The Meteoritical Society

Meteoritics & Planetary Science 58, Nr 4, 446–462 (2023)
doi: 10.1111/maps.13964

The Ries impact and its distal effects in sediments of Central Europe—A review

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(Received 31 March 2022; revision accepted 17 February 2023)

Abstract–The Ries impact is the most important cosmic event in the younger geological history of Europe. Its effects reach far beyond the area considered so far and are documented in manifold evidence. In this paper, the widely scattered reports in the literature are compiled and supported with investigations by the authors. Besides well-known ejecta features like the Brockhorizont, Reuter's blocks, and moldavites, little known or forgotten indications, like a lechatelierite and β-cristobalite occurrence in Bavaria and unusual sedimentation phenomena in northern Germany, are presented. The paleogeographic reconstruction shows that the Ries impact occurred on the southern side of the Neogene Central European mainland. Large parts of this erosional area were devastated by the impact. Pressure waves and thermal radiation had a lasting effect on the landscape within hundreds of kilometers around the impact site. Destruction of the vegetation cover by impact-induced storms, wildfires, and heavy rainfall generated intense erosion. The adjacent sedimentation area to the north (Paleo-North Sea) experienced an increased and short-term supply of terrestrial debris to the marine environment. The stratigraphic coincidence of these exceptional sediments with the Ries event leads us to conclude that the distal effects of the impact are present here, which have so far received little or no attention in this context. The paper considers the different indications and sets them in a large-scale context.

INTRODUCTION

The Nördlinger Ries is one of the best-studied meteorite craters on Earth. Despite a large number of publications on the Ries event, it is striking that, except for the so-called Brockhorizont (brock horizon) and the moldavites, the remote effects of the impact have received only little attention in the literature until recently. Only in the last years, some papers have been published that also consider seismic and resulting sedimentological effects in the Molasse Basin (Buchner et al., 2021, 2022; Lange & Suhr, 2022; Schmieder et al., 2022). One of the significant problems is the difficulty in identifying synchronous deposits across different facial zones. Furthermore, the literature on this topic is scattered, partly challenging to access, and little known.

In the present paper, we give a summary of assured and potential distal impact effects for a range up to a distance of 500 km from the Ries crater (Figure 1). Limitations in this consideration arise naturally in post-Ries uplift areas and in areas with primarily missing sedimentation (erosion areas) at the time of the Ries event. A further difficulty for the preservation history of Ries-synchronous sedimentation areas is that the primary distribution of the Middle Miocene has been disintegrated in an island-like manner by post-Middle Miocene erosion in large parts of northern Central Europe.

To capture the long-range effects of such a short-term event as an asteroid impact, the paleogeography and stratigraphic correlation of the synchronous sedimentary basins must be known as accurately as possible. However, a better temporal resolution than an "age/stage" (<2 Myr) for a larger area, such as Central Europe, is currently not achievable. The same applies to the exact correlation of stratigraphic sequences between different sedimentary basins

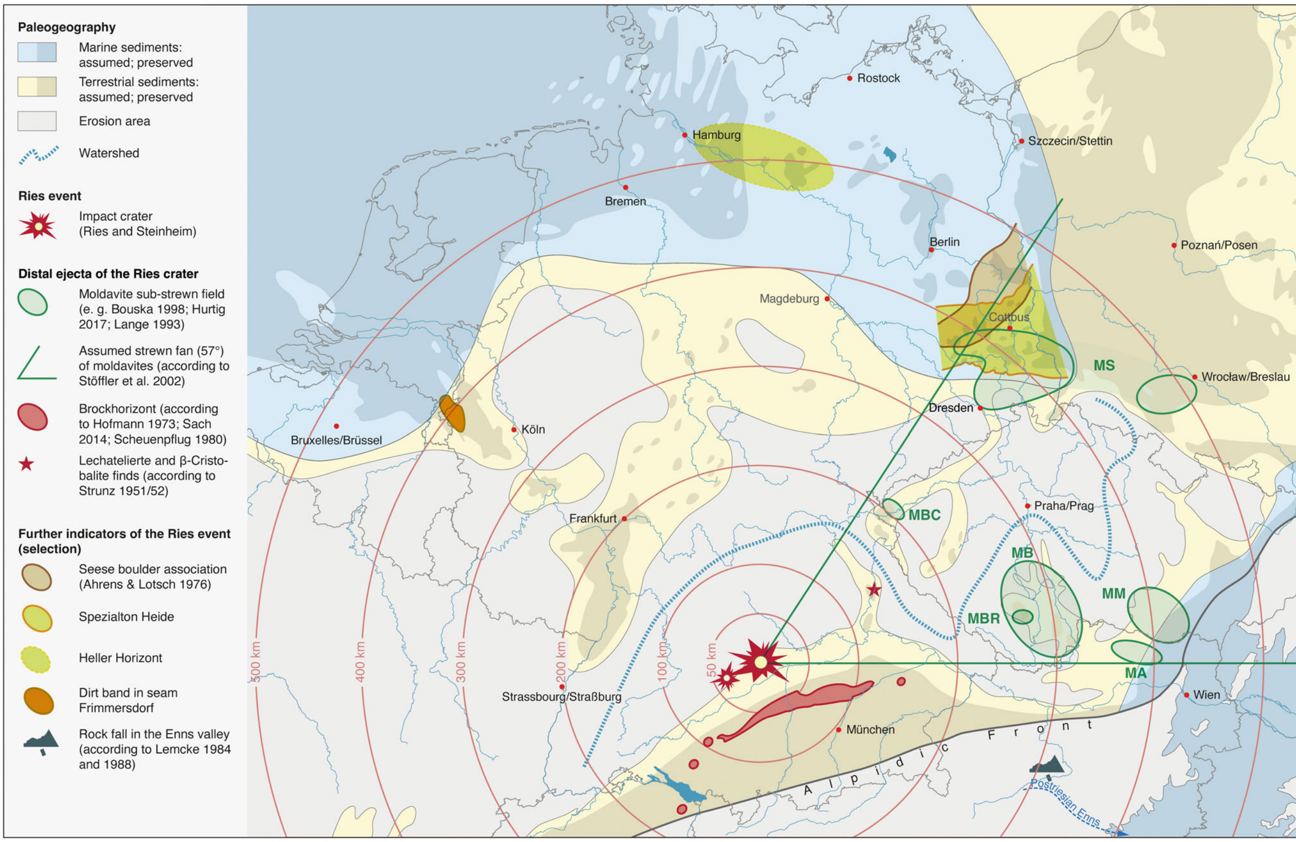


FIGURE 1. Paleogeographic situation of Central Europe in the Middle Miocene at the time of the Ries event (Escher et al., 2016; Gibbard & Lewin, 2016; Grimm et al., 2011; Jarosiński et al., 2009; Katzung, 2004; Meschede, 2015; Stackebrandt & Manhenke, 2010; Standke, 2015; Vinken, 1988; Ziegler & Dèzes, 2007—further citations for this figure can be requested from the authors). (Color figure can be viewed at wileyonlinelibrary.com.)

(Figure 2). The best way to correlate them is by radiometric ages. However, these ages are usually not available for sedimentary units. Biostratigraphic correlations often have too low of a time resolution for detecting a short-termed event, such as an impact. Precise stratigraphic knowledge is the key to finding the Ries impact event in deposits and its correlation between different sedimentary basins. The distal effects can be of primary nature, like the ejecta masses (ballistic ejected rocks, tektites), or of secondary nature, like unusual sedimentation phenomena, wildfires, or short-term climate changes (Figure 3).

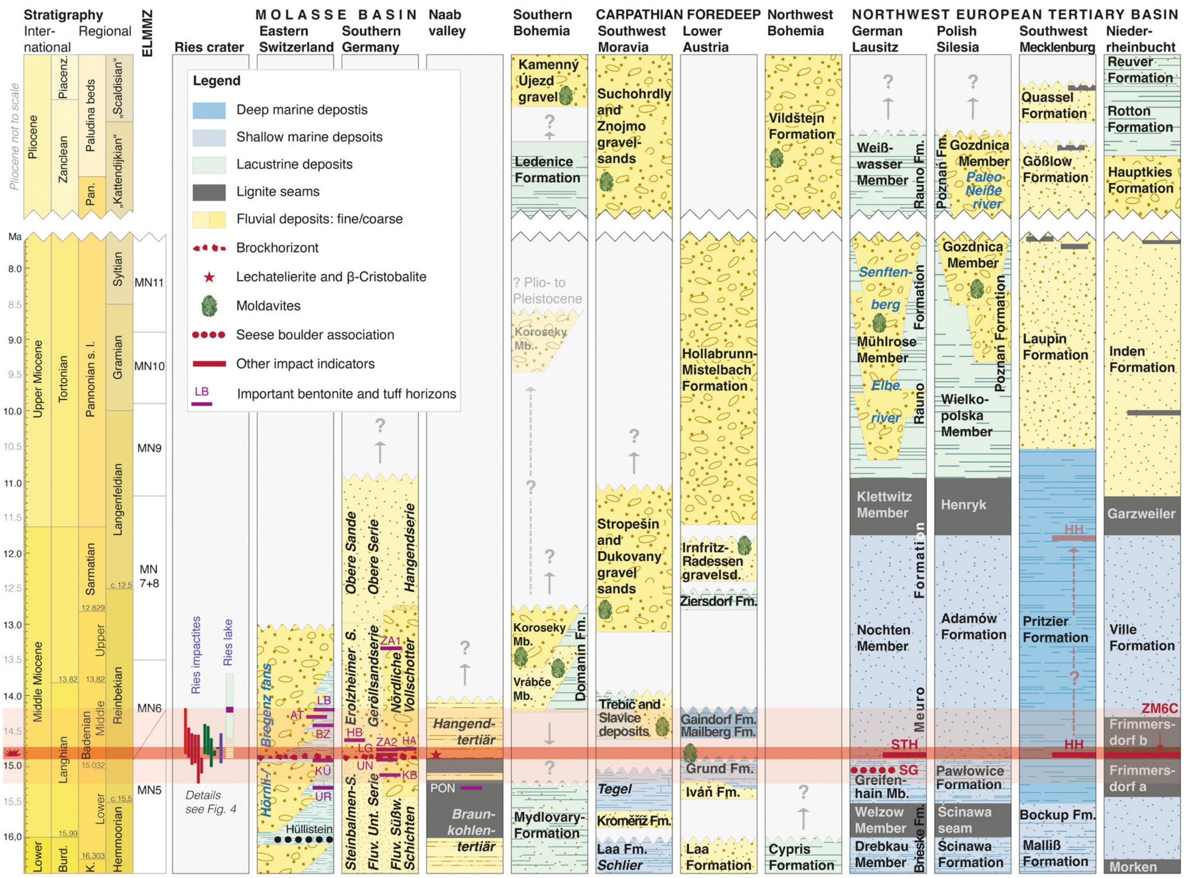
CHRONO- AND MAGNETOSTRATIGRAPHY OF THE RIES IMPACT

Radiometric dating of high-temperature rocks of the Ries crater (suevites and moldavites) was first published by Gentner et al. (1963). Since then, a large number of physical ages have been measured and published. These ages vary between 14 and 16 Ma.

Recent (since 2000) radiometric dating of impactites from the Ries shows ages between 14.50 ± 0.32 Ma (Buchner et al., 2010 recalculated in Schwarz et al., 2020) and 14.98 ± 0.11 (Aziz et al., 2008; recalculated in Rocholl, Schaltegger, et al., 2018; see Figure 4).

Furthermore, magnetostratigraphy has been established as an additional method of controlling radiometric ages. The period covered by the error limits of radiometric ages for the Ries event falls in a phase of frequent polarity reversals.

The Ries suevite shows reverse polarity (Iseri et al., 1989; Petersen et al., 1965; Pohl, 1977; Pohl et al., 2010; Pohl & Angenheister, 1969), so the impact can only have occurred in a reverse polarized section of the Astronomical Tuned Neogene Time Scale (ATNTS; Raffi et al., 2020). Whereas the deeper Ries lake sediments (crater filling) are normally polarized, the impact event must be placed close to the polarity change from reverse to normal polarity (Pohl, 1977, 1978). It follows that only two timeframes for the Ries event



Lorem ipsum

FIGURE 2. Stratigraphic correlation scheme for the period from 16.5 to 7.5 Ma with additions in the Pliocene using Bouška (1994), Coric et al. (2004), Hager and Prüfert (1988), Menning and Hendrich (2016), Piller et al. (2004), Raffi et al. (2020), Rasser and Harzhauser (2008), Rocholl, Schaltegger, et al. (2018), Trnka and Houzar (2002). Synoptic visualization of relevant sedimentary sequences for the Ries event. With the marking of the age range of common datings (14.2–15.2 Ma) and the summarized range of the most precise age (14.72 and 14.89 Ma) of the impact. AT, Aeugstertal; BZ, Bischofszell; HA, Hachelstuhl; HB, Heilsberg; HH, Heller Horizont (bright horizon); KB, Krumbad; KÜ, Küsnacht; LB, Leimbach; LG, Laimering; PON, Ponholz (Weiße Lasse); SG, Seeser Gerölle (Seese boulders); STH, Spezialton Heide (special clay of Heide); UN, Unterneul; UR, Urdorf; ZA1, Zahling 1; ZA2, Zahling 2; ZM6C, Dirt band in the Frimmersdorf seam. ELMMZ, European Land Mammal Mega-Zones Neogene. (Color figure can be viewed at wileyonlinelibrary.com.)

(Rocholl, Böhme, et al., 2018) are possible from the spectrum of modern radiometric ages considering magnetostratigraphy. They are at C5Bn.1r/C5Bn.1n (14.870 ± 0.003 Ma) and C5ADr/C5ADn (14.609 ± 0.004 Ma; Hüsing et al., 2010: table 1; Raffi et al., 2020) boundaries.

The Brockhorizont is now considered the distal ejecta layer of the Ries event (e.g., Holm-Alwmark et al., 2021; Rocholl, Schaltegger, et al., 2018). As it is bracketed by two bentonitic tuffs from acid volcanism of the Pannonian Basin (Gilg & Ulbig, 2017; Rocholl, Schaltegger, et al., 2018; Unger et al., 1990; Unger & Niemeyer, 1985), there is a reasonable dating possibility for the interval.

The stratigraphically closest tuff to the Brockhorizont is the bentonite of Unterneul. It is located 5 m below the Brockhorizont (Fiest, 1989) and has an age of 15.003 ± 0.024 Ma. In the same outcrop, about 15 m above the Brockhorizont is the bentonite of Laimering. For this, an age of 14.925 ± 0.012 Ma is given (Rocholl, Schaltegger, et al., 2018). Rocholl, Schaltegger, et al. (2018: figure 7) correlates the bentonites of Unterneul and Laimering with the tuff horizons VED 0 and VED 1 of La Vedova in Italy, which should therefore come from the same volcanic source. Both geochronological and astronomically tuned dates are available from the Italian tuffs. The U–Pb ages determined here on zircons are generally older than the astronomically tuned ages (VED 0: 14.884 ± 0.010 Ma, VED 1: 14.834 ± 0.010 Ma; Wotzlaw et al., 2014). The difference between the two dating methods is about 22 ka for VED 0 and 210 ka for VED 1. If the correlation between the Italian tuffs and the Bavarian bentonites is correct (Rocholl, Schaltegger, et al., 2018:

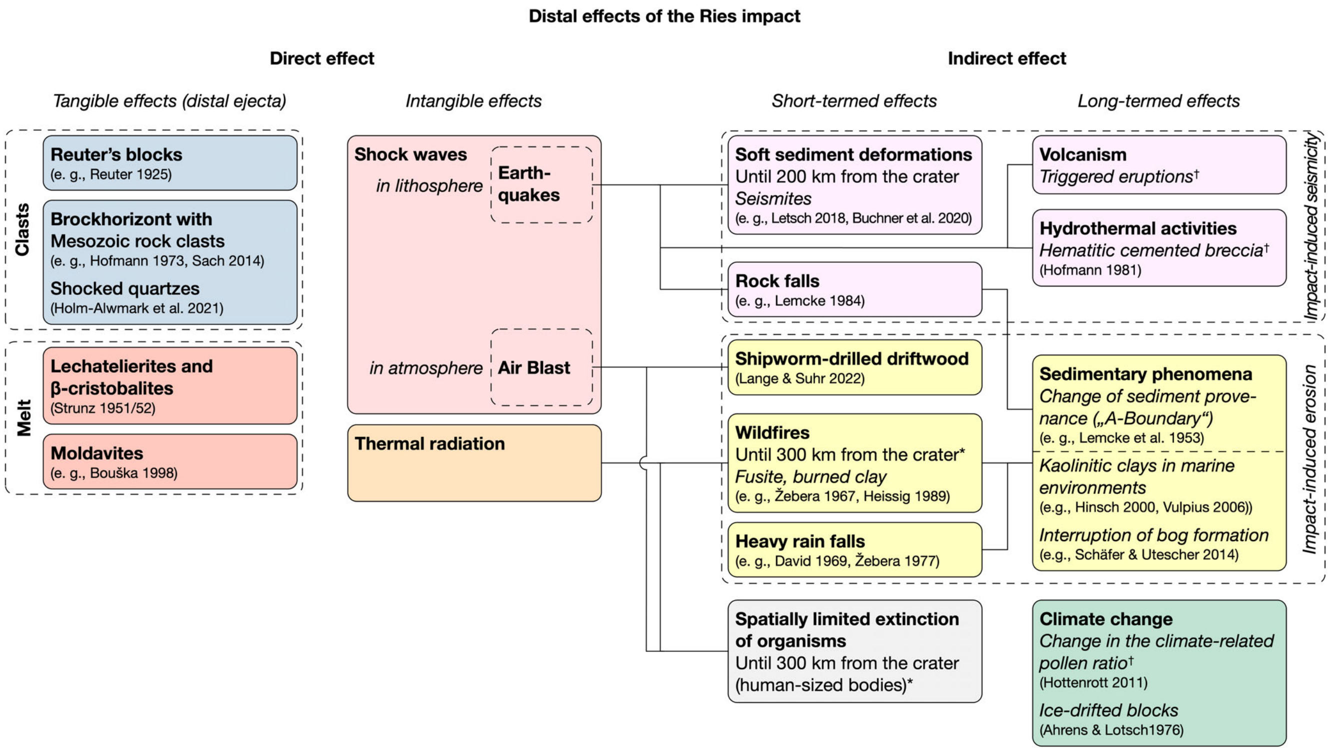


FIGURE 3. Summary of verified and presumed distal effects of the Ries impact. *Calculated by Collins et al. (2005), †not discussed in this work. (Color figure can be viewed at wileyonlinelibrary.com.)

figure 7), then the U–Pb ages of the Unterneul and Laimering bentonites are older than the astronomical ages of their Italian correlates by about 90–120 ka and thus of similar order of magnitude of zircon ages. Rocholl, Schaltegger, et al. (2018) justify the higher U–Pb ages of the zircons with a longer residence time in magma chambers before the eruption.

After extensive discussion of older age determinations, Schmieder et al. (2018) date the Ries event to 14.808 ± 0.038 Ma, based on moldavites. However, the closest reverse interval (C5ADr) ranges from 14.609 to 14.775 Ma (Raffi et al., 2020), which would require the Ries event to be slightly younger than 14.775 Ma and this correlates poorly with the magnetostratigraphic framework (Rocholl, Böhme, et al., 2018). A similar result is obtained by the most recent dating of Di Vincenzo (2022) with 14.7355 ± 0.013 Ma. If the ages of Schmieder et al. (2018) and Di Vincenzo (2022) are appropriate and the Ries impact occurred in the lower part of the reverse interval C5ADr, then there is a time gap of at least 100,000 years until the onset of fine-grained normal-magnetized lake sedimentation. This time interval is represented by coarse-grained fluvial sediments that do not allow polarity determination. It is to be verified whether such a deep depression undercutting groundwater levels could have existed for 100,000 or more years without the formation of a complete water coverage (lake).

In the synopsis of all previous dating, the most precise age for the Ries crater's formation is at #1 14.7355 ± 0.013 (Di Vincenzo, 2022) or #2 between 14.884 ± 0.010 Ma and 14.870 ± 0.003 Ma (Rocholl, Böhme, et al., 2018; Rocholl, Schaltegger, et al., 2018).

ESTIMATION OF THE IMPACT EFFECTS

The impact effects were calculated with "Earth Impact Effects Programs" (Collins et al., 2005) and resulted in a primary (latent) crater of 13.4 km in diameter and 4.75 km in depth. It was produced by an impactor of 1.5 km diameter with a density of 3000 kg m^{-3}, an impact velocity of 20 km s^{-1}, an impact angle of 30° with an impact into a target of crystalline rock with a density of 2750 kg m^{-3}. The final crater is expected to be 18.9 km in diameter and 717 m deep. The difference in the dimensions of the Ries crater (24 km diameter) is mainly due to the presence of a thick sedimentary cap layer, which is not considered in the above program.

From these calculations, it can be estimated that the entire vegetation ignited up to 300 km from the impact site. Heissig (1989) describes some chunks of naturally burned molasse clay with diameters up to 6 cm, which he interprets as evidence of extensive wildfires on the site of Ziemetshausen 1b. Charcoal

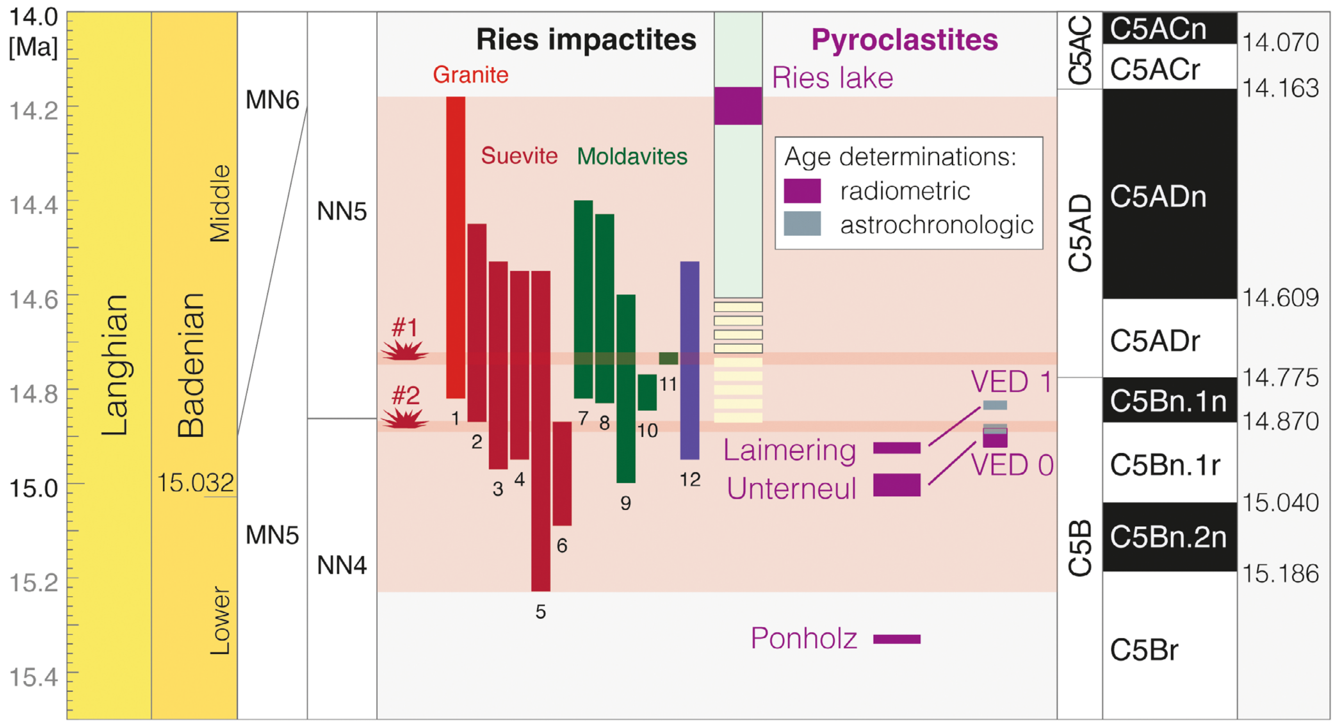


FIGURE 4. High-resolution stratigraphy of the Ries event using selected data from isotopic and magnetostratigraphic age determination. #1 (Di Vincenzo, 2022) and #2 (Rocholl, Böhme, et al., 2018; Rocholl, Schaltegger, et al., 2018) indicate the currently discussed ages of the Ries event. The pink background marks the age range of modern datings. Ages of the Ries impactites: *Recrystallized potassium feldspar in shocked granite*: 1, Buchner et al. (2010) recalculated in Schwarz et al. (2020); *Suevite glasses*: 2, Buchner et al. (2003) recalculated in Schwarz et al. (2020); 3, Schwarz et al. (2020); 4, Schwarz and Lippolt (2014); 5, Schwarz et al. (2020); 6, Aziz et al. (2008) recalculated in Rocholl, Schaltegger, et al. (2018); *Moldavite*: 7, Schwarz and Lippolt (2014) recalculated in Schwarz et al. (2020); 8, Laurenzi et al. (2003) recalculated in Schwarz et al. (2020); 9, Rocholl et al. (2011); 10, Schmieder et al. (2018); 11, Di Vincenzo (2022); *Average ages from suevite and potassic feldspar glasses and moldavites*: 12, Buchner et al. (2010) recalculated in Buchner et al. (2013). Furthermore, the ages of selected pyroclastics important for dating the Ries event (Rocholl, Schaltegger, et al., 2018) are shown. In addition, the stratigraphic position of the Ries lake tuff (after Arp et al., 2021) can be seen. All data, including 2σ-error. MN, Zone in the European Land Mammal Mega-Zones Neogene; NN, Standard Neogene Calcareous Nannoplankton Zonation. (Color figure can be viewed at wileyonlinelibrary.com.)

residues (fusite) are also described from clays of Vrábče (moldavite-bearing; Žebera, 1967, 1977). Toon et al. (1997) estimate the impact energy at about 10^5 Mt TNT, an area of 10^5 km^2 (corresponding to a radius of almost 180 km around the impact center), where vegetation spontaneously ignites.

At 400 km, the shock wave triggered by the impact is still of hurricane strength (Beaufort 12: >32.7 m s^{-1}). At 500 km, it can still be perceived as a severe storm (Beaufort 10: 24.5–28.5 m s^{-1}).

Therefore, it is evident that the destructive effect of an impact of the size of the Ries event can be assumed up to a distance of at least 400 km. Secondary effects, such as wildfires, are likely to have caused considerable damage in this area and possibly beyond. Due to the destruction of the vegetation cover, extreme erosion events are expected. Consequently, large parts of the existing weathering crust was removed. Erosion is also supported by heavy rainfall events, which often occur due to impacts (Buchner et al., 2020; David, 1969; Žebera, 1977).

IMPACT INDICATIONS IN SYNCHRONOUS SEDIMENTARY BASINS

"Brockhorizont" and "Reutersche Blöcke"

The largest, coherent sedimentation area in the vicinity of the impact is located south of the Ries in the North Alpine foreland basin (Upper Freshwater Molasse). There the Brockhorizont distal ejecta occurs in the form of Malm limestone blocks as far as the Augsburg area and southwest of Lake Constance (Figure 5). The larger limestone fragments (up to about 1.5 m in size) are also called Reutersche Blöcke (Reuter's blocks). Findings of shatter cones in the Upper Jurassic limestone blocks (e.g., Hofmann, 1973; Sach, 1997) and shocked quartz (e.g.,

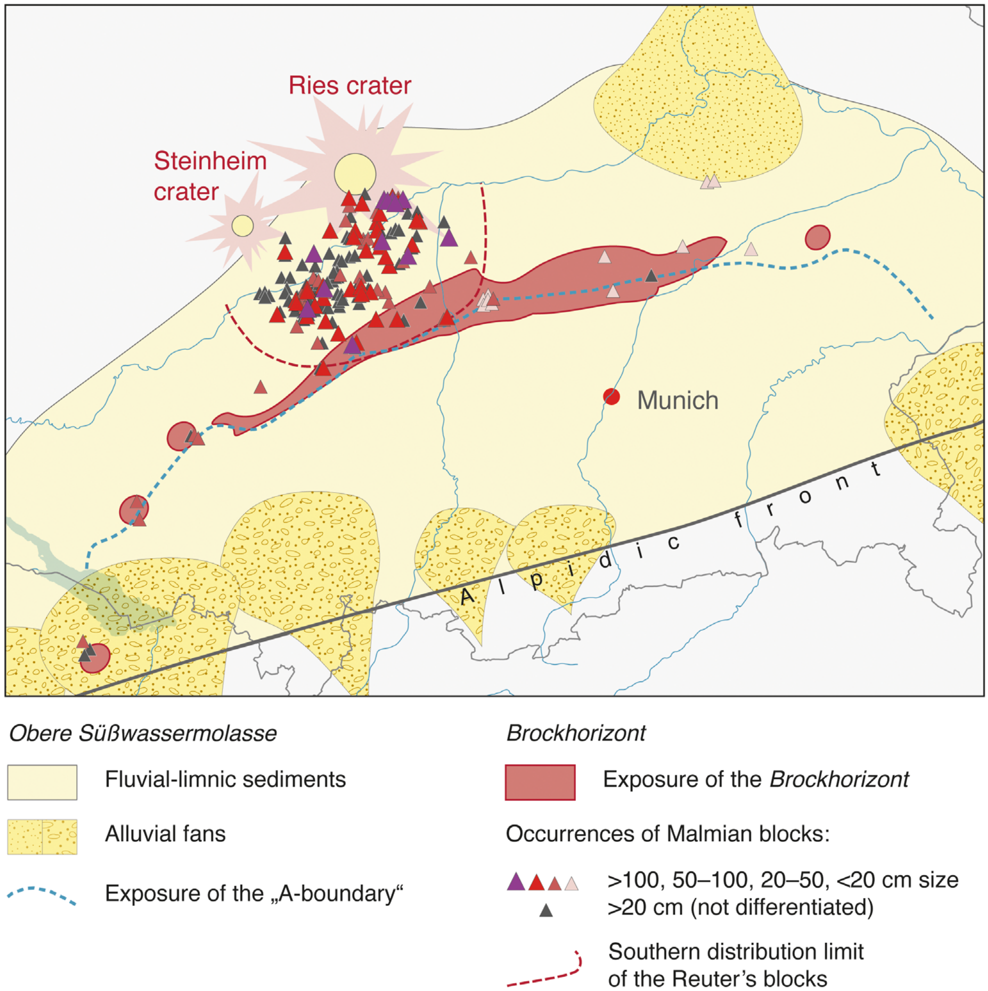


FIGURE 5. Distribution of the Brockhorizont (brock horizon) and the Reuters blocks in the Southern German-Swiss Molasse, compiled according to Reuter (1925), Bayrisches Geologisches Landesamt (1954), Löscher et al. (1979), Scheuenpflug (1980), Aktas (1987), Sach (1997, 2014 and literature therein). (Color figure can be viewed at wileyonlinelibrary.com.)

Holm-Alwmark et al., 2021) can establish a clear connection with the Ries event.

Recently, the Brockhorizont has been identified up to 180 km (Bernhardzell, recently Buchner et al., 2020; Letsch, 2018) away from the Ries crater in numerous outcrops in the Upper Freshwater Molasse (e.g., Sach, 2014 and literature therein). Lithostratigraphically, the distal ejecta, in their primarily impact-related position, are to be placed in the Middle Series (after Dehm, 1951) of the Upper Freshwater Molasse and in the European Land Mammal Mega-Zone Neogene MN6 (Heissig, 1989).

Lechatelierite and β-Cristobalite

Another sedimentation area, synchronous to the Ries event, is the so-called Oberpfälzer Braunkohlentertiär (Upper Palatinate Lignite Tertiary; Gregor, 2011). Stratigraphically, the sequence of several lignite seams, sands, and clays with low-thickness intercalations of diatomites is placed in the Lower to Middle Miocene (Karpatian to Middle Badenian; Viertel, 1995). Jung et al. (1971) compare the section between the Lower and Upper Seam (former open cast mines Oder I and Oswaldmulde) with the Mydlovary Formation of the South Bohemian basins (Figure 2). New dating (Rocholl, Schaltegger, et al., 2018) of the “Weiße Lasse,” a tuff horizon within Seam III at Ponholz (Rohrdorf II open cast mine) with sanidine, biotite, and igneous quartz, assigns an age of 15.3 ± 0.02 Ma to the tuff. The so-called Upper Seam (at least 15 m above the Weiße Lasse) with the “Hangend-Schichtenserie A” (Top Layers Series A; Tillmann & Kirschhock, 1954) is thus certainly of Middle Miocene age and could belong to the Middle Badenian.

With this assumption and the adjacency to the Ries (125 km), distal ejecta of the impact could have been preserved in the sequence. Strunz (1951/1952, p. 198) found probable indicators of Ries ejecta in the northern field of the Wackersdorf open cast mine in the form of lechatelierite and high-temperature cristobalite (β-cristobalite) in the Hangend-Schichtenserie A (diatomites 20 cm thick above the Hangendflöz). Unfortunately, a follow-up investigation with modern methods is impossible, as the find horizon has not been accessible for decades due to flooding of the former open cast mine. The co-occurrence of lechatelierite and β-cristobalite is known from many impact-related rocks (Ferriére et al., 2010).

Moldavites

East and northeast of the Ries, ejecta occur in synchronous sedimentary realms, such as the South Bohemian basin, the Moravian Carpathian foreland basin, and at the southeast margin of the Northwest European Tertiary basin. These occurrences are well known for the moldavites—the tektites of the Central European strewn field (e.g., Bouška, 1972, 1998; Brachaniec, 2020; Hurtig, 2017; Koeberl et al., 1988; Lange, 1995). They are mainly green to brown-colored glasses, which occur in several larger assemblages ("substrewn fields") over a total area of about 10,000 km^2 at distances between 200 and 500 km east and northeast of the Ries crater (see Table 1). The moldavite deposits are mainly located in South Bohemia and Southwest Moravia, also occur in smaller amounts in Northwest Bohemia, North Sudetes (Lausitz/Lusatia and Lower Silesia), and finally in Lower Austria (see Figure 6).

The connection of the Ries impact with moldavites was already established by Cohen (1961) and Weiskirchner (1962). This assumption was supported in many publications by proof of age similarity (e.g., Gentner et al., 1963, 1967; Lippolt cited in Voshage, 1962) and geochemical relationship (e.g., Delano & Lindsley, 1982; Luft, 1982; Preuß, 1934).

The moldavite-bearing strata mostly start with a clear time offset above the Ries event. In South Bohemia, these are the proluvial to fluvial Vrábče member within the Domanín Formation, probably formed shortly after the Ries event. From such sediments of Dobrkovská Lhotka, Kvaček and Teodoridis (2007) describe a mastixiodean flora and correlate it with the macroflora zone XI to XII sensu Mai (1967) and the MN6 (Ševčík et al., 2007). According to these findings, this flora can be placed into the Early to Middle Miocene climatic optimum, immediately preceding the cooling phase in the Late Badenian/Sarmatian (*c.* 14.9–14.5 Ma, see Holbourn et al., 2014; Methner et al., 2020). Thus, only a tiny hiatus of about 10^3 to 10^5 years can exist between the Ries event and the formation of the moldavite- and mastixiodean-bearing Vrábče member. The oldest moldavite-bearing sediments in Southwest Moravia can be classified in stratigraphically similar positions. Deluvial (slopewash deposit) clays and proluvial (sediment accumulated at the foot of a slope) to fluvial gravelly sands of Třebíč and Slavice are considered the oldest units with moldavites in this area (Houzar, 1992; Trnka & Houzar, 2002). Based on their lithological similarity to the South Bohemian Vrábče member, Houzar and Pošmourný (1990) suggest that they represent the approximate distribution of the former impact sediments and thus the fall area of the moldavites. The oldest moldavite-bearing beds in all other sub-strewn fields (Lower Austria, Northwest Bohemia, North Sudetes) are commonly younger (Upper Miocene to Pliocene).

A moldavite find from the Grund Formation near Immendorf (Harzhauser et al., 2020; Roetzel, 2009) in the Weinviertel (Lower Austria) is particularly remarkable. It was discovered while sieving samples from a scientific paleontological excavation in 2004 (Hofmann et al., 2019; Zuschin et al., 2006). According to Rocholl et al. (2011), this is the only record of moldavite from marine sediments so far. Interestingly, the Grund Formation is placed in MN5 (*Cricetodon meini* of Mühlbach and Grund according to Daxner-Höck, 2003) and thus can be synchronous with the Ries event only in the very highest part (boundary MN5/6).

Sedimentary Phenomena

The Ries impact had large-scale effects on the immediate and distant surroundings, which left marks in synchronous sedimentation basins. The event's short duration is problematic, as it typically results in a patchy distribution and poor preservation of resultant deposits in shallow marine and terrestrial depositional environments. Nevertheless, anomalous sedimentation events of a brief duration took place in the Northwest European Tertiary basin (Paleo-North Sea) in the Middle Miocene. The accumulation of exceptional sedimentation phenomena in the Middle Miocene of the southern margin of the Paleo-North Sea can be correlated with the Ries impact.

Rock Fall and Change of the Heavy Mineral Composition

A sedimentary petrographic boundary ("A-Boundary"; Füchtbauer, 1954; Lemcke et al., 1953; see Figures 1 and 5) within the Upper Freshwater Molasse succession is interpreted by Lemcke (1984, 1988) as reflecting a change in the source areas for sediments as a result of the Ries impact. The heavy mineral assemblage changes seriously at this boundary. This change is thought to have been triggered by a shift in the course of the Enns River due to an impact-induced rock fall within the Alps.

TABLE 1. Occurrences of tektite ejecta (moldavites) from the Ries crater.

	Tektite ejecta east of the Ries crater				Tektite ejecta northeast of the Ries crater		
						North Sudetes	
	South Bohemia	South Bohemia (Radomilice)	Southwest Moravia	Lower Austria	Northwest Bohemia	German Lausitz	Polish Silesia
Occurrence data							
First mention	Mayer (1788)	Bouška (1972)	Dvorský (1880)	Suess (1914)	Bouška et al. (1995)	Žebera (1974)	Brachaniec et al. (2014)
Distance to the Ries crater (km)	255–330	≈250	380–455	360–390	185–200	345–405	425–485
Quantity of moldavites[a]	10^7	5×10^4	2×10^4	3×10^1	2×10^3	2×10^3	3×10^1
Area (km^2)	2×10^3	4×10^1	2×10^3	2×10^2	1×10^2	3×10^3	4×10^3
Average find density	Very high	High	Medium	Very rare	Medium	Rare	Very rare
Largest specimen (g)[a]	122	172	258	104	36	74	1.2
Oldest moldavite-bearing formation	Domanín Fm.: Vrábče Mb. (Middle Miocene)	Domanín Fm.: Koroseky Mb. (Middle Miocene)	Slavice and Třebíč deposits (Middle to Upper Miocene)	Grund Fm. (Middle Miocene); Irnfritz-Radessen Fm. (Miocene)	Vildštejn Fm. (Pliocene)	Rauno Fm.: Mühlrose Mb. (Upper Miocene)	Poznan Fm.: Gozdnica Mb. (Upper Miocene to Pliocene)
Main element composition (wt%)							
SiO_2[a]	78.6	82.6	79.3	79.7	78.7	79.3	77.5
Al_2O_3[a]	10.1	8.2	11.0	9.8	10.1	10.5	10.8
FeO as ΣFe[a]	1.62	1.18	2.26	1.54	1.62	1.84	1.9
CaO+MgO[a]	5.31	4.2	3.03	4.13	5.10	3.75	3.9
Physical properties							
Predominant color[b]	Bottle green (80%)	Pale to bottle green (90%)	Olive green to brown (89%)	Bottle green	Bottle green	Bottle to olive green (70%)	Pale to bottle green (100%)
Homogeneity[b]	+	+++	+++	n.d.	+	+++	n.d.
Lechatelierite abundance[b]	+++	+	+	n.d.	+++	++	+
Bubble abundance[b]	+++	+	+	n.d.	+++	+	++
Crystal inclusions[b]	×	×	○	○	○	○	○
Muong Nong type[a]	Found	○	○	○	○	○	○
HCa/Mg-Type[b]	Found	○	○	○	○	○	○
Density ($g \cdot cm^{-3}$)[b]	2.280–2.294	2.270–2.395	2.332–2.383	n.d.	2.340–2.380	2.305–2.379	n.d.
Refraction index[b]	1.486–1.503	1.483–1.484	1.487–1.538	n.d.	1.489–1.494	1.481–1.495	n.d.

Note: Semiquantitative information on amounts or properties +++, higher; ++, medium; +, lower; ×, rare; ○, unknown; n.d., not determined.

[a]Trnka and Houzar (2002), Hurtig (2017), Brachaniec (2020).

[b]Bouška (1998), Koeberl et al. (1988), Lange (1995).

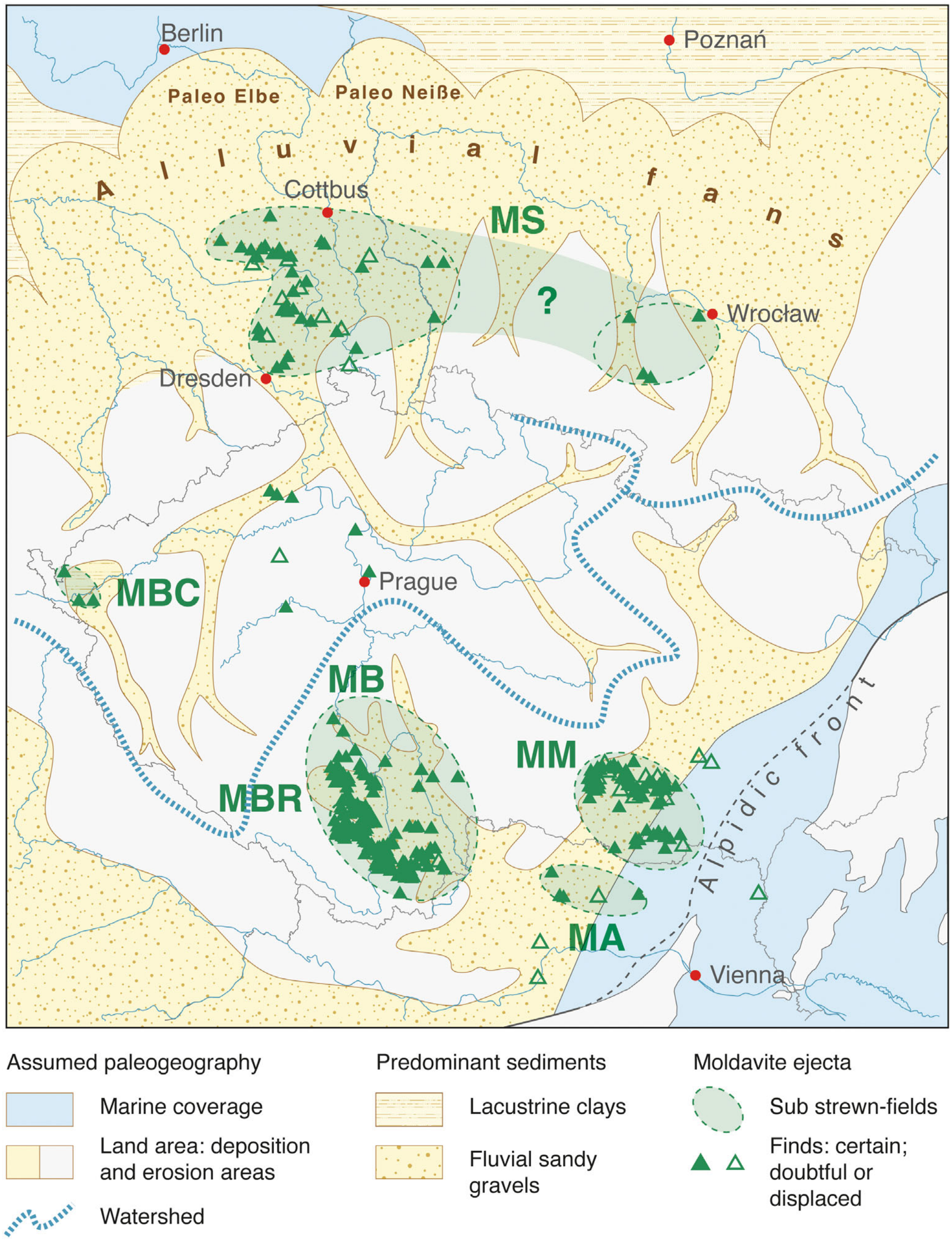


FIGURE 6. The tektite ejecta of the Ries crater. Moldavite sub-strewn fields: MA, Lower Austria; MB, South Bohemia; MBR, Radomilice; MBC, Northwest Bohemia (Cheb/Eger); MM, Southwest Moravia; MS, North Sudetes with Lausitz and Silesia (Hurtig, 2017; Lange, 1993). The moldavite sites also include occurrences in Pliocene and Quaternary deposits. The paleogeography of the Upper Miocene—the time of the most important moldavite-bearing sediments present today—is shown. (Color figure can be viewed at wileyonlinelibrary.com.)

Soft Sediment Deformations, Seismites (Foreland Molasse Basin)

Letsch (2018) was the first to discuss sandstone dikes (clastic dikes) from the Brockhorizont of Bernhardzell as paleoseismic formations. Buchner et al. (2020) succeeded in detecting seismites immediately below the Brock horizon in outcrops 110 km (Biberach and Ochsenhausen), 140 km (Ravensburg), and 180 km (Bernhardzell) from the Ries center. These are slip folds, convolute beddings, ball-and-pillow structures, flame structures, clastic dikes, and sand spikes in sandy and silty sediments of the Upper Freshwater Molasse (Buchner et al., 2020, 2021). However, some clastic dikes penetrate the Brockhorizont (Buchner et al., 2022; Sach et al., 2020). They may be associated with the Steinheim impact, which may have occurred somewhat later than the Ries impact (Buchner et al., 2022).

Seese Boulder Association (Lausitz/Lusatia, Northwest European Tertiary Basin)

In Lausitz (East Germany), early Paleozoic boulders with silicified fossils from the southern Scandinavian and eastern Baltic region occur abruptly in the Middle Miocene Meuro Formation (Figure 7; Ahrens & Lotsch, 1976; Krueger, 1990, 1994: figure 12). There is a remarkable occurrence of large (up to 50 cm long, see also Krueger, 1990: plate 1) and subangular components from Cambrian quartzites (Lotsch, 1969), which can neither be reconciled with the marine character of the enclosing sediment nor with a fluvial transport. Ahrens and Lotsch (1976) and Ludwig (2015) explain these enigmatic conditions by ice-drift transport. However, evidence of short-term cooling is required, which cannot be proven paleobotanical and paleoclimatological with certainty. The connection between the origin of the Seese Member and the Ries event is already assumed by Göthel (2002), who also assumes an additional impact in the Paleo-North Sea of the Northwest European Tertiary basin and explains the peculiar sedimentation conditions with a tsunami. However, transport of half meter-sized blocks from the northern and eastern coasts (South Scandinavia and East Baltic region) across the Paleo-North Sea to the southern coastal region (South Brandenburg) is difficult to imagine. From our point of view, the input of coarse clastic components into the fine-grained marine Seese sands can best be explained according to Ahrens and Lotsch (1976) with a short-term cooling event and thereby triggered ice-drift transport as a consequence of the Ries impact.

The "Spezialton Heide" (Lausitz/Lusatia, Northwest European Tertiary Basin)

Within the Meuro Formation of the Niederlausitz (Lower Lusatia), the so-called Spezialton Heide (special clay of Heide) at the top of the Greifenhain Member occurred in the Klettwitz–Heide area (Figure 7). This layer can be traced by a characteristic double peak of the gamma ray curve of the geophysical borehole measurement in large parts of the Lausitz. The Spezialton Heide and its equivalents are a kaolinitic clay that is occasionally coal bearing and always contains glauconite. The presence of glauconite indicates a marine sedimentary environment. Striking is the abundance of xylite and other plant remains (Lotsch, 1969) and the occurrence of driftwood, colonized by shipworms (*Teredo* sp.; Lange & Suhr, 2022) directly in the top of the clay (open-cast mine Klettwitz-Nord, own observation 1992). The clay shows fine stratification.

The mineralogical composition (Vulpius, 2006), with the predominance of kaolinite (63%), subordinate quartz (16%), muscovite and illite (16%), and montmorillonite (5%), indicates the erosion of a weathering profile with a high degree of maturity that had achieved deferrization and almost complete kaolinite formation. The short-term deposition of such weathering material in the marine environment implies a singular event caused by a widespread erosion of the weathering crust on land. Together with the accumulation of shipworm-drilled driftwood on the top of the clay, extensive destruction of the vegetation in the hinterland of the sedimentation area is assumed. This destruction, combined with heavy rainfall events (Buchner et al., 2020; David, 1969; Žebera, 1977), led to an intense erosion of the kaolinized basement. The resulting erosion products were washed into the marine sedimentation realm as kaolinitic clays and sedimented with autochthonous glauconite.

The "Helle Horizont" (Northern Germany, Northwestern European Tertiary Basin)

In Southwest Mecklenburg, the so-called Helle Horizont (bright horizon) interrupts the sedimentation of the black mica-bearing silts ("Glimmerschluffe") of the Pritzier Formation (Lotsch, 1981). The Pritzier Formation is placed in the Middle and Upper Miocene and comprises the upper part of the Langhian, the Serevallian, and deeper parts of the Tortonian (Menning & Hendrich, 2016).

The lithology of the Helle Horizont is described by Zimmerle (2000) as a beige silty clay with driftwood. The horizon level can be traced to the Hamburg area, based on a characteristic double peak in the gamma ray curves of the geophysical borehole measurements (Bülow, 2000; Hinsch, 2000). This is similar to the situation with the Spezialton Heide in the Lausitz area (Figure 8).

According to Zimmerle (2000), the mineralogical composition of the Helle Horizont differs fundamentally from that of the rest of the Pritzier Formation. In the Helle Horizont, the main mineralogical component is kaolinite, whereas quartz predominates in the mica-bearing silts. The occurrence of gibbsite is restricted to the Helle Horizont. Like kaolinite, it is an indicator for deep weathering and, among others, occurs in subtropical and tropical soil profiles.

A complete change in sediment supply can explain the abrupt lithological change in an otherwise monotonous sedimentary sequence. This may have caused large-scale destruction of the vegetation cover in the southern hinterland of the Northwest European Tertiary basin triggered by the Ries impact, combined with heavy rain events (Buchner et al., 2020; David, 1969; Žebera, 1977). Hinsch (1999, 2000) also considers this horizon to be a significant geologic event in the Miocene and correlates it with the Ries impact.

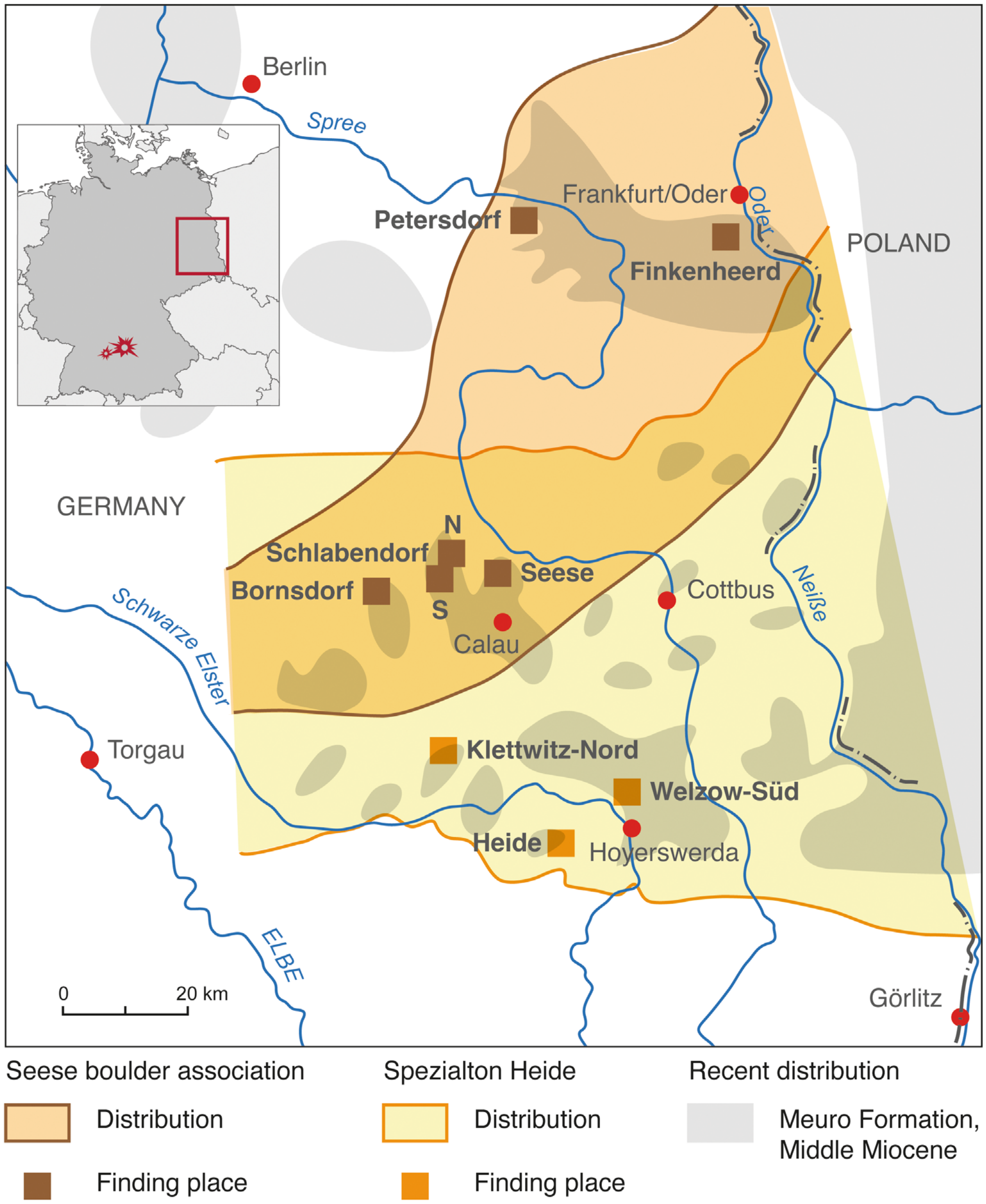


FIGURE 7. Distribution of the Seeser Gerölle (Seese boulders) and the Spezialton Heide (special clay of Heide) in the Lausitz area (modified after Ahrens & Lotsch, 1976). (Color figure can be viewed at wileyonlinelibrary.com.)

Dirt band in the Frimmersdorf seam (Niederrheinische Bucht/Lower Rhine bight, Northwest European Tertiary Basin)

In the marginal area of the subsidence field of the Niederrheinische Bucht, an almost continuous lignite seam (Main seam, Ville Formation) was formed from the upper Lower Miocene up to the Middle Miocene. From the North, marine sands (Frimmersdorf sand and Neurath sand) interfingered into the seam. Their deposition was due to transgressive processes (Figure 9). In contrast, the dirt band (Zwischenmittel) ZM6C in the Frimmersdorf seam was formed by braided and meandering rivers (Prinz et al., 2017: figure 2). This fluvial fill must have breached the continuous peat belt (Main seam). Such a paleogeographic situation is unique in the Middle Miocene of the Niederrheinische Bucht. The striking event is correlated with the Middle Miocene Unconformity (MMU) in the North Sea region by Schäfer and Utescher (2014) and Prinz et al. (2017: figure 2). A connection with the Ries event is conceivable, as it may have triggered an erosional impulse in the hinterland of the Niederrheinische Bucht by destroying vegetation. The emplacement age of the dirt band at about 14.8 Ma (Prinz et al., 2017: figure 2) would support this connection.

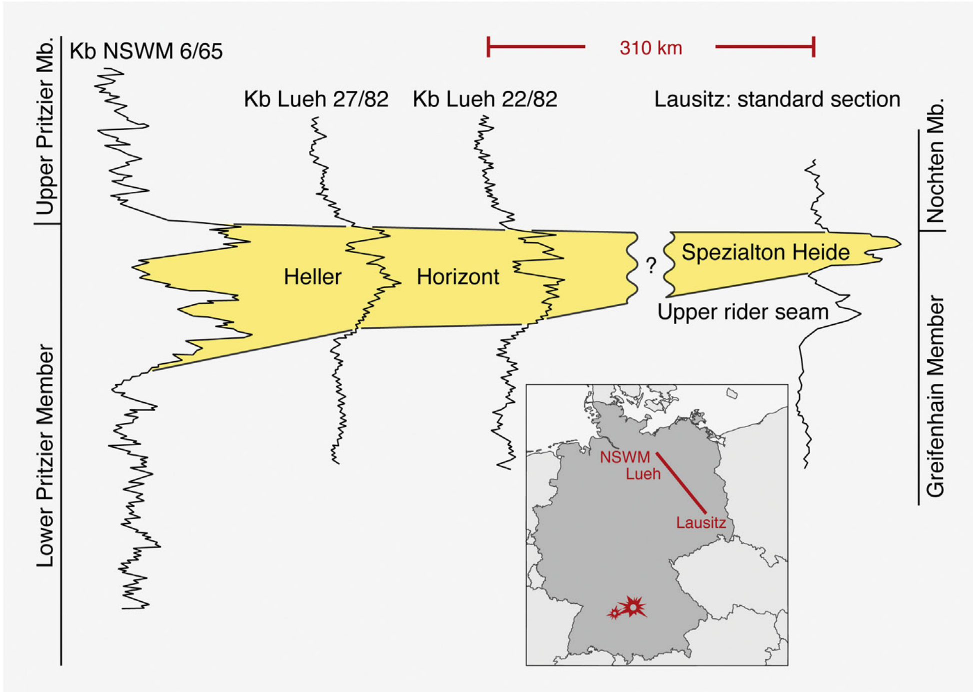


FIGURE 8. Correlation of gamma ray logging from boreholes in the Helle Horizont (bright horizon) and the Spezialton Heide (special clay of Heide). (Color figure can be viewed at wileyonlinelibrary.com.)

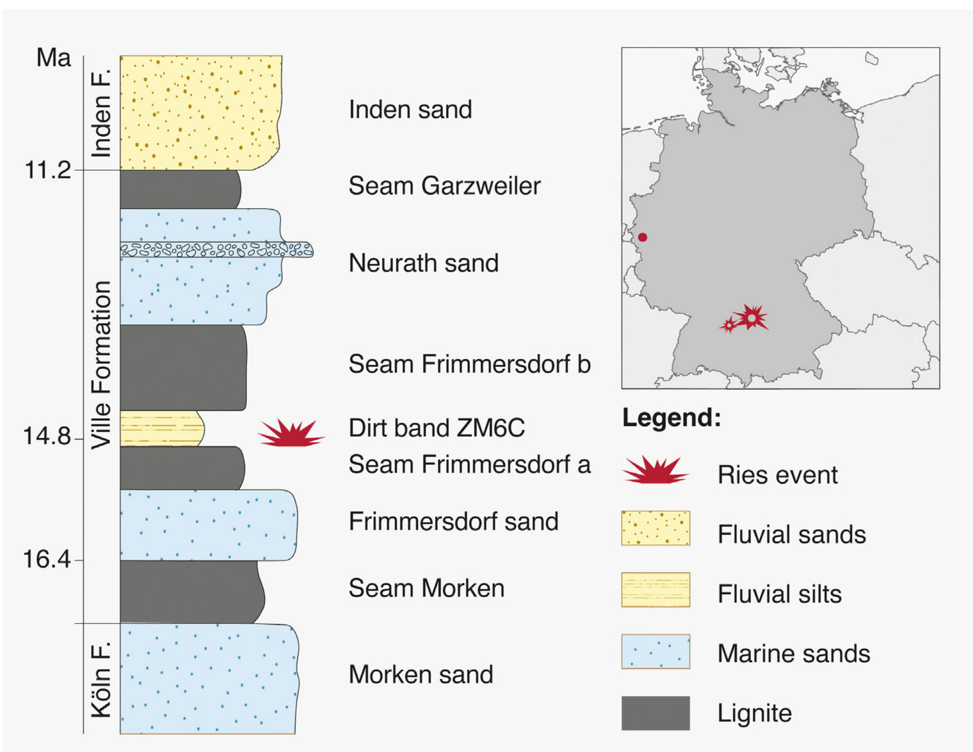


FIGURE 9. Profile of the Frimmersdorf seam from the Niederrhein lignite area (Ville Formation) with the fluvial dirt band ZM6C (following Schäfer & Utescher, 2014). (Color figure can be viewed at wileyonlinelibrary.com.)

All three horizons described above in the Northwest European Tertiary Basin (Spezialton Heide, the Helle Horizont, and the dirt band ZM6c) are to be considered as sedimentological signals of intensified erosion in the hinterland devastated by the Ries event.

Conclusions

The Ries impact event had catastrophic consequences for large parts of Central Europe. For a comprehensive evaluation of this event, an interdisciplinary view is necessary. Previous literature usually only examines selected distal phenomena (e.g., moldavites, Brockhorizont). This paper deals with various indicators for impact hazards over a larger area of the paleoenvironment (up to 500 km) and provides a synopsis. The event's short duration is the main obstacle to identifying and correlating the phenomena. Despite this, manifold clues in sediments could be found, which can be related to the Ries event with some probability. The validity and the precision of the correlations are of different quality. If the study of correlative sedimentary sequences also takes the Ries impact at a greater distance into account, then further indications of the event could be found.

Acknowledgments—This work was developed over several years and is based significantly on the joy of discussion and the extensive willingness of many colleagues to provide information. Among them, we especially mention (in alphabetical order) Gareth S. Collins (London), Ingomar Fritz (Graz), Mathias Harzhauser (Vienna), Vít Krsul (Český Krumlov), Karsten Obst (Güstrow), Jean Pohl (Munich), Roman Rönick (Cottbus), Andreas Schäfer (Bonn). Astrid Engelhardt (Dresden) carried out parts of the final drawings. We thank all the colleagues mentioned above for their support. The authors thank the very helpful reviews by Michael Poelchau, Martin Schmieder, and Bruce Simonson who all made insightful comments to this contribution. Open Access funding enabled and organized by Projekt DEAL.

Data Availability Statement—The data that support the findings of this study are available from the corresponding author upon reasonable request.

Editorial Handling—Dr. Michael H. Poelchau

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