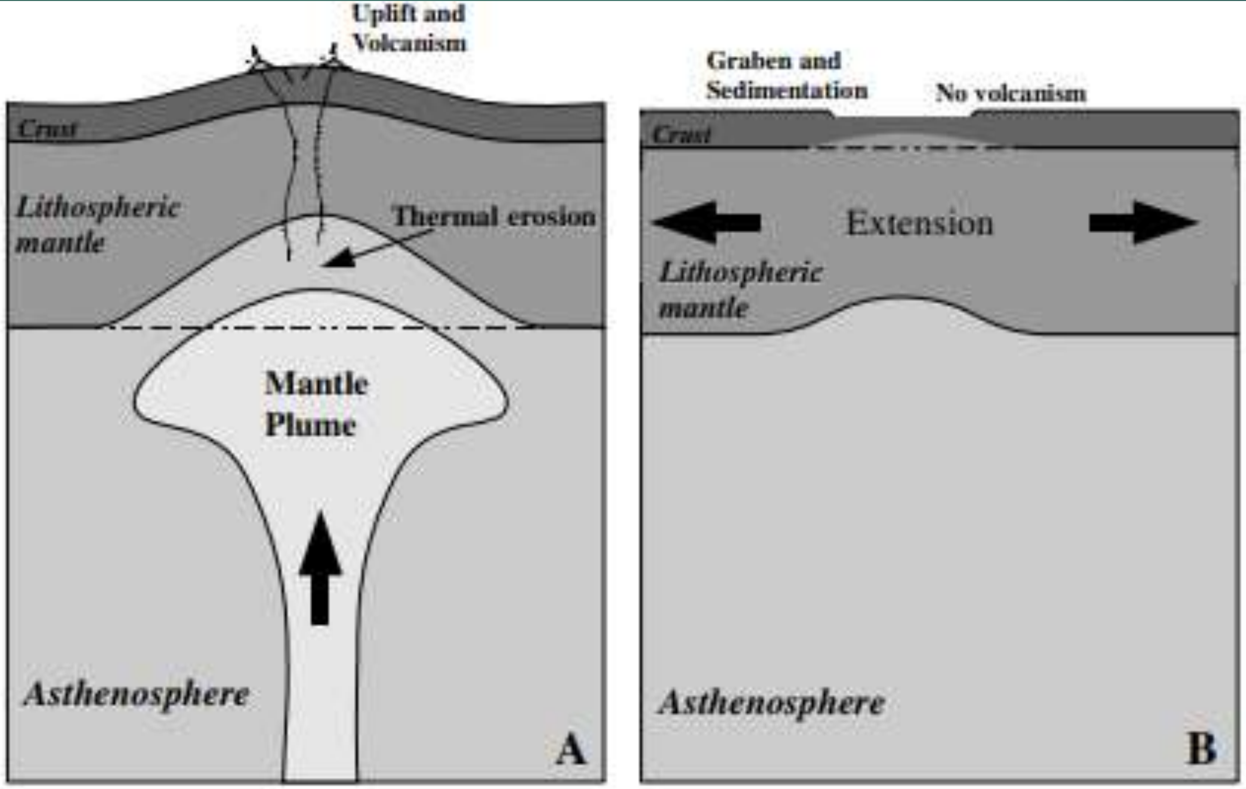
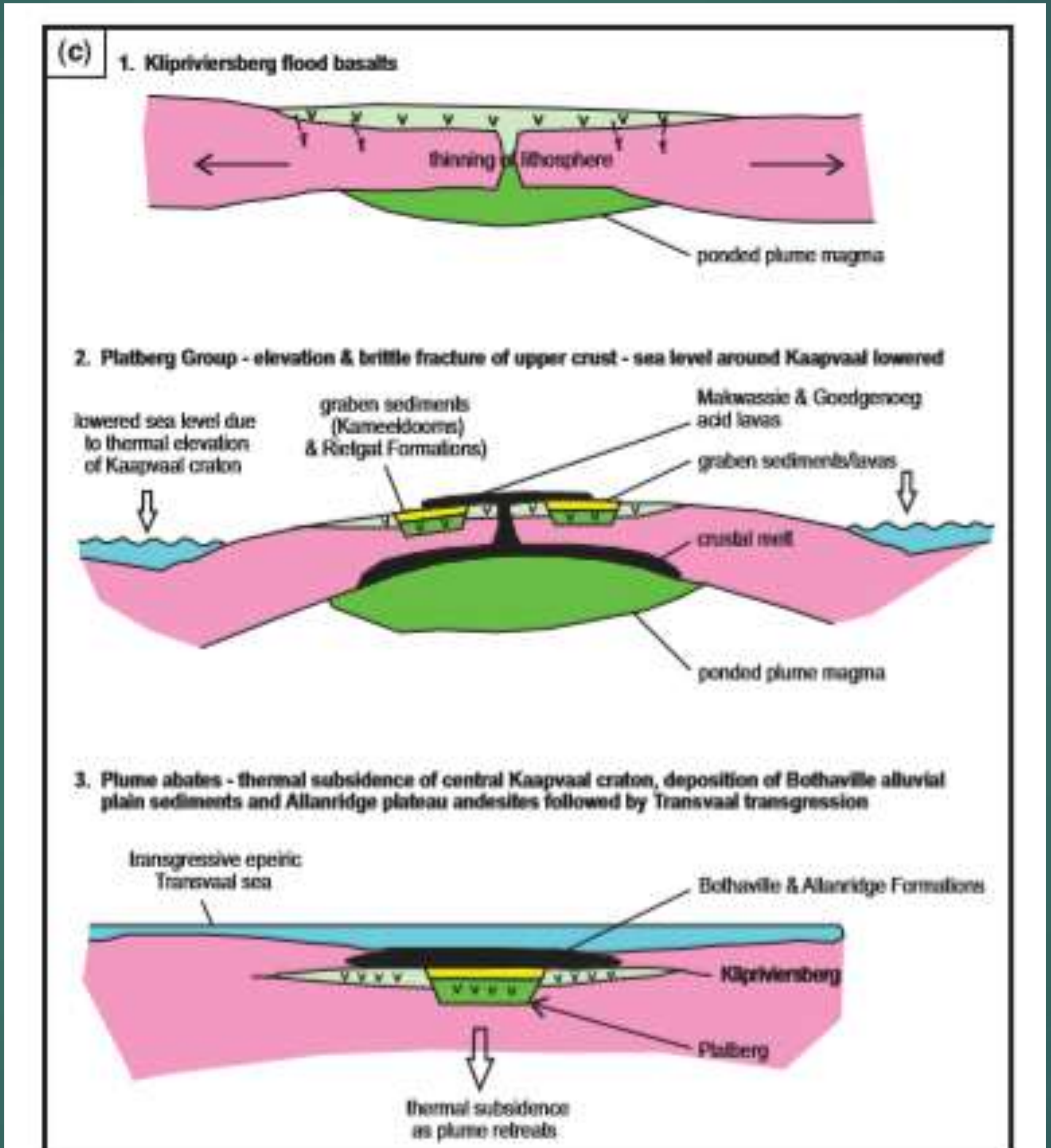


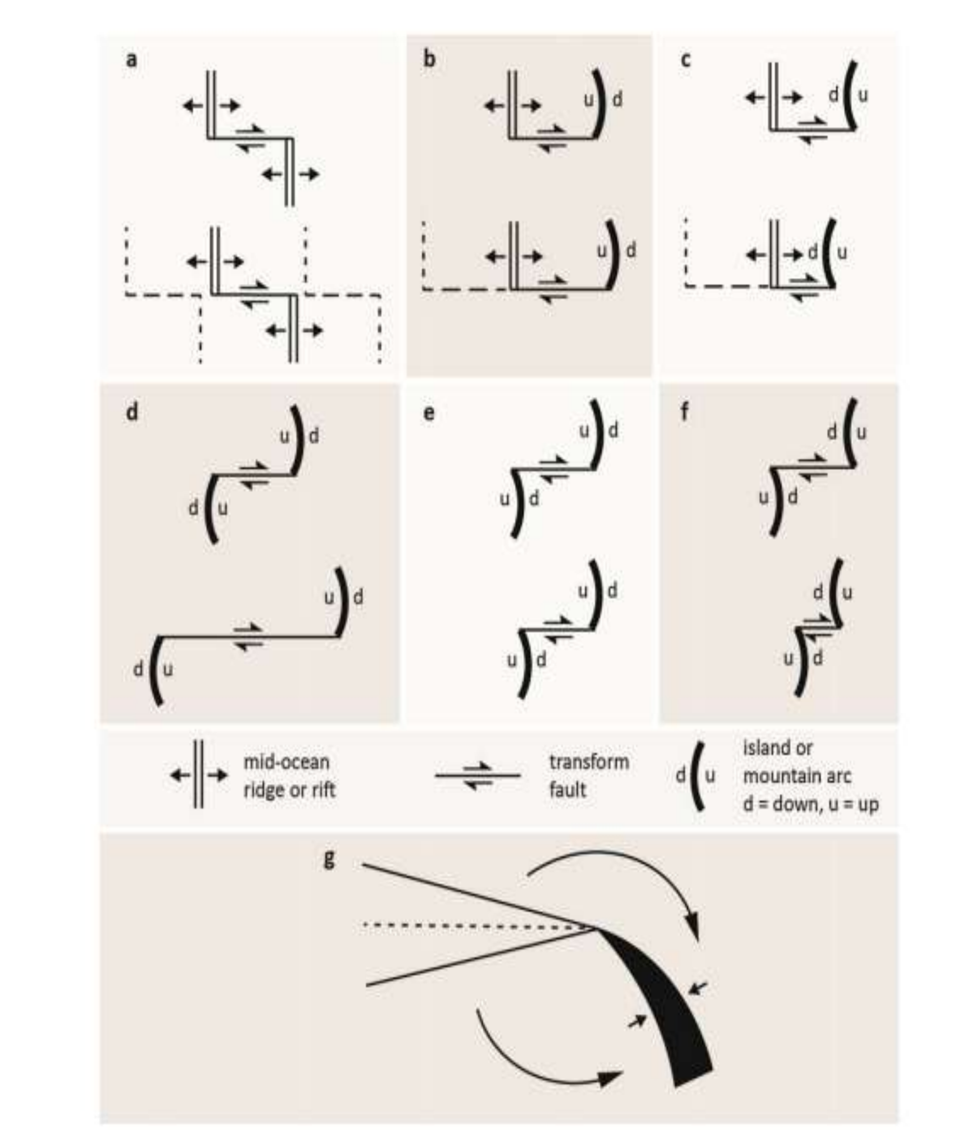
Fig. 1. The early stage of the tectonic evolution for "active" (A) and "passive" rifting (B). "Active" rifting displays lithospheric uplift and volcanism resulting from thermal erosion at the base of the lithosphere, whereas "passive" rifting displays graben formation and sedimentation without volcanism as a result of horizontal extension of the lithosphere.

Mantle plume and Ventersdorp LIP



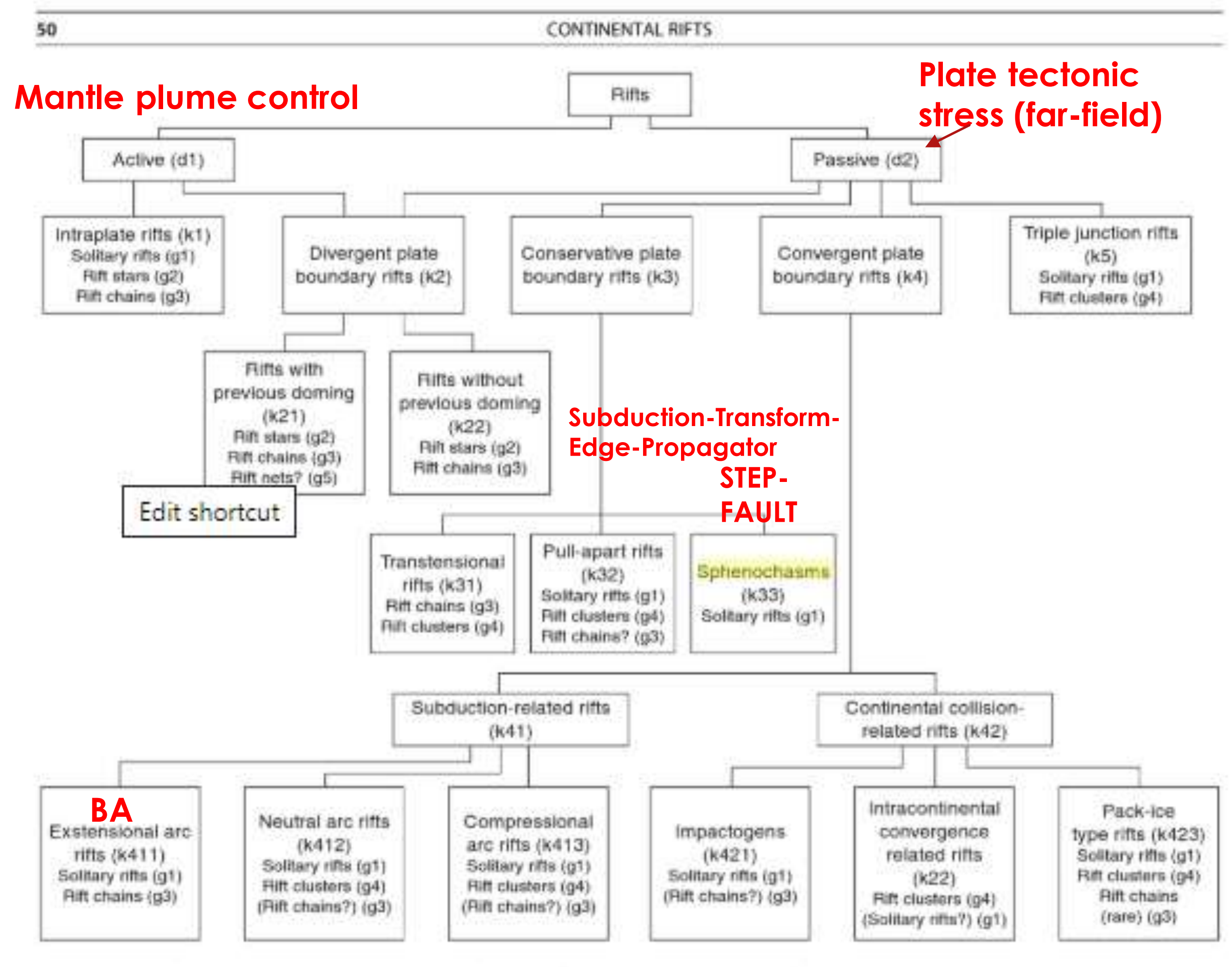
From Bumby et al.

Convectional plate boundary types; Mid ocean ridges, transform faults, subduction and continental collisions: which boundaries dominated Mesoarchean Kaapvaal?



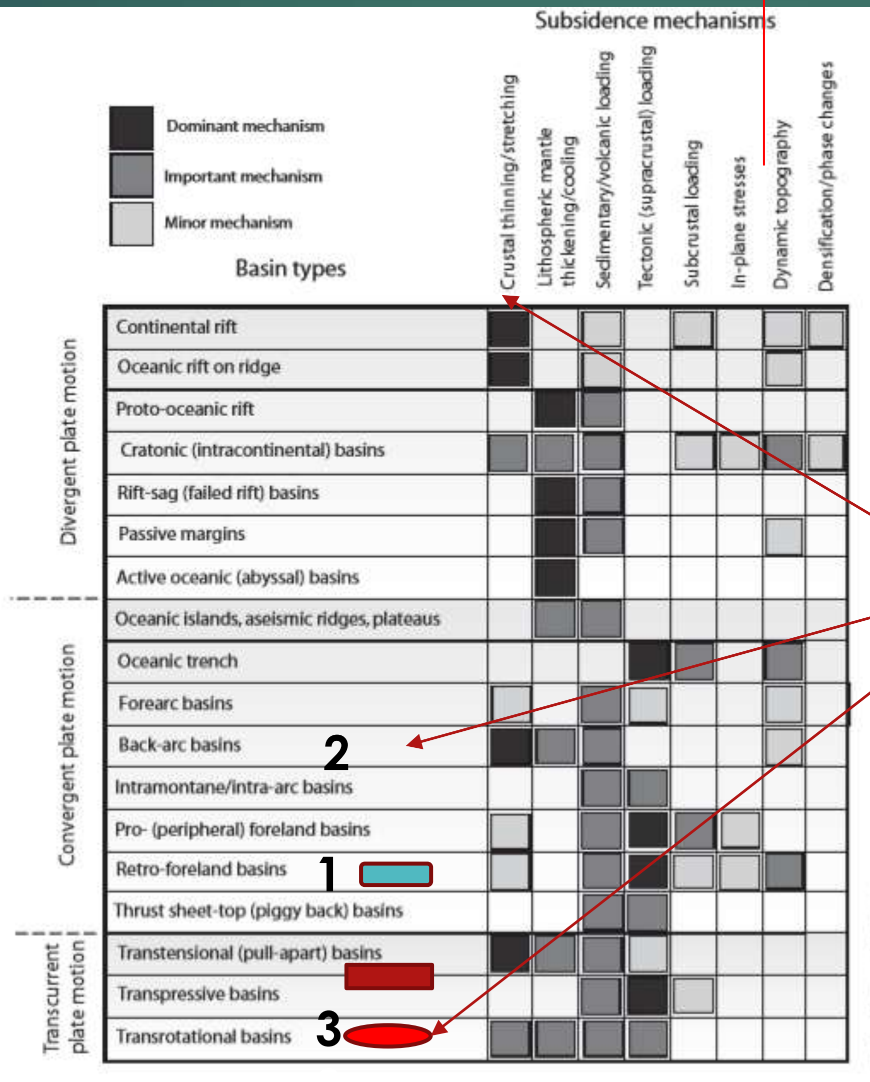
After Wilson, 1965

Witwatersrand basin as sphenochasm along Colesberg STEP-tear fault



Continental Rifts, Figure 8 The kinematic classification of rifts and taphrogens. (After Şengör, 1995.)

Witwatersrand basin as subduction-related back arc extensional superposed on earlier foreland basin



Retreating orogen

&Transform (STEP)

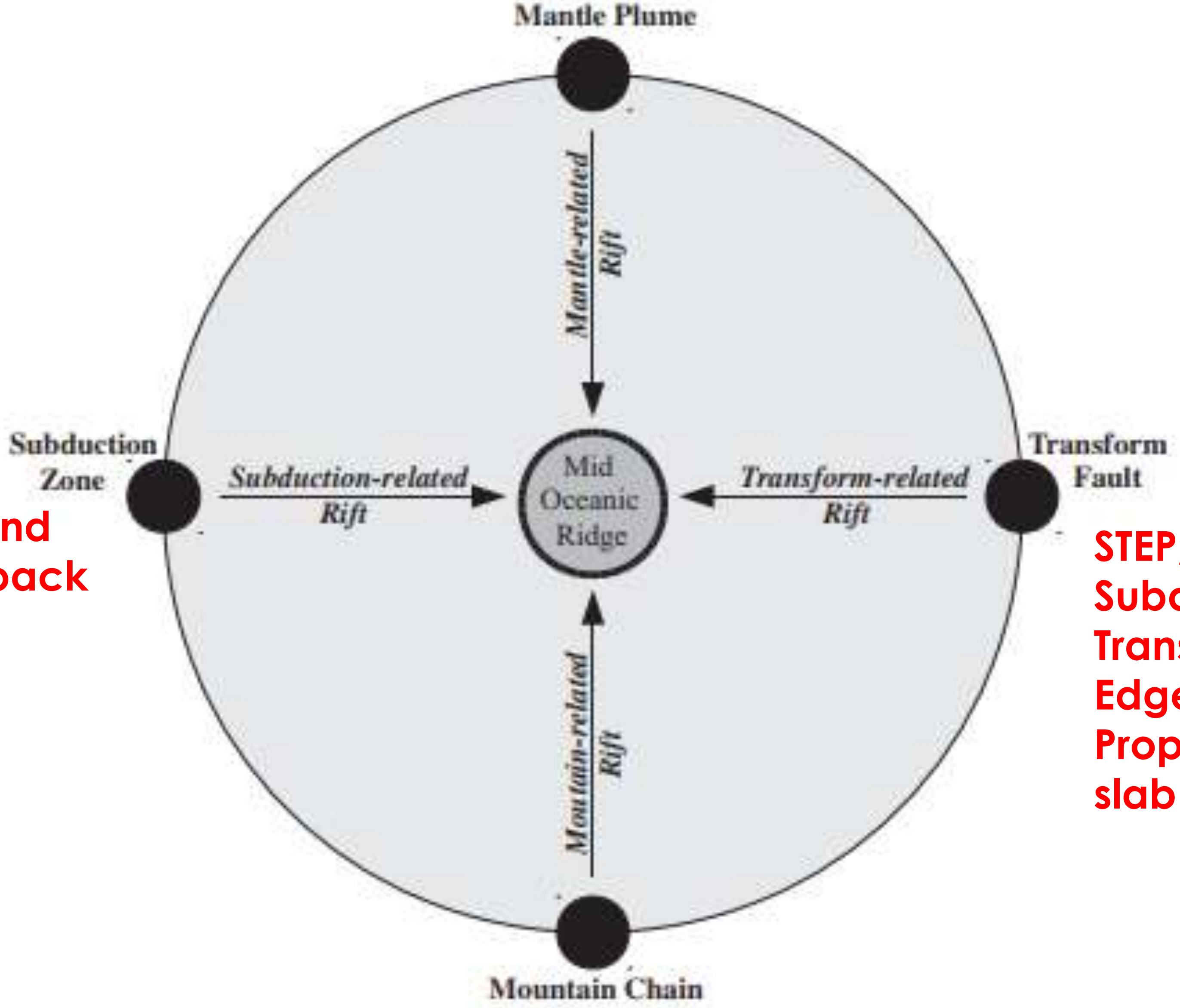
Oblique convergence (TP/TT)

Fig. 2.4. Matrix of sedimentary basins in relation to subsidence mechanisms, from Allen & Allen (2013, p. 17, fig. 1.16) adapted from Ingersoll & Busby (1995). Sedimentary basins are listed according to divergent, convergent, strike-slip kinematics. The main processes acting in these basin types are shown by the shaded cells.

Kinematic environment of Witwatersrand sphenochasm & upper plate dynamics

O. Merle / Tectonophysics 513 (2011) 88–95

Trench retreat and slab rollback

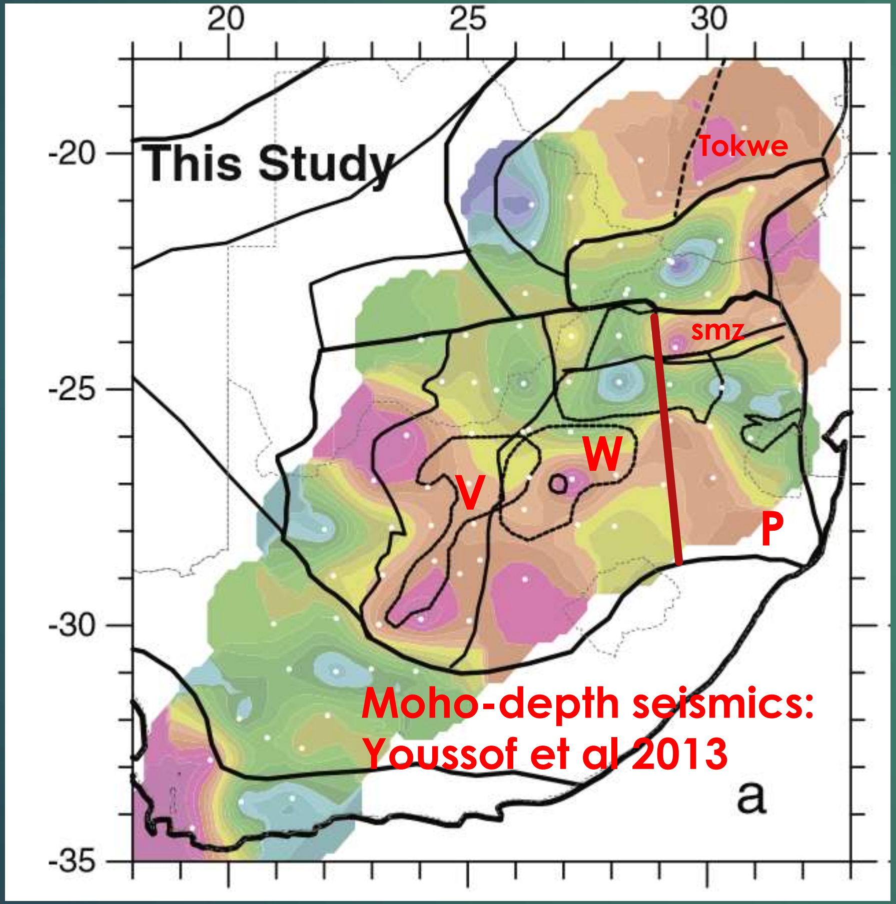


STEP; Subduction-Transform-Edge-Propagator, slab tear

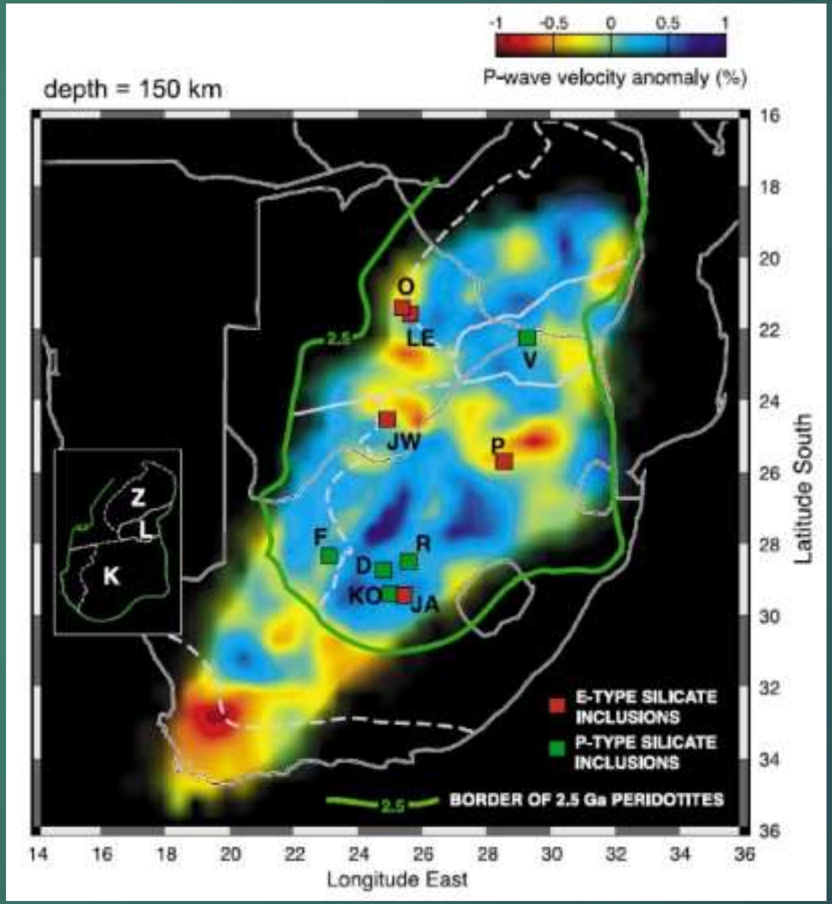
Fig. 2. Continental rift classification according to the four tectonic environments at the origin of their formation (see text for explanation).

Witwatersrand, Pongola and Ventersdorp basins linked by thinned lithosphere as dominant subsidence mechanism

Thinned crust & basins setting

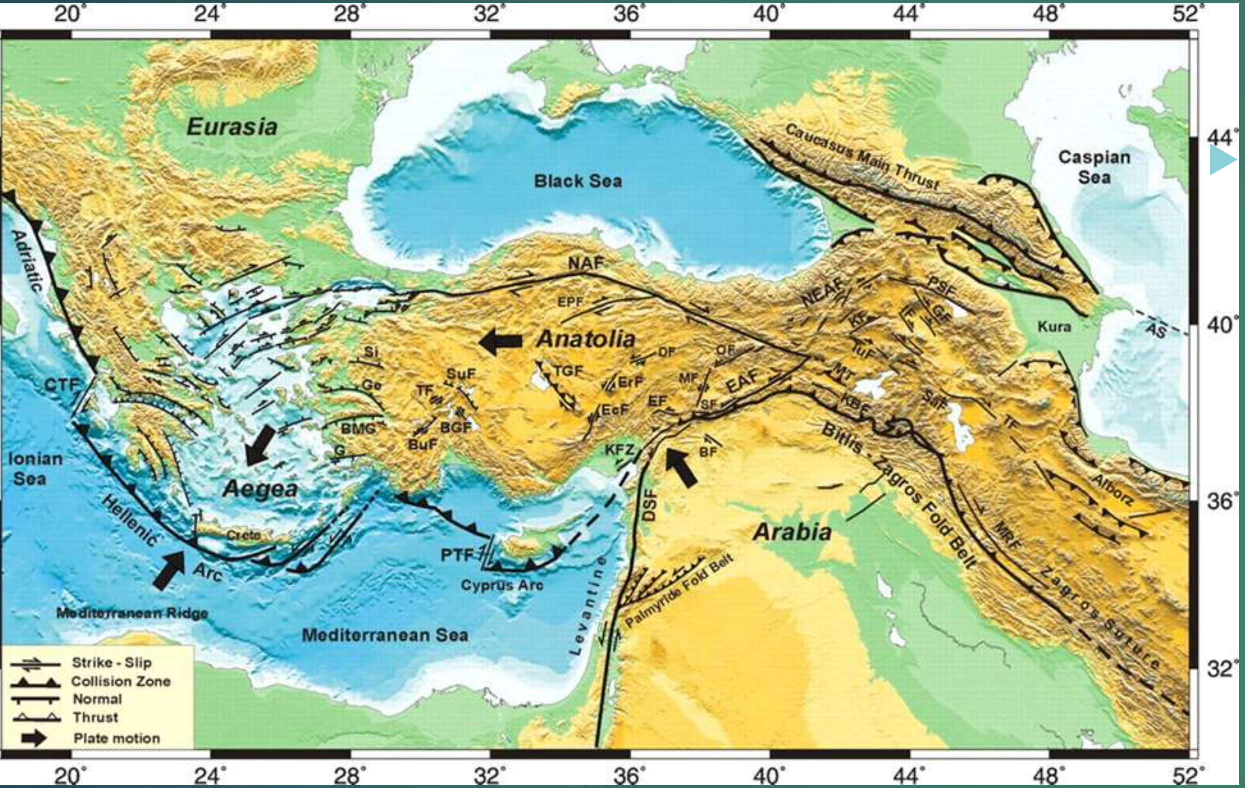


Finsch & Kimberley mines underthrust by >3.2 protoKaapvaal basement



Shirely et al.

Aegean arc in classic work of sedimentary basin formation by **lithospheric stretching** (McKenzie, 1978) :analogue of Kaapvaal south margin and tectonic escapes of Witwatersrand basin: Stanistreet and McCarthy, 1991



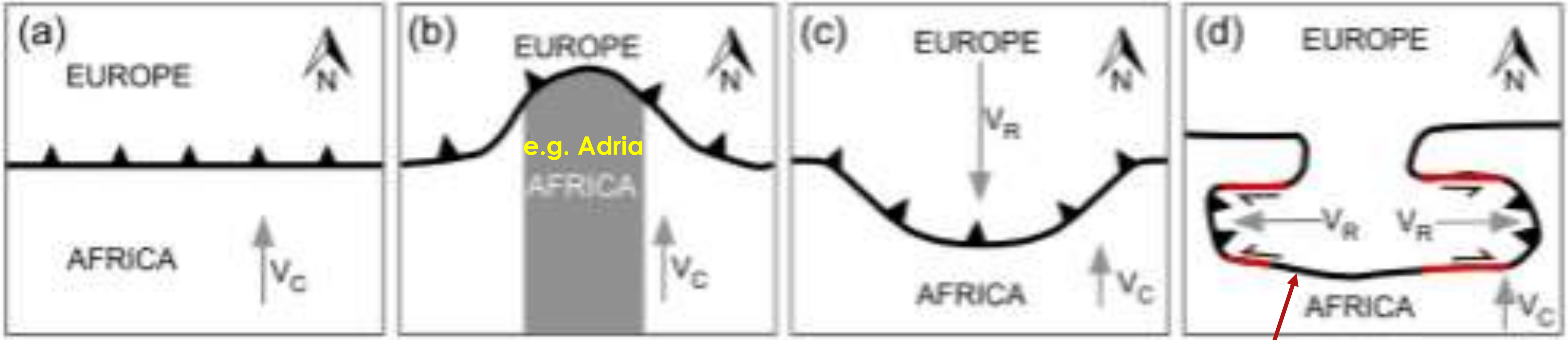
Aegean tectonics: Strain localisation, slab tearing and trench retreat

Laurent Jolivet, Claudio Faccenna, Benjamin Huet, Loic Labrousse, Laetitia Le Pourhiet, Olivier Lacombe, Emmanuel Lecomte, Evgenii Burov, Yoann Denèle, Jean-Pierre Brun, et al.

Back arc zones of extension & subsidence
Calc-alkaline volcanism
Hot underlying upper mantle

At the centre of the debate is formation of back arc basins in Archean convergent margin settings
And back arcs as proxy for granite-greenstone settings e.g. Witwatersrand & Ventersdorp basins
Paradoxically, it is extensional tectonics in convergent margin settings: Retreat and advance

Indentation (b), retreat (c) and lithospheric (d) tear-assisted trench retreat (cf Kaapvaal Orocline)



[redacted] Schematic illustration of possible changes in the geometry of the Africa–Europe plate boundary. V_C – rate of plate convergence; V_R – rate of trench retreat. (a) Fixed plate boundary oriented E–W, with the African plate subducting beneath Europe. (b) Northward convex boundary in response to indentation. (c) Southward convex boundary due to trench retreat ($V_R > V_C$). (d) Eastward and westward convex boundaries due to trench retreat perpendicular to plate convergence assisted by lithospheric-scale tear faulting.

From Rosebaum, 2014

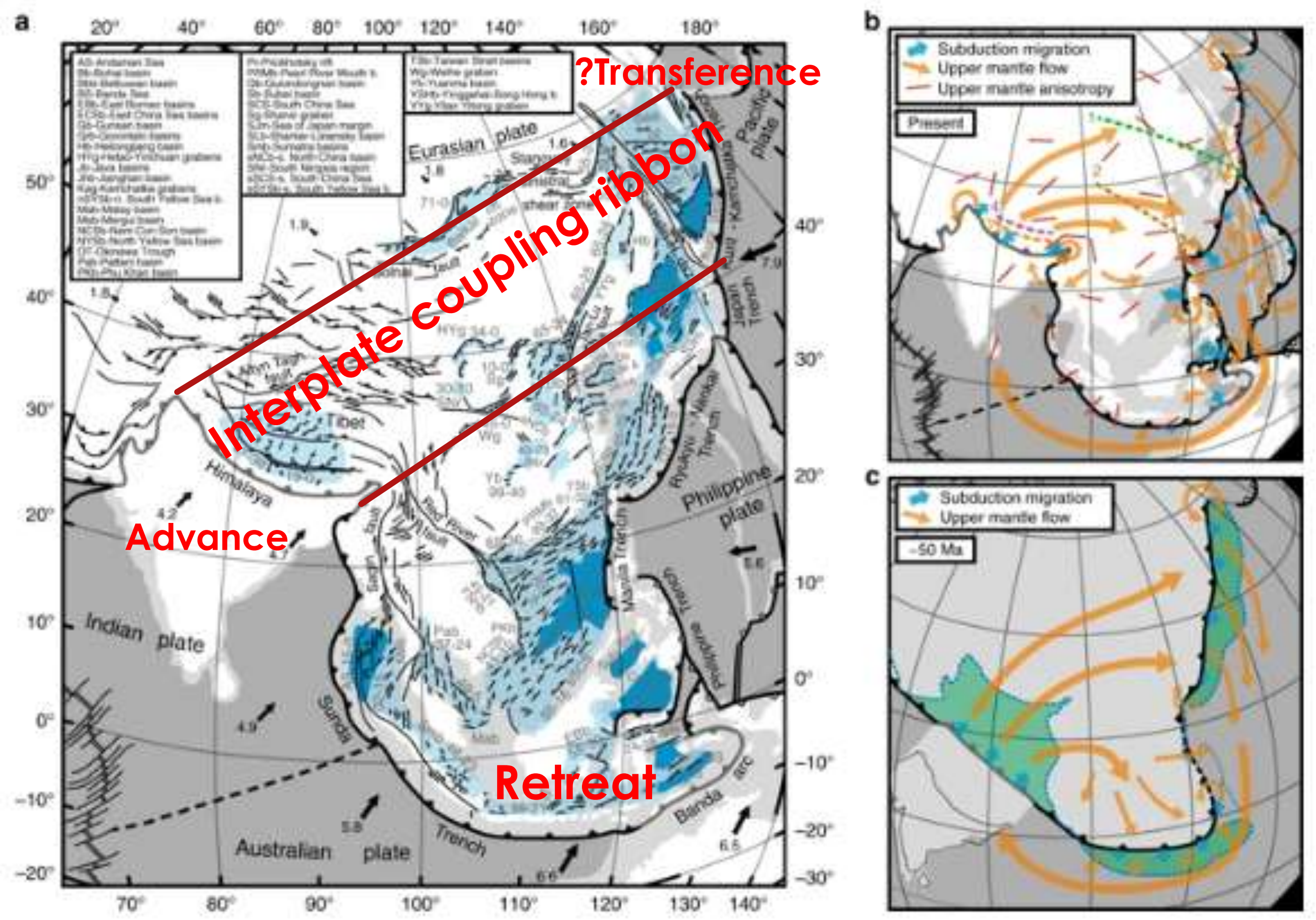
Compare & contrast with doubly-vergent Kaapvaal Orocline & medial Colesberg tear

Deforming crust and mantle flow patterns: inserted is concept of interplate coupling by crustal beams of Kalahari supercontinent

Note concept of attachment, not orogenic float of Oldow et al., 1989

Inter-plate coupling partitions crust deforming differently in convergent-collisional-extensional regimes

Consider case as lower plate to upper plate transition dynamics



Structural-tectonic maps showing widespread Cenozoic continental deformation in Central, East and Southeast Asia. **a** Structural-tectonic map showing structures and ages of extensional basins (see Supplementary

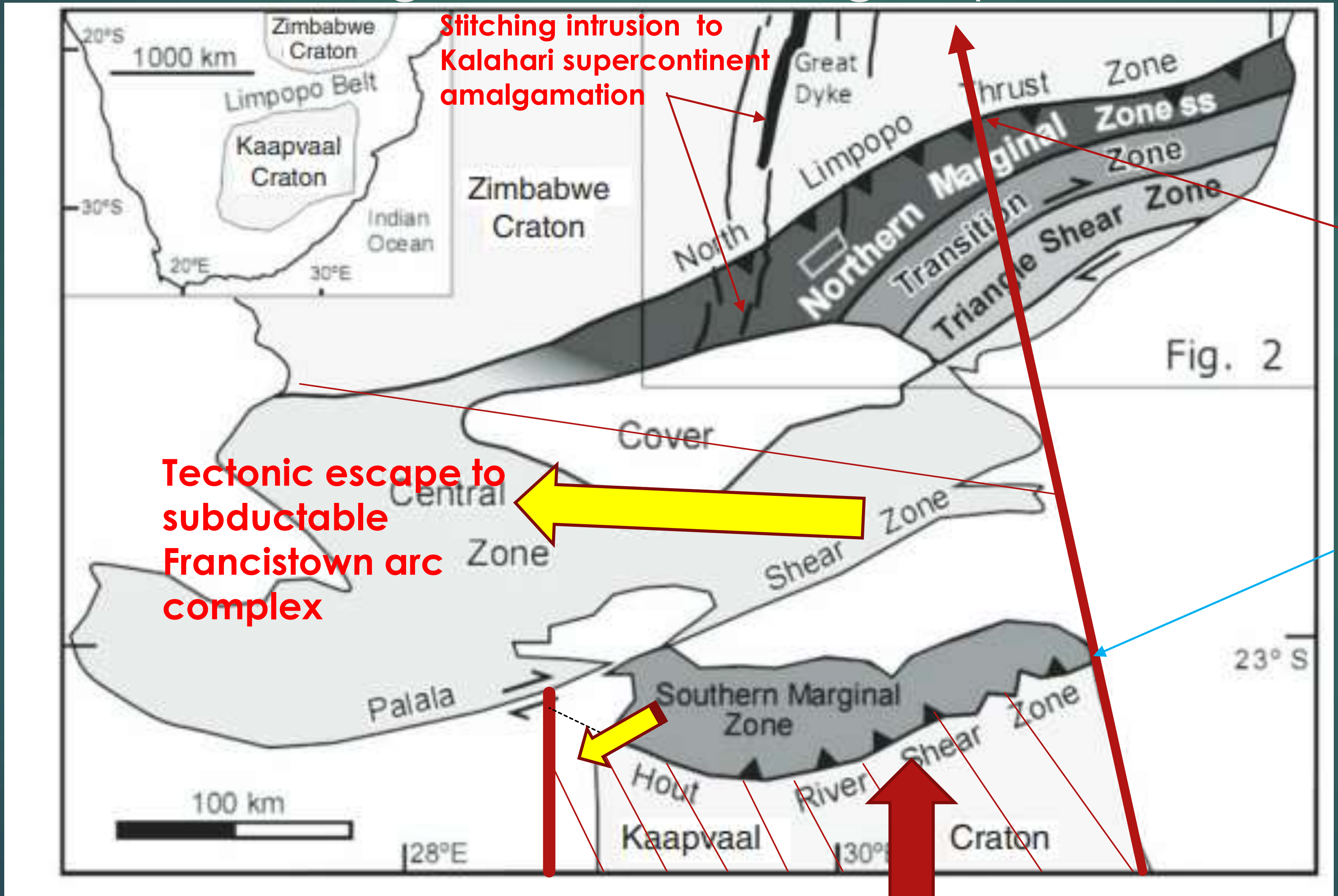
In Archean Kalahari supercontinent ; Retreat preceeds & transforms to Limpopo continent-continent collision via Swazi ribbon

India-type, Swazi ribbon indenter face decorated by exhumed HP-UHT wedge of SMZ

In blue: back arcs and marginal basins

From Schellart et al.2019

Swazi indenter face decorated by Southern Marginal Zone HP-UHT wedge extruded orogen-parallel

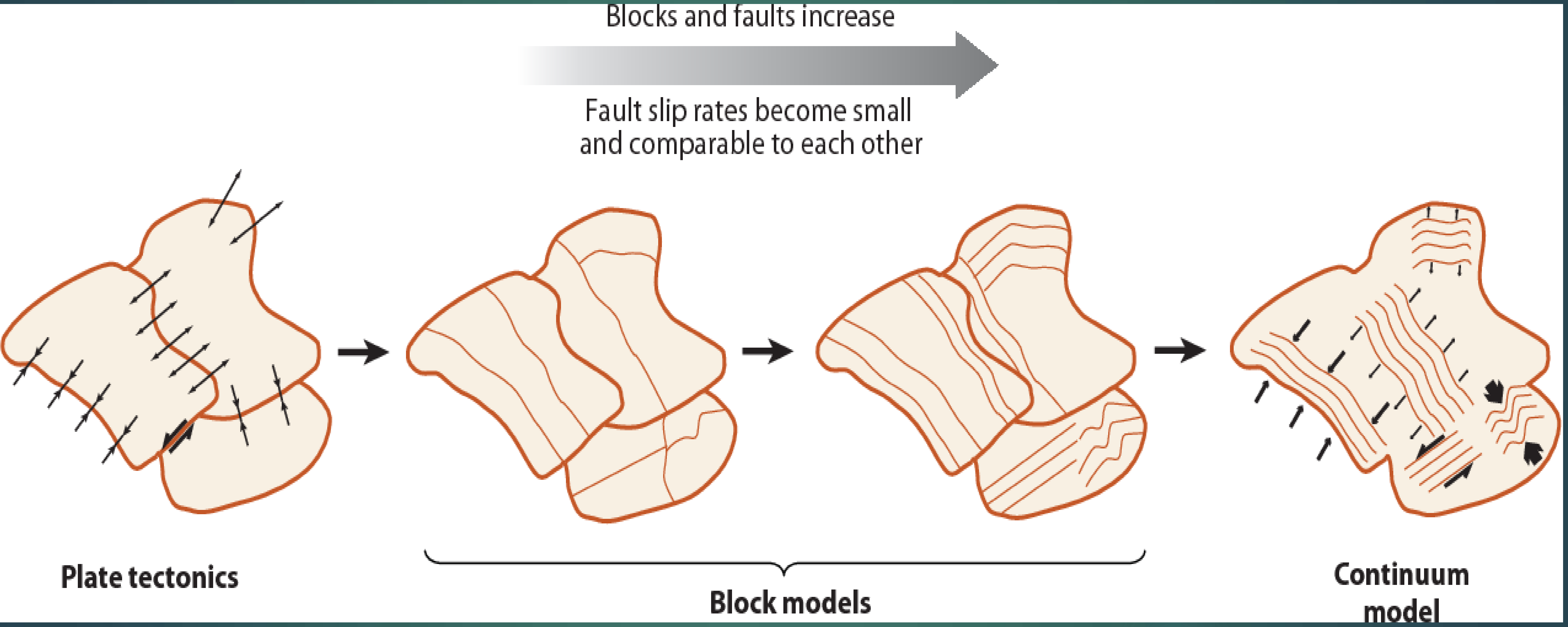


Indentation knickpoint

Giyani syntaxis

From Blenkinsop 2011

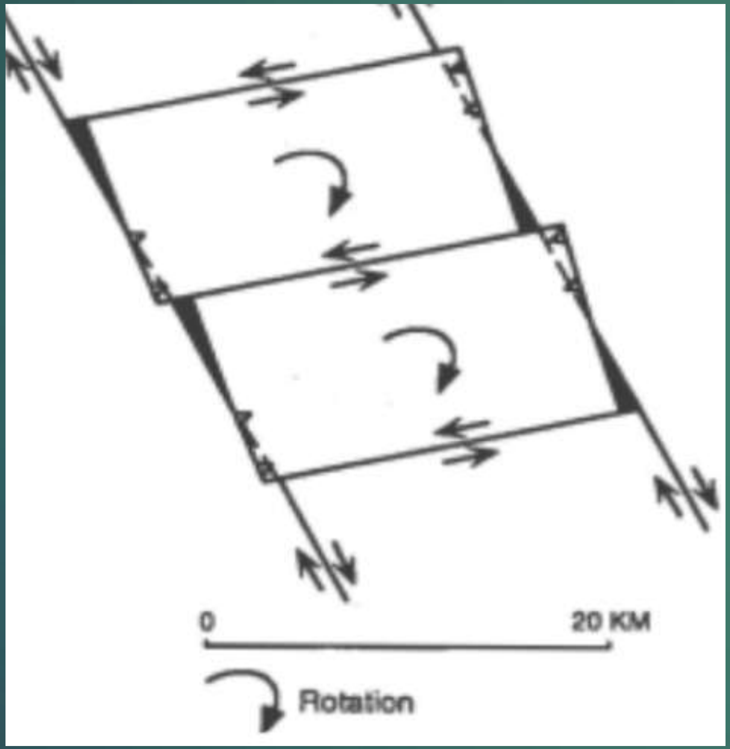
Block tectonics as proxy plate tectonics on KC



Transrotation in models of plate interactions and vertical axis rotation

What if the Pongola and Witwatersrand basins are related via extension under transrotation?

Transrotation



Northeast Caribbean

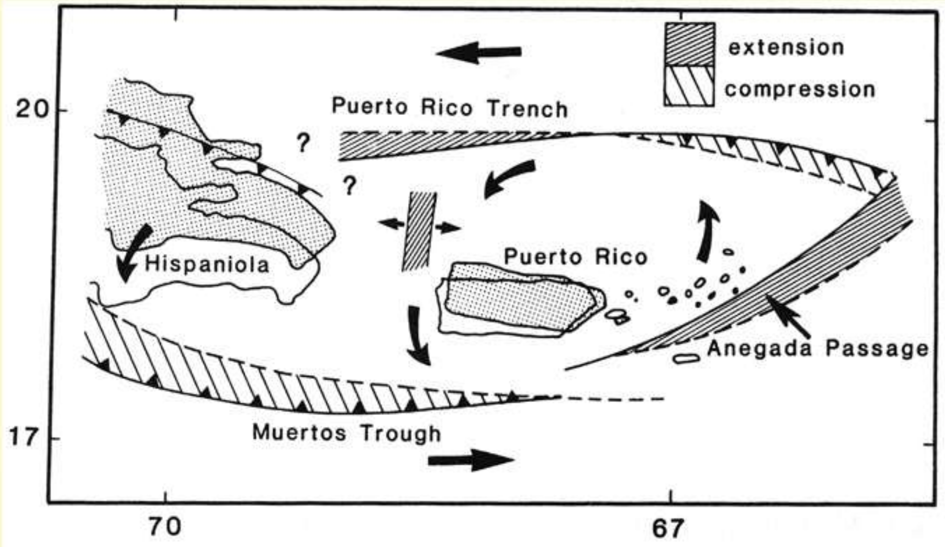
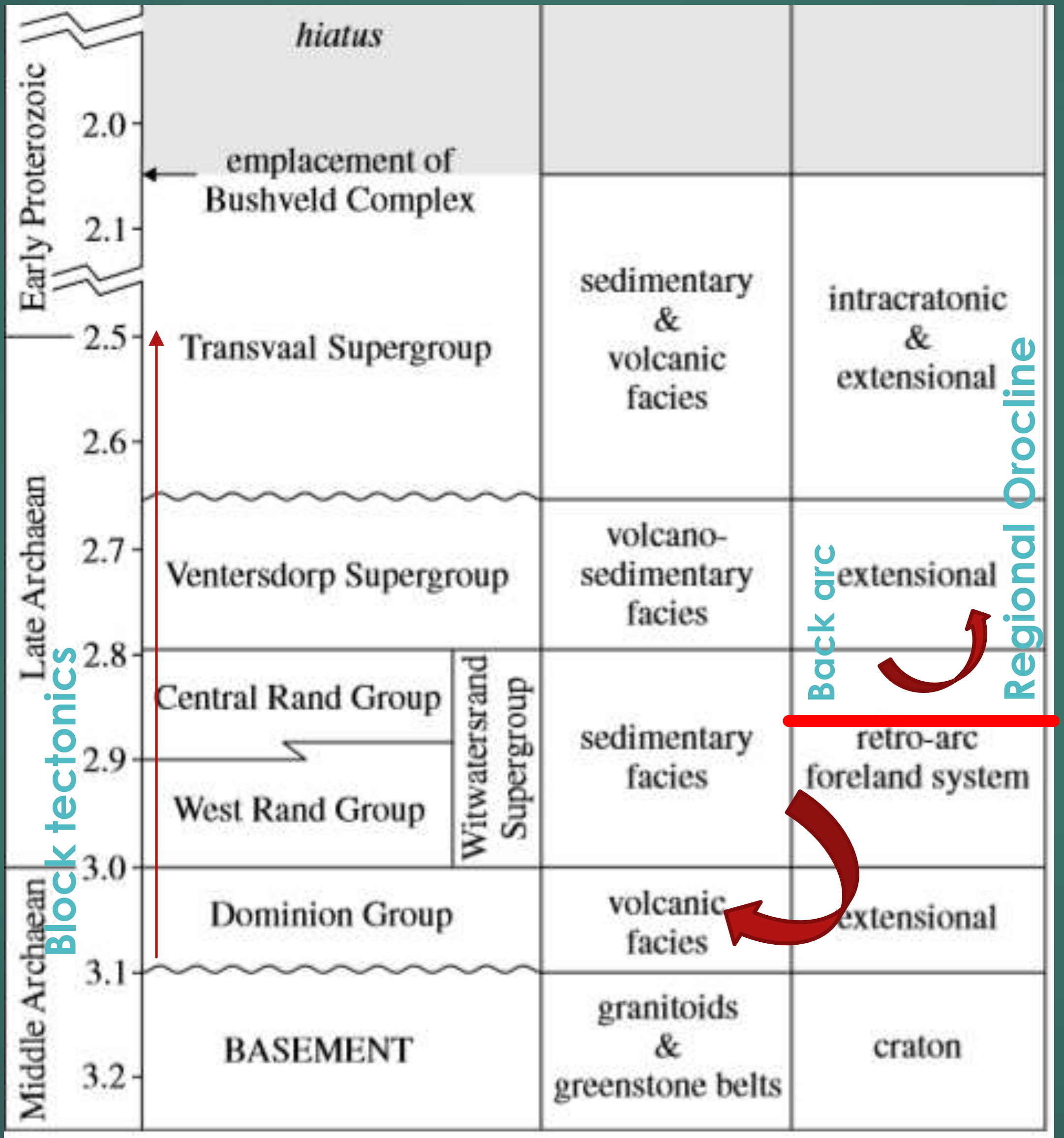


Figure 10. The model of plate interaction in the northeast Caribbean has a rotating Puerto Rico block within the strike-slip plate boundary. Stippled land areas and dashed tectonic boundaries show former configuration; unstippled areas and solid boundaries are present configuration.

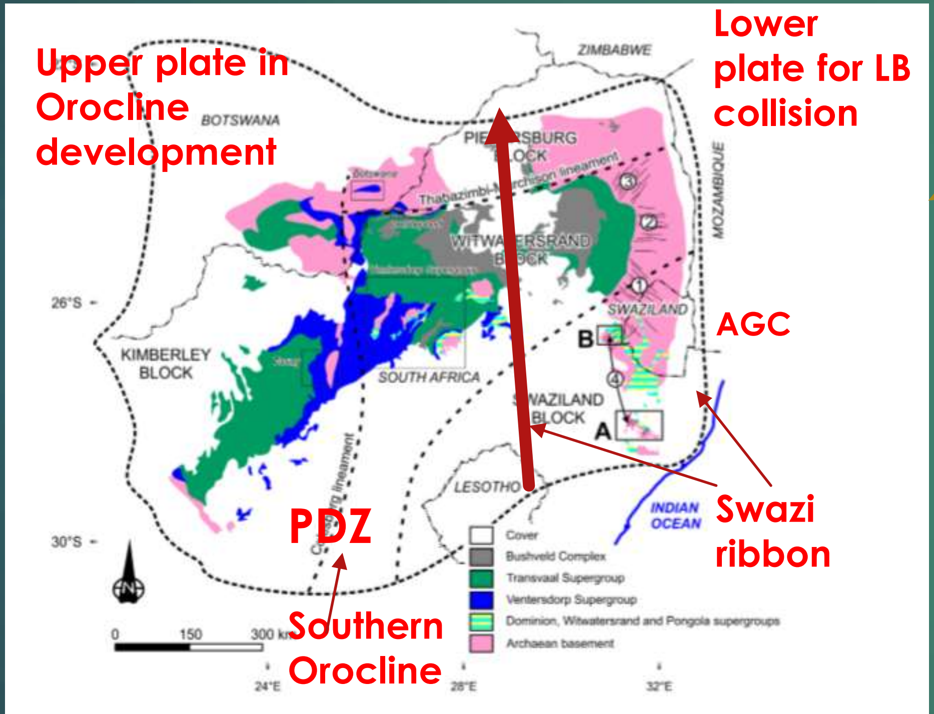
Most previous work on both Zimbabwe and Kaapvaal craton understated rotation

Main tectonic events in Witwatersrand basin region

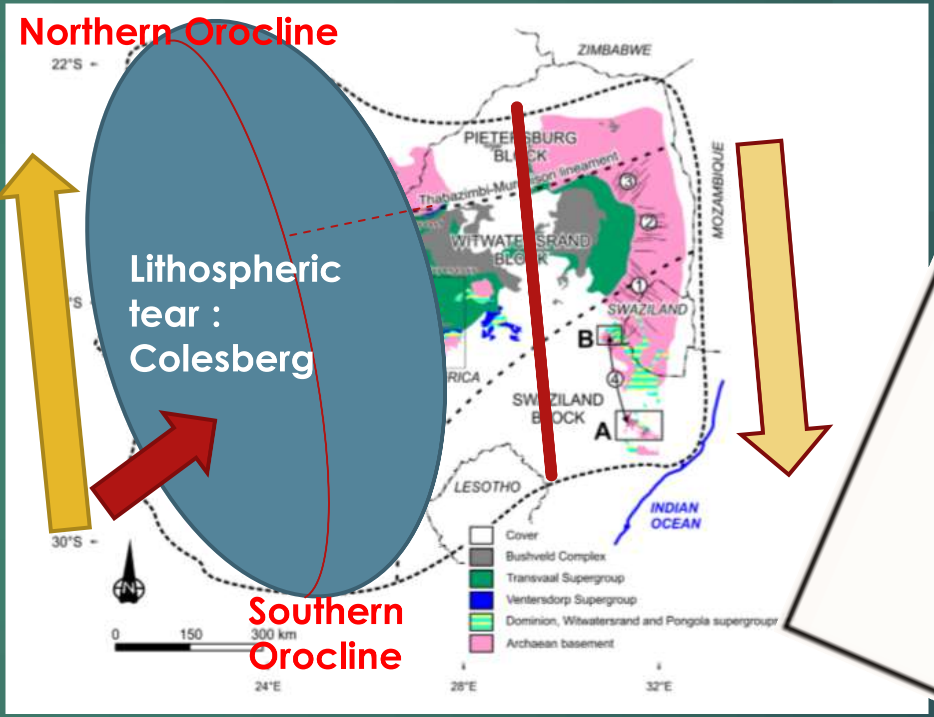


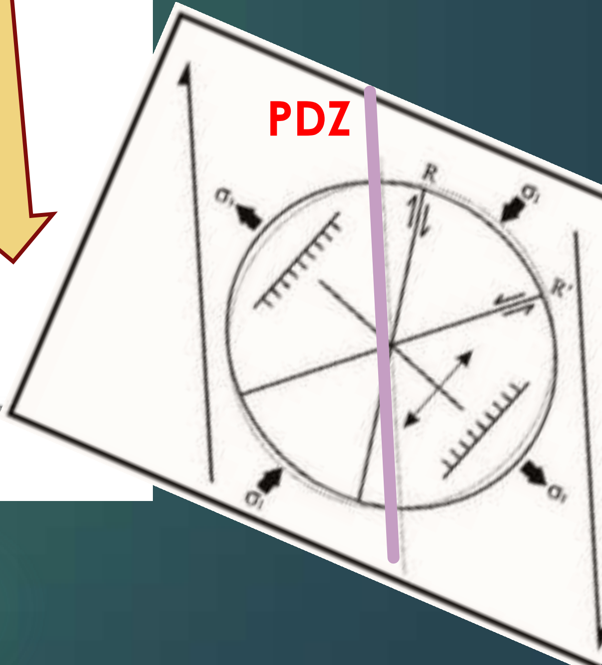
Kaapvaal craton as ear-shaped in Mesoarchean to Neoarchean

Kaapvaal Orocline & ribbon



Strain model & dextral Riedel shear



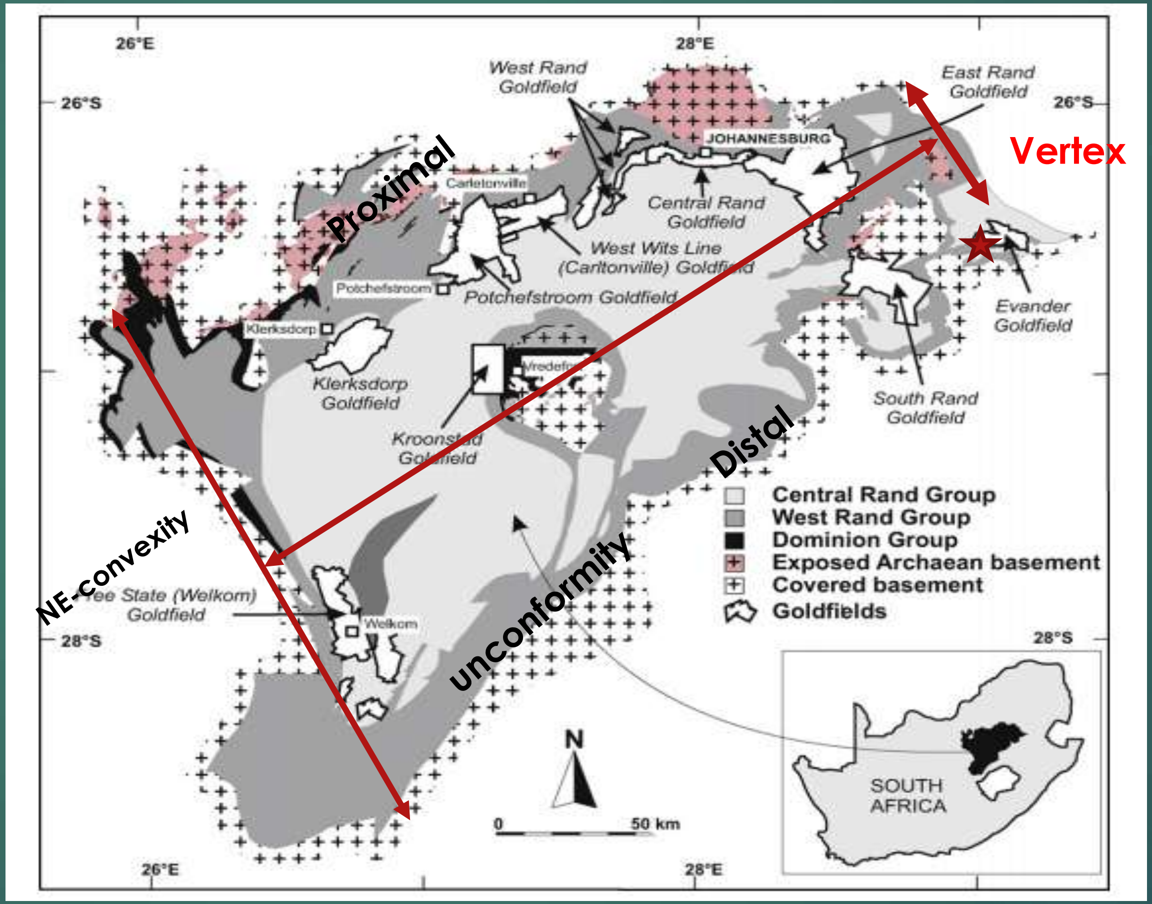


Note upper plate to lower plate (Swazi ribbon) evolutionary dynamics

Encyclopedia of Solid Earth Physics: Sphenochasm

- "not all basins associated with strike-slip faults are pull-apart basins. Some represent tears caused by an asperity or differential drag along the strike-slip fault in one of the fault walls, in which the amount of extension changes from a maximum along the fault to zero at the pole of opening.
- S.Warren Carey called such a wedge-shaped rift that open towards a major strike-slip fault sphenochasm".
- The western fault-bounded boundary of the Witwatersrand basin is 200km long (Pretorius, 1974) to zero at the pole or vertex of opening in the Evander region
- The east-curved Colesberg linear (or asperity) favours releasing bend over the Witwatersrand basin
- The regressive hinge migration south in Southern Orocline is at least 200km!

What is the length and width of Wits basin? Thin-or thick-skinned? Basement strike-slip controlled? Nature of basal detachment? Thinned/stretched crust beneath



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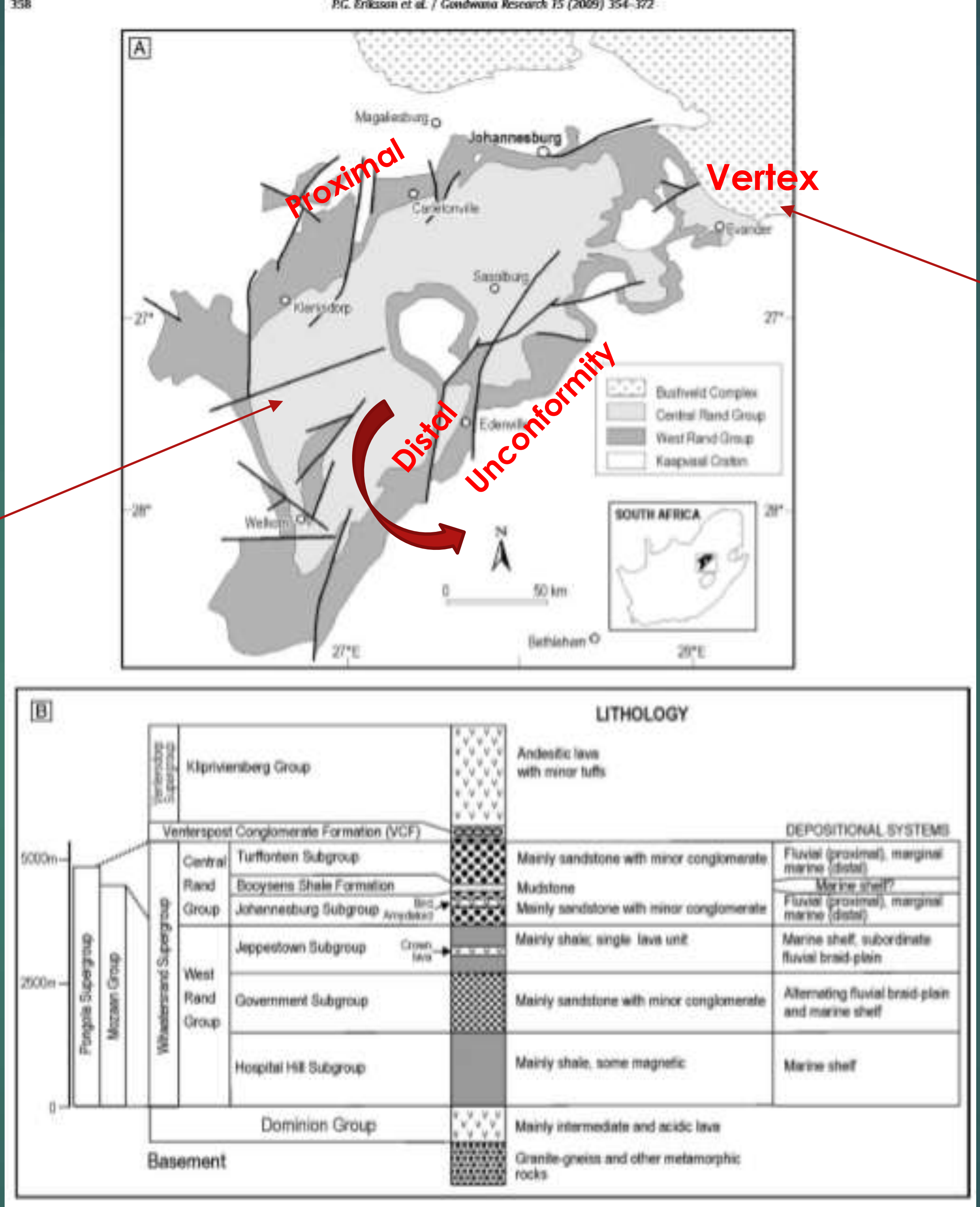
Witwatersrand basin as sphenochasm linked to lithospheric thinning from regressive hinge migration in Southern Orocline

Releasing bend



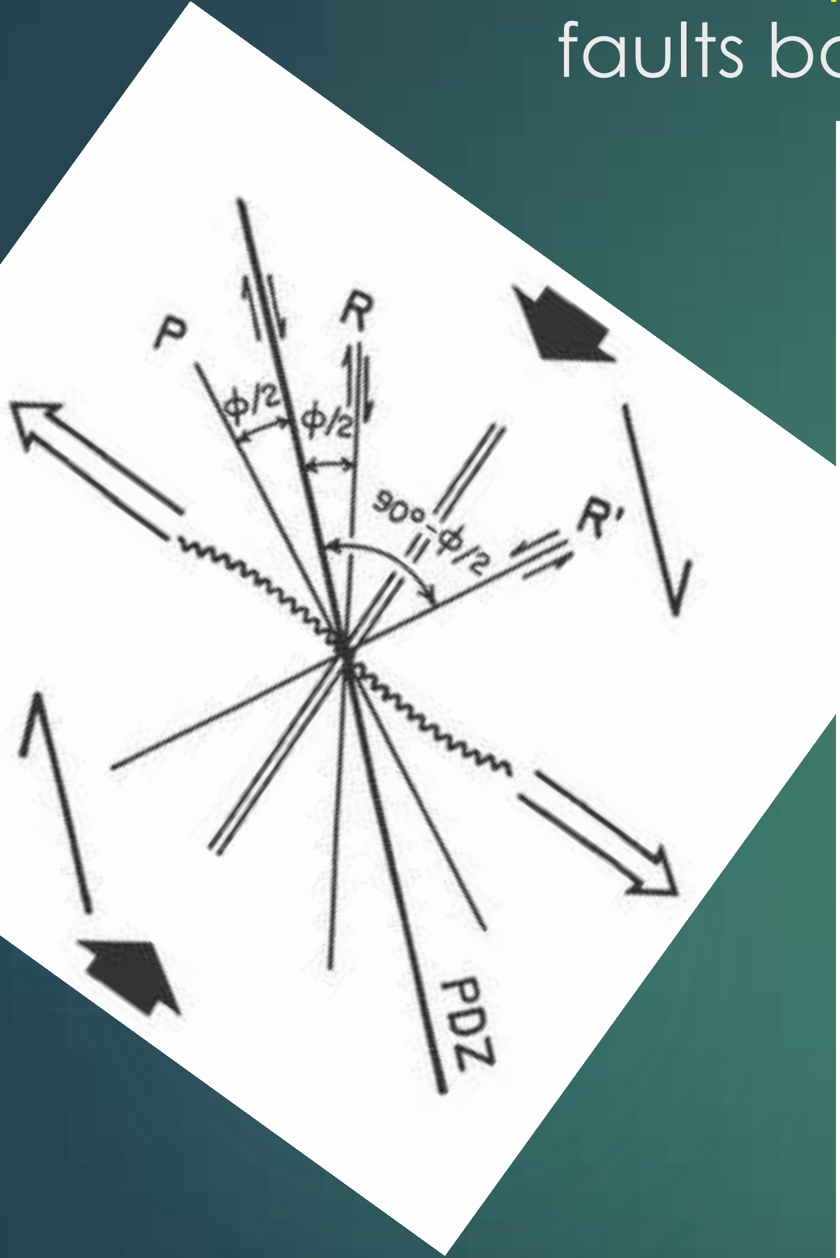
Vertex around Evander pinned against Swazi ribbon margin

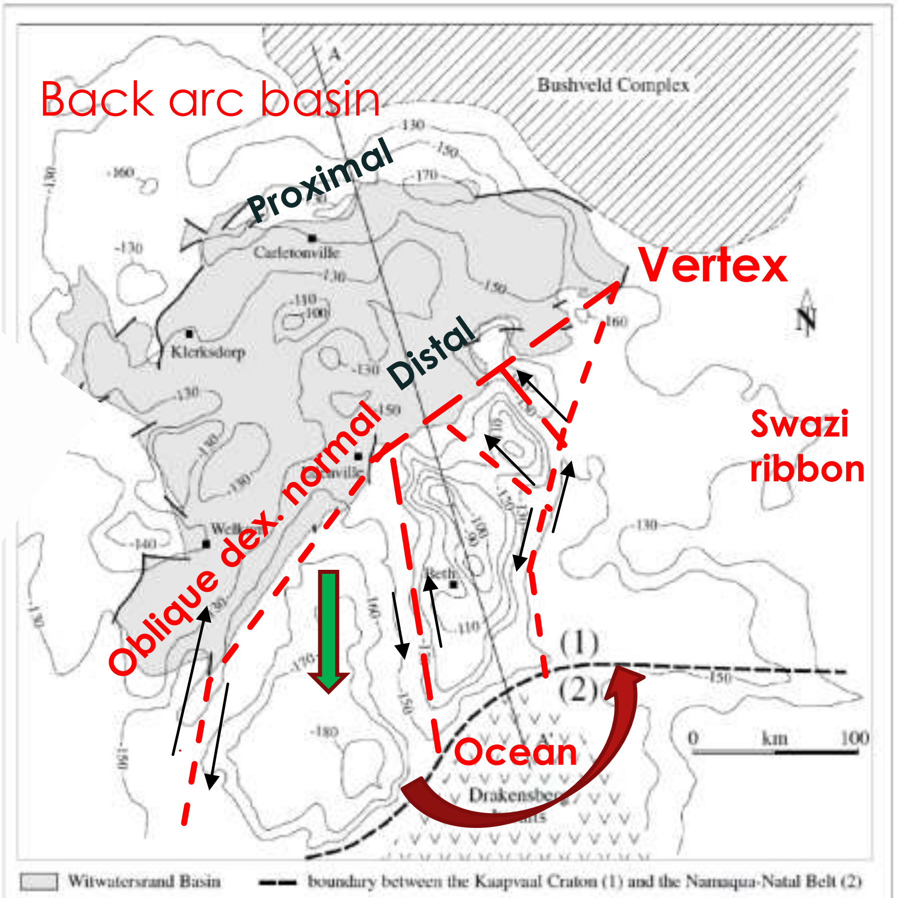
Triangular pull-apart basin against Colesberg-related faults in west e.g. Pretorius, 1974

Note: Vredefort conundrum as bolide-impact post-Transvaal in ccw transrotational domain

From Eriksson et al., 2009

Witwatersrand sphenochasm-note new interpreted faults based on gravity results to SE





Simplified gravity map showing basic structure of gravity field in SE part of craton (after Fourie and Cole,1997).

Transrotation as main extensional structures of the Wits basin. Qou vadis 2.02Ga Vredefort dome?

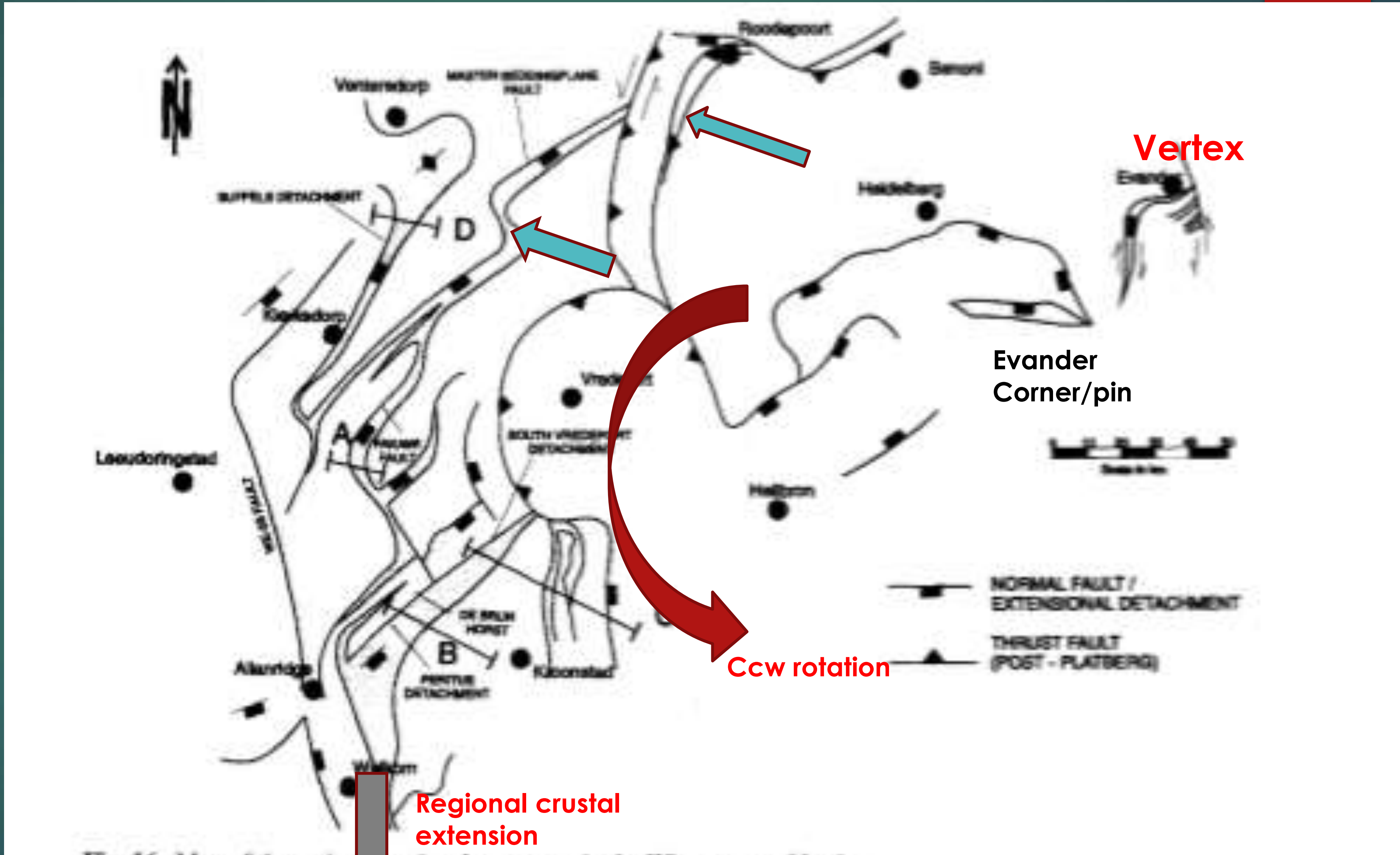
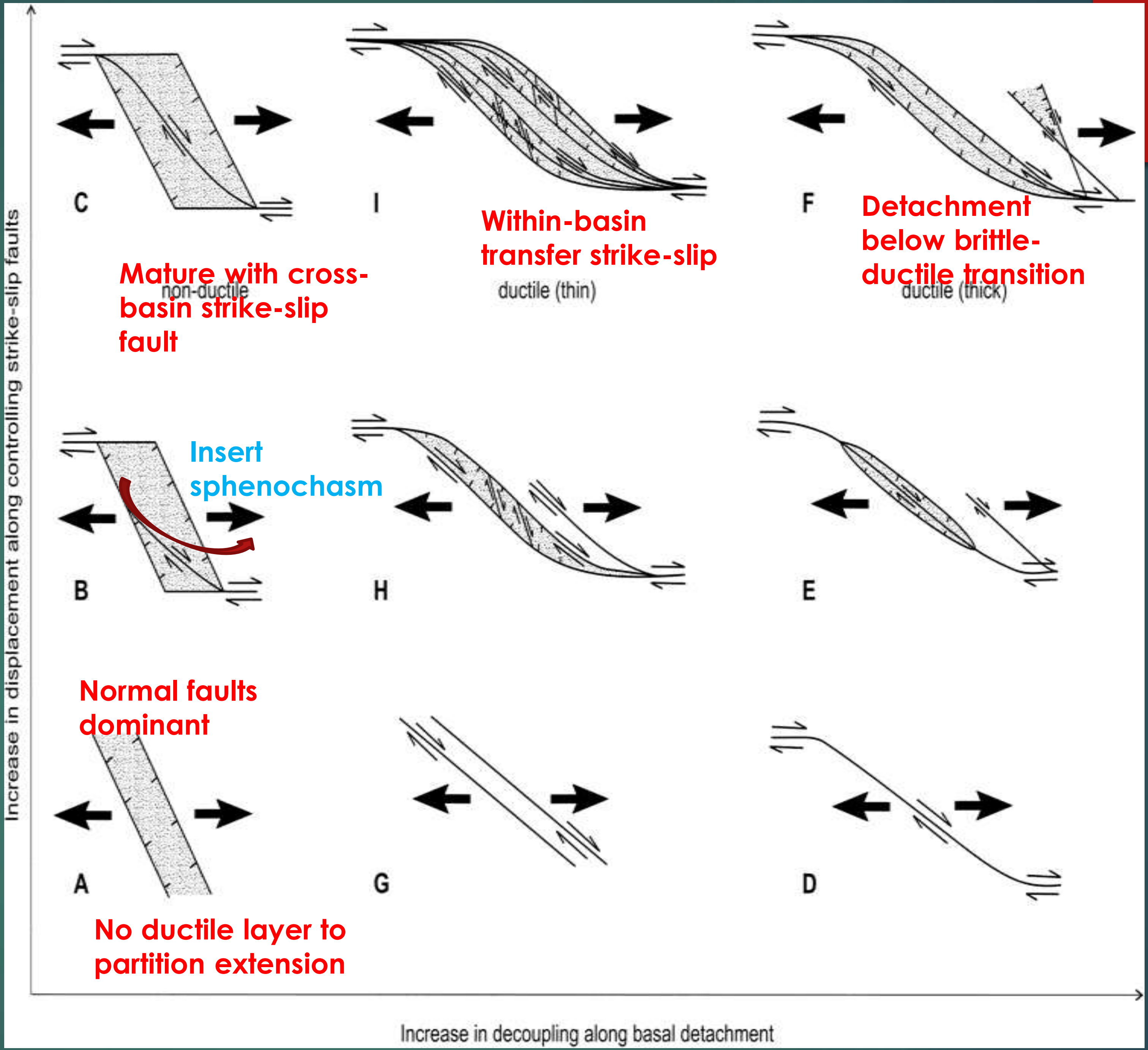


Fig. 16. Map of the main ...sional structures in the Witwatersrand basin

Models of pull-apart basin detached along a brittle, thin ductile and thick ductile detachments (Sims et al. 1999); no sphenochasm; triangular pull apart

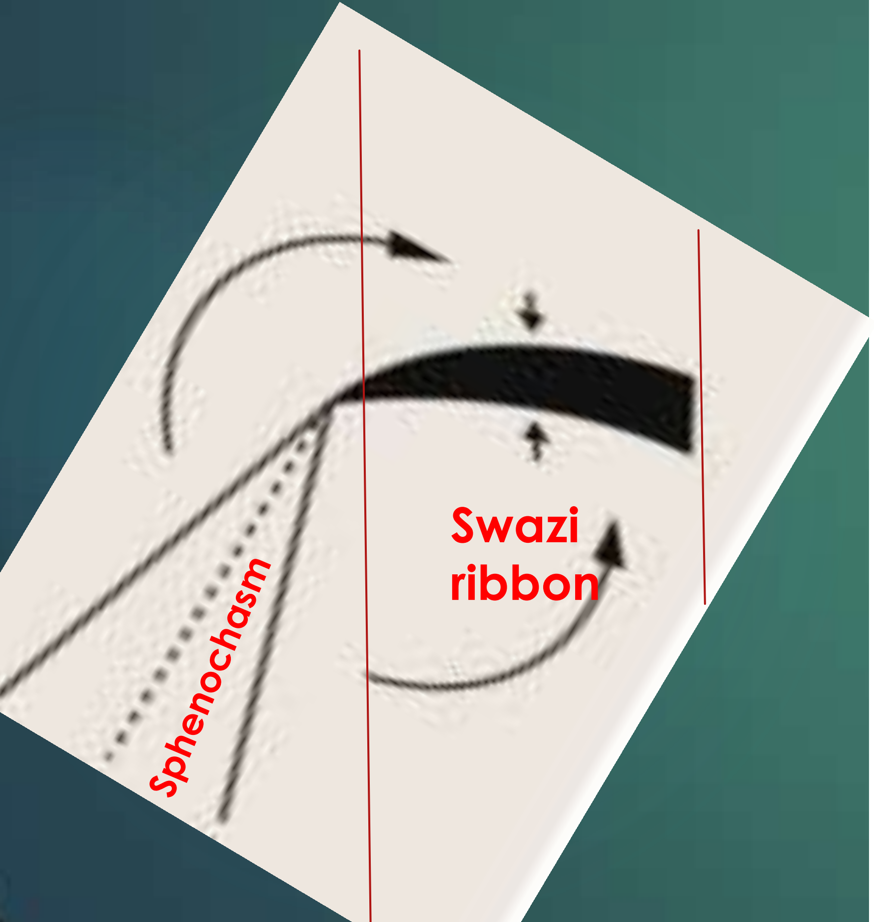
Passive rifting: Control by dextral transform Colesberg linear –with fault bend geometry favouring releasing bends and antithetic sinistral faults

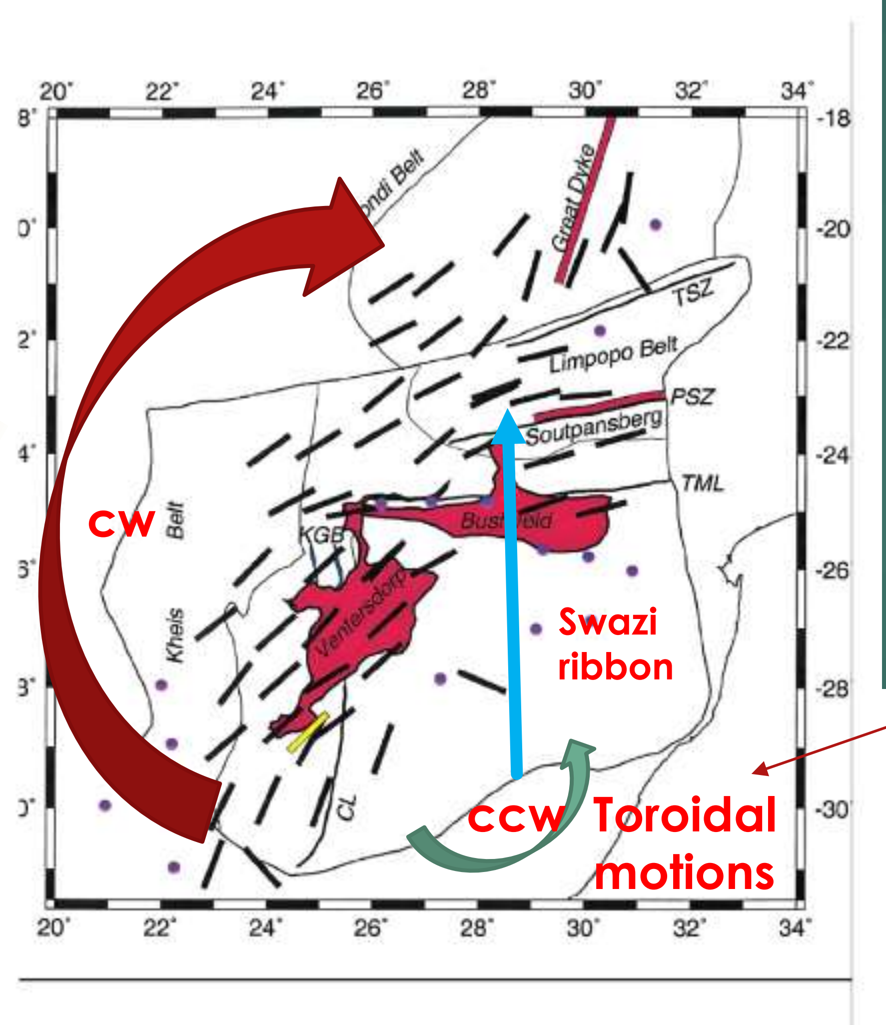
STEP: Subduction-Transform-Edge-Propagator in south associated with slab rollback process



Riedel shear space through out

Proposal: Ventersdorp basin as stage 2 sphenochasm in cw and ccw rotations



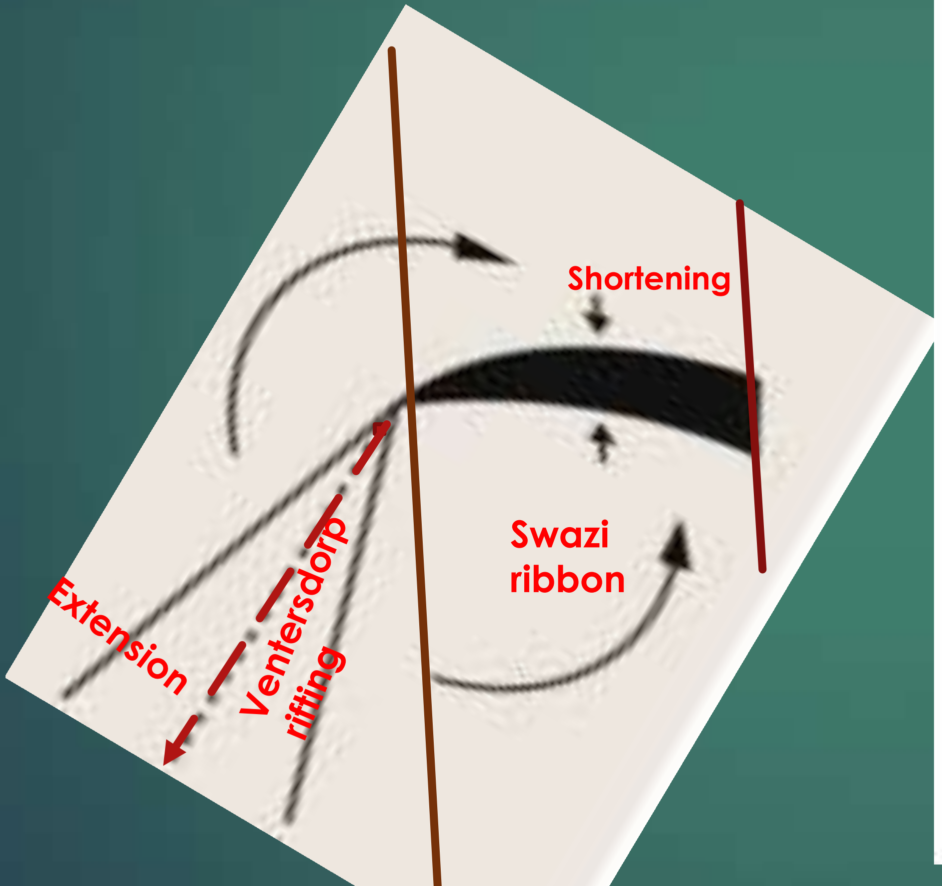


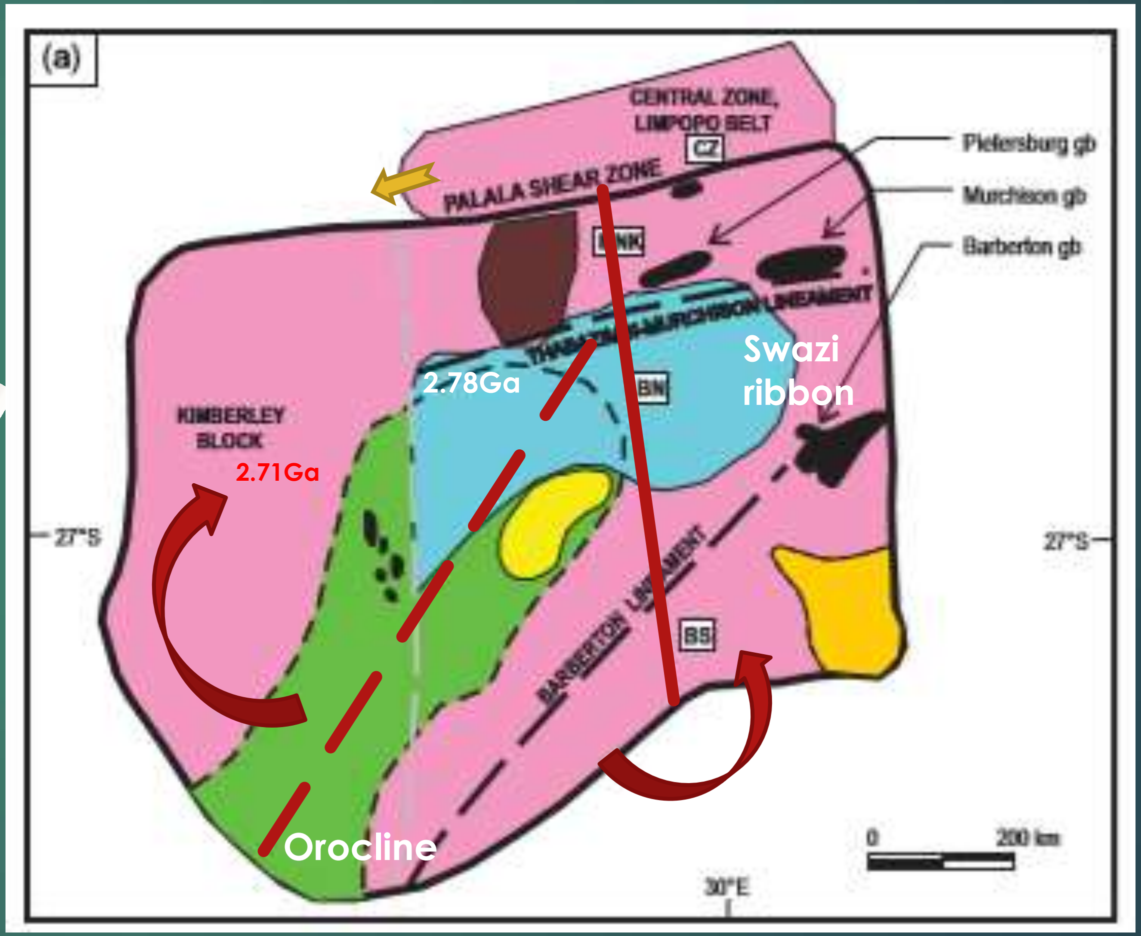
From Kiraly et al., 2017: Vorticity vector next to slab edge

Ventersdorp LIP as back-arc spreading or sphenochasm

Back-arc spreading & shortening

Swazi ribbon & BA spreading





Thank you

Rift scenarios (Merle, 2010)

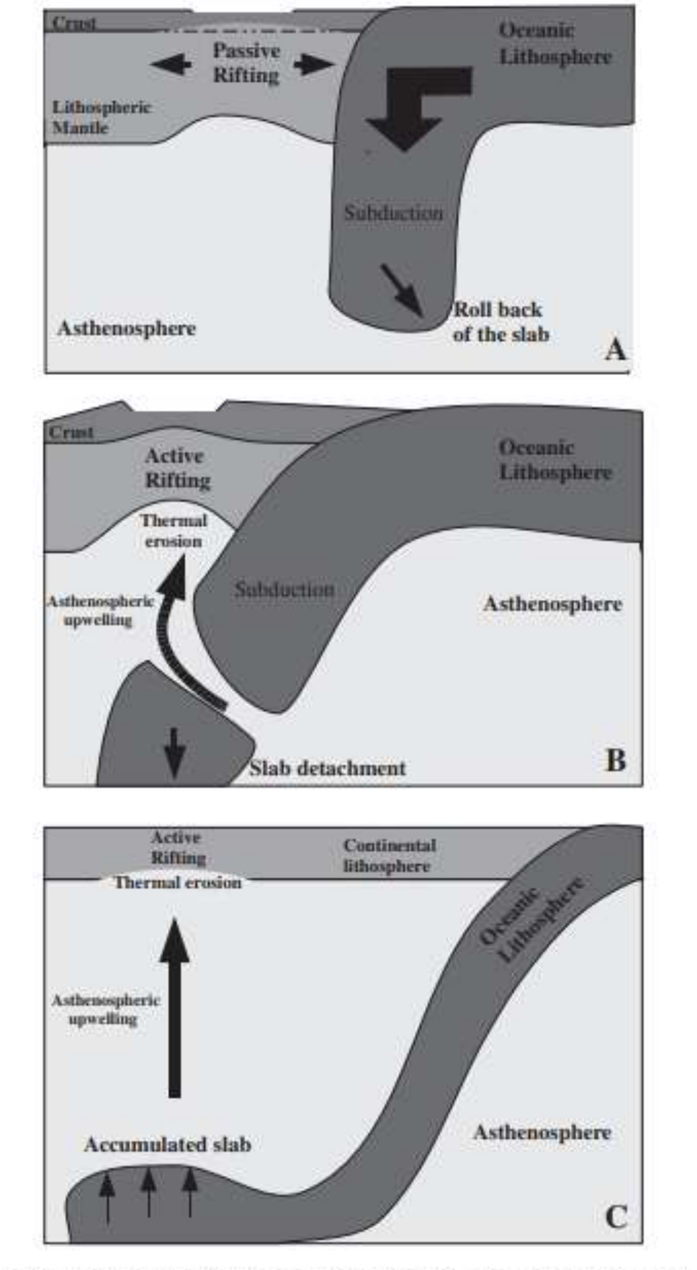


Fig. 3. Distinct tectonic evolutions in subduction-related rifts. A "passive" process is expected for slab roll-back (A) whereas an "active" process is expected for slab detachment (B) and for stagnant slab (C). C is inspired by Zou et al. (2008).

	Tectonic evolution 'Active' and 'Passive' processes	
Plume-related rifts	ACTIVE *(Possibly with a passive component at a late stage)*	
Mountain-related rifts	PASSIVE *(Possibly with an active component at a late stage)*	
Subduction-related rifts	Slab retreat	PASSIVE
	Stagnant slab	ACTIVE
	Slab detachment	ACTIVE
Transform-related rifts	PASSIVE	

Orocline, Swazi ribbon & Pongola Supergroup