Oceanic magmatic evolution during ocean opening under influence of mantle plume

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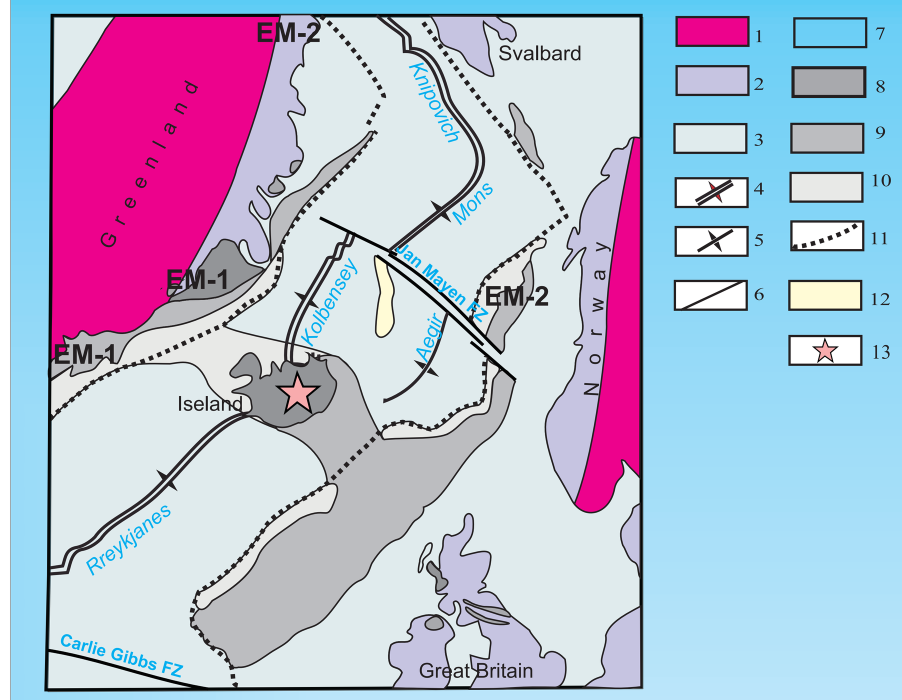
A comparison of the magmatism at the margins of Central and North Atlantic related to plumes

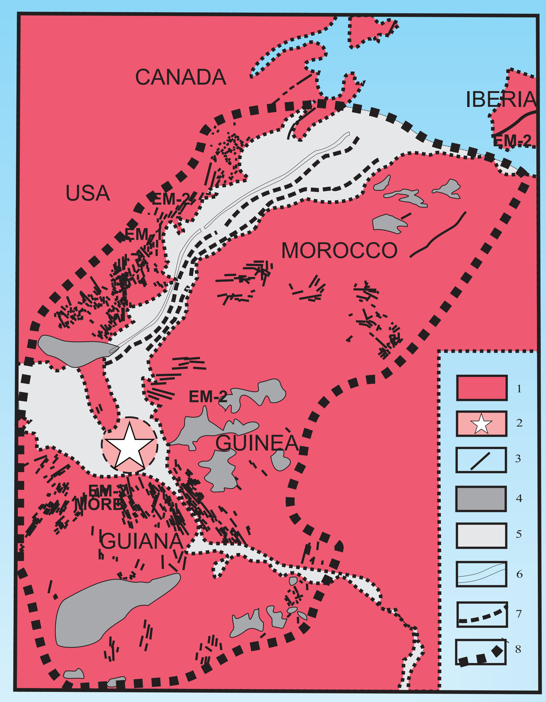
Tectonic scheme of the North Atlantic Ocean and its margins, modified after (Eldholm et al., 1989; Larsen and Saunders,1998; Mosar et al., 2002)



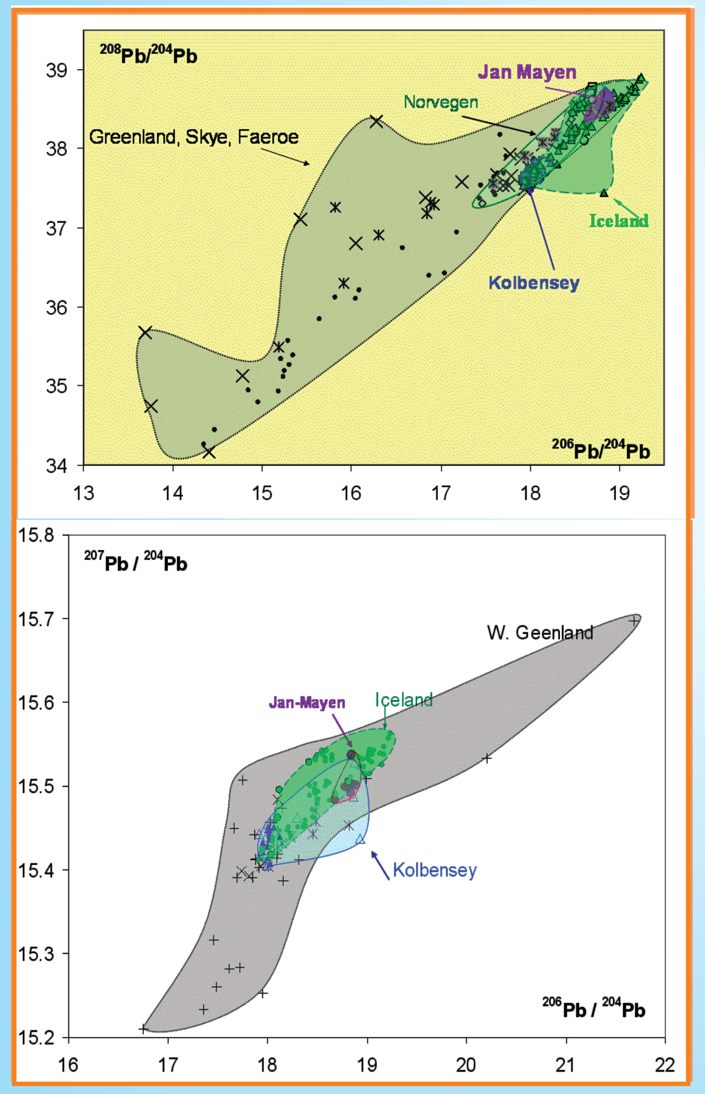
1–2 - regions with the continental crust: 1 - cratons, 2 - Caledonian foldbelts; 3-6 regions with the oceanic crust: 3 - oceanic bottom, 4 - axial zones of active spreading ridges, 5 - abandoned spreading center, 6 - fracture zones; 7-11 - passive continental margins: 7 - Cretaceous–Cenozoic sedimentary cover, 8 - onshore lava flows and sills (at proximal margins), 9 - near-shore lava flows and sills (at distal margins) and 10 - wedges of seaward deeping reflectors (SDRs), 11 - continent–ocean boundary; 12 - Jan Mayen; 13- Iceland plume.

The Central Atlantic Magmatic Province (CAMP) is one of the largest igneous provinces on Earth, extending more than 5000 km north to south, on both sides of the Atlantic Ocean. Its emplacement occurred about 200 Ma ago, at the Triassic–Jurassic boundary, and is linked to the initial breakup of Pangaea.

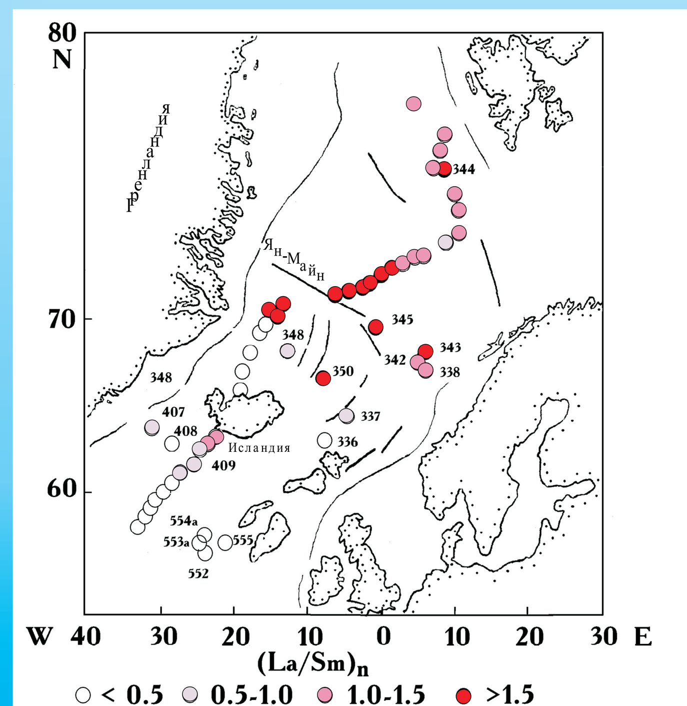
Tectonic scheme of Central Atlantic: reconstruction at 195 Ma
Modified after (Melankholina, 2008; Cebria et al., 2003; Cuppone, 2009; Gouiza, 2011; Jourdan et al., 2009; McHone, 1996; 2000; Sahabi et al., 2004 ; Schlische et al., 2003).



1 - Fragments of Pangea supercontinent in Africa, North and South America; **2** - Central Atlantic plume; **3–7** - passive volcanic margins: **3, 4** - igneous rocks at proximal margins: 3 - dikes, 4 - sills and lava flows; **5–7** - elements of distal margins: 5 - igneous rocks of seaward deeping reflectors (SDRs); 6 – newly formed crust of distal margins and Atlantic Ocean, 7 - magnetic anomalies along continent–ocean boundary; **8** - boundary of CAMP.

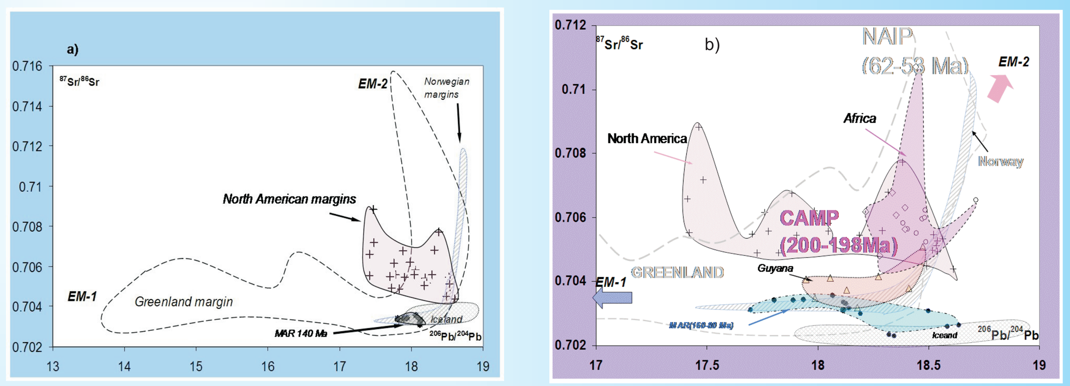


Variations of the Pb isotope ratios in the basalts of the East Greenland margin based on the analytical data from (Fitton et al., 1998; Graham et al., 1998; Hanghoj et al., 2003; Hart and Blusztajn, 2006; Peate et al., 2003: Saunders et al.,1998; Thirlwall et al., 2004; Upton et al., 1998)



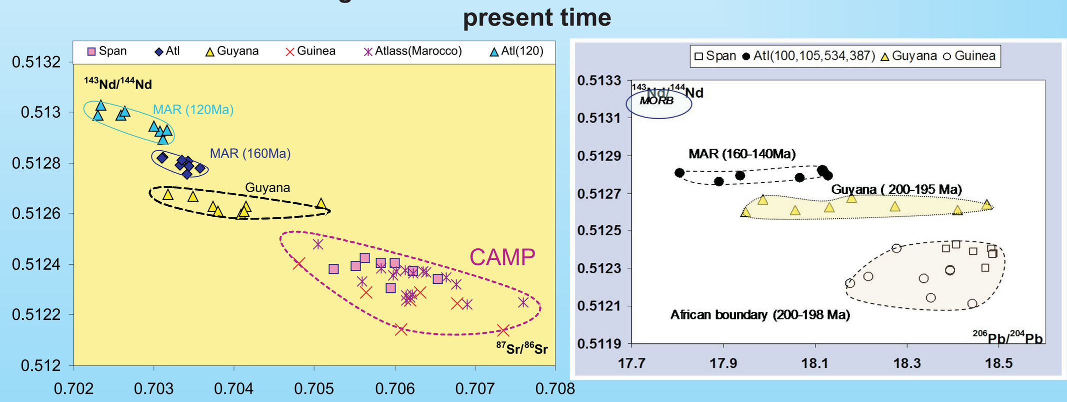
Distribution of enrich and depleted glasses along MAR.

The shallow Central-Atlantic plume formation can be seen as the result of upwelling activation and reconstruction of deep structure in the Triassic-Jurassic time. For the main part of CAMP magmas free of MORB material admixture, unlike a typical region NAIP, the model of enriched lithospheric source melting could be realized. Decompression and melting conditions in the lithosphere could be determined by anomalously hot plume upwelling. Some evidences of this process are the extent of melting as manifested in a short time interval over a large area with the generation of melts fairly constant composition and making of a strong magmatic crust, and radial dikes intruded when plume upwelling. Seismic tomography data (but very limited) give evidence of hot upper mantle material existent within this region, which retains a "memory" of the Mesozoic time events.

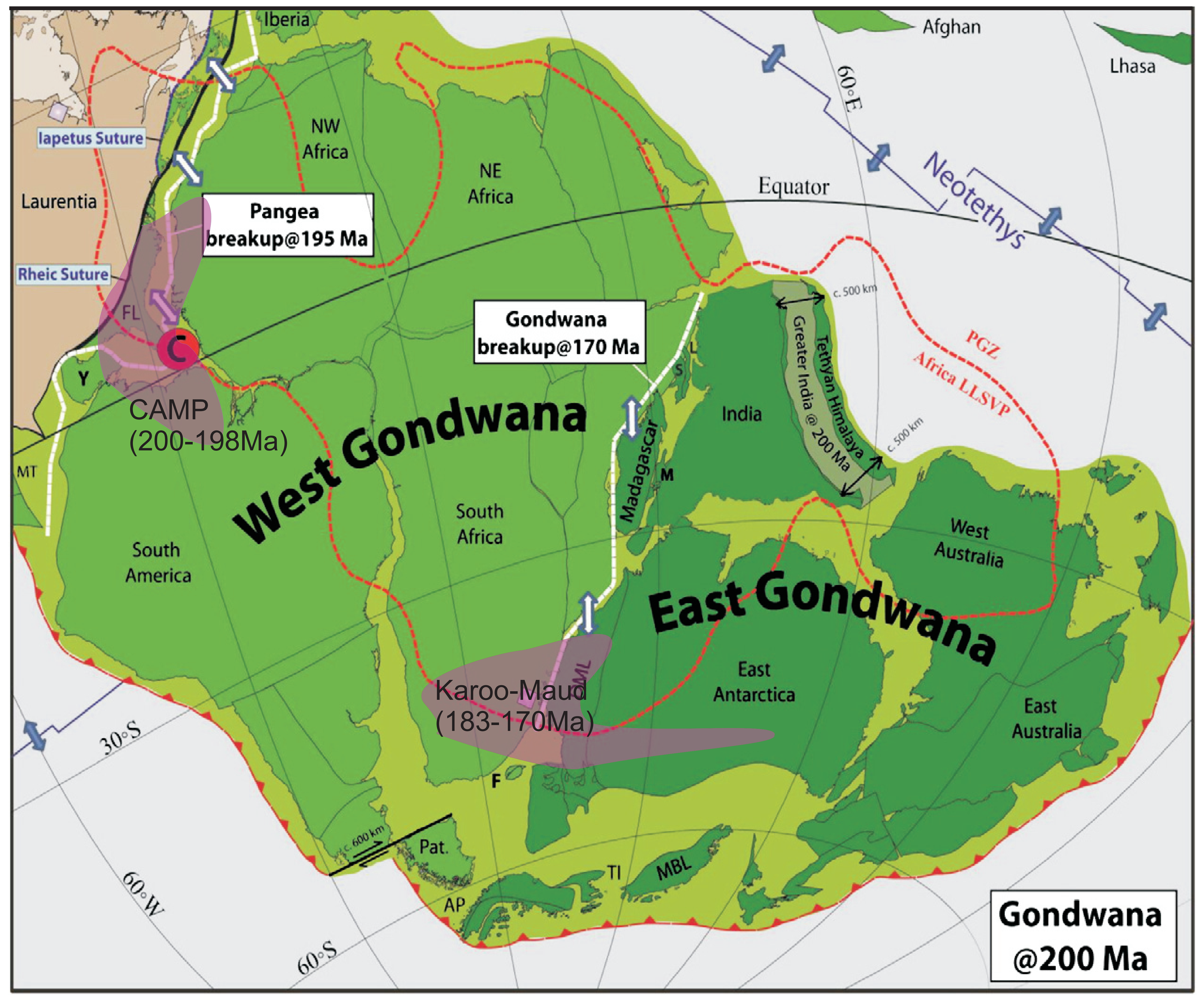


Comparison of magmatism in CAMP and NAIP related to deep-seated plumes
(a) general pattern of $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ isotope ratios for magmatism related to Iceland plume (within NAIP) and Central Atlantic plume (within CAMP). Range of isotope ratios in CAMP is narrower than in NAIP;
(b) more detailed pattern of $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ isotope ratios in igneous rocks from particular CAMP regions against the background of isotope ratio fields at Greenland and Norwegian margins, present-day Iceland, Jan Majen Island, and Kolbeinsey Spreading Ridge.
Similarity in $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ isotope ratios for tholeiites of Guyana margin and early stages of Atlantic opening is pointed out.

Variation of enrichment degree and character for Central Atlantic rocks from 200 Ma to present time



Isotope signature variations for CAMP lavas according to data [*Callegaro et al., 2013; Cebria et al., 2001; Deckart et al., 2005; Janney, Castillo, 2001*].



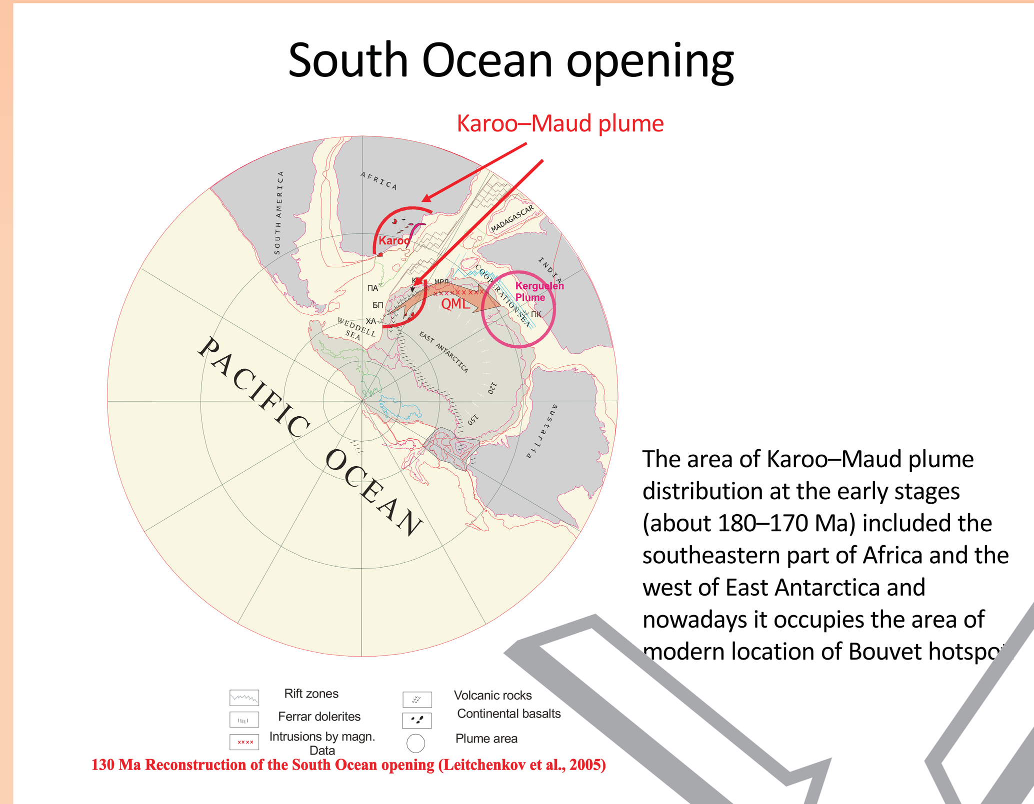
GONDWANA - 200 Ma (Torsvik, Cocks, 2013)

Palaeolongitudes at 30° intervals were calculated from the position of Pangea over the Africa LLSVP. The black dotted lines indicate the closed Iapetus and Rheic sutures, and the white dotted lines the future zones of the breakup of Pangea to form the Atlantic Ocean at 195 Ma and the Indian Ocean at 175 Ma. The island arcs which undoubtedly surrounded parts of the supercontinent are omitted. AP, The Antarctic Peninsula; CAMP,- the Central Atlantic Magmatic Province; DML, Dronning Maud Land, Antarctica; F, Falkland Isles, FI, Florida; MBL, Marie Byrd Land, Antarctica; MT, the Mexicanterranes of Mixteca-Oaxaquia and Sierra Madre; Pat., Patagonia; TI, Thurston Island, Antarctica; Y, Yucatan.
Dotted red lines are the plume generation zones (PGZ). Solid red lines are subduction zones, with teeth on their downward sides. Blue lines are ocean spreading centres.

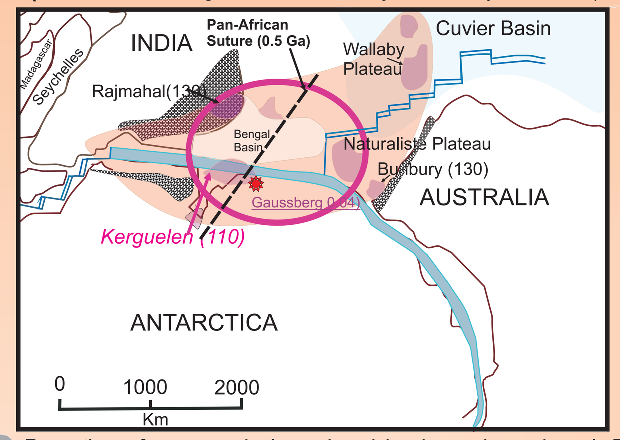
On the basis of obtained isotopic data two magmatic melt evolution trends have been determined: QML-Kerguelen-Af.Nikitin- Schirmacher and Jetty oasises. The eastern part of Indian Ocean, the place of Kerguelen plume melts distribution, is surrounded by rest of the earliest (maybe primary) continental fragments (Enderby Land granulites, for examples, have lead isotope signatures as low as 13.0-14.0) and addition of such substances into magma-generation would result in the lowest lead ratios within mesozoic magmas (EM-1).

Further evolution of this mantle source resulted in addition of admixture of EM2 component substances and growth of its share was directly connected with formation of magmatic sources of Schirmacher Oasis dolerites, and partly of QML basalts, and more prominently has been marked by isotopic signatures of Kerguelen basaltic melts. Alkaline-ultrabasic magmas of Jetty Oasis have could be derivatives of the sources connected crustal fluid of sediment origins, subducted sediments etc. with high Rb/Sr ratio.

Karoo-Maud superplume is an example of deep plume, born at the border core-mantle. Its penetration into the upper layers of lithosphere caused disintegration of Gondwana and separation of Africa from Antarctica. Distribution of plume substance along the weakened zones of Gondwana to the south (province Ferrar in the Transantarctic Mountains) and to the east (from the west part of QML towards the Prince Charles Mountains) of the Antarctic reflects the possible deep dislocations of the plume which possibly took place at different levels of lithosphere and underlithospheric mantle. This can be explained by the long history of Karoo-Maud plume which started about 180 million years ago and its expansion to the east along collision zones of East Antarctic till the Jetty Oasis and further to the Indian Ocean where it is still alive as Kerguelen plume for about 110 Ma.

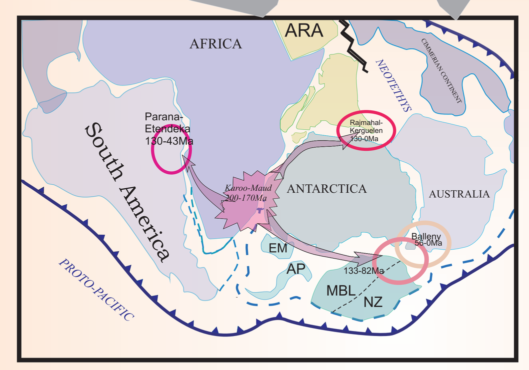


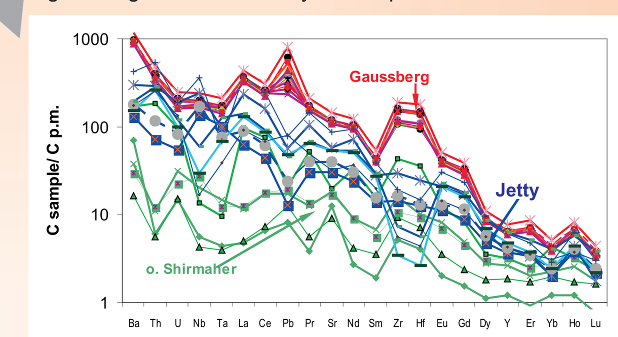
Kerguelen-plume distribution on reconstruction at 130 million years ago
(modified after Segev, 2002; Chatterjee, Nicolaysen, 2013)



Proection of supposed plume head is shown by red oval. Pink colour notes distribution of plume in process of its development. By black shading are noted trapp provinces within continental suburbs. Dark blue are marked spreading zones. In brackets the age of magmatism in million years is specified.

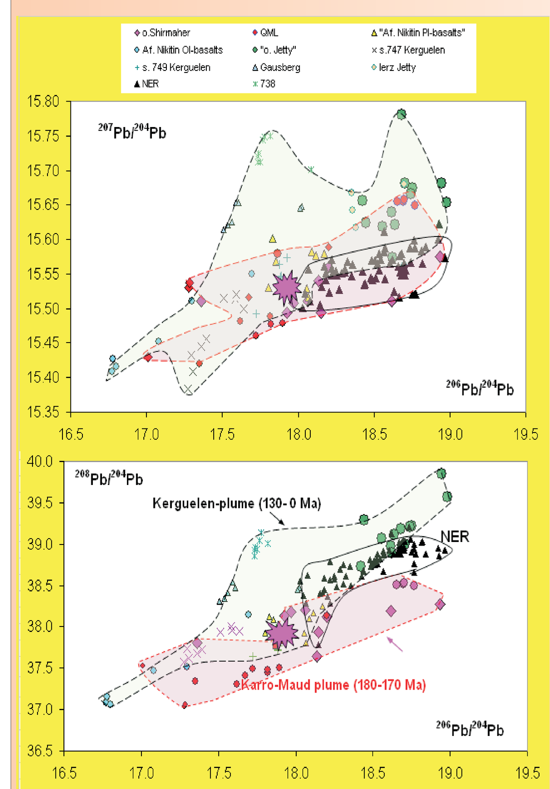
Development of Gondwana Plume provinces (reconstruction modified after Lawver et al., 1992, Segev, 2002) EM=Ellsworth-Whitmore Mountains, TI=Thurston Island.



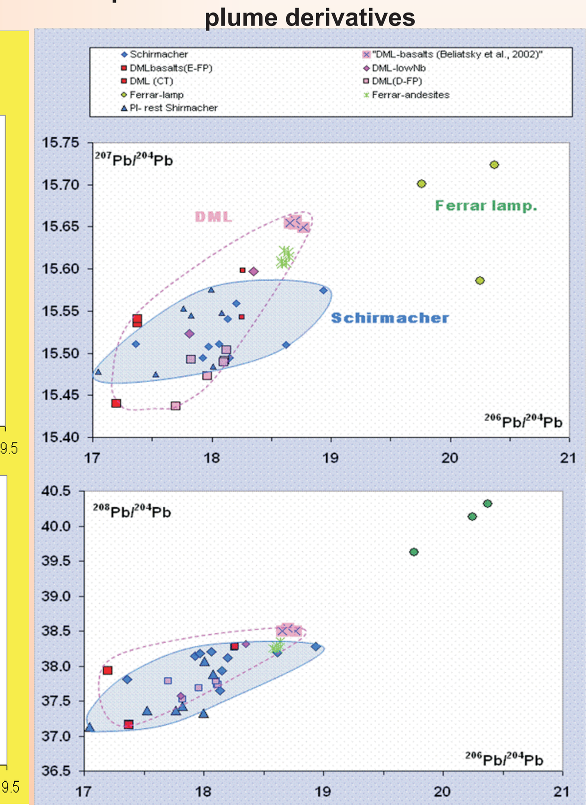


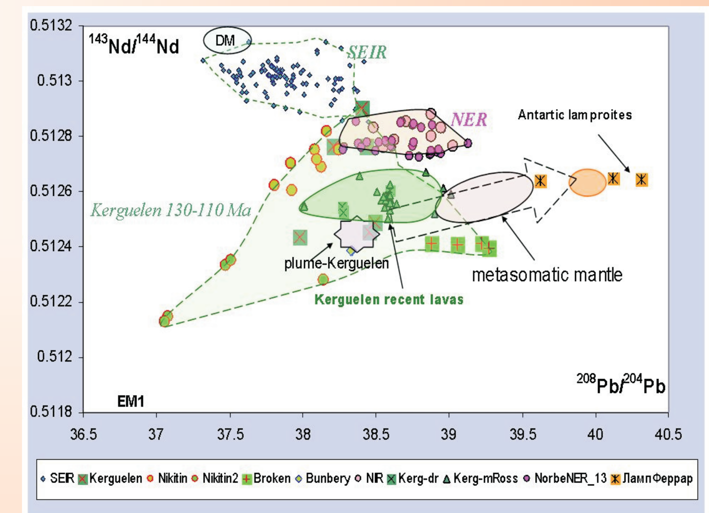
The primitive mantle-normalized (Sun, McDonough, 1989) patterns indicate different degrees of lithophile element enrichment in the dolerites of Kerguelen (Jetty Oasis, Gaussberg volcano) and Karoo (Schirmacher Oasis) plumes There are distinct positive Pb and negative Ta and Nb anomalies.

Pb isotopic characteristics for the Karoo and Kerguelen plume sources

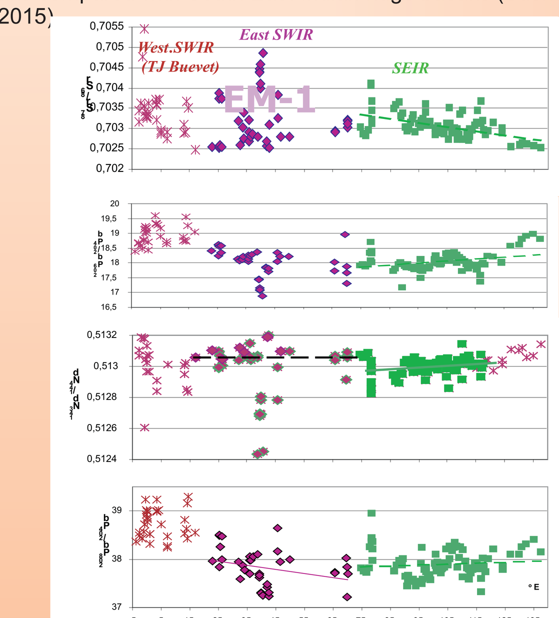


Queen Maud Land and Schirmacher magmatism Pb isotope signatures in comparison with characteristics of Karoo-plume derivatives





Diagrams of $^{143}Nd/^{144}Nd$ vs $^{208}Pb/^{204}Pb$ for the Ninetyeast Ridge, Kerguelen basalts compared with South East Indian ridge basalts (Sushchevskaya et al., 2015).



Isotopic characteristics of rift glasses along SEIR and SWIR

Melts near 40°E are generated from enriched source characterized by low $^{206}Pb/^{204}Pb$ ratio (<17.0), typical for Indian Ocean, then enriched basalts of Bouvet triple junction region correspond to the HIMU component. Trace element and isotopic investigation was shown that two MORB enriched provinces were: western province related to separation of western Africa and Antarctica, and eastern province connected to separation of Antarctica from India and Australia. The influence of plumes preceding the early stages of the continents break-up can be resulted in rift magmatism features. The enriched characteristics of rift melts outpouring in different points of spreading zone are inherited from magmatism developed upon the adjacent continental areas and connected with crustal contamination. It is possible to suppose that the upwelling plume was heterogeneous but in general it had geochemical features of depleted mantle, and enrichment took place during the process of its spreading along the base of lithosphere and further intruding.

Conclusions:

Under interaction of large plume and continental landmass the plume can contribute to splitting off individual lithosphere blocks, and their subsequent movement into the emergent ocean. At the same time enriched plume components often have geochemical characteristics of the intact continental lithosphere by early plume exposure. This is typical for trap magmatism in Antarctica, and for magmatism of North and Central Atlantic margins.
Comparison of CAMP magmatism with that developing at volcanic margins of the NAIP 60–53 Ma ago is shown that the material of the ancient continen tal lithosphere in the NAIP could have been incorporated into the plume during its ascent, whereas in the main area of CAMP, magmas are devoid of asthenospheric admixture, providing evidence for only an ancient lithospheric source (Melankholina, Sushchevskaya, 2015).
CAP activity was brief enough (200 ± 2 Ma), but Karoo-Maud plume worked for a longer time and continued from 180 to 170 Ma ago in the main phase. Plume impact within Antarctica distributed to the South and to the East, leading to the formation of extended igneous provinces along the Transantarctic Mountains and along the east coast (Queen Maud Land province and Schirmacher Oasis). Moreover, this plume activity may be continued later on, after about 40 million years cessation, as Kerguelen plume within the newly-formed Indian Ocean, significantly affects the nature of the rift magmatism;
The conducted comparison of plume magmatism at the eastern edge of the Queen Maud Land with the early magmatic stages of the Kerguelen plume and spreading zones of the Indian Ocean (130-90 Ma) which are under its influence, has demonstrated the similarity of the enriched source of continental and oceanic lavas, this could evidence to possible spreading of global Karoo-Maud plume during at least 180 my in the eastern direction and further towards the opening Indian Ocean till its modern position within the Kerguelen plateau.
A large extended uplift in the eastern part of the Indian Ocean – Ninetyeast Ridge was formed on the ancient spreading Wharton ridge near active Kerguelen plume. The strongest plume influence on the NER formation occurred 70-50 Ma years ago, when the process of primary magma generation happened at high degrees of melting (up to 30%), which is not typical for spreading ridges of the Atlantic and Pacific Oceans. According to geochemical characteristics of the Kerguelen Plateau and NER magma sources close to each other, and have an enriched source of more typical for Kerguelen plume magmas and diluted by depleted substance for NER melts.
The enriched mantle source of the modern western SWIR tholeiites in the vicinity of the Bouvet Triple Junction also resembles the HIMU mantle component, but has slightly lower isotope ratios, indicating its mixed nature (HIMU + EM2). The DUPAL anomaly distinguished at 40° E displays the influence of EM1 material in the mantle source. The composition of this source could be produced by the addition of material from the continental lithosphere of the ancient Gondwana continent. The influence of this source can be distinguished in magmas related to the Mesozoic plumeactivity in Antarctica, as well as in basalts from the eastern Indian Ocean rises, which were formed under theinfluence of the Kerguelen plume at about 100–90 Ma.The mantle source of younger magmas that were generated within and near the proto SEIR and modern SEIR is characterized by the presence of an enriched mantle component EM-2 typical of the mantle sources of ocean-island volcanics.