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First direct evidence for a contiguous Gondwana shelf to the south of the Rheic Ocean

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ABSTRACT

Sea-level rise after the Hirnantian glaciation resulted in the global inundation of continental shelf areas and the widespread formation of early Silurian black shales. Black shales that were deposited on shelves receiving drainage from earlier glaciated areas have high uranium (U) contents because large-scale glacial erosion brought rocks with leachable U to the surface. In contrast, black shales receiving drainage from non-glaciated areas that had lost leachable U earlier have low U contents. Early Silurian U-rich shales formed only on shelf areas that had not been separated from earlier-glaciated mainland Gondwana by oceanic lithosphere. Therefore, early Silurian U-rich black shales within the Variscan orogen provide direct evidence that these areas had not been separated from mainland Gondwana, but were part of the same, contiguous shelf. This implies that the Rheic Ocean was the only pre-Silurian ocean that opened during the early Paleozoic extension of the peri-Gondwana shelf.

INTRODUCTION

The assembly of western Pangea included the collision between Laurentia and the East European Craton to form Laurussia (Caledonian orogeny) followed by the collision of Gondwana with Laurussia in Europe (Variscan orogeny) and the final closure of the remaining Rheic Ocean between western Africa and North America (Alleghanian orogeny). Avalonia, which is the most important Gondwana-derived terrane to the north of the Rheic Ocean, had separated from Gondwana before the late Cambrian and docked to the East European Craton before colliding with Laurentia (Matte, 2001; Kroner and Romer, 2013; Franke et al., 2017; Stephan et al., 2019a). There is a long-lived disagreement about the number of pre-Silurian oceans and, thus, independently moving blocks of continental crust (microplates) between mainland Gondwana and mainland Laurussia (Fig. 1).

Basically there are two end-member groups of models for the Variscan orogen. The first group of models involves two plates (Gondwana and Laurussia) and several independently moving microplates or terranes—now preserved in the various Variscan massifs—between them, all of which were separated by oceanic lithosphere (e.g., Matte, 2001; Franke et al., 2017). The Rheic Ocean is the only ocean common to all models of this type. Other proposed oceans commonly are of limited extent and are not necessarily present in all models (Fig. 1B). The second group of models includes two plates (Gondwana and Laurussia) (e.g., Robardet, 2003) and one single divergent plate boundary, i.e., the mid-ocean ridge of the Rheic Ocean. In these models, post-Silurian collision resulted in long-lasting subduction-accretion processes of the segmented shelf of both plates, culminating in intraplate continental subduction during the late stages of the Variscan collision (Kroner and Romer, 2010, 2013).

THE DEBATE: CONTIGUOUS SHELF VERSUS SEVERAL MICROPLATES

Models of the Variscan orogen involving the presence of several independently moving microplates separated by pre-Silurian oceanic lithosphere use essentially the same data as models for a contiguous shelf. The debate originates from the contrasting weighting of the various data sets, none of which is decisive. For instance, paleomagnetic data were widely believed to provide key evidence for viewing the Variscan massifs between mainland Gondwana and mainland Laurussia as independently moving microplates that were separated by wide oceans (e.g., Tait et al., 1997). The latter point has seen major modifications: Franke et al. (2017, p. 257)—favoring models involving several microplates separated by oceanic lithosphere—stated "only the Rheic Ocean between Avalonia and peri-Gondwana was wide enough to be unambiguously recorded by biogeography and palaeomagnetism". The limitation of paleomagnetic constraints was additionally highlighted by Franke et al. (2017, p. 277): "it is worth remembering that Palaeozoic palaeomagnetic poles from Armorica, Iberia, Saxothuringia and Bohemia, are few and of variable quality, and there are time gaps with no data". These statements support the view that current paleomagnetic data cannot be taken as evidence against a contiguous shelf (Kroner and Romer, 2010, 2013).

The late Cambrian to Early Ordovician extension in peri-Gondwana eventually leading to the separation of Avalonia resulted in the redistribution of chemically distinctive sandstones. The occurrence of such redeposited sandstones implies that the corresponding pre-Variscan basement blocks had not separated from mainland Gondwana before the Early Ordovician (Noblet and Lefort, 1990). Moreover, there are numerous additional indirect arguments favoring a contiguous pre-Silurian shelf to the south of the Rheic Ocean. Ordovician to Devonian fossil assemblages suggest that the Variscan massifs to the south of the Rheic Ocean and mainland Gondwana were part of the same shelf (Robardet, 2003). The age distribution of detrital zircon in Cambrian to Devonian sedimentary rocks demonstrates that the different Variscan massifs were part of the Gondwana shelf (Stephan et al., 2019a, and references therein), with different zircon assemblages on the western and eastern parts of the contiguous shelf. The presence of detrital zircon of eastern-shelf provenance in Ordovician and Silurian sediments of the western shelf requires a contiguous shelf during redeposition of sedi-

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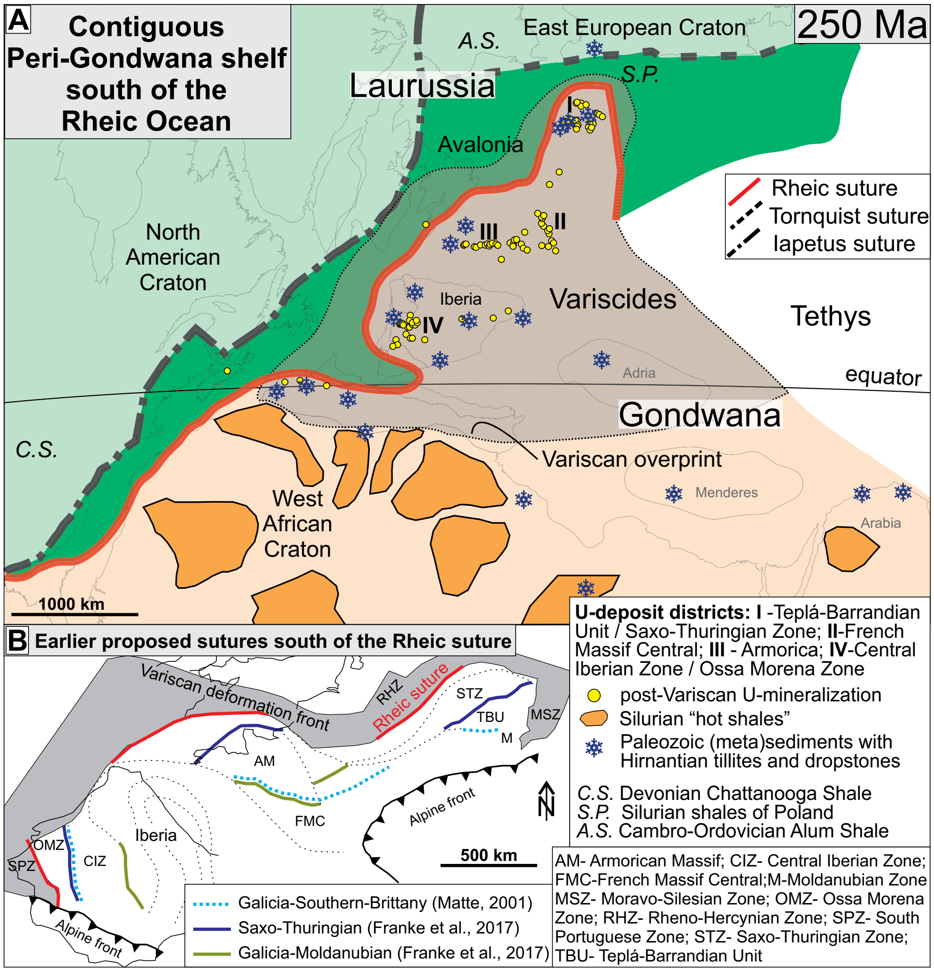

Figure 1. A: Pangea reconstruction for 250 Ma (Stephan et al., 2019b) showing distribution of Hirnantian tillites and dropstones, early Silurian hot shales, and post-Variscan uranium mineralization (as a proxy for hot Siluran shales in orogenically overprinted peri-Gondwana crust; yellow dots). Note early Silurian hot shales are restricted to the Gondwana mainland and Variscan blocks to the south of the Rheic suture. Data sources: Thickpenny and Leggett (1987), Lüning et al. (2000), Le Heron et al. (2009), Romer and Cuney (2018), Porębski et al. (2019). B: Simplified tectonic map of Variscan orogen showing earlier proposed oceanic sutures (compiled from Matte, 2001; Franke et al., 2017).

ments from the eastern shelf onto the western shelf (Stephan et al., 2019b).

Post-Silurian ophiolitic complexes, which classically are interpreted as remnants of different oceans (Matte, 2001; Franke et al., 2017), are spatially related to the Gondwana-Laurussia plate boundary zone and not in conflict with a contiguous shelf to the south of the Rheic Ocean (Kroner and Romer, 2013, and references therein). The Variscan high-pressure, ultrahigh-pressure, high-temperature, and ultrahigh-temperature metamorphic units far from the Rheic suture, which in part have been interpreted as traces of oceanic sutures (e.g., Matte, 2001), have been reinterpreted as remnants of intracontinental subduction within previously stretched peri-Gondwana lithosphere (Kroner and Romer, 2013, and references therein). Hence, present evidence does not require additional oceanic spreading centers to the south of the Rheic Ocean.

FORMATION OF HOT SHALE

Black shales reflect anoxic conditions on the local, regional, or global scale. The most important black shales form on continental shelves in settings of high organic production and restricted circulation, which eventually results in the oxygen depletion of the water body, combined with limited carbonate production and limited detrital silicate input (e.g., Werne et al., 2002). Black shale deposits typically are enriched in redox-sensitive elements that are scavenged from the water column. Average black shale has ~8.5 ppm U (Ketris and Yudovich, 2009). There are, however, black shale occurrences that may have >1000 ppm U (e.g., Leventhal, 1991). Even if all U contained in the water column is concentrated in a 1-m-thick layer of black shale, this shale would have <10 ppm authigenic U. Thus, high U contents in shale require a continuous supply of U provided by surface runoff from the continent. Under reducing conditions, U sourced from terrestrial weathering becomes preferentially sequestered in the proximal shelf, eventually resulting in a drawdown of U supply to the distal shelf and the adjacent abyssal plain.

Paleozoic hot shales reflecting major global anoxic events are known for instance from Baltica (middle Cambrian to Early Ordovician Alum Shale), northern Gondwana (early Silurian Lower Graptolite Shale), and North America (mid-Devonian Chattanooga Shale). The most important feature of these shale deposits—apart from their high U content—is that coeval black shale deposits on *other* continental shelves do not have particularly high U contents (Fig. 2). This implies that continuous input of U is essential, i.e., the fertility of the drainage area serving as the U source controls whether a black shale turns into a hot shale or not (Romer and Cuney, 2018). High U input from surface runoff on one shelf cannot be trapped in black shale deposited on another shelf, i.e., U source and U trap cannot be separated by oceanic lithosphere.

Uranium is readily mobilized in the continental environment, in particular in a highly oxygenated or CO_2-rich atmosphere by oxidation of U-rich sedimentary rocks, oxidation of uraninite in granites, and leaching of metamict silicate minerals (Romer and Cuney, 2018). Thus, near-surface rocks are readily depleted in U and, thereafter, do not represent a U source. For black shales to become hot, they have to receive drainage from an area that still is a U source, i.e., leachable U must not have been lost previously. Tectonic uplift followed by strong erosion is a process that brings rocks not depleted earlier in U to the surface and thereby establishes a U source. Major glaciation also removes rocks that have lost their leachable U and brings rocks with leachable U to the surface. Because a U source may be rapidly depleted in U, the presence of a U trap at the time a U source becomes available is essential for the formation of hot shale.

Early Silurian black shale is directly related to the Hirnantian glaciation, more closely to the melting of the Hirnantian ice sheet that resulted in eustatic sea-level rise and transgression on shelf areas. Paleo-depressions such as former glacial outwash valleys and structural intrashelf basins eventually developed anoxic conditions that reflected the effects of high organic production and restricted circulation (Lüning et al., 2000; Le Heron et al., 2009). Anoxic conditions on the shelf may have persisted for a relatively short period, as the continued rise of sea level (1) moved the coastline inland, which is essential to reducing dilution of the black shale by coarse siliciclastic material that gets entrapped in retrograding river mouths, and (2) eventually resulted in better water circulation on the shelf and, thus, less-anoxic conditions (Lüning et al., 2000).

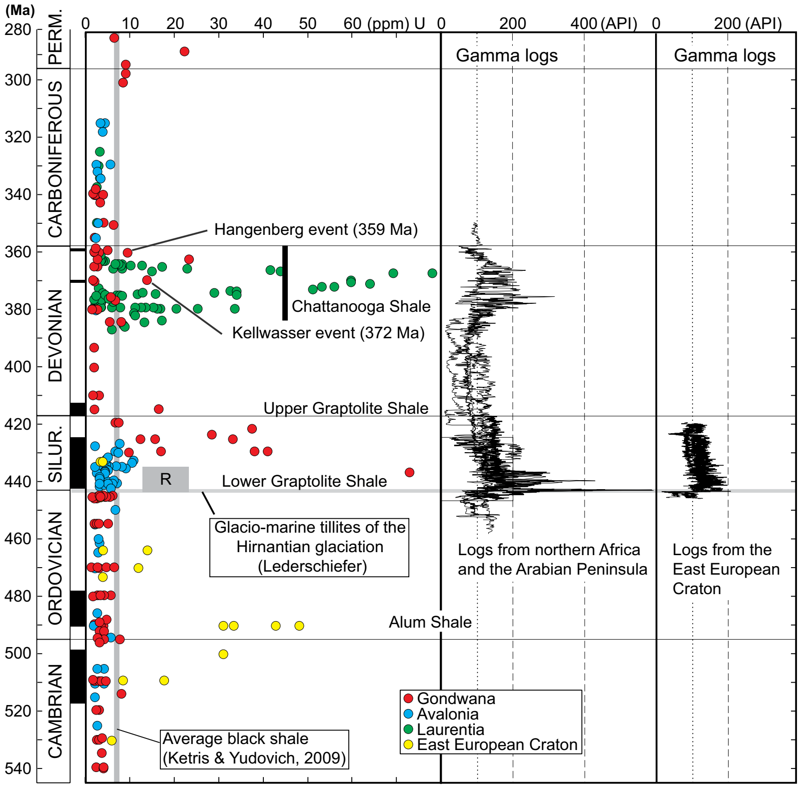

Figure 2. Temporal variation of uranium in Paleozoic sedimentary rocks (mostly shales) from Gondwana, Avalonia, Laurenita, and the East European Craton. Periods of global black shale (black boxes along time axis) and Hirnantian glaciation are shown schematically. Note hot shale occurs on all continents, but is not coeval, which reflects the need of a suitable local or regional uranium source for development of hot shale. Early Silurian hot shale is restricted to Gondwana; i.e., northern Africa, Arabia, and Variscan rocks to the south of the Rheic suture (Fig. 1). Silur.—Silurian; Perm.—Permian. Left side: Bulk rock chemical data. R—major U deposits (Lederschiefer and Lower Graptolite Shale) in Ronneburg district (present-day Germany). Right side: Gamma logs for drill holes from hydrocarbon exploration. (100 API [American Petroleum Institute] units correspond to the radioactivity of a typical shale.) Data sources: Lüning et al. (2000, 2003), Linnemann and Romer (2002), Cruse and Lyons (2004), Ross and Bustin (2009), Romer and Hahne (2010), Linnemann et al. (2012), Porębski et al. (2013), Smolarek et al. (2017).

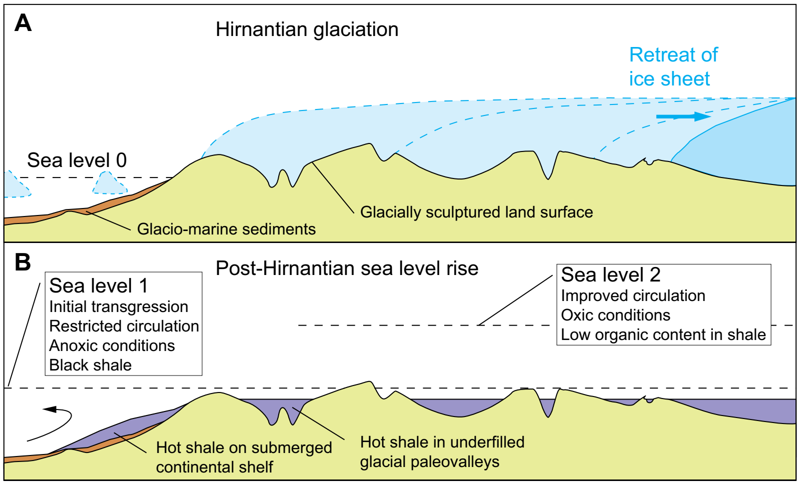

Figure 3. Schematic diagram connecting melting of ice sheets with sea-level rise and formation of black shale (modified after Le Heron et al., 2009). Note hot shale only forms on shelf areas receiving drainage from an area that had not been depleted in uranium previously; i.e., areas bordering (1) tectonic active areas, e.g., eroding orogen, or (2) glacially eroded areas. For early Silurian hot shales, melting of Hirnantian ice sheet is the causal link for coeval development of uranium source and uranium sink.

The high U content of early Silurian black shale on the northern Gondwana shelf is directly related to the Hirnantian glaciation. The Hirnantian glaciation removed U-depleted near-surface rocks. Thus, formerly glaciated areas, as well as fine-grained glacial and peri-glacial sediments, represented for a short time source rocks for U leaching (Romer and Cuney, 2018). The melting of the Hirnantian ice sheet made glacially exposed source rocks available for U leaching, whereas the rising sea level, which was the direct result of the melting of the ice sheets, resulted in the development of anoxic conditions on the shelf areas (Fig. 3). Thus, the same process that made U available for redistribution also gave rise to the U trap. On other continents without major ice sheets, the rising sea level also resulted in anoxic conditions on shelf areas, but there was no U source available because U on stable continents had been lost previously.

DISTRIBUTION OF SILURIAN HOT SHALES

The spatial distribution of early Silurian black shale is well documented, largely because these rocks represent an important source lithology for oil and shale gas (Lüning et al., 2000; Le Heron et al., 2009). On northern Gondwana, i.e., present-day North Africa, Arabia, and Middle East (Jordan, Iraq, Iran), such shale is characterized by anomalously high U contents that produce very distinctive peaks in gamma logs of drill holes (Fig. 2). Although it is a typical feature of black shale to have enhanced U contents because of the cumulation of authigenic U during deposition of these sediments (Ketris and Yudovich, 2009), early Silurian black shale of northern Gondwana is particular because of the following reasons. (1) The hot shales were deposited on a post-glacial shallow shelf or in intrashelf basins (Le Heron et al., 2009). (2) Black shale deposited directly on top of Hirnantian (ca. 445–443 Ma) glacial and glacio-marine sediments has higher U contents than younger Silurian black shale (Lüning et al., 2000). Early Silurian (and locally also latest Ordovician) black shale on the Cadomian basement of Iberia, Armorica, and the Saxo-Thuringian zone (all crustal blocks that became involved in the Variscan orogeny) also is characterized by anomalously high U contents. In contrast, early Silurian black shale from Avalonia, the East European Craton, and Laurentia does not show such anomalously high U contents (Fig. 2) even though there may be local dropstones derived from Gondwana-derived icebergs (Porębski et al., 2019).

The spatial distribution of post-Variscan U mineralization indirectly reflects the distribution of U-rich early Silurian shales within the Variscan orogen, in part because these shales served as a direct U source, and in part because they were involved in Variscan crustal melting eventually leading to uraninite-bearing granites that served as a U source for later mineralization (Romer and Cuney, 2018). Major U mineralization occurs in all Variscan massifs to the south of the Rheic suture, but is absent or only minor within the Variscan belt to the north of the Rheic suture (Fig. 1).

DISCUSSION AND CONCLUSIONS

The Hirnantian glaciation is restricted to Gondwana (Le Heron et al., 2009). In the early Silurian, deglaciating areas of Gondwana represented the major source of leachable U. Such a source was lacking on continents that had not been glaciated. Consequently, black shale deposited on the Gondwana shelf is U-rich, whereas black shale deposited on the shelves of other continents has low U contents (Fig. 2). Because under anoxic conditions U is precipitated on the proximal shelf, the presence of U-rich early Silurian black shale represents evidence that the corresponding crustal block was part of the contiguous Gondwana shelf. Thus, the distribution of U-rich early Silurian black shale within the Variscan orogen (Fig. 1) demonstrates that Iberia, Armorica, and the Saxo-Thuringian zone in the early Silurian could not have been separated from the contiguous Gondwana shelf by early Paleozoic divergent plate boundaries. Actually, the distribution of mostly post-Variscan U mineralization, which largely derives its U content from U-rich early Silurian black shale or from granites that have melted such U-rich sedimentary rocks, indicates that the Variscan metamorphic rocks of Armorica, the French Massif Central, and the Saxo-Thuringian zone (Fig. 1) were part of the Gondwana shelf in the early Silurian.

The distribution of early Silurian U-rich black shale (and post-Variscan U mineralization; Fig. 1) is not compatible with pre-Silurian oceanic lithosphere separating Iberia, Armorica, or the Saxo-Thuringian zone from mainland Gondwana. All of these Variscan massifs are located to the south of the Rheic suture. The distribution of U in early Silurian black shale and Variscan mineralization implies that the Rheic was the only pre-Silurian ocean between Gondwana and Laurussia. Tectonic models considering crustal fragments like the Central Iberian zone, Armorica, the Teplá-Barrandian unit, and the Saxo-Thuringian zone as continental parts of independent microplates separated by pre-Silurian oceanic lithosphere are in conflict with the distribution of U-rich early Silurian black shale.

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