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A review of Wilson Cycle plate margins: A role for mantle plumes in continental break-up along sutures?

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ABSTRACT

The Wilson Cycle theory that oceans close and reopen along the former suture is a fundamental concept in plate tectonics. It was named after J. Tuzo Wilson who recognised that dissimilar marine palaeo-faunas on both sides of the present-day Atlantic Ocean were best explained by an earlier proto-Atlantic ocean. The Wilson Cycle theory implies that collision zones may localise extensional deformation hundreds of millions of years after collision has waned. We review the passive margins of the Atlantic and Indian Oceans with the aim to evaluate the extent in which oceanic openings used former sutures and analyse the potential role of mantle plumes in continental break-up. We summarise the time of collision, onset of rifting, break-up, and main phase of flood basalt emplacement (if applicable) for eighteen conjugate margins. We find that conjugate margins open along former sutures with the exception of the Madagascar–Seychelles–India system. There is no relationship between suture age and break-up age. Continental break-up occurred on relatively young sutures, such as Morocco–Nova Scotia, and on very old sutures, such as the Greenland–Labrador and East Antarctica–Australia systems. We identified two cases where a suture was reactivated as a transform fault: the Charlie Gibbs Fracture Zone follows the Iapetus suture and the Agulhas–Falkland Fracture Zone possibly follows a Late Palaeozoic–Early Mesozoic suture between Patagonia and Western Gondwana. Continental extension and break-up is not always associated with large amounts of volcanism, as illustrated by the magma-poor margins of Iberia–Newfoundland, the Equatorial Atlantic Ocean, and East Antarctica–Australia. But twelve of the conjugate margins in our review are linked to large igneous provinces, such as, the North Atlantic margins (NAIP), Northwest Africa–Florida (CAMP), Arabia–Northeast Africa (Afar), and South Africa–East Antarctica (Karoo). For these margins we find that break-up occurs concurrent with emplacement of the associated large igneous province. In many margins, rifting began before the main phase of volcanism. This suggests that rifting was initiated by tectonic forces and that plume material flowed to the thinned rifted lithosphere to help trigger final continental break-up.

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1. Introduction

Wegener (1912) proposed that Europe and Africa, on the one hand, and North and South America, on the other hand, were together in Late Palaeozoic times. His theory about a supercontinent (Pangea), which was dispersed through continental drift, was not generally accepted until several decades later. However, already in the 1920s, Argand (1924) extended Wegener's theory by proposing that the North American Caledonides formed by continental collision after closure of what he named the proto-Atlantic, an Early Palaeozoic geosyncline. Four decades later, Tuzo Wilson (1966), apparently without being aware of Argand (1924), recognised that the diverse faunal distributions on both sides of the present-day North Atlantic Ocean required the existence of an Early Palaeozoic proto-Atlantic Ocean. By this time, plate tectonic processes were understood to have been operating before Pangea, in Palaeozoic and even Precambrian times. The proto-Atlantic Ocean closed in the Middle to Late Palaeozoic and, starting from the Cretaceous, the present-day Atlantic Ocean opened in the vicinity of its older suture (Fig. 1) (note that Wilson assumed a Jurassic rifting age). It was soon recognised that the proto-Atlantic Ocean in fact consisted of two oceans, the Iapetus and Rheic Oceans, which were separated by smaller terranes such as Avalonia (Harland and Gayer, 1972; McKerrow and Ziegler, 1972; Cocks and Fortey, 1982). However, the observation that the present-day Atlantic Ocean opened mainly along a former suture was a crucial step in the formulation of the Wilson Cycle theory (Dewey and Burke, 1974). There are several reasons why rifting would occur at or near a former suture: a) Extension may be initiated by the previous mountain-building phase because of gravity-driven flow of thickened crust, which is observed in, for example, the Himalaya, or by delamination of the crustal root or an over-thickened thermal boundary layer (Houseman et al., 1981; Dewey, 1988; Platt and England, 1993). This process could start during or shortly after the orogenic phase and thus result in a short time between suturing and the onset of extension. An example can be found in the Devonian extensional basins of western Norway that formed shortly after the Silurian Caledonian collision (Andersen and Jamtveit, 1990). b) A collisional orogen can become weaker relative to its surroundings because of long-term thermal heating in response to the enhanced heat production in the thick crustal root of the orogen (England and Thompson, 1984; Cloetingh et al., 1995; Ryan and Dewey, 1997). The former orogen then becomes a thermally weak region compared with its surrounding and could localise later extension. This process would explain longer (hundreds of Myr) time delays between collision and rifting. c) Tectonic inheritance in the form of thrust faults can weaken collisional margins over long times, resulting in repeated localisation of deformation in these regions (Audet and Bürgmann, 2011). Margin weakening because of inherited structures acts independent of time, unless fault-healing processes are involved.

However, extension does not always follow the former suture exactly as pointed out by Wilson (1966): "Since the beginning of the Cretaceous period the present Atlantic Ocean has been opening, but this reopening did not follow the precise line of junction formed by the closing of the early Palaeozoic Atlantic Ocean" (Fig. 1). This could have different reasons. Other weak areas in a continent, such as former back-arc basins or boundaries of previously accreted terranes, could be thought to 'compete' for strain localisation of far-field stresses and lead to rifting in a different location than the suture. Collision generally leads to a wide region of deformation (200–500 km), especially for systems that experienced earlier terrane accretion phases, thus creating a heterogenous lithosphere cross-cut by old thrust systems. In wide collision zones, it might not immediately be clear where extension would be localised. Alternatively, the suture may not everywhere be geometrically optimally aligned for extensional reactivation. In addition, the Earth's mantle may play an active role through which rifting and break-up might be aided, or perhaps even initiated, by mantle plumes. Several studies have pointed to a link between continental break-up and large-scale mantle upwellings (e.g., Dewey and Burke, 1974; Gurnis, 1988; Coffin and Eldholm, 1992; Storey, 1995). It is, however, much debated whether plumes use existing rifts as a pathway, or whether plumes play an active role in causing rifting (Burke and Dewey, 1973; White and McKenzie, 1989; Sleep, 1997; Courtillot et al., 1999), or possibly both.

In this study, we review margin pairs of the Atlantic and Indian Oceans (Fig. 2) with the aim of evaluating the extent in which oceanic opening used former sutures, to summarise times between collision and break-up, and to analyse the possible role of mantle plumes in aiding break-up. We discuss emplacement time of large igneous provinces (LIPs) in relation to break-up time for those margins that are associated with LIPs. We use LIP interchangeably with continental flood basalts to denote a province that was deposited fast (in a few Myr) and covers a large area (>100,000 km^2) (Coffin and Eldholm, 1992; Saunders, 2005). Even though the origin of LIPs is debated (Anderson, 2005; Foulger, 2010), a mantle plume origin is usually assumed (Campbell and Griffiths, 1990; Garfunkel, 2008; Torsvik et al., 2010; Sobolev et al., 2011; Kerr, 2013) and accepted in this review.

2. Passive margins of the Atlantic Ocean

2.1. The Arctic margins

Several sutures exist in the Arctic region north of Norway and Greenland: the Timanian, Ellesmere, Svalbardian, Iapetus, and Eurekan sutures (Fig. 3). The Timanian suture runs along the north coasts of Norway and Russia, along the Kola Peninsula to the Timan Range in Northwest Russia. It marks the accretion of the areas of Timan-Pechora, Novaya Zemlya, and the northern Ural to Baltica in the late Neoproterozoic (560–550 Ma) Timanian (Baikalian) Orogeny (Roberts and Siedlecka, 2002; Cocks and Torsvik, 2005). That suture has not been reactivated since. The Late Devonian/Early Carboniferous Ellesmere Orogeny affected parts of Southern Ellesmere Island, NE Greenland, and Svalbard (where it is called the Svalbardian event). We will discuss extensional reactivation of the Ellesmere and