K-rich mantle metasomatism control of localisation and initiation of lithospheric strike-slip faulting

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Abstract

A conceptual model is proposed where bulk transtension, or local transtension during bulk simple shear (resulting from mantle anisotropy- or lithosphere rheology contrasts), of heterogeneously enriched lithospheric mantle, trigger localised K-rich magmatism, which focusses strain and causes nucleation of lithosphere-scale transtensional or strike-slip shear zones. Transtension-triggered magmatism is most likely to be located at sites of maximum metasomatism of the lithospheric mantle. Magma-generated fractures propagate upwards, nucleating zones of lithospheric weakness, which focus shear in narrow transcurrent faults or at basin margins. In this way, magmatism controls fault timing and location. Although volcanism will be coeval with fault development and volcanoes will appear fault-controlled, counterintuitively, our model suggests that faults are, in a sense, volcano-controlled. We suggest that this new transtension–K-rich magmatism–transcurrent faulting association represents a hitherto unrecognised genetic relationship as significant as, for example, the ocean island magma series.

Introduction

K-rich basalts and associated potassic plutonic rocks, of diverse tectonic contexts (Wilson 1989), are the shallow-level expressions of K-rich metasomatism of the lithospheric, i.e. non-convecting, mantle (McKenzie 1989). This mantle is melted to form K-rich magmas in two main mantle thermal regimes: i. A high thermal regime associated with processes such as mantle plume impact, e.g., Paraná flood basalt province (Gibson et al. 1997; Fig. 1), lithospheric delamination, e.g., Harghita volcanic rocks, eastern Carpathians (Gîrbacea and Frisch 1998; Fig. 1), or lithospheric extension with β-factor > 2, e.g., Rio Grande rift, USA (Gibson et al. 1993; Fig. 1), and ii. a low thermal regime where potassic mafic and felsic rocks are associated with transtension of the lithosphere; in many cases hosted by transtensional strike-slip shear zones, e.g., Caledonian shoshonitic magmatism, northern British Isles (Vaughan 1996; Fig. 1). Here we present a tectonomagmatic model for regime ii, arguing that heterogeneously metasomatized lithospheric mantle undergoes decompression during Type B transtension (Fossen and Tikoff 1998), either regionally, or locally due to deviations in stress trajectory, and melts to form potassic mafic magmas. Magma-driven fracturing focusses strain, controls the site of initiation and propagation of fault systems and, consequently, determines the local yield strength of the lithosphere.

Fault control of magmatism

Structural studies have suggested that pre-existing strike-slip fault systems can act as conduits for and create accumulation spaces for magma (e.g., Pe-Piper et al 1998). The subject of fault control of magmatism is a vast one and a comprehensive review is far outside the scope of this paper, however, a few key papers are worth summarising to give some indication of the depth of study and the range over which the relevant questions have been addressed. Links between regional deformation and magmatism were first proposed by Balk (1937) and in more detail by Anderson (1951). The modern debate on the links between magmatism and faulting has focussed mainly on granitic magma and began with work on the Donegal granite in northwest Ireland by Hutton (1982; thoroughly reviewed in Hutton 1988a). Recent important papers on granite emplacement include Hutton et al. (1990), Hutton & Ingram (1994), Petford et al. (1996), Benn et al. (1998); for a counter argument view see Patterson & Vernon (1995). Recently, anisotropy of magnetic susceptibility has emerged as a new and powerful technique for determining magma emplacement mechanisms (e.g. Bouchez 1997, Moyen 2003). For mafic magmatism, apart from the well-documented relationship between extension of β-factor>2 and basaltic magmatism (e.g. McKenzie & Bickle 1988), there is a lot less, although dyke emplacement has been implicated in normal fault movement in rift zones (Rubin & Pollard 1988) and mafic plutons in the Ivrea-Verbena zone of northern Italy appear to be syn-extensionally emplaced (e.g. Quick et al. 1994). We review the evidence for tectonic control of K-rich magmas below. In this paper, we turn the argument for fault control of magma emplacement on its head, and argue that in one major case, deep-seated magma genesis controls faulting.

Magmatism from K-rich metasomatized mantle and transtension

Structural emplacement settings for K-rich magmatism, where control is well known, can be summarised as follows: i. fault bends in strike-slip zones (e.g. Turkish Anatolian cinder cones, Adiyaman et al. 1998): ii. strike-slip fault terminations (e.g. Caledonian Strontian granite, Scotland; Hutton 1988b): iii. en echelon fissure systems (e.g. Caledonian lamprophyres; Vaughan 1996); iv. transverse structures in extensional zones (e.g. Virunga Range potassic lavas, East African Rift; Kampunzu et al. 1998), v. intersections between extensional and offsetting faults (e.g. alkaline rocks associated with the Canadian Cordilleran miogeocline; Goodfellow et al. 1995), vi. oblique rift zones (e.g. alkaline volcanism in the Dead Sea rift zone, Southeast Turkey; Alici et al. 2001), vii. rift flanks where β-factors are small (less than 1.2) (e.g. the North Sea; Latin and Waters 1991). What links these sites of magma transfer and emplacement is that they form in zones of transtension (strike-slip deformation that deviates from simple shear because of a component of extension orthogonal to the deformation zone, Dewey *et al.* 1998).

Lamentably few studies synthesise geochemical and structural data. Nonetheless, a close temporal and spatial association between magmatism generated from K-rich metasomatized lithospheric mantle and transcurrent shear has been documented at deep and shallow crustal levels in many tectonic settings worldwide (see below). Although a more comprehensive review is beyond the scope of this paper, some well-documented examples will serve to illustrate our case.

Transtension

In the Caledonian of Scotland and Ireland (Fig. 1), the initiation of Silurian-Devonian orogen-parallel bulk sinistral transtension is coeval with the onset of an episode of K-rich magmatism across a width of the orogen from northwest Scotland to the north of England and eastern Ireland, a zone spanning 1000 km (Vaughan 1996). The range of magmatism is diverse, including shoshonitic lavas, hypabyssal and subvolcanic lamprophyres, and large volumes of K-rich plutonic rocks. Sigmoidal pluton shapes in plan, en echelon dyke arrays, syn-magmatic deformation and juxtaposition of plutonic, hypabyssal and volcanic rocks suggest strongly that transtensional shear zones hosted these magmas (Hutton 1988a, Jacques and Reavy 1994, Vaughan 1996). In the Ross Sea, the potassic McMurdo dyke swarm of the Meander Intrusive Suite is coeval with a brief dextral transtensional phase that preceded full rifting (Rossetti et al. 2001, Rocchi et al. 2002). In Turkey (Savascin et al. 1994), alkaline magmatism occurred during dextral transtensional episodes along the Kirka-Afyon-Isparta structural trend, from Miocene to Recent (calc-alkaline magmatism occurs during compressive phases; the Cretaceous Antarctic Peninsula shows similar relationships; Scarrow et al. 1997). More recently still, sinistral strike slip faults associated with the transtensional development of the Lake Baikal rift in Siberia (Fig.1) localize K-rich monogenetic volcanoes (Delvaux et al. 1997, Lesne et al. 1998). Likewise, in the trans-Mexican volcanic belt (Fig. 1), potassic monogenetic volcanoes are aligned along arc-parallel fault associated with extension (Alaniz-Alvarez 1998) and sinistral strike-slip (Suter et al. 1995, Suter 1999). Carboniferous, high-K calc-alkaline plutons and potassic to ultrapotassic basalts coincide with a brief phase of extension (Apraiz and Eguiluz 2002) during sinistral strike-slip movement on the Ossa-Morena suture zone in central western Spain (Casquet et al., 2001).

Strike-slip

Contemporaneous intrusion of K-rich plutonic rocks and lamprophyres are directly related to strike-slip along the Elbe Zone of the Bohemian Massif (Wenzel et al., 2002). Triassic shoshonitic magmas are associated with sinistral strike-slip in the Dolomites of northern Italy (Sloman 1989) (Fig. 1). Mid-Cretaceous dextral strike-slip is associated with the emplacement of voluminous potassic granitic rocks in north-central British Columbia (Gabrielse 1991) (Fig. 1). In the Tertiary, Eocene emplacement of ultra-alkaline magma into strike-slip faults in eastern Paraguay was controlled by east-west trending dextral shear (Riccomini et al., 2001). In marine settings, Tertiary lamprophyres are associated with transform faults on the Sierra Leone rise in the Atlantic Ocean (Jones et al. 1991)(Fig. 1) and the Owen Fracture Zone ridge off Oman in the Indian Ocean (Whitmarsh et al 1974)(Fig. 1).

Model

McKenzie (1989) argued that, over geological timescales, perturbation of the asthenosphere during convection causes the first-formed small volumes of potassic melt to percolate up through the upper thermal boundary layer of this mantle. These small-volumes of melt freeze in the cooler top of the thermal boundary layer, the so-called mechanical boundary layer, forming a zone of lithospheric mantle that is rich in volatiles and incompatible elements. This enriched zone is easily fusible, i.e. close to its solidus, and is argued to be the source of the earliest magmas during advection of heat to the base of the lithosphere (Harry and Leeman 1995). Extreme compositional heterogeneities in this zone occur on 10-km-scales (e.g. Zhang et al. 2000), with a large range of compositions, e.g. εSr from -2 to +180 and εNd from +2 to –12 interpreted from potassic and ultrapotassic magmas in the Roman Province (Conticelli et al. 2002).

The tectonic associations outlined above suggest that K-rich alkaline magmatism is linked with small degrees of extension (β ~ 1.2), and commonly is found in zones of transtension. The relationship between K-rich alkaline magmatism and small degrees of extension suggests a positive relationship between degree of metasomatism and ease of melting, and suggests that metsomatised mantle is close to the solidus for normal ranges of lithospheric basal temperature and thickness (e.g. Harry and Leeman 1995). Transtensional zones are associated with β-factors of c. 1.2 (e.g. 1.19–1.34 for the Dead Sea rift; Alzoubi and ten Brink 2002; Fig. 1), which is more than enough to achieve adiabatic decompression partial melting in the upper asthenospheric mantle (Pedersen 1994) or in the metasomatically altered lithospheric mantle at depths > 60 km (Harry and Leeman 1995).

The case is simple for bulk transtension (Fig. 2i). However, bulk simple shear will not produce extension. Fortunately, the lithosphere and mantle are not rheologically homogeneous. Recent studies show that mantle seismic anisotropy is common (Tommasi and Vauchez 2001), probably reflecting mantle flow structures produced during orogenesis, and studies of transform fault behaviour in areas of strong oceanic lithosphere indicate that stress fields cause strike–slip faults to avoid very thick and strong lithosphere (Ligi et al. 2002). We propose that for lithosphere and upper mantle with realistic variations in rheological contrast (e.g. cratons separated by mobile belts or upper mantle with pre-existing anisotropy (Fig. 2ii) stress trajectories during bulk simple shear will deviate to produce localized zones of transpression and transtension (of probable Type B, Fossen and Tikoff 1998) (Fig. 2ii). For example, strike-slip dominates west of the Siberian Craton, whereas to the south, a zone of extension to transtension (forming the Baikal Rift) is active (A. Vauchez pers. comm. 2002; Lesne et al. 1998). Adiabatically induced melting is likely to occur first in the most volatile-rich and most easily fusible volumes of the lithospheric mantle (Fig. 2b). So, during the initiation of bulk transtension or horizontal simple shear, adiabatic decompression in zones of transtension will trigger partial melting in small-scale (i.e. 10-km) zones of metasomatically enriched mantle at the base of the lithosphere, at β-factors of c. 1.2. Transtension will nucleate dykes in the manner of tension veins in a homogeneous deforming solid. Magma-driven fractures will then propagate rapidly to upper levels of the lithosphere, nucleating a zone of lithospheric weakness that will focus shear strain and form the zone of initiation of a strike-slip fault (Fig. 2c). Shear systems may show initial tensional arrays of K-rich basaltic dykes cut by later more planar P shear zones hosting granite magma (e.g.

Vaughan 1996; Fig. 2c). In this way, K-rich mantle metasomatism controls the location of faulting and the resulting K-rich magmas control fault propagation.

Discussion

Timing relationships are key to our model. So far it has not been possible to demonstrate that bulk lithospheric shearing predates magmatism, although in the best-documented examples, i.e. the Caledonian (Vaughan 1996) and the Ross Sea (Rossetti et al. 2001, Rocchi et al. 2002), magmatism and transtension are at least coeval. Vauchez et al. (1997) have also proposed mutual relationships between strike-slip faulting and potassic magmatism, and Neves et al. (1996) have suggested that magma accumulations in the lithosphere form nuclei for transcurrent shear zones, but further work is required. A key consequence of our model is that magmatism associated with transtension in the early stages of lithospheric strike-slip or rifting will focus strain and nucleate major faults. Heterogeneities in K-rich metasomatism will fundamentally control the local yield strength of lithosphere, even if over a very large scale, thermal effects are important, such as those induced by delamination of the base of the lithosphere. Another consequence is that decompression melting of metasomatised mantle and subsequent alkaline magmatism may also control rift localisation.

Given that this model concentrates strain in a narrow zone, defusing more distributed lithospheric shear, it could be argued that once a fault system is initiated in this way it should become the main focus of strike-slip shear at the expense of formation of any further systems. This indeed appears to be the case for the Red River shear zone in China (Fig. 1), where an alkaline-magma-lubricated zone is taking up much of the differential movement associated with the extrusion of Southeast Asia during the India–Eurasia collision (Zhang and Scharer 1999).

Strike slip faults nucleated in this way will create space for the accumulation of K-rich granite magma and a site of preservation of continental crust. Volumetrically, potassic granites, such as the Newer Granites of the Caledonide orogen (e.g. Soper 1986), form a significant proportion of the crust, particularly in post-orogenic settings. The intimate connection between potassic magmatism and strike-slip faulting argued for here suggests that the relationship has the characteristics of a tectonomagmatic association such as the orogenic magma series, and this echoes recent suggestions that strike-slip related K-rich magmatism is common in post-orogenic settings (Bonin et al 1998). This represents a hitherto unrecognised tectonomagmatic association as important as, for example, the ocean island magma series. Finally, our model, although not invalidating the generally accepted view of fault control of magma transport and accommodation, proposes the converse i.e. that K-rich magmatism, generated at the base of metasomatized lithosphere by regional or local transtension, controls the nucleation and location of transcurrent fault systems. Even though resulting magmatism will be coeval with fault development and volcanoes will appear fault-controlled, our model suggests the opposite. Magmatism will control fault timing and location, i.e., faults will be volcano-controlled. The distinction may appear to be a subtle one, but our model allows for the formation of new faults in unfaulted lithosphere, which has a bearing on the formation of plates (Bercovici 2003).

Conclusions

i. A close temporal and spatial association exists between K-rich magmatism and transtension, having been documented at deep and shallow crustal levels in many tectonic settings worldwide.

ii. Our new model indicates that bulk transtension, or local transtension during bulk simple shear, of heterogeneously enriched lithospheric mantle triggers localised K-rich magmatism.

iii. The resulting magma-driven fractures focus strain and cause nucleation of lithosphere-scale transcurrent faults.

iv. This association represents a hitherto unrecognised genetic relationship between tectonics and magmatism as significant as, for example, the ocean island magma series.

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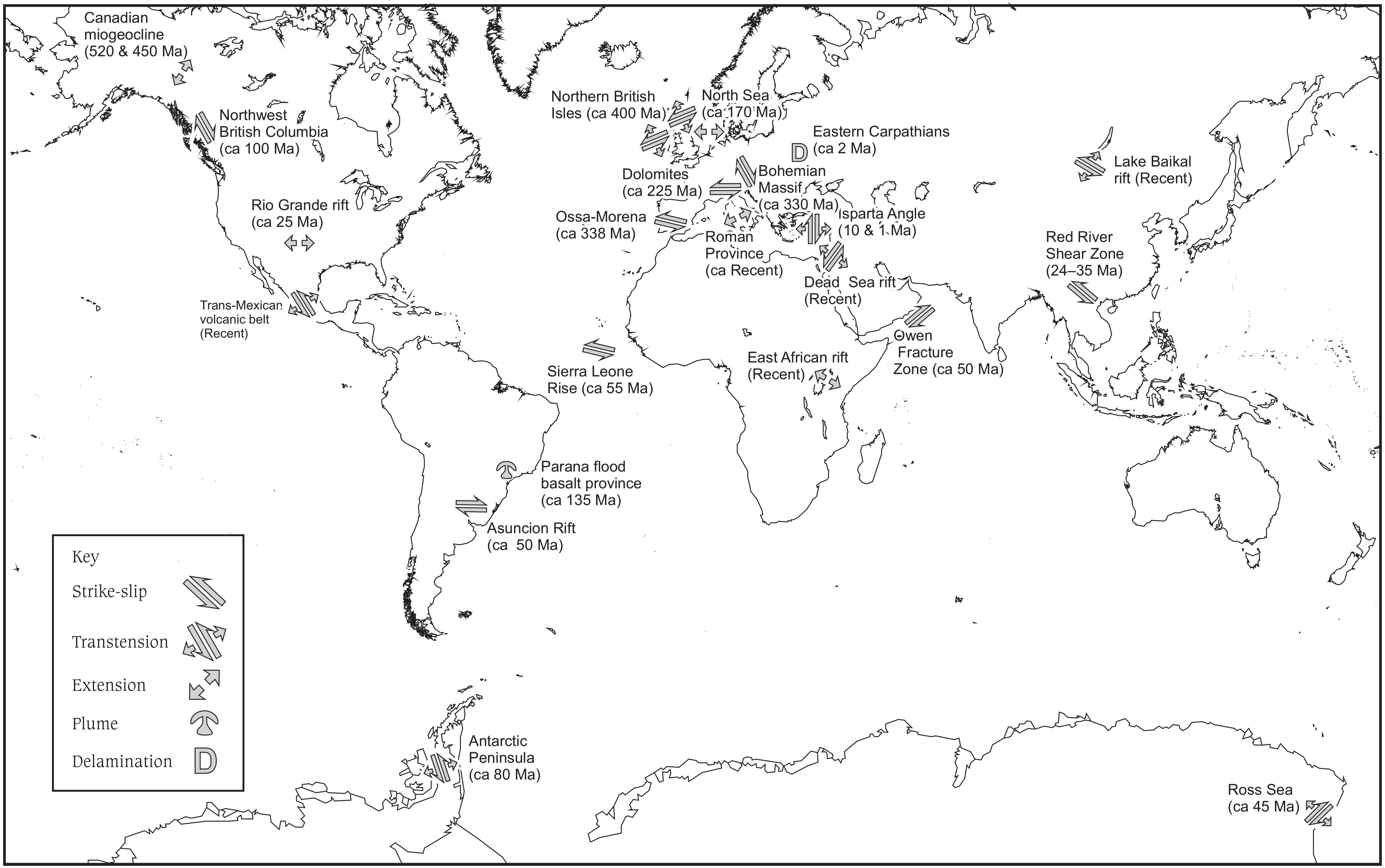
Figure Captions

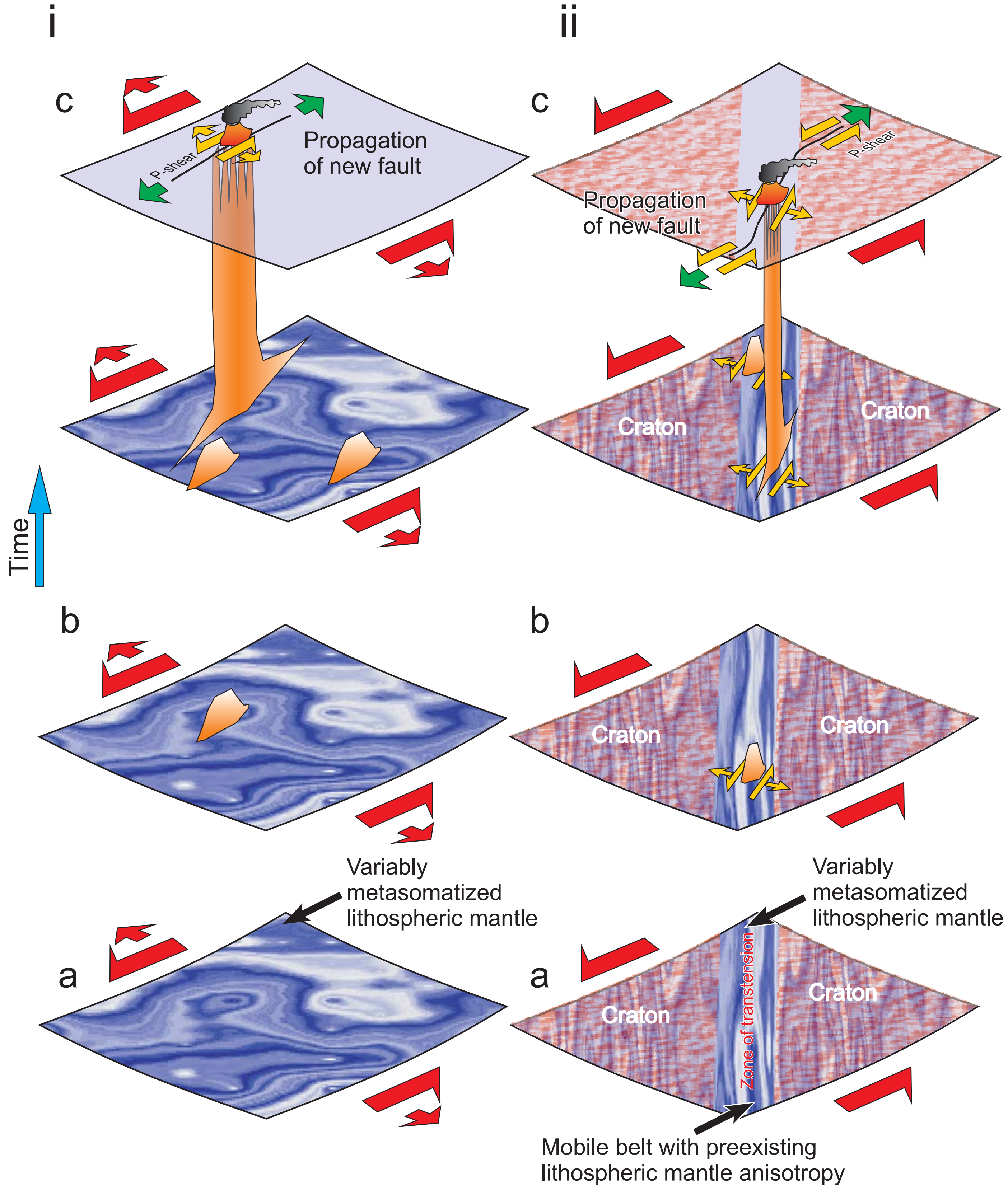
Figure 1: Distribution of K-rich magmatism localities mentioned in the text and tectonothermal regimes associated with emplacement.

Figure 2: Notional lithospheric blocks undergoing bulk horizontal shear strain. i) Regional transtension a) Contoured ornament shows stylised heterogeneous enrichment of the lithospheric mantle at base of lithosphere > 60 km thick (Harry and Leeman 1995). Darker suggests greater enrichment. b) Adiabatic decompression melting under transtension of metasomatized layer in zone of maximum enrichment. c) Ascent of potassic magma-driven fractures to shallow levels.

Tensional dykes are initially emplaced, with associated volcanoes, followed by break-through of *Primary* or P-shear (after Tchalenko 1970), which propagates away from the zone of nucleation, forming a new, discrete, transtensional strike-slip shear zone, in this case sinistral. ii) Bulk simple shear but with pre-existing mantle anisotropy and lithospheric mobile belt between cratonic blocks. a) as for i), b) partial melting as before but in localized zone of transtension associated with stress deviation. c) As for i) but P-shear propagates away from the localized transtensional zone of nucleation, to form a new, discrete, strike-slip shear zone, not characterized by transtension, in adjacent blocks.



Vaughan & Scarrow Figure 1



Vaughan & Scarrow Figure 2