^{40}Ar/^{39}Ar geochronology of basalts in Scania, S Sweden: evidence for two pulses at 191-178 Ma and 110 Ma, and their relation to the break-up of Pangea

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Master Thesis

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$^{40}Ar/^{39}Ar$ datering av basalter i Skåne, S Sverige: bevis för två pulser vid 191-178 Ma och vid 110 Ma, samt deras relation till uppsprickning av Pangea

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Sammanfattning: Under karbon och perm sammansmälte huvuddelen av jordens kontinenter till en gigantisk landmassa som fått namnet Pangea. Denna blev efterhand instabil och började mot slutet av trias, men framför allt under Jura, att fragmentera i ett antal mindre kontinentala plattor. Detta skedde under omfattande och ibland våldsam vulkanism.

Detta projekt handlar om basaltvulkanismen i centrala Skåne och som tidsmässigt ansetts sammanfalla med Pangeas uppsprickande. För att bekräfta en tidsmässig relation har fokus lagts på att erhålla exakta och pålitliga åldrar för de skånska basalterna. Åtta vulkanrester med representativa mineralogiska sammansättningar och geografisk utbredning daterades med modern $^{40}Ar/^{39}Ar$ teknik vid argon-laboratoriet i Lund. Resultaten bekräftar en puls av basaltisk vulkanism vid 191-178 Ma och en, betydligt yngre, vid 110 Ma. Dessa resultat gör det möjligt att länka en större del av den skånska vulkanismen till Pangeas fragmentering i undre jura.

Tidigare publicerad geokemiska data tillsammans med opublicerade data på prover från de skånska basalterna visar att smältorna som genererat vulkanismen har anmärkningsvärt snarlika sammansättning. Identiska spårelementsammansättningar för den jurassiska och kretaceiska basaltvulkanismen indikerar att smältorna generades direkt (dvs. utan fraktionering och nämnvärd kontamination) från samma mantelkälla, omfattade samma uppsmältningsgrad och sannolikt skedde under snarlika tektoniska situationer. Graden av uppsmältning måste ha varit måttlig ($\leq$ 10%) för att generera smältor med en eutektisk sammansättning. Dessa omständigheter är mest förenliga med adiabatisk uppsmältning av manteln, medan s.k. ”plume”-relaterad vulkanism måste anses mindre sannolikt. Vulkanismen i jura och krita var troligen kontrollerade via rörelser längs Tornqvist-zonen, som vidare har relaterats till Pangeas fragmentering och senare tektoniska rörelser.

I denna studie diskuteras också den globala vulkanismens betydelse för biosfärens utveckling under framför allt tidig jura (toarcian).

Nyckelord: Skåne, basalt, jura, krita, geokronologi, $^{40}Ar/^{39}Ar$, geokemi

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Abstract: During the Carboniferous and the Permian periods the great majority of the Earths continentinental blocks were assembled into one giant landmass – Pangea. This became, however, unstable leading to fragmentation that started in Late Triassic but intensified during the Jurassic period. The fragmentation was associated with violent volcanic eruptions that occasionally developed into active rifting.

This project is focused on the basaltic volcanic activity in Scania, which has been considered to be largely synchronous with the break-up of Pangea. To confirm a temporal relationship the aim has been to obtain exact and reliable ages for the Scanian basalts by using radiometric methods. Eight volcanic basalt remains, with representative mineralogical compositions, were dated with modern $^{40}Ar/^{39}Ar$ technique at the argon laboratory in Lund. The results confirm one pulse of volcanic activity at 191-178 Ma and another, much later pulse, at 110 Ma. These results allow the possibility to link the majority of basalt necks to the fragmentation of Pangea during Jurassic times.

Geochemical data of the Scanian basalts reveal that the melts had a remarkably similar composition. Identical trace element composition for the Jurassic and the Cretaceous events of volcanic activity indicate melts derived directly (e.g. no fractioning and no contamination) from the same mantle source, comprised the same (and low) degree of partial melting and probably occurred under similar tectonic regimes. These conditions are better explained by eutectic melting of the mantle than by "plume-generated" volcanism. The Scanian volcanic activity during the Jurassic and the Cretaceous periods was probably tectonically controlled via movements along the Sorgenfei-Tornqvist zone. This zone has previously been suggested to relate to the break-up of Pangea and later events.

In this study the implication of the global volcanic events on the development of the biosphere in particularly during Early Jurassic times (Toarcian) – is also discussed.

Keywords: Scania, Basalt, Jurassic, Cretaceous, Geochronology, $^{40}Ar/^{39}Ar$, Geochemistry

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Cover picture: A newly discovered basalt neck not included in SGU maps. Working name ANNABJER

1 Introduction

1.1 Break-up of Pangea and the Scanian volcanic province

Pangea, the latest supercontinent, was formed during the late Carboniferous through the Permian periods (310-250 Ma) (Torsvik & Cocks 2004; Veevers 2004). The name Pangea – "all land" - was originally coined by Alfred Wegener already in 1912 when he proposed his theory of plate tectonics that, however, became refuted by the expertise at that time.

This gigantic landmass was created by a fusion of the great northern continent Laurussia (North America, Greenland and Baltica) and the great southern continent Gondwana (South America, Africa, Antarctica, India and Australia).

Pangea was wholly assembled by the end of the Permian period, forming an enormous landmass stretching from the North Pole to the South Pole. This supercontinent exerted major influence on the terrestrial and the marine biospheres. It also had a major influence on the environmental and climatic conditions, such as the wind pattern (Loope et al. 2004), the precipitation (Tabor & Montanez 2002), the ocean circulation (Beauchamp & Baud 2002), and the oxic/anoxic state of the oceans at that time (Isozaki 1997).

The global climate, from the time of the agglomeration of Pangea to the dawn of the Mesozoic, was changing from icehouse to greenhouse conditions. Icehouse conditions prevailed through the Carboniferous to Early Permian with great icecaps on the South Pole and a global mean temperature at 12°C during the second

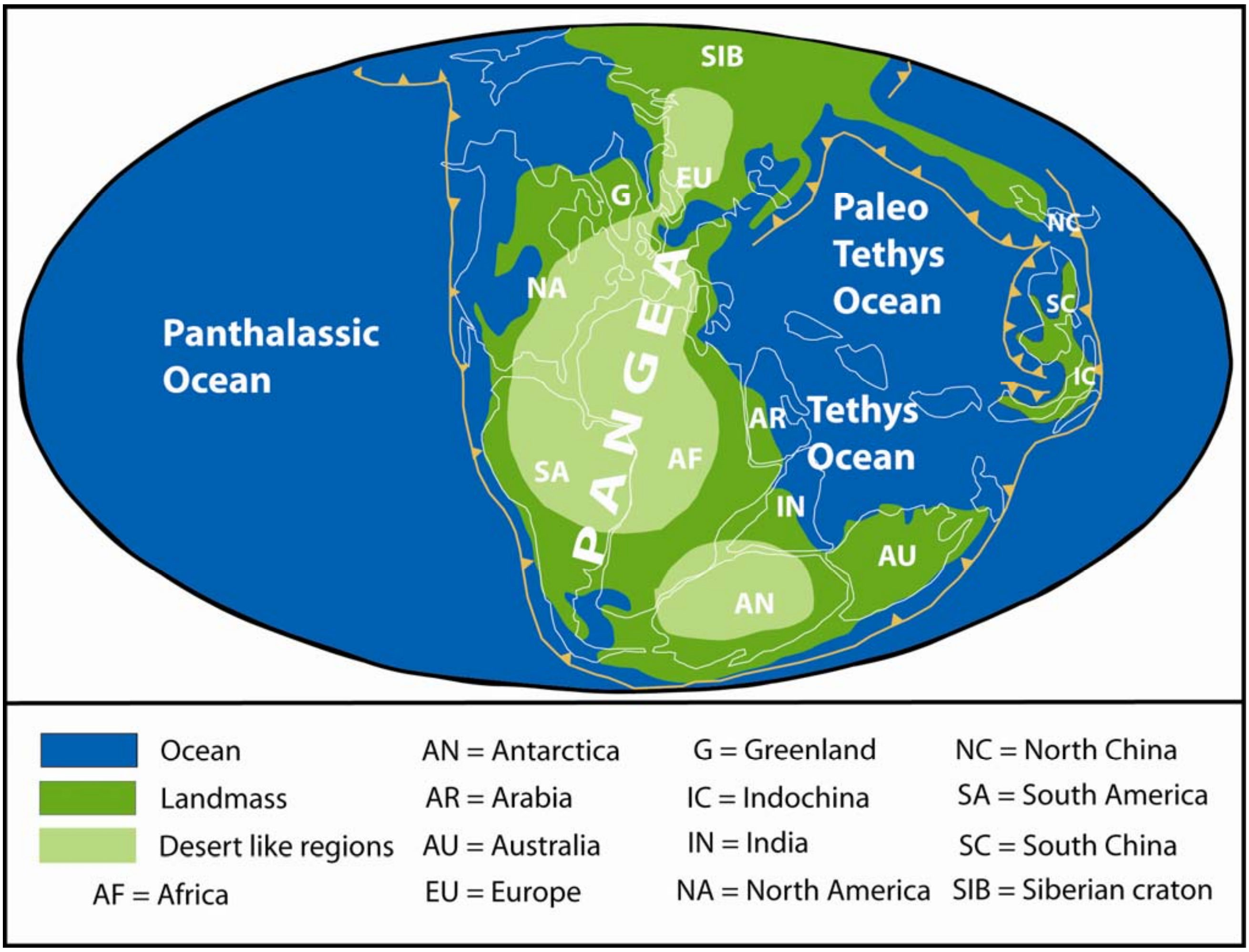

Fig. 1. Paleomap of Pangea during early Triassic time. The yellow tagged lines mark subductions zones. The map shows the extent of the desert-like conditions in the interior of the supercontinent. (Modified from http://www.scotese.com).

half of Carboniferous and the first half of Permian (Scotese et al. 1999). This was followed by an increase to 22°C during the remaining part of the Permian, the Triassic and the majority of the Jurassic periods.

However, the huge Pangean landmass was unstable and towards the end of the Triassic, and particularly during the Jurassic, the supercontinent started to break apart manifested by rifting and formation of Large Igneous Provinces (LIP). Magmatic remains from one of these, the Central Atlantic Magmatic Province or CAMP in short (Knight et al. 2004; Hames et al. 2000; Marzoli et al. 2004), now appears on both sides of the Atlantic Ocean, in the coastal areas of Africa, North and South America.

Other important LIPs are the Karoo and Ferrar igneous provinces, formed in the Gondwanan part of Pangea, now located in South Africa, South America and Antarctica (Riley & Knight 2001). A third and more proximal tectonic activity was created by sea floor spreading in the western Tethys domain (Bortolotti & Principi 2005), roughly located at present Mediterranean Sea.

Extensive magmatic activity and plate movements exerted stresses in various crustal regions and old suture zones between ancient tectonic plates became vulnerable sites for reactivation. One such zone, the Sorgenfrei-Tornquist Zone (STZ), intersects Scania from the NW to SE, and it is north of the junction between STZ and west of the N-S trending Protogine Zone (a Proterozoic tectonic zone in south-central Sweden) that the remains of the Scanian volcanism are found.

Basalt necks (and tuffs) in Scania are concentrated within a limited area in the northern part of the region (Fig. 3), and they stem from a former violent past in the Scanian geological history. The surface exposures of basalt necks vary from 300 000 - 400 000 m^2 down to only some few m^2 and their height from some few meters to around 60 m above the surrounding terrain. Some necks are not exposed and have been tracked solely from geophysical investigations.

The timing of the volcanic activity in Scania is relatively poorly constrained. The latest attempts to date the basalts with direct radiometric methods using K-Ar chronology took place over three decades ago (Printzlau & Larsen 1972; Klingspor 1976).

The primary aim of this study was to date the Scanian volcanic activity by using exact and modern $^{40}Ar/^{39}Ar$ isotope geochronology. This study also highlight the Scanian volcanism in the perspectives of the local and regional palaeoenvironment, and the global fragmentation of Pangea.

1.2 Previous age constraints of Scanian volcanism

Estimates regarding the timing of the Scanian volcanic activity has varied considerably, from the Jurassic period (Bylund & Halvorsen 1993) to the Eocene period (Magnusson et al. 1957). Some of the previous constraints refer to indirect assessments. Tralau (1973) argued for a lower Jurassic (Toarcian) age for the Scanian volcanic activity based on a palynological investigation of tuff sediments near Korsarödssjön (ca. 10 km northeast of Höör, Fig. 2).

The microflora contained spores and pollen which Tralau (1973) stated to be typical from lower to middle Jurassic in southern Sweden, including *Lycopodiacidities rugulatus* (Couper) Schulz 1967, *Quadraeculina anellaeformis* Maliavkina 1949 (as *Parvisaccites enigmatus* Couper 1958) and *Alisporites robustus* Nilsson 1958. He also found spores of *Zebrasporites interscriptus* (Thiergart) Klaus 1960, which he stated typical for mid Keuper to Lias strata, but absent in mid-Jurassic sediments. He concluded that the volcanic event ejecting the tuffs in Korsaröd took place in the Toarcian. However, none of the spores and pollengrains that Tralau (1973) listed as present in the tuff restricted to the Lower to Middle Jurassic. Most of the taxa are long-ranging, with the first appearences in the Upper Triassic and the last appearances in the Upper Jurassic (Batten & Koppelhus 1996). Other taxa, e.g. *Z. interscriptus,* have their latest occurrence in the Lower Jurassic, but are frequently found reworked in younger strata (pers. comm. Sofie Lindström 2006).

Another indirect age of Scanian volcanism was reported by Bylund & Halvorsen (1993). They established paleopoles for twenty-three Scanian basalt necks of which six were the same as those sampled for this investigation (i.e. Rallate, Bonnarp, Knösen, Säte, Hagstad and Bosjökloster). They arrived at the conclusion that "the palaeomagnetic data obtained imply that the Scanian basalts are of Toarcian age, i.e. c. 194 to 188 Ma old, thus largely synchronous with the initial stage of Jurassic volcanism in the North Sea" (op. cit. Bylund and Halvorsen 1993). This corresponds to 176-183 Ma according to the current time scale (Gradstein et al. 2004).

The first attempt to date the basaltic necks in Scania using radiometric methods was performed by Printzlau & Larsen (1972). They sampled nine different basalt necks and used the K/Ar dating technique. They obtained ages ranging from 79 Ma to 131 Ma, placing the volcanic activity much later than previous estimates, namely during the Cretaceous period.

Klingspor (1976) sampled three basalt necks for K/Ar chronology on both whole rock fragments as well as on clean mineral separates of plagioclase and pyroxene. Her ages span from 59 Ma and 169 Ma, which place the volcanic activity both in the Jurassic (Göbnehall) and in the Cretaceous periods (Rallate and Lönnebjär).

Augustsson (2001) investigated volcanic tuffs in central Scania and classified these as pyroclastic products originating from the Scanian volcanic eruptions. She also carried out petrographic examinations on samples from eight tuffs. These are described as moderately sorted with less than 10-20 mm large lapilli fragments and ashes. The tuffs are altered to swelling clay minerals indicating major diagenetic changes.

The moderately sorted appearance of the tuffs was interpreted by Augustsson as indicative for volcanic ejections on land. In one location, however, she reports finds of sorted tuffs probably ejected into an aquatic environment. She describes the vulcanos as being of strombolian type with scoria cones ejecting the tuff material in close proximity to the vulcanos. She did not, however, date the tuffs but concluded that the volcanic event probably took place in the late Early Jurassic.

In conjunction of a Jurassic age, she referred both to the palynologic dating by Tralau (1973) and to an unpublished $^{40}Ar/^{39}Ar$ date of 176±4 Ma (as pers. comm. from T. Torsvik), i.e. near the boundary between Early and Middle Jurassic.

2 Geological setting and tectonic framework

2.1 Sorgenfrei - Tornquist Zone (STZ) and the surrounding geology

STZ cuts diagonally through the Scanian landscape from NW to SE. The zone principally divides the Scanian bedrock in two sections with proterozoic granites and gneisses in NE and phanerozoic sediments in SW. The zone itself is characterised by horst and graben tectonics formed by dominating vertical movements of crustal blocks, particularly during Mesozoic times.

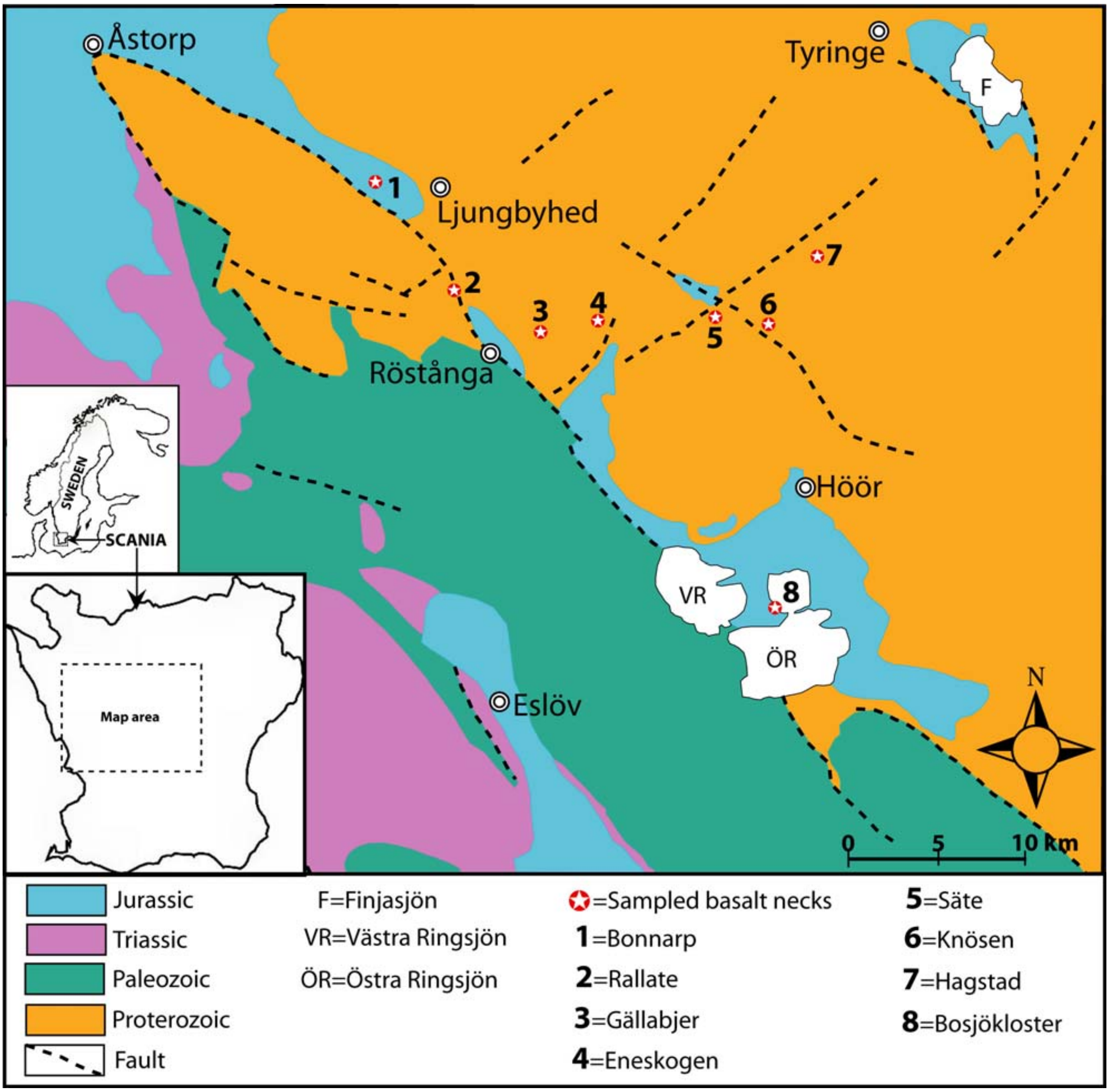

Fig. 2. Bedrock map of the central and northern parts of Scania with sampled basalt necks (star 1-8). Two necks (Bonnarp and Bosjökloster) are located in areas of Jurassic sediments, whereas the other six basalts are located in Proterozoic crustal rocks.

Remnants of the Scanian Mesozoic volcanism are distributed along parts of the STZ but limited to a small area of roughly 30 x 35 km between Ringsjön and Finjasjön in S to N direction and Ljungbyhed and Äsphult in a W to E direction (Fig. 2). Two of the necks penetrates Jurassic sediments whereas the others are located in the proterozoic bedrock region. Field work, finds from bore holes and ground cuttings together with aerial magnetic survey have resulted in an estimate of between 100 to 200 volcanic remains (basalt necks, basalt and/or tuffs) in Scania (pers. comm. Mikael Erlström, SGU Lund 2006).

Finds of basaltic boulders in distal areas, and possible tuffs in deep drillings, have also been reported. There is, however, uncertainty as to their relationship with the Scanian volcanism. The distribution of Mesozoic volcanism is described in the following bedrock maps by the Swedish Geological Survey (SGU): 3C Helsingborg SO – SGU serie Af nr 180 (1994), 3D Kristianstad SV –

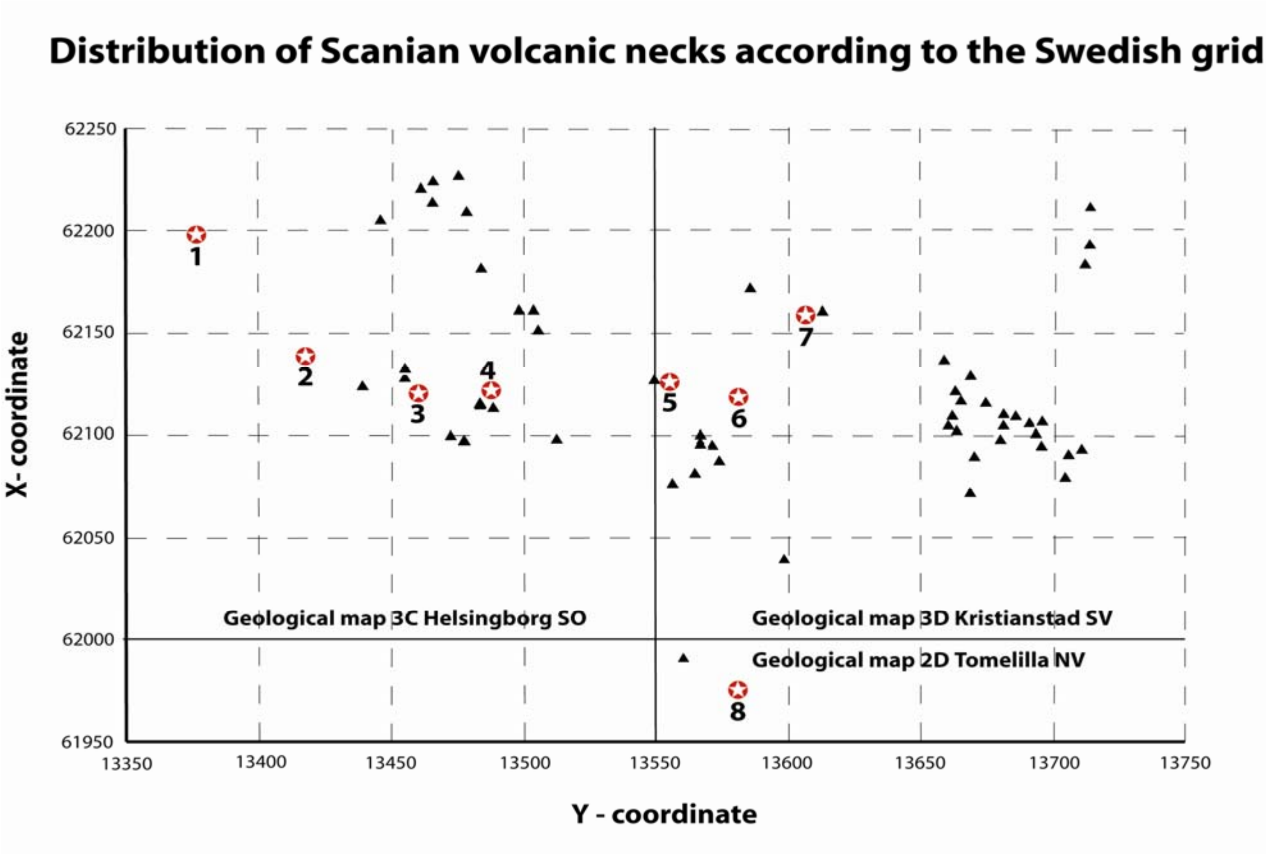

Fig. 3. Graph illustrating the position of the various Scanian basalt necks (black triangles) according to the Swedish Grid. Stars (1-8) are basalts sampled for Ar geochronology. Reference numbers to the stars are explained in the bedrock map figure 2. Each square of the grid occupies an area of 5x5 km.

Table. 1. North and the east coordinates for basalts following the Swedish Grid. The table also lists rock type (B=Basanite, M= Melanephelinite), and facies (M= Microcrystalline and G= Glassy) according to the definition by Tappe (2004). Names in brackets are alternative names appearing in the literature.

Name of basalt neck	**Coordinates**	**Rock type**	**Facies**	**Comments**
Bonnarp (Bonarp)	6219783 / 1337615	B	M	Penetrates present Jurassic sediments close to the airfield of Ljungbyhed. Constitutes a hill of about 5-6 m height and covers roughly 5 000 m^2
Rallate	6213865 / 1341677	B	M	Situated close to the northern fault of Söderåsen. Small neck about 4 m high and covers roughly 50 m^2. It has well developed basalt pillars.
Gällabjer (Jällabjär,	6211784 / 1346095	M	G	The largest neck some 64 m over surrounding terrain and covers an area of roughly 1,4 x 0,4 km.
Eneskogen (Anderstorps	6211841 / 1348297	M	M	Covered by quaternary sediments. Some few boulders and basalt pillars remain.
Säte (Vägasked)	6212748 / 1355163	B	G	Comprise two basalt pipes, each roughly 4-6 m high and some few 100 m^2 in area.
Knösen	6211839 / 1358085	B	M	About 25 m high with basalt pillars at the top. It covers an area of roughly 180 x 280 m.
Hagstad (Hagstad bjär)	6215774 / 1360645	M	M	About 35 m high over the surrounding terrain and covers about 80 000 m^2.
Bosjökloster	6197629 / 1358046	M	M	Penetrates present Jurassic sediments, was hard to detect as its locality is not shown in bedrock map.

SGU serie Af nr 155 (1987) and 2D Tomelilla NV – SGU serie Af nr 212 (1999).

In bedrock maps (SGU 1987), some 70 basalt necks in Scania have been marked. Three of these, marked to be found in the south-eastern part of Scania nearby Brösarp and Degerberga, do not exist. A fourth basalt in this area is merely represented as a loose boulder (pers. comm. Mikael Erlström, SGU Lund 2006).

2.2 Overview of the sampled basalt necks

For this investigation eight different locations of basalt necks were selected for sampling. The individual sample sites among other basalt locations are given in Fig. 2 and 3. Their exact position and a short description of each sampled neck are given in Table 1.

The selection of sampling sites was based on three principles. Samples should:

1. be representative on the basis of their mineralogical and compositional characteristics following Tappe (2004). For four sample sites the basalts were classified as basanites and for the remaining four as melanephelinites.

2. cover a broad geographical distribution. The results of Printzlau and Larsen (1972) indicated a possible geographic age difference of basalt necks, though refuted by Klingspor (1976).

3. be fresh with no signs of weathering or other type of secondary alteration.

3 Material and methods

3.1 The K-Ar and the ^{40}Ar/Ar^{39} methods

3.1.1 Basic requirements & considerations in K-Ar geochronology

K-Ar geochronology is based on radioactive decay of ^{40}K to the stable daughter isotope of ^{40}Ar. In principle the age of a sample is determined by the relative abundances of mother and daughter isotopes. Minerals suitable for K-Ar dating must have relatively high concentrations of potassium such as white mica, biotite, feldspars, clay minerals and certain evaporate minerals (Faure 1986).

In order for a K-Ar date of a mineral (or whole rock fragment) to be geologically significant, the following prerequisites must be fulfilled:

1. The sample was a closed system with respect to potassium and argon from the time of initial cooling, or in other words when the sample passed through its “blocking temperature”.

2. No Ar was incorporated into the sample at the time of formation (so called “excess argon”) or lost during a later metamorphic event (Ar-loss).

3. An appropriate correction is made for the presence of atmospheric ^{40}Ar.

4. The isotopic composition of potassium in the mineral (or whole rock sample) was not changed by any other process than by decay of ^{40}K, e.g. by fractionation or any other process.

5. The decay constant of ^{40}K is correct.

6. The relative abundances of ^{40}Ar and ^{40}K were determined accurately.

Generally it is considered that fresh basalt samples are well suited for K-Ar dating. Basaltic rocks cool quickly which means that the time between extrusion and cooling to a temperature at which all phases quantitatively retain their Ar is insignificant relative to the age of the sample.

3.1.2 Principles of the K/Ar dating method

^{40}K has a branched decay to ^{40}Ca and ^{40}Ar, where 88,8% of the mother isotopes decay to ^{40}Ca and 11,2% to ^{40}Ar. The decay constant (λ) of ^{40}K to ^{40}Ar has been determined to $0{,}581 \times 10^{-10} y^{-1}$ and of ^{40}K to ^{40}Ca to $4{,}962 \times 10^{-10} y^{-1}$. This yields a total λ of $5{,}543 \times 10^{-10} y^{-1}$ for ^{40}K (Steiger & Jäger 1977). The age of the sample is calculated according to:

$$\mathbf{T=1/\lambda \times \ln[(^{40}Ar^{*}/^{40}K) \times (\lambda/\lambda_e)+1]}$$

where T= the age of the sample, λ=the total decay constant for ^{40}K and λ_e=the decay constant for ^{40}K to ^{40}Ar. The amount of potassium in the sample can be determined by one of many methods, including flame photometry, atomic absorption spectrometry, isotope dilution, x-ray fluorescence or gravimetric chemistry. The amount of ^{40}Ar in the sample is determined by isotope dilution, which means that spiked argon enriched in ^{38}Ar is mixed with the gas from the sample. The ratio $^{40}Ar/^{38}Ar$ is determined in the mass spectrometer and from the known amount of spiked ^{38}Ar the abundance of ^{40}Ar in the sample is calculated.

The drawbacks of the K/Ar method are: [1] the content of potassium and argon are determined by different techniques where the potassium content requires to be measured from a separate split of the sample. This may cause erroneous results in the case of sample heterogeneity, [2] Since a K-Ar date is based on the total abundances of ^{40}K and ^{40}Ar in a sample, the radiometric age may be too old (in the case of excess Ar) or too young (in the case of Ar-loss), and the technique precludes investigating neither one of these possibilities.

3.1.3 Principles of the Ar/Ar dating method

Dalrymple & Lamphere (1971) developed the Ar-Ar technique in order to overcome the drawbacks of the K/Ar method. In principle, the Ar-Ar technique is an advanced variety of the K-Ar method. By treatment of a sample in a nuclear reactor with fast neutron bombardment, part of its content of ^{39}K is converted to ^{39}Ar.

Conversion of ^{39}K to ^{39}Ar is dependent on the neutron flux density and the capture cross section during radiation of the sample. These effects are corrected for by using a standard sample with a known age, i.e. a “flux monitor”, which is treated in the same way as the sample to be dated. The following formula is used for determining the flux value (J) of the monitor:

$$\mathbf{J=(e^{\lambda tm}-1)/(^{40}Ar^{*}/^{39}Ar)}$$

where t_m= the age of the flux monitor and ($^{40}Ar/^{39}Ar$) is determined by repeated mass spectrometry analyses. The determined J value is put in the age equation:

$$\mathbf{T=1/\lambda \times \ln[(^{40}Ar^{*}/^{39}Ar) \times J+1]}$$

where T= the age of the sample, λ=the total decay constant for ^{40}K.

A great advantage of this technique is that it allows for incremental step-heating of the sample. This means that portions of Ar extracted from the mineral (or minerals in a whole rock sample) are analysed step-by-step. In the case where a laser is used for degassing Ar from the sample a stepwise increase in laser energy is applied. For each step the ratio of $^{40}Ar/^{39}Ar$ in the gas released from the sample is determined by the mass spectrometer through a number of consecutive scans. Loosely bound Ar in the rock fragment will be released at lower temperature while the more tightly enclosed Ar will require higher temperature before released.

The detected abundance of various isotopes from the samples and that from the flux monitor are transferred to a computer that in principle, uses the above formulas to calculate ages of individual steps. The final results are illustrated in the form of a diagram with apparent age versus the percentage of ^{39}Ar released (Fig. 4).

Providing the conditions 1-6 above (see 3.1.1) are fulfilled ages will be identical between steps and the mean of the “plateau” will yield the age of the sample. Quite often, however, the fist steps give either higher or lower apparent ages than subsequent steps, which can be interpreted to reflect excess Ar or loss of Ar, respectively. The praxis and minimum requirements for a result to be geologically meaningful is that at least three contiguous steps yield statistically undistinguishable ages.

The $^{40}Ar/^{39}Ar$ dating technique is superior over the K-Ar method in that it allows recognition of Ar whose isotopic composition is age-irrelevant (e.g. in the cases of excess Ar or Ar-loss). Stepwise outgassing of Ar also enables interpreting the geological history of the rock.

3.2 Sampling and preparation

Fresh rock samples were knocked off from solid basaltic necks (in two cases Hagstad and Eneskogen from loose boulders). The rock pieces were cut into slices of about 8 mm thickness using a diamond saw. Each slice was inspected for signs of possible diagenetic alterations. A 2 x 2 cm unaltered piece was cut out and crushed with a sledge hammer.

The recovered rock fragments were sieved under tap water. Rock fragments >250 µm and <750 µm were then washed vigorously by water. 12 to 15 rock fragments per sample were hand picked under a microscope. Finally the fragments were placed in a plastic container for storage until the final preparation.

Each collection of rock fragments were transferred to a small trough prepared by folding a 5 x 5 mm piece of aluminium foil, and subsequently carefully sealed. Each aluminium foil package was marked with a code number and then placed in special aluminium holder allowing a total of four packages of rock fragments to ensure safe transportation of the samples to and from the nuclear reactor in Holland and during the irradiation process.

The samples were irradiated together with the Taylor Creek sanidine standard (28,34 Ma recalculated by Renne et al.1998) for 35 hours at the NRG-Petten HFR RODEO facility in the Netherlands. After irradiation the sample container was kept at the nuclear site for 5 weeks to allow the radioactivity to decline to safe levels before shipment back to the argon laboratory in Lund.

3.3 Isotopic measurements

The $^{40}Ar/^{39}Ar$ geochronology laboratory at the University of Lund is equipped with a Micromass 5400 mass spectrometer with possible choice between a Faraday and an electron multiplier detector depending on signal intensity. A metal extraction line, which contains two SAES C50-ST101 Zr-Al getters and a cold finger cooled to ca –155°C by a Polycold P100 cryogenic refrigeration unit, is also present. 12-15 whole rock fragments were loaded into each of eight 3 mm holes in a copper planchette.

Samples were step-heated using a defocused 50W CO_2 laser. Sample clean-up time, that made use of the two hot Zr-Al SAES getters and a cold finger with a Polycold refrigeration unit, was five minutes. The laser was rastered over the samples to provide even-heating of all grains. The entire analytical process is automated and runs on a Macintosh-steered OS 10.2 with software modified specifically for the laboratory at the University of Lund and developed originally at the Berkeley Geochronology Center by Al Deino.

Time zero regressions were fitted to the data collected from 10 scans over the mass range of 40 to 36. Peak heights and backgrounds were corrected for mass discrimination, isotopic decay and interfering nucleogenic Ca-, K-, and Cl-derived isotopes. Isotopic production values for the cadmium lined position in the Petten reactor are $^{36}Ar/^{37}Ar(Ca) = 0.000270$, $^{39}Ar/^{37}Ar(Ca) = 0.000699$, and $^{40}Ar/^{39}Ar(K) = 0.00183$. ^{40}Ar blanks were calculated before every new sample and after every three sample steps.

Blank values were subtracted for all incremental steps from the sample signal. The laboratory was able to produce very good incremental gas splits. Age plateaus were determined using the criteria of Dalrymple & Lamphere (1971), which specify the presence of at least three contiguous incremental heating steps with statistically indistinguishable ages and constituting greater than 50% of the total ^{39}Ar released during the experiment.

The mean error of J was calculated with a precision of 0.25% (2 σ), which sets the limit of highest precision in age for these samples to circa ± 0,5 Ma.

4 Results

4.1 Geochronology

The results of the eight basalts are presented in Figure 4, and analytical data of mass spectrometry analysis are listed in Table 2.

4.1.1 Knösen and Gällabjer

The geochronology of the Knösen and Gällabjer basalt necks yielded statistically significant plateau ages of 190,9 ±0,5 Ma and 183,5 ±0,8 Ma respectively. The steps defining the plateaus correspond to about 50% of the ^{39}Ar released. In no case was any excess argon detected. Knösen yields the oldest age of all the samples analysed in this study.

4.1.2 Eneskogen, Bonnarp and Säte

Samples of these three basalt necks yielded results which do not fulfil all the criteria for being significant plateau ages. The amount of ^{39}Ar released from the first evaporation step for the Eneskogen and, in particular, the Säte was too large (35-50%). Degassing at a lower temperature may have enhanced achievement of significant plateau ages of these two samples.

The age of Bonnarp calculated from steps 2-7 is 185,4 ±4,6 Ma, but includes step with successively lower ages that do not overlap at 2σ level (MSWD >> 1). Including a shorter range of steps (2-4) yields an age of 190,4 ±4.2 Ma (MSWD=62).

The preferred ages of these three basalt necks are 182,1 ±0,6 Ma for Eneskogen, 185,4 ±4,6 Ma for Bonnarp (with a possibility of 190,4 ±4,2 Ma), and 180,0 ±0,7 Ma for Säte. Together with the age results of Knösen and Gällabjer the total range is 191-180 Ma, which places the volcanic event in the late Early Jurassic, late Sinemurian to Toarcian times.

4.1.3 Bosjökloster and Hagstad

The results of these two basalt necks yielded no plateau ages. The first step of the Bosjökloster sample yielded again too much of ^{39}Ar (50%), and a future re-run of this sample may give a more definite result for this sample. The oldest step ages (170,6 and 180,4 Ma) are believed to represent a minimum age of the samples. They are thus interpreted to belong to the Jurassic Scanian volcanic pulse.

4.1.4 Rallate

The Ar spectra of this basalt neck is almost ideal with a very distinct plateau age stretching over the duration of 90% of the entire ^{39}Ar release, and which involves five contigous steps. The age of 110 ±0,4 Ma is 70-80 Ma younger than the older main eruption event. Clearly, this result evidences two generations of basalts in Scania, with a younger eruption event in the middle of the Cretaceous period – Albian.

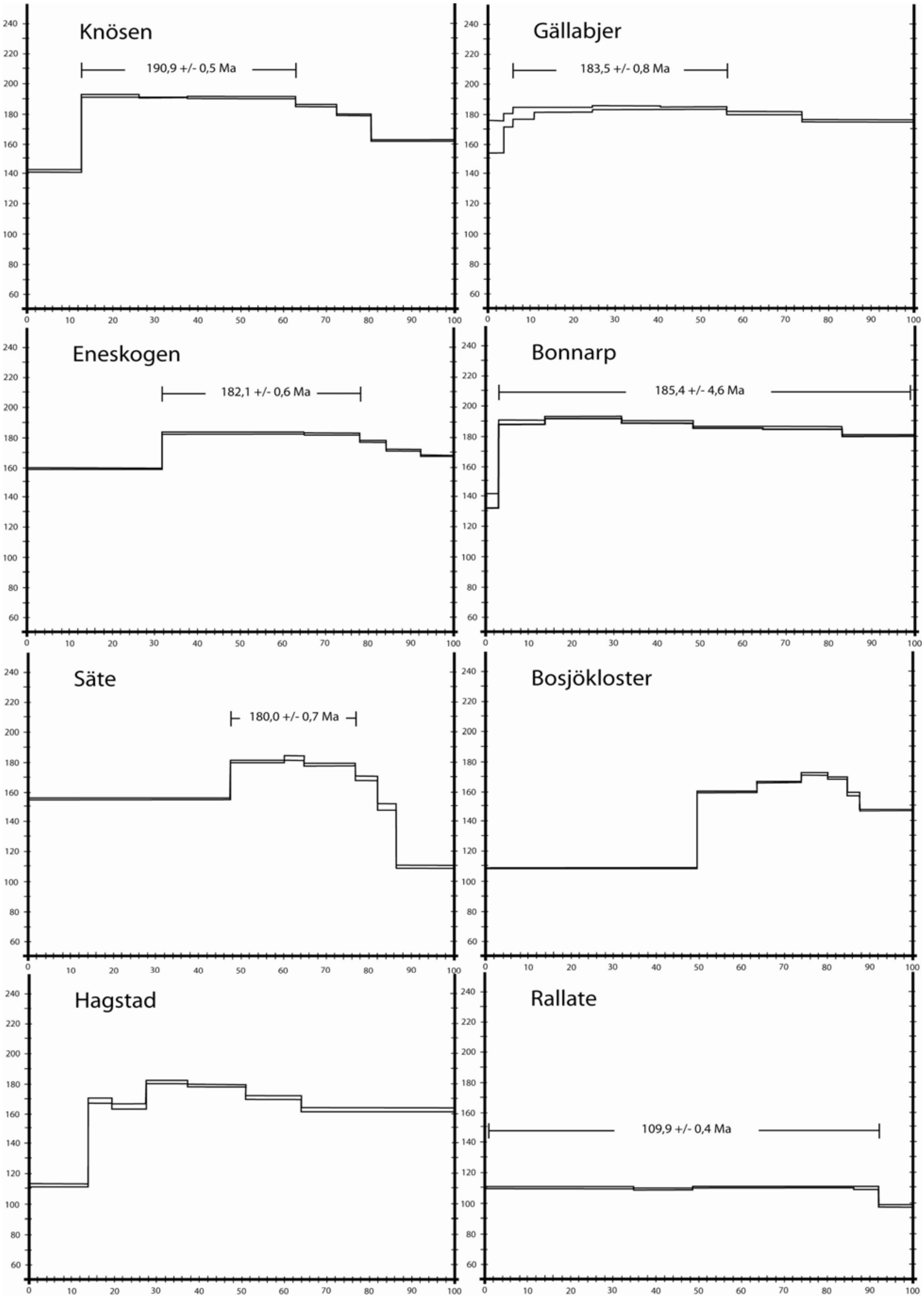

Fig. 4. Stepwise argon release spectra for whole-rock fragments from basalts in Scania. All errors are at 2 sigma level, taking into account the errors on J-factor, Ca-, Cl- and K-corrections. Knösen, Gällabjer and Rallate define statistically significant $^{40}Ar/^{39}Ar$ ages. Vertical and horizontal axes define age (Ma) and percentage of ^{39}Ar released.

Table 2. ^{40}Ar/^{39}Ar analytical data of the Scanian basalts. Codes for the columne titels are: Step=number of heating steps, Pwr/T°C=degassing power (dot indicate plateau), Ca/K and Cl/K are element ratios, Mol ^{39}Ar=mol ^{39}Ar released at each step, % Step=%of total ^{39}Ar released at each step, Cum. %=cumulative ^{39}Ar release, %^{40}Ar*=% of ^{40}Ar released.

Step	Pwr/T°C	Ca/K	Cl/K	^{36}Ar/^{39}Ar	^{40*}Ar/^{39}Ar	Mol ^{39}Ar	% Step	Cum. %	%^{40}Ar*	Age (Ma)	± Age
Bonnarp											
1	2,2	0,00013	0,19101	0,239088	7,36398	0,294	2,9	2,9	9,4	136,9521	2,48863
2	•2.4	0,00015	0,18647	0,065339	10,3064	1,0938	10,8	13,7	34,8	188,8935	0,78415
3	•2.6	0,00008	0,14278	0,015707	10,48751	1,8109	17,8	31,5	69,3	192,0423	0,38386
4	•2.8	0,00011	0,13248	0,006716	10,32998	1,7149	16,9	48,4	83,9	189,3038	0,36486
5	•3.0	0,00046	0,09319	0,007563	10,12794	1,6509	16,2	64,6	81,9	185,7856	0,23508
6	•3.2	0,00028	0,07142	0,006185	10,10003	1,8791	18,5	83,1	84,7	185,2989	0,4004
7	•3.5	0,00043	0,061	0,005781	9,80405	1,716	16,9	100	85,2	180,1309	0,24414
Rallate											
1	•2.2	0,00018	0,13619	0,019368	5,87551	3,6171	34,8	34,8	50,7	110,096	0,30103
2	•2.4	0,00058	0,13159	0,018327	5,83334	1,4542	14	48,7	51,9	109,3292	0,35234
3	•2.6	0,00027	0,13636	0,011055	5,87134	2,6106	25,1	73,8	64,3	110,0201	0,2721
4	•2.8	0,00048	0,13931	0,008234	5,86467	1,2731	12,2	86,1	70,7	109,8988	0,2668
5	•3.0	0,00119	0,1452	0,0108	5,86469	0,6117	5,9	92	64,8	109,8992	0,3616
6	3,4	0,00122	0,15519	0,013112	5,21243	0,8374	8	100	57,4	98,00209	0,28484
Gällabjer											
1	2,2	0,00141	0,17589	0,460457	8,91621	0,2569	3,7	3,7	6,1	164,5393	5,44841
2	2,4	0,00595	0,24213	0,193419	9,54919	0,154	2,2	5,8	14,3	175,6691	2,36398
3	•2.6	0,00147	0,26947	0,166557	9,81419	0,3469	4,9	10,8	16,6	180,3083	1,86749
4	•2.8	0,00066	0,22698	0,094608	9,93721	0,9605	13,7	24,5	26,2	182,4578	0,952
5	•3.0	0,00021	0,21118	0,050545	10,02872	1,1167	15,9	40,4	40,2	184,0551	0,65263
6	•3.2	0,00087	0,20669	0,026566	10,01135	1,0992	15,6	56	56,1	183,7521	0,47499
7	3,5	0,00082	0,13171	0,023083	9,80528	1,2393	17,6	73,7	59	180,1525	0,50108
8	3,8	0,00005	0,08863	0,021779	9,51732	1,8503	26,3	100	59,7	175,1103	0,38339
Eneskogen											
1	0	0,00018	0,97294	0,006804	8,5885	2,5366	31,7	31,7	81,1	158,75	0,34515
2	•2.4	0,00003	0,00363	0,001437	9,93737	2,6734	33,4	65,1	95,9	182,4607	0,26156
3	•2.6	0,00004	0,00801	0,000732	9,90251	1,0398	13	78	97,9	181,8517	0,22889
4	2,8	0,00183	0,0097	0,001262	9,62697	0,4885	6,1	84,1	96,3	177,0319	0,24334
5	3	0,0013	0,01347	0,002092	9,29239	0,6529	8,2	92,3	93,8	171,1619	0,22775
6	3,4	0,0008	0,01955	0,002714	9,07422	0,6176	7,7	100	91,9	167,3241	0,20925
Säte											
1	1,8	0,00092	0,2319	0,005187	8,40212	0,9064	47,5	47,5	84,6	155,4492	0,32113
2	•1.9	0,00074	0,15541	0,002882	9,82955	0,2437	12,8	60,2	92	180,5767	0,41224
3	•2.0	0,00147	0,11846	0,00147	9,9484	0,0861	4,5	64,7	95,8	182,6532	0,74332
4	•2.2	0,00011	0,05245	0,002372	9,69735	0,2309	12,1	76,8	93,3	178,2642	0,44881
5	2,4	0,00004	0,03772	0,002328	9,177	0,0997	5,2	82	93	169,1332	0,73171
6	2,7	0,00212	0,05273	0,005156	8,08387	0,0866	4,5	86,6	84,1	149,7988	1,01967
7	3,3	0,00068	1,07471	0,013906	5,83045	0,2562	13,4	100	58,7	109,2767	0,48931
Knösen											
1	1,7	0,00005	0,1976	0,016833	7,62401	0,9364	12,6	12,6	60,5	141,603	0,33042
2	•1.8	0,00022	0,21897	0,005233	10,46103	1,0007	13,5	26,1	87,1	191,5823	0,3091
3	•1.9	0,00001	0,15757	0,002959	10,41559	0,8552	11,5	37,6	92,3	190,7925	0,20253
4	•2.0	0,00001	0,11225	0,002846	10,41533	0,8839	11,9	49,5	92,5	190,788	0,29935
5	•2.2	0,00017	0,08255	0,002242	10,41575	0,9944	13,4	62,8	94	190,7954	0,33592
6	2,5	0,0001	0,05913	0,001907	10,10062	0,7232	9,7	72,6	94,7	185,3093	0,30546
7	2,8	-0,0002	0,06083	0,002711	9,76078	0,5972	8	80,6	92,4	179,3742	0,29452
8	3,5	0,00013	0,08435	0,005198	8,77622	1,4421	19,4	100	85,1	162,0685	0,27716
Hagstad											
1	1,7	0,00018	0,02142	0,013128	5,96137	0,6589	13,9	13,9	60,6	111,656	0,35137
2	1,8	-0,0013	0,02057	0,023197	9,10464	0,2649	5,6	19,4	57	167,8597	0,59008
3	1,9	-0,0014	0,02841	0,031224	8,87033	0,2172	4,6	24	49	163,7299	0,82704
4	2	0,0032	0,04194	0,047708	8,89683	0,1678	3,5	27,5	38,7	164,1974	1,03951
5	2,2	0,00045	0,0511	0,016316	9,82014	0,4622	9,7	37,3	67,1	180,4123	0,42768
6	2,5	0,00023	0,07471	0,002205	9,66647	0,6454	13,6	50,9	93,7	177,7237	0,26425
7	2,8	0,00015	0,09619	0,009066	9,21954	0,6227	13,1	64	77,5	169,8814	0,35788
8	3,5	0,00041	0,39271	0,009879	8,7564	1,7128	36	100	75	161,7184	0,46277
Bosjökloster											
1	2	0,00024	0,15538	0,001212	5,7671	2,9539	49,7	49,7	94,2	108,1241	0,1495
2	2,1	0,0008	0,07827	0,001	8,59531	0,8342	14	63,7	96,7	158,8705	0,2378
3	2,2	0,00077	0,06202	0,001498	8,96564	0,6188	10,4	74,1	95,3	165,4109	0,21548
4	2,3	0,00201	0,04185	0,001465	9,26232	0,3614	6,1	80,2	95,5	170,6335	0,29886
5	2,5	0,00144	0,05638	0,001136	9,11909	0,2736	4,6	84,8	96,5	168,114	0,29682
6	2,7	0,00113	0,09019	0,001101	8,49989	0,1711	2,9	87,7	96,3	157,1815	0,47638
7	3,1	0,00108	0,12352	0,002462	7,89575	0,7319	12,3	100	91,6	146,4505	0,20887

5 Discussion

5.1 Geochronology and comparison to previous age determinations

The most important result of this dating campaign is the evidence for two separate pulses of volcanic activity: one seemingly prolonged pulse or volcanic phase at 191-180 Ma and a late pulse at 110 Ma.

There are two additional Ar/Ar ages from basalts belonging to the older pulse: Göbnehall 178 ± 4 Ma and Hästhallarna 179 ± 4 Ma (Elisabeth Eide, pers. comm. 2005). These two unpublished results slightly expand the range of Jurassic volcanism, i.e. 191-178 Ma.

The quality of some of the analysed samples are not sufficiently robust for deducing whether or not the Jurassic volcanism was continuous or episodic, neither is it possible to constrain the exact age limits for this event. More samples have to be analysed (and some of the above samples must be re-analysed) before giving definite answers to these questions.

The Rallate result corroborates with the inferences by Klingspor (1976) and Printzlau and Larsen (1972) of two different generations of basalt in Scania, though their interpretations were based on strongly scattered age data. Klingspor´s mean age for Rallate is 91 Ma (Table 3), i.e. 19 Ma younger than reported here.

Printzlau and Larsens´ (1972) age of 98 ±7 Ma for the basalt neck at Säte is much younger than the present Ar-Ar result (180,0 ± 0,7 Ma) for this basalt. Altogether, these age discrepancies between the Ar-Ar and the K-Ar ages clearly reflect the advantages of the former technique.

Printzlau and Larsen (1972) also presented an age for Lönnebjär (120 ± 3 Ma), which place this eruption in the middle of the Cretaceous period but is still older than the age reported by Klingspor (1976, Table 3). Ongoing studies are expected to confirm a Cretaceous age for this basalt when a sample of this basalt will be analysed in the near future at the Ar-lab in Lund. A regional grouping of basalts of different generations in Scania, as proposed by Printzlau and Larsen (1972), is not supported by the Ar-Ar results in this study (Fig. 2 and 4).

Table. 3. Summary of 22 datings on three Scanian basaltic necks reported by Klingspor (1976). The mean age of whole rock analyses of 98 Ma for Lönnebjär, 91 Ma for Rallate and 159 Ma for Göbnehall. In all cases the mineral separates yielded younger ages than did the whole rock samples.

Neck name	Sample type	Age range (Ma)	# of datings
Lönnebjär	Whole rock	104 - 92	4
	Plagioclase	79	1
Rallate	Whole rock	101 - 84	5
	Plagioclase	59	1
Göbnehall	Whole rock	169 - 149	7
	Plagioclase	140 - 134	2
	Pyroxene	135 - 119	2

5.2 Implications of combined geochemical and radiometric data for the origin of Scanian basalts

Tappe (2004) published a detailed mineralogical and geochemical study on 28 of the Scanian basalt necks. Based on the mineralogical composition of the volcanic rocks these are classified as basanites and melanephelinites, where basanites are mostly plagioclase-bearing and melanephelinites are virtually lacking plagioclase, and always contain modal nepheline in the groundmass.

Some of the basalts contain xenolites from the lithospheric mantle, which can approach 10 cm in size, and are classified as ultramafic (peridotites, pyroxenites) and mafic xenoliths (Rehfeldt et al. 2006). Both the Rallate and Lönnebjär necks are classified as basanites, according to Tappe (2004).

The core of Tappe´s (2004) trace element geochemical data on basanites is illustrated in Figure 5 (grey area). A first observation is that these samples have very similar trace element contents with a very limited range in all incompatible elements. The strong LREE/HREE fractionation suggests melting in the presence of garnet in the source (preferentially retaining the HREE). From these observations, and other geochemical evidences, Tappe (2004) came to the

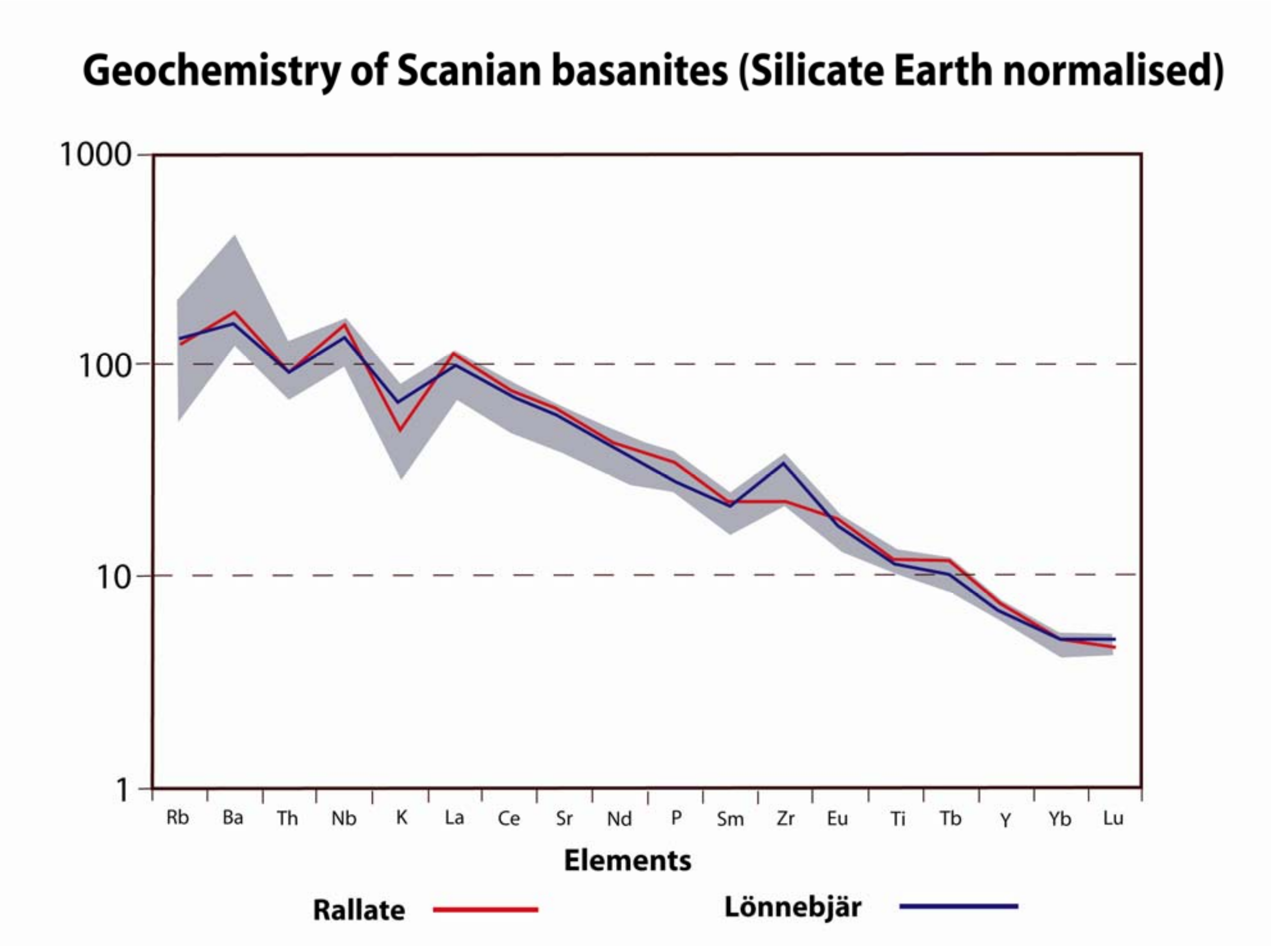

Fig. 5. Silicate Earth normalised trace elements for 23 basanite samples defining a very narrow spread (grey line) in the graph (data from Tappe 2004, and K. Obst as pers. comm.2006). The upper and lower boundaries represent maximum and minimum values respectively. Red and blue lines depict trace element data of Rallate and Lönnebjär (data from K. Obst, pers. comm. 2006). The Silicate Earth values and element order follow McDonough & Sun (1995).

conclusion that all basalts must have originated from melting of the same mantle source, and argued for only one generation of basalts in Scania.

The results by Tappe (2004) combined with the here presented new evidence of two pulses of basalt volcanism has critical bearings on the origin of these basalts. The consistency in trace element contents between basalts which differ in age by approximately 70-80 Myr is truly remarkable. This means that basaltic magmas associated with these events *both* must have [1] been withdrawn from the same mantle source, [2] involved a similar degree of melting, and [3] occurred under eutectic melting conditions (i.e. low degree of melting).

Tappe (2004) showed that the Scanian basalts could be modelled by 6-12% batch partial melting of wet garnet lherzolite, but that these values should be considered as maximum values, which further substantiate eutectic compositions of the basalt magmas. In the case of a larger degree of melting, garnet should be exhausted and lead to a more flat trace element profiles of these samples than seen for the Scanian basalts.

Plume-generated magmatism, as have been proposed for many magmatic provinces related to break up of Pangea, appears highly unlikely based on these circumstances. These magmas are believed to originate from the core-mantle boundary, possibly by partial melting of subducting oceanic crust (e.g. Zhao 2004), which then slowly rise as growing diapirs as they ascend through the mantle.

Identical source compositions and the same degree of magma-host rock interaction are difficult to envisage for two plumes derived from such depths, and that are separated in time by 70-80 Ma. Furthermore, plume-generated magmas are often characterised by a high degree of melting, at least magmas triggered by heating from a plume head at the base of the lithosphere. Therefore, a plume origin for any of these generations of basalts is not credible, and hence rejected as a mechanism for basalt volcanism in Scania.

A more plausible origin involves repeated events of lithosphere stretching that caused decompressional melting of astenospheric mantle along the central rift, and of the lithospheric mantle in the flanks, as proposed by Tappe (2004) and Latin & Walters (1992). Likewise the Scanian basalts, the North Sea rifting event (Latin & Waters 1992) is located along the Sorgenfrei-Tornqvist Zone.

In the North Sea, however, volcanism took place during many pulses over some 70 Ma, at 170 ± 2 Ma (the Egersund Basin), 151 ± 2 Ma (the Netherlands sector), 130 ± 2 Ma (the flanks of the Central Graben) (Latin & Waters 1992) and during Aptian-Albian 125-100 Ma (Ziegler 1990). Nevertheless, there is a clear temporal as well as spatial correspondence between volcanism in the North Sea and in Scania.

Furthermore, there were several tectonic phases in the Cretaceous – the Kimmerian and the Carpathian tectonic phases – that affected the Scanian bedrock causing block movements along earlier existing faults (Norling & Bergström 1987), and which could have caused renewed pathways for mantle melts and a new phase of basalt volcanism.

It is thus attractive to envisage that events of basalt volcanism in both the North Sea and Scania were controlled by tectonic movements along the Sorgenfrei-Tornqvist, associated with lithosphere stretching and small-scale decompressional melting of mantle under eutectic conditions. Tectonics may have created pathways so that small portions of magmas could ascend rapidly from the mantle to the surface. If so, magmas may have existed over longer time periods at depth.

5.3 Jurassic volcanic and magmatic activity in other parts of the world related to Pangea break-up

Magmatic activity in conjunction with the break-up of Pangea occurred on a global scale during the early Jurassic period.

At the same time these events opened up for a new ocean basin - the Central Atlantic, which started to have an influence on the European continent. At the same time the influence of the Tethys ocean in the region was reduced due to landmass restriction.

Figure 6 illustrates the extent of some of the more prominent igneous processes during the major part of the Mesozoic, both in time and extent in both hemispheres. Coeval with the Jurassic volcanism in Scania major magmatic activities occurred in various parts of the fragmenting Pangea.

It demonstrates the wider extent and shorter duration of the equatorial and southern hemisphere LIP related eruptions (particularly those during Jurassic) as opposed to the less extended but instead more long-lasting northern hemisphere eruptive phases. The gradual demise of the Tethyan Ocean and the birth and expansion of the Atlantic Ocean is also schematically depicted. The different igneous processes are briefly summarized and reviewed below.

5.3.1 The CAMP volcanic activity

One of the initiation processes in the break-up of Pangea was the formation of rift basins along the eastern margin of North America, and the formation of rocks that now constitute the Newark Supergroup (Dunning & Hodych 1990). The age of 204 ±4 Ma for diabase dykes was interpreted to date the initial stages of the massive flood basalt volcanism of the CAMP.

Investigation of this gigantic magmatic event place it at the transition between the Triassic and the Jurassic periods (Hames et al. 2000; Marzoli et al. 1999). The magmatic activity during the CAMP event was very short-lived, lasting only a couple of million years, as reported by these authors. In spite of its short duration, the eruption

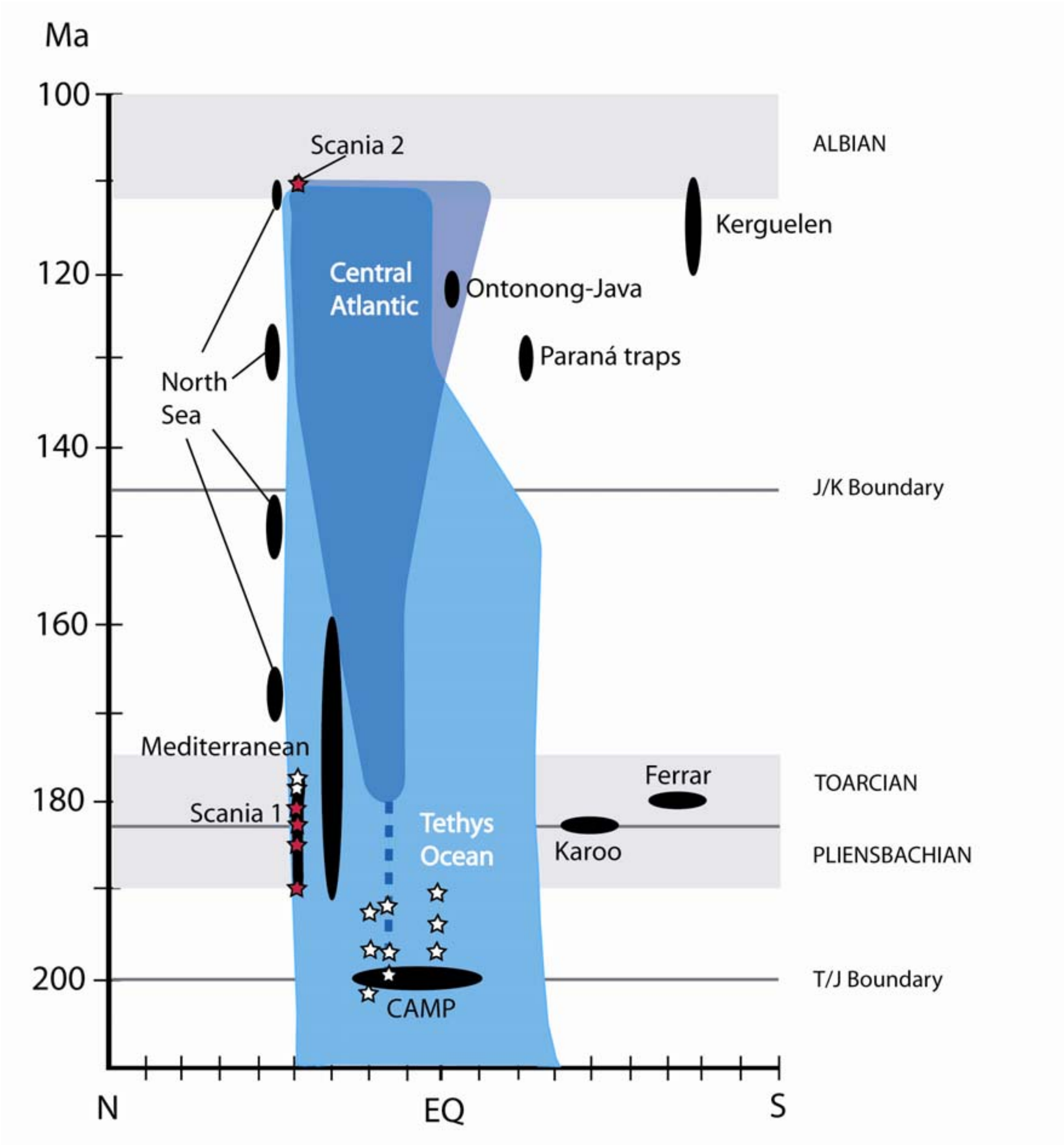

Fig. 6. Schematic outline of igneous activities that have been linked to the break-up of Pangea, in particular, during the Jurassic. The graph relates these activities to the geological timescale and to their geographical distribution in both hemispheres. The graph is based on paleoglobe reconstructions by Torsvik et al. (2002) and Golonka & Bocharova (2000). Age data for the various igneous provinces are compiled from publications referred to in the text. Open stars refer to previously reported eruptions and those with red stars refer to volcanic events in Scania dated in this paper. The dotted blue line from Central Atlantic down to CAMP illustrates the link between the CAMP event and the beginning of the Central Atlantic Ocean, which gradually started to expand in the Jurassic.

created a large magmatic area exceeding 7 million square kilometres (Marzoli et al. 1999). Two phases of the CAMP volcanic activity (Knight et al. 2004) have been identified based on Ar/Ar geochronology, and apart from the main peak around 200 Ma there was also a later one around 190 Ma.

Recently all published age data of CAMP volcanism have been recalculated to obtain more reliable information of the timing and the course of this event (Nomade et al. 2006). The following new picture emerged: The main first pulse of magmatic activity commenced in Africa at 199,1 Ma and, presumably also, in North America at 198,7 Ma. The magmatic activity then migrated south along the South American margin over roughly 1 Ma, with intrusive and extrusive magmatism in South America commencing around 198,5–198,0 Ma.

Cohen & Coe (2002) presented indirect evidence for this massive volcanic event on the basis of an observed Os and Re excursion in sea water, detected in marine mud rock samples from the Triassic-Jurassic boundary in the UK.

Various theories have been put forward to explain the mechanism behind the CAMP volcanism, such as mantle plume activity (Janney & Castillo 2001; Hill 1991) and massive dyke feeding of magma (Beutel et al. 2005).

Some have refuted the plume theory (e.g. McHone 2000) arguing that such processes are rarely observed in conjunction with mid-ocean rifts and generation of ocean crust and spreading.

5.3.2 The Karoo and Ferrar volcanic activity

CAMP was not the only magmatic manifestation during the break-up of Pangea. In the south, great flood basalt eruptions occurred in what is now referred to as the Karoo and Ferrar igneous provinces that eventually lead to fragmentation of Gondwana. The remains of these events are found in the Karoo province of South Africa, and in Antarctica in Dronning Maud Land and the Transantarctic Mountain range along the Ross Sea into Victoria Land.

Riley & Knight (2001) recalculated a number of already published Ar/Ar data from the Ferrar province inferred to suffer from various types of analytical discrepancies. This resulted in a more coherent dataset showing that the main peak of Ferrar magmatism occurred at 180-181 Ma, which is slightly younger than the peak age of Karoo volcanism (183-184 Ma). This places both volcanic events in Pliensbachian-Toarcian and coeval to the main Scanian volcanic event.

5.3.3 The Mediterranean magmatic activity

From studies of ophiolites originating from Middle–Late Triassic mid-oceanic ridge basalt (MORB), Middle–Late Jurassic MORB and island arc tholeiite (IAT) in the peri-Mediterranean region Bortolotti & Principi (2005) highlighted an additional process for the break-up of Pangea, namely progressive ocean floor spreading in the western part of the Tethyan Ocean.

The ophiolites are today found imbedded in mountain ranges such as the Alps, the Pyrenees, the Apennines and equivalent ones in the Iberian Peninsula and present Turkey. Ar-datings of basalts related to ophiolites from the Balkan region have yielded dates in the range 189-160 Ma (Pliensbachian through to Oxfordian). Bortolotti & Principi (2005) consider the duration of this sea floor spreading as short-lived (some 20 Myr), and that it progressed at slow pace.

5.3.4 The North Sea magmatic activity

During oil prospecting activities in the Forties and Piper areas of the North Sea, basic igneous rocks were unexpectedly discovered during early 1970-ties (Gibb & Kanaris-Sotiriou 1976). The lavas from this igneous province in north-western Europe have a maximum thickness of over 740 m and are described as porphyritic olivine basalts with a tendency towards an alkaline affinity.

The North Sea rifting event is considered to have lasted for some 70 Myr from Jurassic (170-160 Ma) to Cretaceous time with magmatic peaks at 170 ± 2 Ma (the Egersund Basin, southwest off the coast of Norway), 151 ± 2 Ma (the Netherlands sector) and 130 ± 2 Ma (the flanks of the Central Graben) (Latin & Waters 1992). All referred ages are based on $^{40}Ar/^{39}Ar$ geochronology. In addition to this Ziegler (1990) have indicated volcanic activity in the North Sea area in Aptian-Albian times 125-100 Ma.

5.4 Tectonic and volcanic activity during the middle of the Cretaceous period

On a global scale several LIPs were active during the Cretaceous period. The Paraná traps in South America have been dated at 133 ± 1 Ma, based on $^{40}Ar/^{39}Ar$ plateau ages (Courtillot & Renne 2003).

The Ontong–Java plateau in the south-western Pacific is the largest of all oceanic plateaus, and its surficial extent reaches $2x10^6$ km^2. It had a short outbreak at 122 Ma (Courtillot & Renne 2003). The Kerguelen oceanic plateau in the southern Indian Ocean is the second largest. Its southern part, which is the most voluminous, was recently dated at 119–109 Ma (Coffin et al. 2002) (Fig. 6).

On a regional perspective a major volcanic province was developed in Negev (Israel) during late Aptian and early Albian times. This magmatism is considered to be plume derived, with a time interval of volcanic activity between 116 and 109 Ma (Segev et al. 2005). Eruptions were episotic in nature and also includes the formation of a lava lake.

In the south eastern part of the Tornquist zone, in the region of the Black sea, SE-directed extension and rifting activity took place from Aptian to Coniacian (125-100 Ma) (Hippolyte 2002). Prolonged tectonic activity occurred in the Carpathian region both in conjunction with orogenic process and tectonic influence from the early phases of the Alpine orogeny (Csontosa & Vörös 2004; Iancu et al. 2005). These events started prior to the Albian time and continued into the Tertiary period. These tectonic movements also effected the evolution of the Polish sedimentary basin north of the Carpathian orogeny. Subsidens and rifting occurred during Albian but was more pronounced during Cenomanian (112-100 Ma) (Dadlez et al. 1995; Stephenson et al. 2003).

In Scania the central European tectonic processes induced movements along earlier existing fault zones such as those in conection with the horst and graben structures of the STZ (Norling & Bergström 1987), and may have initiated the basalt volcanism in Scania at 110 Ma. These Kimmerian related movements also effected sedimentary basins in Scania, e.g. inversion led to denudation of strata overlying the early Palaeozoic sediments in the Colonus Shale Trough, and tilting preserved an almost overturned Mesozoic sequence along the Fyledalen Fault Zone (Erlström et al. 1997).

5.5 Local environment during the Jurassic main peak of Scanian volcanism

In the Early Jurassic the expanding Tethys Ocean lead to a transgression that submerged parts of Scania. This transgression created an open seaway between the Tethys Ocean in southeast continuing over major parts of the present western European continent through a passage between the present Greenland and Norway into the Boreal Ocean in the north (Doré 1991) (Fig. 7).

In Scania, the transgression caused progression of the Tethys ocean shoreline towards the Scanian volcanic province (Fig. 8). Augustsson (2001) observed that the majority of the volcanic tuffs she investigated were deposited on dry land. However, at least in one site she concluded that deposition took place in shallow waters (Guy-Ohlson 1986; Grigelis & Norling, 1999).

The Early Jurassic transgression was maintained during the Middle Jurassic epoch; however, local tectonic events resulted in pronounced faunal separation between the Boreal and Tethyan realms (Doré 1991).

The most important tectonic event of the Middle Jurassic, affecting the marine connection between the Boreal Ocean and the Tethys Ocean, was a widespread uplift and restriction in the central North Sea area, associated with the igneous activity described under section 5.3.4 above. In addition to volcanic activity the uplifted area formed a focal point for a series of radiating draining fluvial-delta systems following the major structural trends (Petersen & Andsbjerg 1996).

During the Jurassic period the described seaway was frequently affected by anoxic events generating deposition of organic-rich shales. Late Jurassic organic-rich shales are found in the English Channel and southern England, in the North Sea, on both sides of the NE Atlantic rift and thence to the Barents Sea (Doré 1991).

These shales constitute the petroleum-rich source rocks, which are most important for the giant oil and gas fields of the North Sea, Mid-Norway, Barents Shelf and West Siberia.

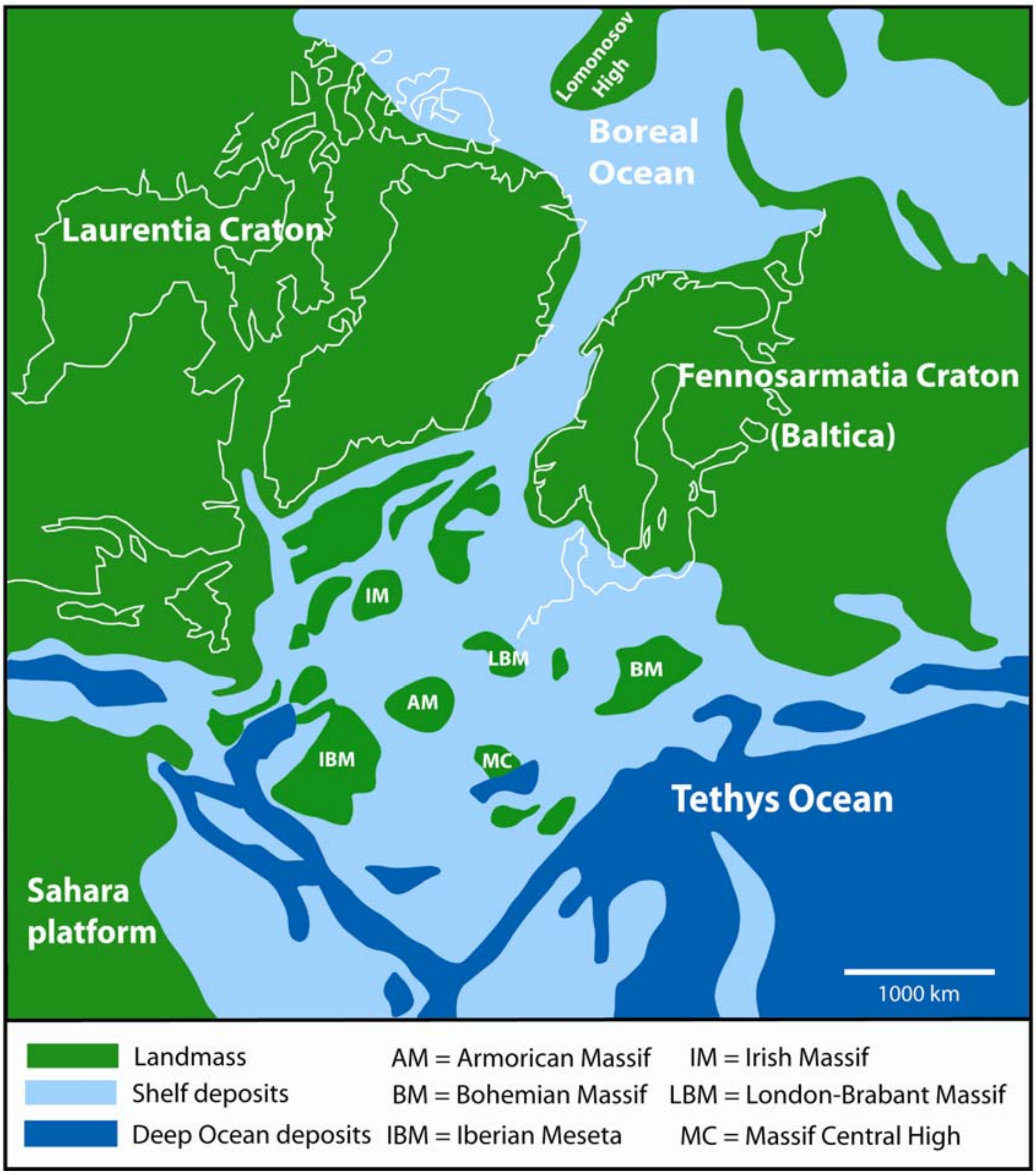

Fig. 7. Early Jurassic (Sinemurian-Toarcian) transgression of the Tethys Ocean. The transgression flooded the present European continent leaving a number of islands surrounded by sea water. Note also the connection between the Tethyan Ocean and the Boral Ocean in the north. The figure is modified from Ziegler (1990).

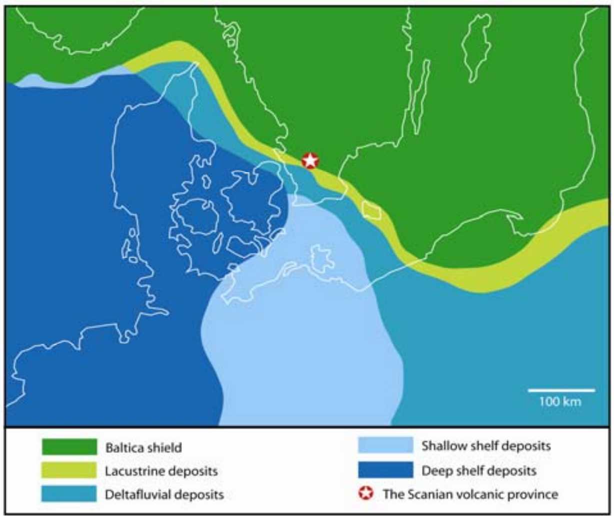

Fig. 8. Map showing the local environment during early Jurassic (Sinemurian-Aalenian) transgression of the Tethys Ocean. Note that the Scanian volcanic province is on the border between the Baltica Shield and the costal region of the Tethys Ocean.

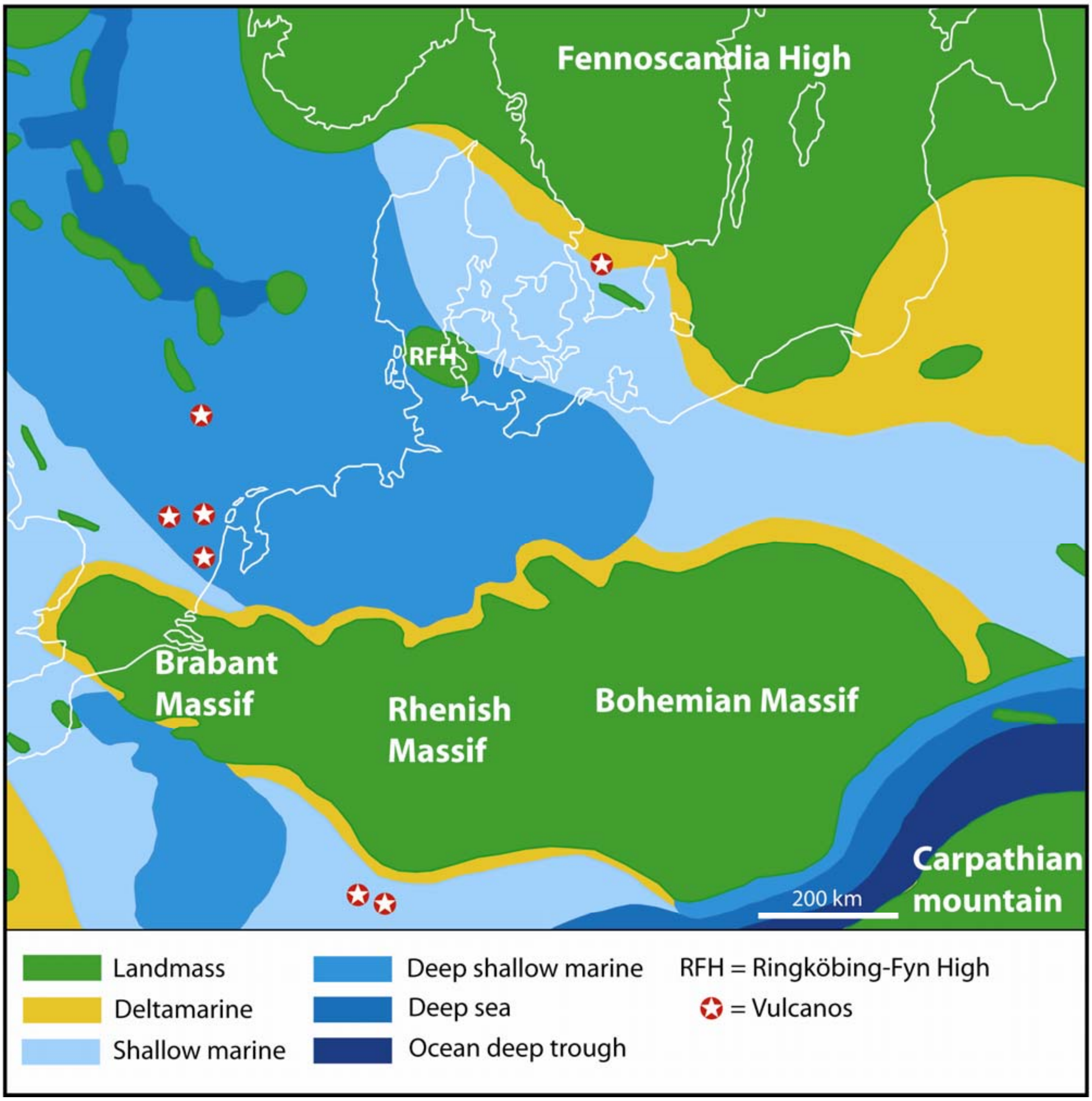

Fig. 9. Map illustrating northern Europe during the transition between Early and Late Createaceous (Aptian-Albian). It shows the transgression of the Central Atlantic Ocean in the west and the Tethys Ocean in the east. The transgression flooded the European continent after a "low stand" during early Cretaceous. A number of "highs" remained as islands in the ocean. Note the Carpathian mountain massif in SE, which was in an active tectonic phase at that time, and the volcanic activity in the North Sea area and south of the Rhenish Massif. Modified from Ziegler (1990).

5.6 Local environment during earliest Late Cretaceous times

During the latest Jurassic to earliest Cretaceous (Berriasian), the worlds ocean level had subsided leaving large parts of central Europe as dry land (Ziegler 1990). In Scania the depositional environment alternated between lacustrine and deltafluvial, and marginal marine and marine environments (pers. comm. Sofie Lindström 2006).

The sea level gradually increased through the Lower Cretaceous and in the Albian a major transgression event occurred (Hansen et al. 2005; Erlström et al. 1997; Dadlez et al. 1995; Ziegler 1990).

A new oceanic connection was now opened up due to the expanding Central Atlantic in the west, whereas the Carpathian massif restricted the influence of ocean exchange from the Tethyan realm (Ziegler 1990).

5.7 A fragmenting Pangea and its consequences for the biosphere with focus on events in the Jurassic

5.7.1 Volcanic consequences

The immense volcanic eruptions comprising three major LIPs – CAMP, Karoo, Ferrar and, in addition the magmatic activity in the present-day Mediterranean region, in the North Sea and to a minor extent the activity in the Scanian volcanic province, exerted a pronounced effect on the biosphere. A plausible scenario as a result of outpouring large volumes of lava (several million cubic kilometres) within a short time period (Wignall 2001), involves a dramatic climate shifts due to massive outburst of CO_2, SO_2 and Cl_2 in the atmosphere, without allowing sufficient time for atmospheric recovery.

The volcanic gases CO_2 and SO_2 have opposite effects on the climate (Wignall 2001). CO_2 is a greenhouse gas that contributes to the increasing of the global temperature over a longer (100 Ka) time frame whereas SO_2, in the form of aerosols, increases the Albedo effect of the atmosphere, thus reducing the temperature but over shorter times of some 10 years or so.

In addition, SO_2 contributes to acid rain which increases weathering and exerts deleterious effects on terrestrial plants. Finally Cl_2 influences the ozone layer, over some 10 years after eruption, allowing more UV light to penetrate to the biosphere. All of these events, although short-lived in a geological perspective, might have acted as triggering factors to those events detected in biostratigraphic records from Jurassic times.

5.7.2 Mass extinction events during Jurassic

The Jurassic period was affected by two mass extinction events. The first one happened at the Triassic – Jurassic boundary and is considered to be one of the great five extinctions during the Phanerozoic eon (Palfy et al. 2000).

This extinction event affected both the terrestrial and the maritime realms of the biosphere and opened up for new niches to be exploited. The increased global temperature caused by volcanic ejection of greenhouse gasses during Early Jurassic also increased the temperature in the oceans. During the Pliensbachian and, in particular, early Toarcian massive release of methane from its hydrated store in the ocean floor has been suggested as cause of the faunal, floral and sedimentological changes that took place at that time (Hesselbo et al. 2000; Kemp et al. 2005).

This event led to a runaway greenhouse effect increasing the already high global temperature to extreme levels (Kemp et al. 2005). A contributing factor to the greenhouse effect was that Karoo and Ferrar magmas intruded into Permian coal deposits generating increased CO_2 levels (McElwain et al. 2005).

The massive release of methane and CO_2 also caused a shift in the carbon budget favouring light ^{12}C over ^{13}C. This event coincided in time with a second order of mass extinction (Palfy & Smith 2000; Riley & Knight 2001). The anoxic condition during Toarcian is often referred to as the Toarcian Anoxic Event, which is manifested as rich carbon burial in shale deposits. Negative excursion of ^{13}C isotope has been recorded in the immediate neighbourhood to Scania namely in the upper Bagå Formation at Korsodde, southwestern Bornholm (Hesselbo et al. 2000).

The effects on biota of the Toarcian Anoxic Event primarily affected the marine biosphere and the effects have been recorded on a global scale (Vörös 2002; Rubana & Tyszka 2005; Kottachchi et al. 2002; Aberhan & Baumiller 2003).

Consequently the break-up of Pangea created turbulent conditions for the biosphere, particularly during the Jurassic period. Many species ceased to exist whereas new opportunities arose for those surviving. During the Jurassic the reptiles diversified and occupied many terrestrial niches as well as maritime equivalent ones. During the Jurassic a new vertebrate class - Aves – also developed. In Scania we have relicts in the form of volcanic remains from this dramatic and dynamic time period in the Earth´s history.

6 Conclusions

1. Ar-Ar geochronology of eight basalts in Scania reveals two pulses of volcanic eruptions. The first and main event occurred in the Early Jurassic (late Sinemurian to Toarcian) at 191-178 Ma. The second event took place in the earliest Late Cretaceous period (Albian) at 110 Ma.

2. Trace element data for the Jurassic and Cretaceous volcanic rocks combined with the new age results suggest the magmas to have originated from the same mantle source by decompressional melting (i.e. not generated by the influence of a plume). Geochemical data of incompatible trace elements suggests a low degree of partial melting for the production of eutectic compositions of magmas.

3. Temporal correspondence of volcanic activity in Scania and the North Sea, and their proximate locations relative to the Sorgenfrei-Tornquist zone, suggest that episodic volcanism was largely controlled by tectonic activity. The Scanian volcanism is coeval with major global magmatic and biosphere events in conjunction with the violent break-up of the latest supercontinent Pangea and coeval with other magmatic and tectonic events around the middle of the Cretaceous period.

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