Plate interactions of Laurussia and Gondwana during the formation of Pangaea — Constraints from U–Pb LA–SF–ICP–MS detrital zircon ages of Devonian and Early Carboniferous siliciclastics of the Rhenohercynian zone, Central European Variscides

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⁎ This paper is dedicated to Dr. Peter Bender, Marburg, Germany.
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A B S T R A C T
The southern Rheinisches Schiefergebirge, which is part of the Rhenohercynian zone of the Central European Variscides, exhibits several allochthonous units: the Gießen-, and the Hörre nappe, and parts of the Frankenbach imbrication zone. These units were thrust over autochthonous and par-autochthonous volcano-sedimentary complexes of the Lahn and Dill–Eder synclines. This paper reports a representative data set of U–Pb LA–SF–ICP–MS ages of 1067 detrital zircon grains from Devonian and Lower Carboniferous siliciclastic sediments of the autochthonous and the allochthonous areas, respectively. The cluster of U–Pb ages from the allochthonous units points to a provenance in the Saxothuringian zone. Zircon populations from the Saxothuringian zone are representative of a Gondwanan hinterland and are characterized by age clusters of ~530–700 Ma, ~1.8–2.2 Ga, ~2.5–2.7 Ga, and ~3.0–3.4 Ga. Further samples were taken from the autochthonous and par-autochthonous units of the Lahn–Dill and Kellerwald areas. A Lower Devonian sandstone sample from the Siegen antcline provides a reference for siliciclastic sediments derived from the Old Red Continent. These samples show a provenance representative of Laurussia with debris primarily derived from Baltica and Avalonia. U–Pb zircon age clusters occur at ~400–450 Ma, 540–650 Ma, 1.0–1.2 Ga, ~1.4–1.5 Ga, ~1.7–2.2 Ga, and ~2.3–2.9 Ga. Provenance analysis and geochemical data of the Rhenohercynian zone provide new information on the evolution of magmatic arcs in the Mid-Paleozoic. The data set constrains top-SE and top-NW directed subduction of the oceanic crust of the Rheic Ocean. Subduction-related volcanism lasted from the Early Devonian to the Early Carboniferous and thus confirms the existence of the Rheic Ocean until the Early Carboniferous. The tectonic model outlined for the Rhenohercynian zone suggests a wide Rheic Ocean.

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1. Introduction

The Central-European part of the Variscan Orogen is one of the most significant type areas for the continent–continent collision between Laurussia and Gondwana that resulted in the formation of the supercontinent Pangaea. Traditionally, the Central-European Variscides have been subdivided across strike from NW to SE into three zones, the Rhenohercynian, the Saxothuringian, and the Moldanubian zones, respectively (Kossmat, 1927). Later, Brinkmann (1948) included a separate Mid-German Crystalline zone to this model, which is interpreted as a structural high between the Rhenohercynian and Saxothuringian zones (Fig. 1). This concept has been adapted to modern plate tectonic views in which the Variscan Orogen resulted from the accretion of peri-Gondwanan terranes or microplates by the closure of several oceans, among which the Rheic Ocean has been considered the most important.

The Rhenohercynian zone, which crops out preferentially in the Rheinisches Schiefergebirge, constitutes a classical fold-and-thrust belt and is one of the structural units of the European Variscides interpreted as a collage of microplates (e.g., Matte, 1986; Franke and Oncken, 1990; Franke et al., 1990; Franke and Oncken, 1995; Franke, 2000).

It is now widely accepted that the Rheinisches Schiefergebirge is part of the Avalonia terrane, which separated from Gondwana in the Early Ordovician and drifted northwards (e.g., Oncken et al., 2000; Tait et al., 2000; Torsvik and Cocks, 2004; Linnemann et al., 2008, 2010; Romer and Hahne, 2010). This resulted in the opening of the Rheic Ocean. In Late Ordovician, around 450 Ma, Avalonia collided with
Baltica, which led to the closure of the Tornquist Sea. The ensuing collision of both Baltica and Avalonia with Laurentia closed the intervening Iapetus Ocean at about 420 Ma. As a result the continent Laurussia (=Old Red Continent) was formed (Kroner et al., 2007; Linnemann et al., 2008; Nance et al., 2010). According to Sánchez Martínez et al. (2007) and Nance et al. (2010), the closure of the Rheic Ocean began in the Late Silurian–Early Devonian and continued until the Early Carboniferous by successive advancing from west to east.

Several plate tectonic models exist for the Variscan orogeny. The two-plate model involves the collision of Laurussia (Baltica + Avalonia + Laurentia) with West Gondwana (Amazonia + West Africa + Cadomia) as a result of the closure of the Rheic Ocean (e.g. Linnemann et al., 2004; Kroner et al., 2007; Linnemann et al., 2010). The multi-plate model accounts for the existence of a number of terranes and narrow oceans between the principal plates of Laurussia and Gondwana (e.g. Franke, 2000; Tait et al., 2000; Torsvik and Cocks, 2004; von Raumer and Stampfl, 2008). Different microplates are assigned to the “Armorican Terrane Assemblage (ATA)” by Franke (1995) and are composed of Bohemia, Saxothuringia, Iberia and the Armorican Massif. ATA is believed to have separated from Gondwana during the Early Devonian (Franke and Oncken, 1995; Franke, 2000). This arc is documented by magmatic rocks of Silurian age in the “Northern Phyllite zone” and in the “Mid-German-Crystalline zone (MGCZ)” (Altenberger et al., 1990; Sommermann, 1993; Dombrowski et al., 1995; Reichschmull, 2001).

One model for the Rhenohercynian proposes successive rifting of a passive southern margin of Laurussia during Devonian times caused by the opening of a Rhenohercynian Ocean (e.g. Franke, 2000; Tait et al., 2000; Doublier et al., 2012). Conversely, Floyd (1982), Flick and Nesbor (1988), Oczlon (1994), Smith (1996), von Raumer and Stampfl (2008), and Zeh and Gerdes (2010) interpreted the Rhenohercynian as an active continental margin whereby a northward dipping subduction zone triggered the opening of a Rhenohercynian back arc ocean.

The MGCZ, a NE–SW trending basement wedge, represents the Variscan collision zone and separates the Rhenohercynian zone (Avalonia) from the Saxothuringian zone (Armorica; Zeh and Gerdes, 2010; Zeh and Will, 2010). However, Zeh and Gerdes (2010) presented provenance data that the MGCZ was not completely Armorican, but was partly Avalonian as indicated by certain rock units of the Ruhla Crystalline complex. Accordingly, the Spessart and the Böllstein Odenwald can be interpreted as belonging to Avalonia as well.

According to Plesch and Oncken (1999), the final Variscan continental collision occurred along two suture zones, one separating the external Rhenohercynian zone from the Saxothuringian zone, the other separating the latter from the Tepla-Barandium part of the internal Moldanubian zone. However, collisions occurred earlier between the different microcontinents of the ATA. For example, Bohemia and Saxothuringia collided with the Armorican Massif and consequently became part of Armorica during the Late Devonian (Schäfer et al., 1997; Dörr and Zulauf, 2010). The final stage of the Variscan orogeny is primarily characterized by diorites and granites, usually of calc-alkaline composition (Altherr et al., 1999; Stein, 2001) and with a distinct subduction signature (Henes-Klaiber, 1992). But the rock pile was also overprinted by regional HT/LP metamorphism and segmentation in folds and thrusts (Oncken, 1997; Kroner et al., 2007). Within the Rheinisches Schiefergebirge, deformation combined with very low to low-grade metamorphism progressed from the SE (330 Ma) to the NW (300 Ma) in the Late Carboniferous (Ahrendt et al., 1978, 1983). The Variscan orogeny led to a crustal shortening there of about 50% (Bahrman et al., 1991; Oncken et al., 1999). This is also suggested for the allochthonous units (Doublier et al., 2012).

Geochronological and kinematic studies (e.g. Ahrendt et al., 1983; Engel and Franke, 1983; Klügel, 1997; Plesch and Oncken, 1999; Huckriede et al., 2004) have improved our knowledge of the structural evolution of the Rhenohercynian fold and thrust belt. 40K/40Ar-ages of detrital muscovites from non- to low-grade metamorphic sediments in the Hörre nappe provide information only about final cooling below ~350 °C (Huckriede et al., 2004). U-Pb-ages of zircon...
grains, on the other hand, exhibit a much higher temperature regime since zircons equilibrate at 800 °C or higher. Therefore, the original crystallization age of the zircon or rather the age of the last magmatic event survives later sedimentary or metamorphic processes. Accordingly, the provenance of these sediments is best deduced from the distribution of zircon age populations.

The aim of this study is to present U–Pb LA–SF–ICP–MS ages of detrital zircons derived from Devonian and Lower Carboniferous siliciclastic sediments of the southeastern Rheinisches Schiefergebirge. The samples were collected from autochthonous to par-autochthonous and allochthonous units in order to clarify their stratigraphic, sedimentary, magmatic and plate tectonic relationships and thereby obtain a better understanding of Variscan collisional tectonics and the provenance of particularly allochthonous units within the Rhenohercynian zone.

2. Geological setting and geotectonic units

2.1. Introduction

The Rheinisches Schiefergebirge is part of the Rhenohercynian zone of the Variscan Orogen (Fig. 1). In its eastern part, several autochthonous, par-autochthonous (e.g. Wachendorf, 1986; Meischner, 1991; Schwan, 1991; Bender and Königshof, 1994) and allochthonous units (e.g. Engel et al., 1983; Oczlon, 1992, 1994; Franke, 2000; Salamon, 2003; Huckriede et al., 2004; Salamon and Königshof, 2010) have been defined, the latter having been recognized by Kossmat (1927) who was the first to propose a nappe tectonic concept for the Rhenohercynian zone. In the eastern Rheinisches Schiefergebirge, samples were taken from different structural units: the Lahn–Dill area in the

![Fig. 2. Geological maps of (A) the Lahn–Dill area and (B) the Kellerwald areas (modified after Meischner, 1966; Bender, 2006). Locations of samples are indicated by red dots.](image-url)
southeast, and in the Kellerwald area, a partly separated region in the
northeastern Rheinisches Schiefergebirge. The Lahn–Dill area can be
subdivided into the autochthon, known as Lahn syncline and Dill–
Eder syncline, which are separated by the allochthon of the Hörre
nappe. Southeast of the latter, more allochthonous units occur, such as
the Steinhorn nappe and the Lohra nappe as a part of the Frankenbach
imbrication zone, and the Gießen nappe (Fig. 2A). Additionally, there
are several par-autochthonous units, which can be found imbricated
within the above mentioned autochthon and allochthon as a result of
strong deformation and thrusting. Except for the Lahn syncline all of
these structures extend into the Kellerwald area (Fig. 2B). The deforma-
tion over the entire area shows distinctive differences: the allochtho-
nous and par-autochthonous units have experienced more intense
folding and thrusting, as compared to the autochthonous areas. For de-
tailed sedimentological and facies analysis we refer to the references
cited in the text. The region’s detailed biostratigraphic record is beyond

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*Fig. 2 (continued).*
the scope of this paper, although new and literature-derived biostratigraphic data were used in this study. Here we refer to the short description in the text (see below), which is essential for a better understanding of the complex structures. The general stratigraphy and geotectonic assignment of the investigated samples are shown in Table 1.

2.2. Lahn and Dill–Eder synclines

The geological record of the Lahn syncline and the Dill–Eder syncline generally extends from about the Middle Devonian to the end of the Early Carboniferous and the onset of the Variscan orogeny. Sedimentation in this area was generally controlled by basin development and volcanism, both reflecting the thinning of the crust due to extensional tectonics. In terms of depositional development, the Lahn and Dill–Eder synclines represent a single unit with the Dill–Eder syncline in the north being more influenced by arenaceous siliciclastic sediments derived from the Old Red Continent.

Intensive intraplate volcanism started in the early Givetian, lasting with interruptions for about 50 Ma into the Carboniferous (Nesbor et al., 1993; Nesbor, 2004; see chapter 3). The Devonian volcanic succession allowed for the overgrowth by reef limestones (so-called “Massenkalk”), which flourished during the Givetian and Frasnian. Depending on their depositional setting, reef structures are variable in their morphology and thicknesses (e.g., Königshof et al., 1991; Buggisch and Flügel, 1992; Braun et al., 1994; Königshof et al., 2010). Volcanic activity and reef development led to a considerable submarine relief in the Lahn–Dill and Kellerwald areas, resulting in widespread facies variations during the Upper Devonian. Further Upper Devonian sedimentation in the Lahn and Dill–Eder synclines produced slates and nodular calcareous slates in numerous basins, and condensed limestones on the swells. The slates were supplemented by thick sandstone sequences, especially in the Dill–Eder-syncline (e.g., in the Thalenberg Formation: Pirwitz, 1986; Wierich, 1999), whereas these are rare in the Lahn syncline. Locally, minor amounts of primitive basaltic melts ended the Devonian volcanic cycle.

Crustal thinning on the southern shelf of Laurussia continued into the Early Carboniferous resulting in a moderate increase of water depth in the eastern Rheinisches Schiefergebirge. This resulted in a special facies realm called the “Culm facies” that caused a reduced sedimentation initially characterized by black shales and cherts. This sedimentation was later associated with intensive activity of the Carboniferous volcanic cycle. The volcanic activity was followed by argillaceous sedimentation and, subsequently, by graywackes at the end of the Lower Carboniferous. The latter ones can reach thicknesses of hundreds of meters and represent the final stage of deposition prior to the Variscan orogeny in the area of interest (for overview and references see Bender and Stoppel, 2006; Bender, 2008; Königshof et al., 2008; Nesbor, 2008; Königshof et al., 2010).

Table 1
Stratigraphic position and source areas of the sandstones and graywackes used in this study.

<table>
<thead>
<tr>
<th>Series</th>
<th>Stage</th>
<th>Sample number</th>
<th>Geographic region</th>
<th>Lithology</th>
<th>Geological/ geotectonic unit</th>
<th>Initial geotectonic position</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Early Carboniferous</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tournaissian/ Visean</td>
<td>44352 KE-5a</td>
<td>Kellerwald</td>
<td>graywacke</td>
<td>Jesberg</td>
<td>Kuhl syncline</td>
<td>Armorican terrane A.</td>
</tr>
<tr>
<td>Tournaissian/ Visean</td>
<td>44356 KE-9c</td>
<td>Kellerwald</td>
<td>sandstone</td>
<td>Kamm Quartzite imbrication structure</td>
<td>Baltica</td>
<td></td>
</tr>
<tr>
<td>Visean</td>
<td>44468 Kamm-1</td>
<td>Lahn–Dill area</td>
<td>sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visean</td>
<td>44443 Heu–2</td>
<td>Lahn–Dill area</td>
<td>graywacke</td>
<td>Gießen</td>
<td>Lohra nappe</td>
<td>Armorican terrane A.</td>
</tr>
<tr>
<td><strong>Late Devonian</strong></td>
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<td></td>
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</tr>
<tr>
<td>Famennian</td>
<td>44358 KE-11</td>
<td>Kellerwald</td>
<td>sandstone</td>
<td>Dill–Eder syncline</td>
<td>Baltic</td>
<td></td>
</tr>
<tr>
<td>Early Famennian</td>
<td>45347 Bot–1</td>
<td>Lahn–Dill area</td>
<td>sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early Famennian</td>
<td>44441 Bisch–2</td>
<td>Lahn–Dill area</td>
<td>graywacke</td>
<td>Hörre</td>
<td>Lohra nappe</td>
<td>Armorican terrane A.</td>
</tr>
<tr>
<td>Frasnian/ KE-3</td>
<td>44350</td>
<td>Kellnerwald</td>
<td>graywacke</td>
<td>Gießen</td>
<td>Lohra nappe</td>
<td>Armorican terrane A.</td>
</tr>
<tr>
<td>Frasnian</td>
<td>45438 Kirch–1</td>
<td>Lahn–Dill area</td>
<td>graywacke</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Early Devonian</strong></td>
<td></td>
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<tr>
<td>Late Emsian</td>
<td>44667 Haig–1</td>
<td>Lahn–Dill area</td>
<td>sandstone</td>
<td>Siegen</td>
<td>Anticline</td>
<td>Baltic</td>
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<tr>
<td>Early Emsian</td>
<td>45360 KE-17</td>
<td>Kellerwald</td>
<td>graywacke</td>
<td>Steinhorn</td>
<td>Lohra nappe</td>
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<td>45439 Herm–1</td>
<td>Lahn–Dill area</td>
<td>graywacke</td>
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</tbody>
</table>
2.3. Hörre nappe

The sedimentary development of the Hörre nappe began in the early Famennian. It differs profoundly from that of coeval strata in the Lahn and Dill–Eder synclines (e.g., Bender, 1978; Bender and Homrighausen, 1979; Bender, 1989, 2008). For example, volcanic rocks are notably absent in contrast to the entire Rhenohercynian zone where repeated intense and sometimes explosive volcanism occurred. It is important to note, however, that ash layers are intercalated in the sedimentary pile of some formations of the Hörre nappe, such as in the Gladchen Formation (Early Carboniferous). The succession of the Hörre nappe starts with shales overlain by sandstones and graywackes (Ulmbach Formation). Occasionally detrital limestones are intercalated. The overlying Weitershausen Formation is mainly composed of shales and detrital, thin-bedded carbonates. These rocks are overlain by shales, quartzitic sandstones and thin-bedded graywackes of the Endbach Formation of Early Carboniferous age. The overlying Gladchen Formation is mainly composed of siliceous shales, alum black shales, cherts and turbiditic limestones. These sediments are succeeded by the Bischoffen Formation consisting of shales with intercalations of graywackes, and finally the Elhausen Formation composed mainly of shales and thick-bedded graywackes (Bender, 2008).

2.4. Bicken–Ense and Wildenstein imbrication structures

The Bicken–Ense and Wildenstein imbrication structures have long been regarded as parts of the Dill–Eder syncline bordering the Hörre unit (e.g., Bender, 1997), whereby the Wildenstein imbrication structure is imbricated with rocks of the Hörre nappe. Because of differences in their sedimentological records compared to adjoining rock units of the same age and their tectonic contact (Bender et al., 1997), they are to be considered to be para-autochthonous units. The Bicken–Ense imbrication structure consists almost entirely of the Bicken Formation, which is mainly composed of shales and fossiliferous, pelagic carbonates (e.g., cephalopod limestones) of Early Devonian (Emsian) to Early Carboniferous age. The Wildenstein imbrication structure is composed of reddish and gray shales and siliceous shales of the Wildenstein Formation, which is assumed to be mainly of late Famennian age.

2.5. Kamnquartzite imbrication structure

The Kamnquartzite imbrication structure can be traced for more than 300 km throughout the Rhenohercynian zone (Figs. 1, 2A, B). This and the dominance within the unit of quartzitic sandstones of Early Carboniferous age have been the focus of geological investigations for a long time (Koch, 1858; Kockel, 1958; Schriel and Stoppel, 1958; Homrighausen, 1979; Wierich and Vogt, 1997; Jäger and Gursky, 2000; Huckriede et al., 2004). Originally regarded as part of the Hörre unit, the Kamnquartzite imbrication structure is now considered a separate tectonic unit since it can be found within the Dill–Eder syncline, the Wildenstein imbrication structure, the Hörre nappe, the Frankenbach imbrication zone, and beneath the Gießen nappe. Reflecting its intensive deformation, the quartzitic sandstone slices range in size from more than 100 m to less than 1 cm, embedded in a melange composed of very strongly deformed dark gray and siliceous shales.

2.6. Frankenbach imbrication zone

The Frankenbach imbrication zone, as defined by Bender (2006), has a stratigraphical range from Early Devonian to Early Carboniferous. It is generally strongly deformed and exhibits numerous imbricate structures. The zone consists, on the one hand, of slices of autochthonous rocks typical for the Lahn and Dill–Eder synclines, although massive reef limestones (Massenkalke), which are common in the Lahn syncline and in the northern part of the Rheinisches Schiefergebirge (e.g., Pas et al., 2013 and references therein), are absent. On the other hand, the allochthonous units of the Lohra and Steinhorn nappes, as well as slices of the Hörre nappe, are intercalated in the Frankenbach imbrication zone. The par-autochthonous Kamnquartzite is also imbricated locally into this zone.

2.7. Lohra nappe

The Lohra nappe represents an isolated allochthonous unit in the Kellerwald area, whereas to the southwest in the Lahn–Dill area, it is tectonically integrated into the Frankenbach imbrication zone (Fig. 2A, B). The Lohra nappe consists of the Famennian Lohra unit composed of shales and cherts, with intercalations of sandstones and graywackes, and the Kehna unit of Lower Carboniferous age composed of graywackes and shales.

2.8. Steinhorn nappe

The Steinhorn nappe is here defined as a new tectonic unit with an isolated allochthonous setting in the Kellerwald area (see Fig. 2A, B). Comparable to the Lohra nappe, it can be traced into the Frankenbach imbrication zone as part of the Lahn–Dill area. The Steinhorn nappe consists primarily of Early Devonian sandstones, graywackes (Erbsloch-Grauwacke), shales and carbonates (e.g., the Greifenstein and Schönau limestones), which exhibit Bohemian faunal affinities (e.g., Fick, 1999). Middle/Upper Devonian sequences are represented by shales, alum shales, cherts and graywackes. Those of Early Carboniferous age are composed of shales, cherts and a melange unit of Devonian and Lower Carboniferous rocks. The entire sedimentological record differs from other structural units described in this paper, and is here used to define a new tectonic unit.

2.9. Gießen nappe

The long-disputed Gießen nappe (Fig. 2A, B) was the first allochthonous unit established in the Rheinisches Schiefergebirge (e.g., Eder et al., 1977; Engel et al., 1983), and covers an area of about 250 km². The rocks of the Gießen nappe consist of shales, clayish sandstones, cherts and graywackes, with the latter predominating. At its base, condensed phyllicic shales and radiolarian cherts are imbricated with tectonic slices of MORB-type metabasalts (Wedepohl et al., 1983; Grösser and Dörr, 1986). The Gießen nappe sequence spans the Early Devonian to Early Carboniferous and can be subdivided into two structural units containing graywackes of different ages (Birkelbach et al., 1988; Dörr, 1990). Graywackes of the smaller northern unit are of Frasnian age, whereas those of the larger southern unit are Early Carboniferous (for a detailed stratigraphic and lithologic description see Dörr, 1986).

2.10. Lower Devonian of the Siegen anticline

The Siegen anticline consists of Lower Devonian rocks which are characterized by generally monotonous siliciclastic sequences delivered from the Old Red Continent. Sediments of the Lochkovian are up to 1000 m thick and are mainly composed of reddish mudstones and siltstones with intercalated coarse-grained sandstones and quartzites. Siegenian (mainly Pragian) sediments (the Siegenian stage is used herein in a traditional German sense) of the Siegen anticline comprise more than 4000 m of mudstones, siltstones and fine-grained sandstones with distinct fossiliferous horizons containing abundant plant remains. The lithological character of the lower Emsian sediments is very similar but changes in the upper Emsian due to a general transgressive trend (Possmann and Jansen, 2003; Mittmeyer, 2008). Shallow water, coarse-grained quartzitic sandstones are overlain by argillaceous sediments. Importantly, an intense period of volcanism is documented by numerous intercalations of silica-rich, mainly volcaniclastic rocks in the Lower Devonian sediments (see chapter 3).
3. Volcanism

Sedimentation on the southern shelf of Laurussia was accompanied by a wide diversity of volcanic processes. The oldest volcanic rocks are preserved in the Phyllite zone at the southern margin of the Rheinisches Schiefergebirge. Radiometric dating of these mafic metavolcanic rocks, -rhyodacites and -andesites shows them to be Silurian age (Sommermann et al., 1992, 1994; Meisl, 1995). Rhodacitic to rhyolitic rocks are preserved in the Phyllite zone at the southern margin of the Rheinisches Schiefergebirge, intensive intraplate volcanism started by a wide diversity of volcanic processes. The oldest volcanic magmatism continued through the Devonian until the Visean.

At the beginning of the Eifelian a distinct facies change is evident as very distal ash fall deposits occur. Nevertheless, the dacitic/rhyodacitic volcanism originated far from the NE, E or SE of the Rheinisches Schiefergebirge with deposition of the pyroclastic material on the outer shelf area or on the slope of the southern margin of Laurussia.

Most of the volcanic products are well preserved because of very low-grade metamorphic overprinting. As a result, the typical phenocrysts in the rhyodacites (predominantly quartz and plagioclase, with some alkali feldspar and biotite) can be identified. The feldspar is generally albited and biotite is often altered to chlorite by diagenetic and metamorphic processes. The original glassy matrix is also completely altered to secondary minerals. Nevertheless, the rock type can be classified by immobile elements (Fig. 3; Tables 1–3, Electronic supplement). Primary particles in the frequently coarse grained pyroclastic deposits are often highly vesicular, and Y-shaped former glass shards are a typical feature (Scherp, 1983).

At the beginning of the Eifelian a distinct facies change is evident as very distal ash fall deposits occur. Nevertheless, the dacitic/rhyodacitic composition can still be identified by immobile elements. The volcanic ashes are intercalated as numerous extremely fine-grained layers within the thick pile of autochthonous sedimentary rocks, and are therefore often overlooked (Dehmer et al., 1989). In the Visean, the grain size of the ash layers increases again (van Amerom et al., 2001). Over the entire time span from the Early Devonian to the Early Carboniferous the mineralogical and geochemical variation of these pyroclastic deposits is remarkably low (Fig. 4, Table 3 Electronic supplement). But all of these rocks have been subjected to diagenetic alteration and metamorphic overprint. The main difficulty, however, lies in the evaluation of the intensity of contamination with epilastic (sedimentary) debris and the degree to which sorting processes during their redeposition modified their original composition. Consequently, the immobile HFSE values do not correspond definitively to those of recent fresh samples of subduction-related dacites or rhyodacites.

While this dacitic/rhyodacitic volcanism originated far from the Rheinisches Schiefergebirge, intensive intraplate volcanism started on the subsiding southern shelf of Laurussia in the early Givetian. Hence, a Devonian and an Early Carboniferous cycle can be distinguished (Nesbor, 1997, 2004, 2007). The Devonian cycle comprised two phases, a bimodal (Givetian-Frasnian) main phase and a primitive basaltic (Famennian) late phase.
During the Early Carboniferous continued extension on the southern shelf of Laurussia combined with an increasing subsidence of the continental crust led to a moderate increase of water depth. These processes are reflected in a change in the sedimentary environment and renewed volcanic activity of the Early Carboniferous cycle. The new melts were almost entirely tholeiitic, in contrast with the Devonian alkali basaltic to basanitic compositions, but still exhibit intra-plate affinities. Noticeable is the increase of aluminum in picotites enclosed in the olivine phenocrysts of the basalts. This is an indication of ascending juvenile magma from deep mantle sources.

Sills and dikes of the Devonian and Carboniferous cycles are widely distributed in the Rheinisches Schiefergebirge, demonstrating the widespread extent of the volcanic activity, well beyond the Lahn–Dill and Kellerwald areas.

4. Methods

4.1. Sample material and stratigraphy

Thirty-three samples were investigated, but only 15 representative examples are presented because of page limitations. The additional samples will be published separately in the context of a more regional framework. The samples collected for U–Pb analysis from the different structural units (Fig. 2A, B and Table 1) are described in stratigraphic order.

The stratigraphically oldest sample (sample # 45439 [Herm-1], Damm-Mühle Formation) of early Emsian age was taken from the northeastern part of Steinhorn nappe in the Lahn–Dill area. This graywacke was formerly interpreted as being equivalent to the so-called “Erbsloch-Grauwacke” in the Kellerwald (e.g. Kupfahl, 1953; Ziegler, 1957), but according to Jahnke (1971) profound facies and faunal differences separate the two. Sample # 45360 (KE-17) was taken at the type location of the “Erbsloch-Grauwacke” in the Steinhorn nappe in the Kellerwald area and is also of early Emsian age (Plusquellec and Jahnke, 1999; Fig. 3). Sample # 44467 (Haig-1) was taken from a quartzitic sandstone (the so-called “Ems-Quarzit”) of the Siegen anticline and is of late Emsian age. It is used as a reference sample for siliciclastic sediments derived from the Old Red Continent.

Sample # 45438 (Kirch-1) comes from the (Devonian) graywackes of the Gießen nappe in the Lahn–Dill area, which are covered by siliceous shales and, according to Dörr (1986), is of Frasnian age. Equivalent rocks from the Kellerwald area (sample # 44350 [KE-3])
are also composed of graywackes and siliceous shales and are of Frasnian/Famennian age. The oldest sample from the Hörre nappe in the Lahn–Dill area (sample # 44444 [Bisch-2]), is a graywacke belonging to the Ulmbach Formation and is of early Famennian age.

Samples from Famennian sandstones of the Dill–Eder syncline have been taken from the Lahn–Dill area (sample # 45347 [Bot-1]; early Famennian) and from the Aschkoppen sandstone (Fig. 2A, B, Table 1) in the northern Kellerwald (sample # 44358 [KE-11]; Famennian). Both samples are reference samples for the autochthonous Dill–Eder syncline.

The remaining samples are from the Lower Carboniferous: sample # 44442 (Will-1) belongs to Lohra nappe (Kehna Graywacke Formation), which is a part of the Frankenbach imbrication zone. This unit is located between the Hörre nappe and the Gießen nappe in the Lahn–Dill area.

Lycopsidan plant remains have been found in the Kehna graywacke suggesting a late Tournaisian age (Kerp et al., 2006; Fig. 3). The equivalent in the Kellerwald is the Hundshausen graywacke (sample # 44353 [KE-6]), which is also of Early Carboniferous age (Bender and Stoppel, 2006).

Sample # 44440 (Eln-2) is from the Hörre nappe in the Lahn–Dill area (Fig. 2A) and is a graywacke of Early Carboniferous age (Elhausen Formation). This formation is the youngest sequence of the Hörre nappe beginning in the Pericyclus stage (cu II), its stratigraphical extension is unknown (Bender, 1989; Entenmann, 1991; Bender et al., 1997).

Sample # 44443 (Heu-2, Fig. 2A, Table 1) is a coarse-grained graywacke from the Gießen nappe in the Lahn–Dill area, and is of Early Carboniferous age based on plant remains of Lepidodendron lossenii Weiss (Henningsen, 1962). According to Mosseichik (2007) these...
plants have a stratigraphic range from the late Tournaisian to the Visean. The plant is also known from a Lower Carboniferous section in Plauen (Vogtland) and has been described by Knaus (1994) and, earlier, by Daber (1959) as being of probable Visean age.

Two samples were taken from the complex Kammquartzite imbrication structure. Sample # 44468 [Kamm-1] is a quartzitic sandstone (Kammquartzite) of Early Carboniferous age from the Lahn–Dill area (Jäger and Gursky, 2000). Wierich and Vogt (1997) proposed a new formation name (“Bruchberg-Sandstein”-Formation) and placed the sandstones and quartzites in the Pericyclus stage (early Visean) based on spore assemblages. According to Jäger and Gursky (2000) deposition of the Kammquartzite Formation started at the base of the Visean and lasted into the late Visean. Sample # 44350 (KE-3) of the Kammquartzite imbrication structure comes from the central part of the Kellerwald.

Another graywacke of Early Carboniferous age (sample # 44352 [KE-5a]; Fig. 2B, Table 1) was collected from the “Jesberg–Kulm syncline” in the southern part of the Kellerwald. These graywackes conformably overlie alum shales, which are Early Carboniferous (Tournaisian to Visean) according to Jahnke and Paul (1968).

Samples used for geochemical analyses in the different units are shown in Figs. 3 and 4 and in Tables 1–3 (Electronic supplement).

### 4.2. U–Pb detrital zircon ages and geochemistry

Zircon concentrates were separated from 2 to 4 kg sample material at the Senckenberg Naturhistorische Sammlungen Dresden (SNSD) using magnetic and heavy liquid (LST) methods. Final selection of the zircon grains for U–Pb dating was achieved by hand-picking under a binocular microscope. Zircons of all grain sizes and morphological

![Fig. 5](continued)
types were selected, mounted in resin blocks and polished to half their thickness. Cathodoluminescence (CL)-images of zircon were produced with a Zeiss scanning electron microscope EVO 50. All grains were analyzed for U, Th, and Pb isotopes by LA–SF–ICP–MS techniques at the Museum für Mineralogie und Geologie (GeoPlasma Lab, SNSD), using a Thermo-Scientific Element 2 XR sector field ICP–MS coupled to a New Wave UP-193 Excimer Laser System. A teardrop-shaped, low volume laser cell constructed by Ben Jähne (Dresden) and Axel Gerdes (Frankfurt/M.) was used to enable sequential sampling of heterogeneous grains (e.g. growth zones) during time resolved data acquisition. Each analysis consisted of approximately 15 s background acquisition followed by 30 s data acquisition, using a laser spot-size of 25 and 35 μm, respectively. A common-Pb correction based on the interference- and background-corrected 208Pb signal and a model Pb composition (Stacey and Kramers, 1975) was carried out if necessary. The necessity of the correction is judged on whether the corrected 207Pb/206Pb lies outside of the internal errors of the measured ratios. Discordant analyses were generally interpreted with care. Raw data were corrected for background signal, common Pb, laser induced elemental fractionation, instrumental mass discrimination, and time-dependent elemental fractionation of Pb/Th and Pb/U using an Excel® spreadsheet program developed by Axel Gerdes (Institute of Geosciences, Johann Wolfgang Goethe-University Frankfurt, Frankfurt am Main, Germany). Reported uncertainties were propagated by quadratic addition of the external reproducibility obtained from the standard zircon GJ-1 (~0.6% and 0.5–1% for the 207Pb/206Pb and 208Pb/232Th signal, respectively) during individual analytical sessions and the within-run precision of each analysis. Concordia ages (95% confidence level) were produced using Isoplot/Ex 2.49 (Ludwig, 2001) and frequency and relative probability plots made use AgeDisplay (Sircombe, 2004). The 207Pb/206Pb age was taken for interpretation for all zircons >1.0 Ga, and the 206Pb/238U ages for younger grains. Further details of the instrument settings are available from Table 4 (see Electronic supplement). For further details on analytical protocol and data processing see Gerdes and Zeh (2006) and also Frei and Gerdes (2009). The uncertainty in the degree of concordance of Precambrian–Paleozoic grains dated by the LA–ICP–MS method is relatively large and results obtained from just a single analysis have to be interpreted with care. A typical uncertainty of 2–3% (2σ) in 207Pb/206Pb for a Late Neoerotic zirconogen (e.g., 560 Ma) corresponds to an absolute error on the 207Pb/206Pb age of 45–65 Myr. Such a result leaves room for interpretation of concordance or slight discordance — the latter one could be caused by episodic lead loss, fractionation, or infiltration Pb isotopes by a fluid or on micro-cracks. Thus, zircons showing a degree of concordance in the range of 90–100% in this paper are classified as concordant because of the overlap of the error ellipse with the concordia (e.g. Jeffries et al., 2003; Linnemann et al., 2012 and references therein). The northern margin of the Rheic Ocean is characterized by an Avalonian and Baltic hinterland and therefore delivered Lower Paleozoic sediments that are characterized by a significant population of zircon grains of Mesoproterozoic age (1600–1000 Ma) as well as those with ages of ~450 Ma and ~420 Ma.

Both latter ages originated from events caused by the closure of the Tornquist Sea (Avalonia docking on Baltica at ~450 Ma) and the closure of the Iapetus Ocean (collision of Baltica + Avalonia with Laurentia at ~420 Ma). In contrast, Lower Paleozoic sandstones formed at the southern margin of the Rheic Ocean are derived from a West African hinterland. In this case, ages of detrital zircon populations show a distinct gap in the record of Mesoproterozoic grains. These special features of zircon population patterns from sandstones from different paleocontinents such as Laurussia and Gondwana are a tool for the differentiation and characterization of siliciclastic sediments in orogenic collisional zones. Based on these requirements, we assign the provenance of the Devonian and Lower Carboniferous siliciclastics from the Lahn–Dill and Kellerwald areas to the Rhenohercynian and Saxothuringian margins. As a result, we present a plate tectonic model based on the U–Pb ages of the detrital zircon grains obtained from the 15 investigated sandstones and graywackes as well as on geochemical proxies of the volcanioclastics.

The spectra of zircon ages from siliciclastic Devonian to Lower Carboniferous sediments derived from different tectonic units of the Lahn–Dill and Kellerwald areas allow a distinction of two source areas. The samples of sedimentary rocks of the autochthonous to parautochthonous units show a distinct provenance from Baltica whereas those from the allochthonous units were derived from a Gondwanan source (Fig. 5). Typical Baltic signatures have been found in the Lower Devonian sandstones of the Siegen anticline, the Upper Devonian sandstones of the Dill–Eder syncline and in the “Kammquartzite” of the Lower Carboniferous. The mainly Mesoproterozoic age spectrum points to Svecofennian and Karelian source areas. Remarkably, the signal

Table 2 lists the results regarding measured and concordant grains, youngest and oldest age, and largest zircon population. Combined frequency and probability density distribution plots of each sample are given in Fig. 5A, B.

All samples of the nappe units (Hörre-, Steinhorn-, Lohra- and Gießen nappe) and of the Jesberg–Kulm syncline show a gap in Mesoproterozoic ages. This is typical for a provenance in the West African craton or a related terrane (e.g. Linnemann et al., 2007). The rock units in the nappe complexes of the Lahn–Dill and Kellerwald areas showing such zircon populations are related to the Gondwanan rock units of the Saxothuringian zone. Only few single grains (up to 2 grains per sample) show ages between 1.6 and 1.0 Ga. Such low input can be explained by long-distance along-shore transport and is not significant.

All other samples have their main peaks in the Mesoproterozoic and, hence, have a Laurussian affinity (Linnemann et al., 2012). In 3 samples of the Lower Carboniferous nappe units, distinct peaks around 360 Ma occur. This peak is unique and reflects the input from a magmatic arc source that was active during the closure of the Rheic Ocean.

The results based on the geochemical analyses have been already presented in Section 3 within the framework of the volcanic development of the study area.

5. Discussion

The principal plates and microplates of Gondwanan Europe and their adjoining cratons show distinct differences in the timing of tectonomagmatic and metamorphic events. These orogenic and plate tectonic activities are mirrored in the U–Pb zircon ages of siliciclastic sediments. Because of different geological histories, each continent exhibits its own particular zircon population in the archive of detrital sediments such as sandstones and graywackes. The typical zircon populations from cratons and microplates relevant to this paper are presented in Fig. 6. The results are compiled from our own and published data derived from Precambrian and Paleozoic sandstones (Linnemann et al., 2012 and references therein). The northern margin of the Rheic Ocean is characterized by an Avalonian and Baltic hinterland and therefore delivered Lower Paleozoic sediments that are characterized by a significant population of zircon grains of Mesoproterozoic age (1600–1000 Ma) as well as those with ages of ~450 Ma and ~420 Ma.
for Avalonia is very weak. This implies that the southern shelf of Laurussia (Avalonia) was covered by a thick pile of debris derived from Precambrian rocks of Baltica. Only few outcrops of the Avalonia terrane must have projected through of the plain of Baltic sediments, and so were subject to erosion. Another option could be tectonic stacking, caused by plate tectonic movements (i.e., Baltica was thrust over Avalonia). But such a scenario requires the occurrence of high-grade metamorphic rocks, which are absent in the Rhenohercynian zone.

In contrast, all graywacke samples of the Hörre, Steinhorn, Lohra and Gießen nappes exhibit a gap between 1.7 and 1.0 Ga within the Mesoproterozoic zircon ages. Only very few isolated zircons of Mesoproterozoic age have been detected. Altogether, the analyzed detrital zircon populations are characteristic for Gondwana, especially for the Saxothuringian terrane. These results confirm former interpretations of the geotectonic history of the Hörre and Gießen nappes. Based on the profound sedimentological differences, such as the occurrence of graywackes as early Famennian and the absence of volcanic rocks (Bender, 1978; Bender and Homrighausen, 1979; Homrighausen, 1979; Entenmann, 1991; Herbig and Bender, 1992), as well as facies differences (e.g. Herbig and Bender, 1992; Groos-Uffenorde et al., 2000; Bender and Blumenstengel, 2003), the Hörre unit has been interpreted to be part of the allochthonous unit of the Hörre/Gießen nappe which was derived from the south of the Rheinisches Schiefergebirge (e.g. Franke, 1995; Orken and Weber, 1995; Bender, 2006). Bender and Königshof (1994) considered the Hörre zone to be an autochthonous unit due to the metamorphic patterns based on conodont color alteration of conodonts (CAI), but this interpretation has been disproved.

Further to the east, similar rocks occur in the Kellerwald and the Harz Mountains, which have been assigned to the “Hörre–Gommern zone” (e.g., Stoppel, 1961; Eder et al., 1969; Bender and Homrighausen, 1979; Engel et al., 1983; Meischner, 1991; Bender, 2006; Fig. 1). This structural unit strikes SW/NE for about 300 km and is about 5 to 15 km wide. Based on our results the “Hörre–Gommern zone” as defined by many authors (see above), is not a single structural unit because of zircon data point to different provenances. The Hörre nappe clearly shows zircons delivered from a West African hinterland, whereas the Kammquartzite imbrication structure exhibits a Baltic signature. In contrast to these results, Huckriede et al. (2004) assumed a depositional setting for the Hörre sediments close to the margin of Laurussia. Haverkamp et al. (1992) assigned the “Hörre–Gommern Quartzite” (= Kammquartzite) to the distal passive margin of Laurussia. Dublizer et al. (2012) proposed a pelagic facies setting for the successions of the Hörre and Gießen nappes and a lower slope setting for the “Kammquartzite”. Despite some distal turbidites present for the latter, which were deposited in a narrow channel from NE to SW (e.g. Homrighausen, 1979; Jäger and Gursky, 2000), there are no convincing indications of a deep water facies in the “Kammquartzite”. However, there are clear indications for a shallow water environment. Some sections within the “Kammquartzite” show prominent hummocky cross stratification. Such ripple structures are known to occur in the lower part of a shoreline sequence, especially in fine grained sandstones (Reineck and Singh, 1980). Tongue-like or lobe-like small current ripple marks (lingoid ripples) can also be recognized, indicating a shallow water environment (see also Jäger and Gursky, 2000). Additionally, fossil assemblages in the Steinhorn nappe, situated south of the Hörre nappe (Fig. 2A, B), show advice that the sediments of the allochthonous units were deposited at the northern margin of Gondwana. For example, comparisons in the trilobite fauna between the Suchomsty and Acanthopyge limestones in Bohemia (Chlupč, 1983) and the Greifenstein limestone in the Steinhorn nappe show a close affinity of the latter to the Barrandian (Flick, 1999).

The diversity of provenance and fossil assemblages in the autochthonous to par-autochthonous units and those of the allochthonous units require a distinct spatial separation of the source areas during the Devonian and the lower part of the Lower Carboniferous. Consequently, this period was dominated by oceans separating Laurussia from Armorica as well as the latter one from Gondwana (Fig. 7). Based on the results presented in this paper we conclude that subduction of a wide Rheic Ocean lasted from Late Silurian until Visean times.

Prerequisite for the subduction of such an oceanic realm are different active margins in the north and in the south, as well as intra-

**Fig. 6.** Detrital zircon age distributions for Baltica, Amazonia, East Avalonia (Brabant massif), Armorica (Saxothuringian and Moldanubian zones), and the West African craton (data compilation from Linnemann et al., 2004; Drost et al., 2010; Linnemann et al., 2011, 2012). Note the general occurrence of Mesoproterozoic zircon ages in Baltica, Amazonia (Avalonian hinterland), and Avalonia, and the contrasting scarcity of the same zircon populations in Armorica and the West African craton.

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**Legend:**
- igneous and metamorphic ages (all methods)
- igneous (incl. inheritance) and metamorphic zircon
- detrital zircon
- igneous (incl. inheritance) from pre-Silurian rocks/protoliths

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oceanic arcs such as the Frankenstein complex of the Bergsträsser Odenwald (Fig. 8). However, remnants of such structures are rare or must be detected indirectly. Thus, subduction at intra-oceanic arcs and subduction erosion must have played a decisive role (Nance et al., 2012).

Evidence for a wide Rheic Ocean and an active margin to the north that was later associated with a backarc setting has been postulated in earlier publications (Floyd, 1982; Flick and Nesbor, 1988; Oczlon, 1994; Smith, 1996; von Raumer and Stampfl, 2008; Zeh and Gerdes, 2010). This wide ocean was subducted through the Devonian and the early part of the Early Carboniferous along a northward dipping subduction zone below Laurussia and in a southern direction below the Saxothuringian terrane (Fig. 8). Zircon analysis confirms the existence of magmatic arcs (especially in the south) until the late Visean and less prominently in the north until the Tournaisian (Fig. 5). Our model contradicts the interpretation of sedimentary deposition occurring on a passive margin along the northern border of a relatively small ocean proposed by Franke and Oncken (1990, 1995), Oncken et al. (1999), Franke (2000) and Doublier et al. (2012).

The most important argument suggesting a broad Rheic Ocean is provided by the provenance data of the allochthonous units. These correspond to the spectra of zircon ages derived from the Saxothuringian zone, which proves a source area located on Armorica in contradiction to the interpretation of Huckriede et al. (2004) and Doublier et al. (2012). Differences in provenance data reflecting Baltica and Armorica sources require wide separation between the two source areas during the Devonian and the lower part of the Early Carboniferous. Moreover, all samples of Visean age exhibit an Armorican pattern of zircon ages — i.e., not only the samples from the allochthonous units, but also those from the autochthonous and par-autochthonous units as well. The reason for this reflects the geotectonic situation during the late Early Carboniferous. At that time the Rheic Ocean was closed, and sedimentation into the Rhenohercynian zone was generally supplied from the south. Hence, the distinction of different source areas for the graywackes is no longer possible. Our data support the existence of the Rheic Ocean until the Early Carboniferous, which contradicts the results published by, for example, Kroner et al. (2007) and Linnemann et al. (2010).

Further support for the plate tectonic model presented is provided by the volcanic activity that accompanied the subduction of the Rheic Ocean. This activity is documented in numerous ash layers intercalated within the sedimentary rock pile of the Rhenohercynian (Heyckendorf, 1985; Kubanek and Zimmerle, 1986; Kießbauer, 1991; van Amerom et al., 2001). The magma composition is characterized by predominant dacitic/ryodacitic and minor rhyolitic melts (see Fig. 3). Such silica rich volcanism is typical of thick continental crusts above the subducted slab. Furthermore, the uniform composition of the magmas generated over the whole time span (about 80 Ma) requires a constant process of melt generation that is only provided by the subduction of a large ocean. The geodynamic development of the southern margin of Laurussia is documented by the evolution of the grain sizes of the pyroclastic deposits. During the Lower Devonian typical fall out and ignimbrite deposits occur, often composed of coarse-grained particles. Y-shaped
shards and highly vesicular pyroclasts are common. During that time the dacitic/rhyodacitic and rhyolitic volcanism was active in the Rheinisches Schiefergebirge or nearby. Thus, the subduction zone was situated directly at the southern margin of Laurussia. In the Middle Devonian, extremely fine grained ash fall was deposited, which marks the opening of the Rheohercynian Ocean, triggered by a roll back of the subducted slab (von Raumer and Stämpfli, 2008). As a result Avalonia split up into a northern and a southern segment – North and South Avalonia (Fig. 8). Because of the increasing distance, the grain size of the pyroclastic fall out deposits decreases. These are witnesses of highly explosive Plinian and Ultraplinian eruptions, which can be traced over wide distances. The grain size of the Visean volcanic ashes increased again as a result of the closing of the Rheohercynian Ocean and the approach of the subduction zone dipping beneath South Avalonia.

The existence of South Avalonia is demonstrated by the detrital zircon in the Ruhla Crystalline complex of the Mid-German Crystalline zone (MGCZ), which suggest two different source areas (Zeh and Gerdes, 2010). The northern part of the Ruhla Crystalline complex exhibits a provenance in Avalonia, whereas the southern part has a provenance in Armorica. Consequently, the main suture between Avalonia and Armorica must lie within the MGCZ and not at the southern Taunus margin as previously believed (e.g., Franke and Oncken, 1995; Oncken et al., 2000). Besides the northern part of the Ruhla Crystalline, the Spessart and the Böllstein Odenwald can also be interpreted as belonging to South Avalonia. This assumption is supported by subduction-related magmatism at the Silurian/Devonian boundary (Dombrowski et al., 1995; Reischmann et al., 2001). This magmatism can be correlated to the Silurian volcanic activity at the southern margin of the Rheinisches Schiefergebirge (Sommermann et al., 1992, 1994; Meisl, 1995).

Doublier et al. (2012) suggest that the volcanic belt of the Lahn–Dill area is separated from the volcanic evolution of the Gießen-Lizard Ocean (=Rheohercynian Ocean) by a large non-volcanic belt comprising the Bicken–Ense unit, Hörre nappe, Lindener Mark, Hessische Schieferserie and the Taunus. However, new mappings show that the volcanic rocks of the Lahn- and Dill–Eder synclines were not only limited to their present distribution area. Rather, their subvolcanic dikes and sills were distributed throughout the entire autochthon of the Rheisnliches Schiefergebirge. Likewise, fragments of volcaniclastic rocks of the Givetian–Frasnian phase are found in volcanic breccias of a phreatomagmatic diatreme of Tertiary age in the Taunus anticline (Requadt and Weidenfeller, 2007).

At the southern rim of the Rheic Ocean subduction processes beneath Armorica are demonstrated by typical subduction-related plutonic rocks in the Mid-German Crystalline Rise (MGCZ), the Saxothuringian- and the Moldanubian zone. These plutons often show an I-type signature and a calc alkaline composition (e.g., Altherr et al., 1999; Stein, 2001). Their geochronological ages range from the Late Devonian/Early Carboniferous boundary to the earliest part of the Late Carboniferous. In addition to these active continental margins, intraoceanic island arcs also occur, such as the Frankenstein complex of the Bergsträsser Odenwald with a Late Devonian/Early Carboniferous age (Kirsch et al., 1988). The final stage of the Variscan orogeny with thrust faulting, nappe transport, and strike–slip faults leads to the present complex geotectonic picture.

6. Conclusions

- 33 samples obtained from Devonian and Carboniferous autochthonous to par-autochthonous and allochthonous units of the eastern Rheinisches Schiefergebirge have been investigated for U–Pb detrital zircon ages. A representative selection of 15 samples is presented in this paper in the context of their stratigraphic, sedimentary, magmatic and plate tectonic implications.
- Based on the distribution of zircon age populations, the autochthonous to par-autochthonous sediments exhibits a typical Baltic provenance with weak Avalonian signals, whereas those of the allochthonous units were derived from a Gondwanan source.
- Sediments of the same age of autochthonous to paraautochthonous and allochthonous units show profound differences in their composition.
and facies development. The allochthonous units such as the Lohra, Steinhorn, and Höhr nappes are characterized by the absence of volcanic rocks. At the base of the Gießen nappe metabasalts with MORB-type affinities occur as tectonic slices. Subduction-related volcanism lasted from the Early Devonian to the Early Carboniferous with a source area outside the Rheinisches Schiefergebirge. Intraplate volcanism was confined to the autochthonous to par-autochthonous units of the Rheinisches Schiefergebirge. The existence of different magmatic arcs is mirrored in the frequency distribution of zircon grains. Based on both the provenance analysis and geochemical results, the evolution of these suggests subduction to the north as well as to the south.

The plate tectonic model presented suggests the existence of a wide Rheic Ocean and an active continental margin to the north, which resulted in the opening of the Rhenohercynian Ocean. This was associated with extension and subsidence of the continental crust of North Avalonia (= southern shelf area of Laurussia), which was accompanied by an intensive intraplate volcanism.

In contrast to earlier publications (e.g., Kroner et al., 2007; Linnemann et al., 2010) the data presented here suggest the existence of the Rheic Ocean until the Early Carboniferous.

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