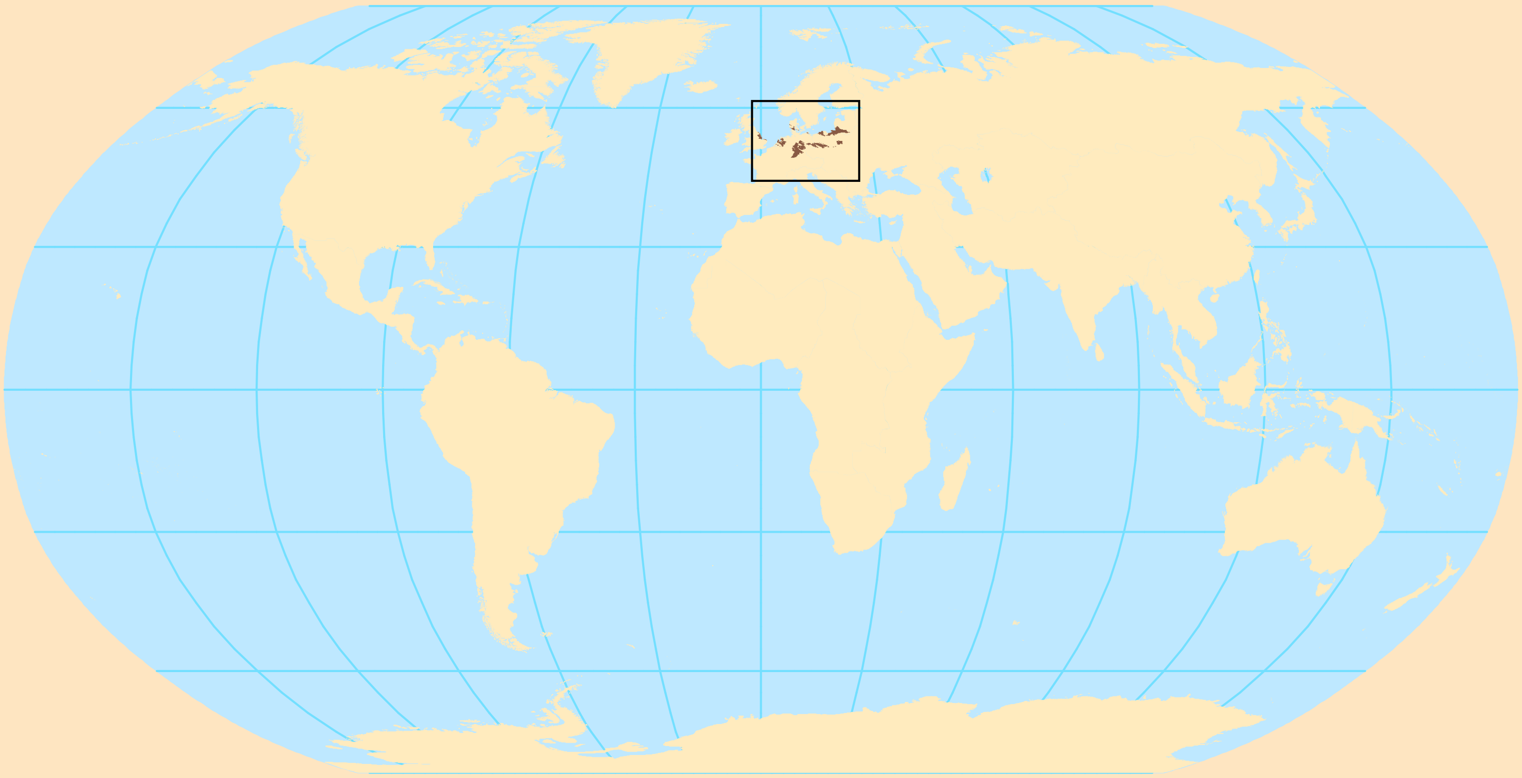
Global Mineral Resource Assessment

Assessment of Undiscovered Copper Resources Associated with the Permian Kupferschiefer, Southern Permian Basin, Europe



Prepared in cooperation with the Polish Geological Institute–National Research Institute

Scientific Investigations Report 2010–5090–U

U.S. Department of the Interior
U.S. Geological Survey

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Michael L. Zientek, Jane M. Hammarstrom, and Kathleen M. Johnson, editors

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
ounce, troy (troy oz)	31.103	gram (g)
ounce, troy (troy oz)	0.0000311	megagram (Mg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
gram (g)	0.03215	ounce, troy (troy oz)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
	Other conversions used in this report	
metric ton (t)	1	megagram (Mg)
troy ounce per short ton	34.2857	gram per metric ton (g/t)
percent (%)	10,000	parts per million (ppm) or grams per metric ton (g/t)

Acronyms and Abbreviations

%	percent
%Ro	vitrinite reflectance
Ag	silver
B	COMECON mineral resource category, which is analogous to measured mineral resources as defined by CRIRSCO.
b.v.	Besloten vennootschap—a Dutch private limited liability company.
C1	COMECON mineral resource category, which is analogous to indicated mineral resources as defined by CRIRSCO.
C2	COMECON mineral resource category, which is analogous to inferred mineral resources as defined by CRIRSCO.
CE	Common Era
COMECON	Sovet Ekonomicheskoy Vzaimopomoshchi (The Council for Mutual Economic Assistance)
CRIRSCO	Committee for Mineral Reserves International Reporting Standards
CSD	copper surface density
Cu	copper
Eh	oxidation-reduction potential
Esri	A software development and services company providing geographic information system software and geodatabase management applications.
g/t	grams per metric ton
GGS	Gaussian geostatistical simulation
GIS	geographic information system
GmbH	Gesellschaft mit beschränkter Haftung (company with limited liability)
K-Ar	potassium-argon
KSL	KSL Kupferschiefer Lausitz GmbH
KGHM	Kombinat Górniczo-Hutniczy Miedzi (Copper Smelting-Mining Combine) Polska MiedźźS.A.—a large Polish copper mining and metallurgical company.
Ltd.	limited
Ma	mega-annum or millions of years before the present
mg/L	milligrams per liter
MOS	Ministerstwo Środowiska (Polish Ministry of the Environment)
Mt	million metric tons
mV	millivolts
P1	Russian mineral resource category, which is analogous to exploration results as defined by CRIRSCO or undiscovered mineral resources as used by the USGS. These prognostic mineral resources estimates refer to extensions to inferred resources and are based on limited direct geological evidence.
P2	Russian mineral resource category used by Russian geologists, which is analogous to exploration results as defined by CRIRSCO or undiscovered mineral resources as used by the USGS. These prognostic mineral resources estimates refer to exploration targets identified by geologic mapping, geophysical surveys, or geochemical data.

PGI	Polish Geological Institute–National Research Institute
pH	a measure of the acidity or alkalinity of an aqueous solution
ppm	parts per million
SPB	Southern Permian Basin
SSC	sediment-hosted stratabound copper
SSIB	small-scale digital international boundaries
USGS	U.S. Geological Survey
Re-Os	rhenium-osmium

Assessment of Undiscovered Copper Resources Associated with the Permian Kupferschiefer, Southern Permian Basin, Europe

By Michael L. Zientek[1], Sławomir Oszczepalski[2], Heather L., Parks[1], James D. Bliss[3], Gregor Borg[4], Stephen E. Box[1], Paul D. Denning[5], Timothy S. Hayes[3], Volker Spieth[6], and Cliff D. Taylor[5]

Abstract

This study synthesizes available information and estimates the location and quantity of undiscovered copper associated with a late Permian bituminous shale, the Kupferschiefer, of the Southern Permian Basin in Europe. The purpose of this study is to (1) delineate permissive areas (tracts) where undiscovered reduced-facies sediment-hosted stratabound copper deposits could occur within 2.5 kilometers of the surface, (2) provide a database of known reduced-facies-type sediment-hosted stratabound copper deposits and significant prospects, and (3) provide probabilistic estimates of amounts of undiscovered copper that could be present within each tract. This assessment is a contribution to a global assessment conducted by the U.S. Geological Survey (USGS).

Permissive tracts are delineated by mapping the extent of the Kupferschiefer that overlies reservoir-facies red beds of the lower Permian Rotliegend Group. More than 78 million metric tons (Mt) of copper have been produced or delineated as resources in the assessed tracts, with more than 90 percent of the known mineral endowment located in Poland. Mines in Poland are developing the deposit at depths ranging from about 500 to 1,400 meters.

Two approaches are used to estimate in-situ amounts of undiscovered copper. The three-part form of assessment was applied to the entire study area. In this approach, numbers of undiscovered deposits are estimated and combined with tonnage-grade models to probabilistically forecast the amount of undiscovered copper. For Poland, drill-hole data were available, and Gaussian geostatistical simulation techniques were used to probabilistically estimate the amount of undiscovered copper. The assessment was done in September 2010 using a three-part form of mineral resource assessment and in January 2012 using Gaussian geostatistical simulation.

Using the three-part form of assessment, a mean of 126 Mt of undiscovered copper is predicted in 4 assessed permissive tracts. Seventy-five percent of the mean amount of undiscovered copper (96 Mt) is associated with a tract in southwest Poland. For this same permissive tract in Poland, Gaussian geostatistical simulation techniques indicate a mean of 62 Mt of copper based on copper surface-density data from drill holes.

Introduction

In response to growing demand for information about global mineral resources, the U.S. Geological Survey (USGS) led a global assessment of undiscovered copper resources (Briskey and others, 2001; Schulz and Briskey, 2003; Zientek and Hammarstrom, 2008; Hammarstrom and others, 2010). Undiscovered resources correspond to mineralized material whose location, grade, quality, and quantity are unknown or incompletely characterized, either in partially characterized sites or completely unknown mineral deposits. The global assessment studies use geoscience information to delineate tracts of land permissive for particular mineral deposit types (permissive tracts) and to probabilistically estimate the quantity and quality[1] of undiscovered resources.

Copper is found in many types of deposits that occur in diverse geologic associations. The USGS assessment effort focused on two deposit types that account for most of the copper that has been discovered—porphyry copper and sediment-hosted stratabound copper (SSC) (Singer, 1995). This report

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[5] U.S. Geological Survey, Denver, Colorado, United States.

[6] V.S. Globalmetal LLC, Tucson, Arizona, United States.

[1] Grade or concentration of the metal or material of interest is a measure of quality of the undiscovered resource (Singer and Menzie, 2010).

presents the results of an assessment of the Southern Permian Basin (SPB) in northern Europe for the occurrence of undiscovered copper associated with reduced-facies-type SSC deposits (fig. 1).

SSC deposits consist of fine-grained, copper- and copper-iron-sulfide minerals that form stratabound to stratiform disseminations in sedimentary rocks (Cox and others, 2003; Hitzman and others, 2005; Zientek, Hayes, and Hammarstrom, 2013). The concentration of sulfide minerals conforms closely, but not exactly, with stratification in the host rocks. Ore minerals such as chalcocite and bornite occur as cements and replacements in the matrix of the sedimentary rocks and, less commonly, as veinlets. Deposits are characterized by systematic changes in ore mineralogy along and across bedding from pyrite to chalcopyrite to bornite to chalcocite to hematite.

Field and laboratory evidence indicates that SSC deposits formed from late diagenetic fluids generated during the compaction and lithification of sedimentary basins containing successions of red beds and evaporites. The metal-bearing fluids are thought to be low-temperature, hematite-stable (oxidized), sulfate- and chloride-rich, and subsurface sedimentary brines. The primary cause of base-metal sulfide precipitation is reduction of sulfate in the brine by organic material.

Subtypes of SSC deposits are distinguished by host lithology and the nature of organic material in the sedimentary strata. The SSC mineralization in the SPB is an example of the reduced-facies subtype. Host beds for many reduced-facies deposits occur at or just above the flooding surface that marks the transgression of a marine depositional sequence over nonmarine red beds. The host rocks of reduced-facies-type deposits contain amorphous organic matter and finely disseminated pyrite. These host rocks overlie, or are locally interbedded with, red to brown or purple, hematite-bearing sandstone, siltstone, and (or) conglomerate (red beds) deposited in an arid climate (Davidson, 1965; Rose, 1976; Kirkham, 1989).

Copper ores have been mined since the 1200s in what is now central Germany and southwestern Poland from a late Permian (Lopingian) unit called the Kupferschiefer [literally, the copper slate]. The Kupferschiefer (and its stratigraphic equivalents) is bituminous shale or marl about a meter thick that underlies an area of about 600,000 square kilometers (km^2) in the SPB. Most copper production from the Kupferschiefer before the 1950s was from central Germany. Mineral exploration studies have been conducted episodically since the 1930s and ultimately led to the discovery of the world-class Lubin-Sieroszowice deposit (fig. 1) in southwestern Poland in the 1950s. Exploration continues in southwestern Poland and in eastern Germany, near the Polish border. Borg and others (2012) provide an up-to-date overview of the Kupferschiefer deposits in Europe.

In this study, two different approaches were used to assess undiscovered mineral resources. The first approach estimates the number of undiscovered deposits. These estimates are combined with grade and tonnage models using Monte Carlo simulation to probabilistically forecast the amount of undiscovered copper. This approach has been widely used in USGS mineral resource assessments since the 1970s (Singer and Menzie, 2010). The second approach, Gaussian geostatistical simulation (Vann and others, 2002; Esri, 2013a, b), uses drill-hole data and geostatistical methods to probabilistically estimate undiscovered mineral resources associated with incompletely explored extensions of stratabound ore deposits in southwestern Poland.

This document includes a brief geologic overview of the SPB and its SSC deposits, a description of the assessment process, and a summary of results. Appendixes provide additional information—appendix A introduces the scientists who participated in the panel that estimated numbers of undiscovered deposits; appendix B describes the spatial data files that accompany this report.

Regional Setting and Context

The Kupferschiefer occurs in the SPB, which extends from the United Kingdom across the southern North Sea, northern Germany, and Poland to Lithuania (fig. 1). The length of the SPB is about 1,700 kilometers (km) and its width varies between 300 and 600 km (van Wees and others, 2000). The Rhenish and Bohemian Massifs[2], which expose parts of the Variscan orogenic belt, define the southern margin of the SPB. To the north, the basin is bounded by the Mid North Sea High, Ringkøbing-Fyn High, and the Tornquist-Teisseyre Zone (fig. 1; Ziegler, 1990; van Wees and others, 2000; Littke and others, 2008; Gast and others, 2010).

The SPB is an intracontinental basin developed on the Variscan Orogen and its northern foreland (fig. 2). Variscan crustal shortening ceased towards the end of the Westphalian Stage, 314–313 millions of years before the present (Ma), and deposition of the lowermost units in the SPB began soon thereafter (Ziegler, 1990; van Wees and others, 2000; Narkiewicz, 2007; Geißler and others, 2008). The SPB overlies crustal domains belonging both to Baltica[3] in the north and Gondwana[4] in the south. The western and central parts of the SPB overlie Caledonian crust in the foreland of the external Variscan thrust belt. This foreland area includes the Anglo-Dutch and Pennine Basins, which contain as much as 9,000 meters (m) of Carboniferous strata including thick coal deposits. The south-central parts of the basin are superimposed on the Variscan fold and thrust belt (the Rheno-Hercynian and Saxo-Thüringian Zones). The eastern parts of the basin subsided on a broad zone of Variscan foreland deformation and on the Precambrian East-European Craton (Baltica).

[2]A massive topographic and structural feature, especially in an orogenic belt, commonly formed of rocks more rigid than those of its surroundings (Neuendorf and others, 2005).

[3]A late Proterozoic to early Paleozoic continent that now includes the East European craton of northwestern Eurasia.

[4]A Paleozoic to middle Mesozoic continent that now includes cratonic areas in landmasses of the Southern Hemisphere.

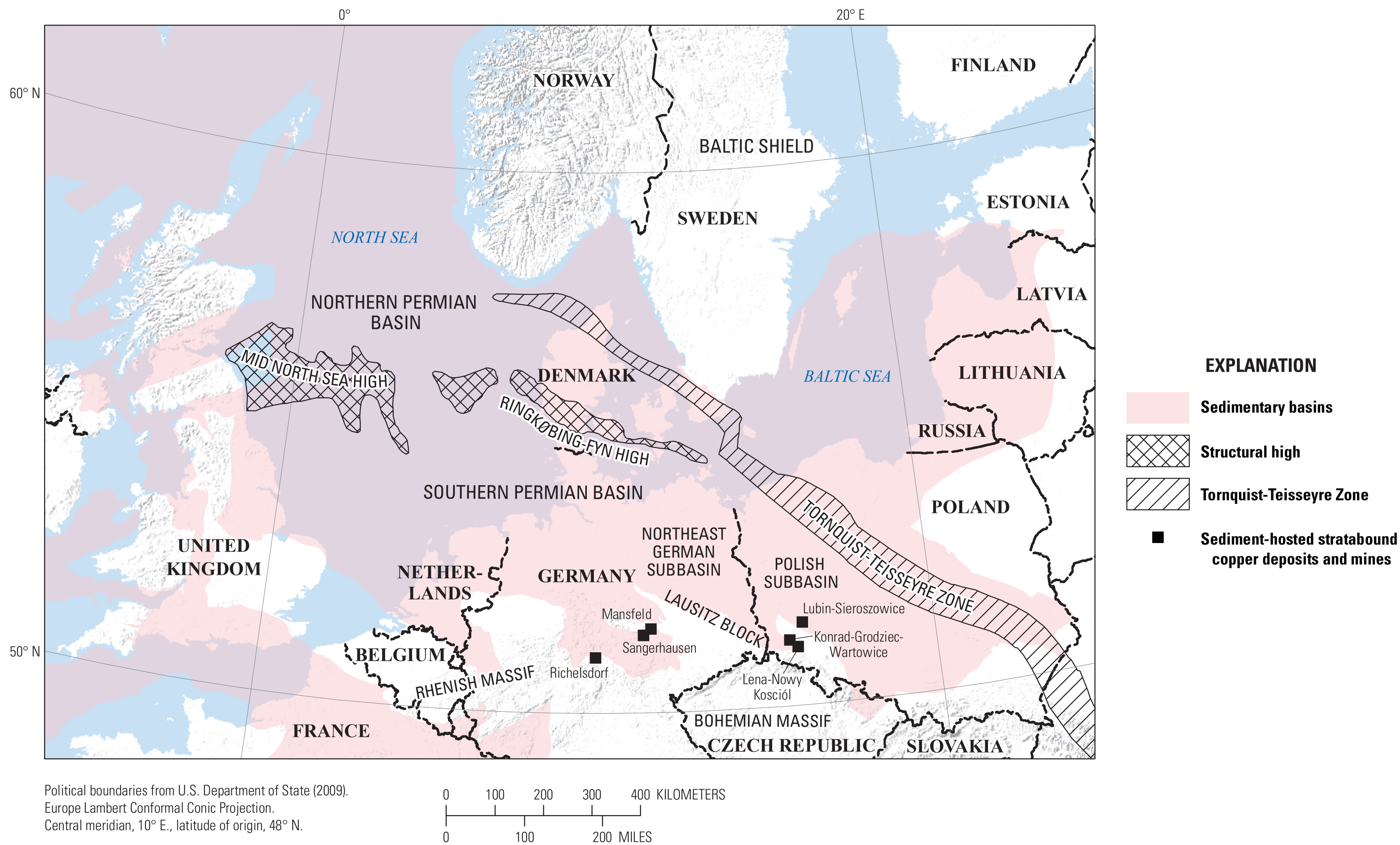


Figure 1. Map showing the distribution of sedimentary basins in northern Europe and the geologic and geographic features that bound the Southern Permian Basin. Sedimentary basins from Fugro Robertson, Ltd. (2008); geologic and geographic features from van Wees and others (2000); Kley and others (2008); Pharaoh and others (2010); and IHS (2014).

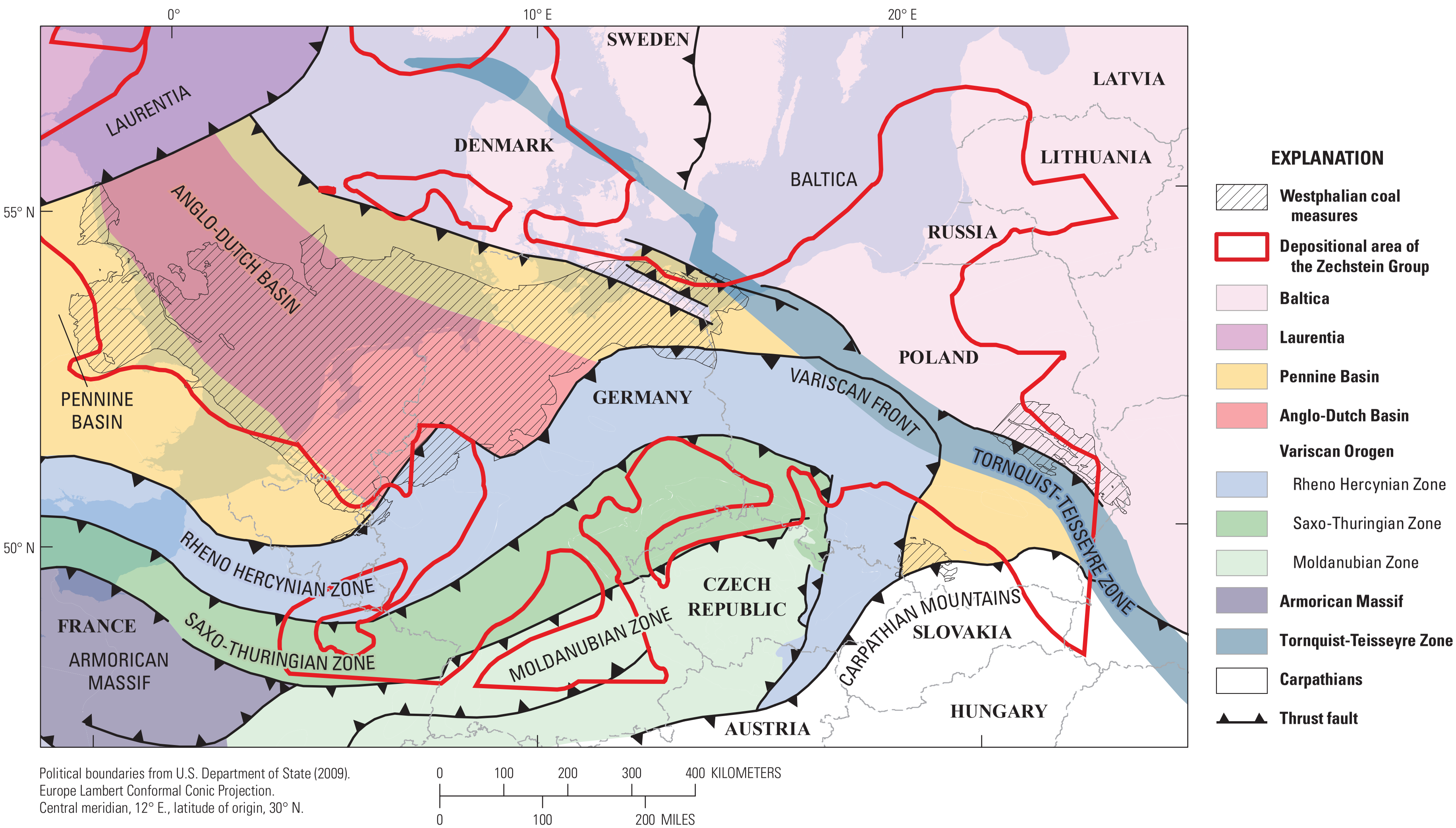


Figure 2. Map showing the pre-Permian basement terranes that underlie Zechstein Group rocks of the Southern Permian Basin in Europe. The southern part of the Southern Permian Basin overlies the Rheno-Hercynian and Saxo-Thüringian Zones of the Variscan Orogen. The northwestern part of the basin overlies rocks deposited in the Variscan foreland basin, including large areas of Westphalian coal-bearing deposits, which are the source rocks for natural gas in overlying reservoir-facies Rotliegend red beds. Information from Maystrenko and others (2008) and Kombrink and others (2010).

Rotliegend Group

At the end of the Variscan Orogeny, Permo-Carboniferous wrench faulting, magmatism, thermal uplift, and lithospheric thinning led to the formation of the SPB (Ziegler, 1990; Wilson and others, 2004; Ziegler and others, 2004). The relative westward movement of the African Plate during the late stages of Permian collision with the European Plate formed west-northwest to westerly trending, deep-seated, strike-slip faults and several transtensional pull-apart basins (Ziegler, 1990; Gast and others, 2010). This tectonic activity is associated with widespread, short-lived tholeiitic (bimodal) magmatism known as the European-northwest Africa LIP[5] event (Ernst and Buchan, 2001; Heeremans and Faleide, 2004; Heeremans and others, 2004; Stollhofen and others, 2008; Gast and others, 2010). The volcanic rocks range in composition from tholeiitic basalt to rhyolite and form large shield volcanoes and lava dome complexes (Geißler and others, 2008). The ages of the igneous rocks bracket the boundary between the Permian and Carboniferous Periods (Heeremans and Faleide, 2004; Heeremans and others, 2004). These volcanic rocks and interbedded fluvial and lacustrine sedimentary strata make up the Permian Lower Rotliegend Subgroup, the lowermost unit in the SPB (fig. 3). Lower Rotliegend Subgroup igneous rocks are found in Denmark, Germany, Norway, Poland, Scotland, and Sweden. The largest volumes of volcanic rocks occur in the Northeast German Subbasin, the Polish Subbasin, the Oslo Graben, and the Horn Graben (fig. 4; Heeremans and Faleide, 2004; Heeremans and others, 2004; Geißler and others, 2008; Gast and others, 2010).

A 20- to 30-million-year-long period of erosion, the Saalian Unconformity, followed the magmatic event (Glennie, 1997a, b). Decay of the thermal anomaly related to the European-northwest Africa LIP event (Pharaoh and others, 2010) or thermal relaxation of attenuated lithosphere that occurred during the early Permian and delayed infilling of paleo-topographic depressions that developed in the early Permian (van Wees and others, 2000) could have caused subsidence that led to the final development of the SPB.

[5]Large igneous province.

Clastic sedimentation resumed towards the end of the early Permian in depressions in eastern Germany and Poland; this resumption is represented by rocks of the Upper Rotliegend I Subgroup. In middle and late Permian times, sedimentation expanded to the west and south, now represented by rocks of the Upper Rotliegend II Subgroup. Upper Rotliegend II strata extend east-west from Poland to west England and north-south from the German-Danish border to northeast of Frankfurt, Germany.

During the Permian, the SPB area was located in the Northern Hemisphere desert belt between about 10 and 30° N. (Glennie, 1997a, b; Gast and others, 2010). The Upper Rotliegend II Subgroup is made up of four distinctive facies associations, characteristic of deposition in fluvial (wadi), aeolian, sabkha, and lacustrine environments in a land-locked basin (fig. 4; Stollhofen and others, 2008). The central part of the basin was occupied by terminal playas and saline lakes where rock salt (halite) was deposited. South of the lakes, transverse dunes derived from fluvial sands and transported by northeast trade winds are preserved (Gast and others, 2010).

Zechstein Group

In late Permian (Lopingian) time, a catastrophic transgression from the Barents Sea inundated the SPB and inundated the Permian continental basin with marine water (Glennie, 1997a, b; Brauns and others, 2003; Geluk, 2005; Stollhofen and others, 2008; Gast and others, 2010). The transgression is associated with a global rise in sea level due to the melting of the Gondwana ice cap and (or) regional lithospheric doming associated with rifting in the Arctic North Atlantic region (Glennie, 1997a, b; Stollhofen and others, 2008). The rapid flooding suggests that the Permian continental basin was significantly below sea level (Gast and others, 2010). During the initial transgression, the topmost parts of the Rotliegend dune sands were reworked to form the Weissliegend sandstone (fig. 5). This flooding event rapidly changed the deposition conditions of the sediments from oxidized to reducing. The catastrophic Messinian flooding of the Mediterranean would be analogous to Zechstein transgression (Garcia-Castellanos and others, 2009).

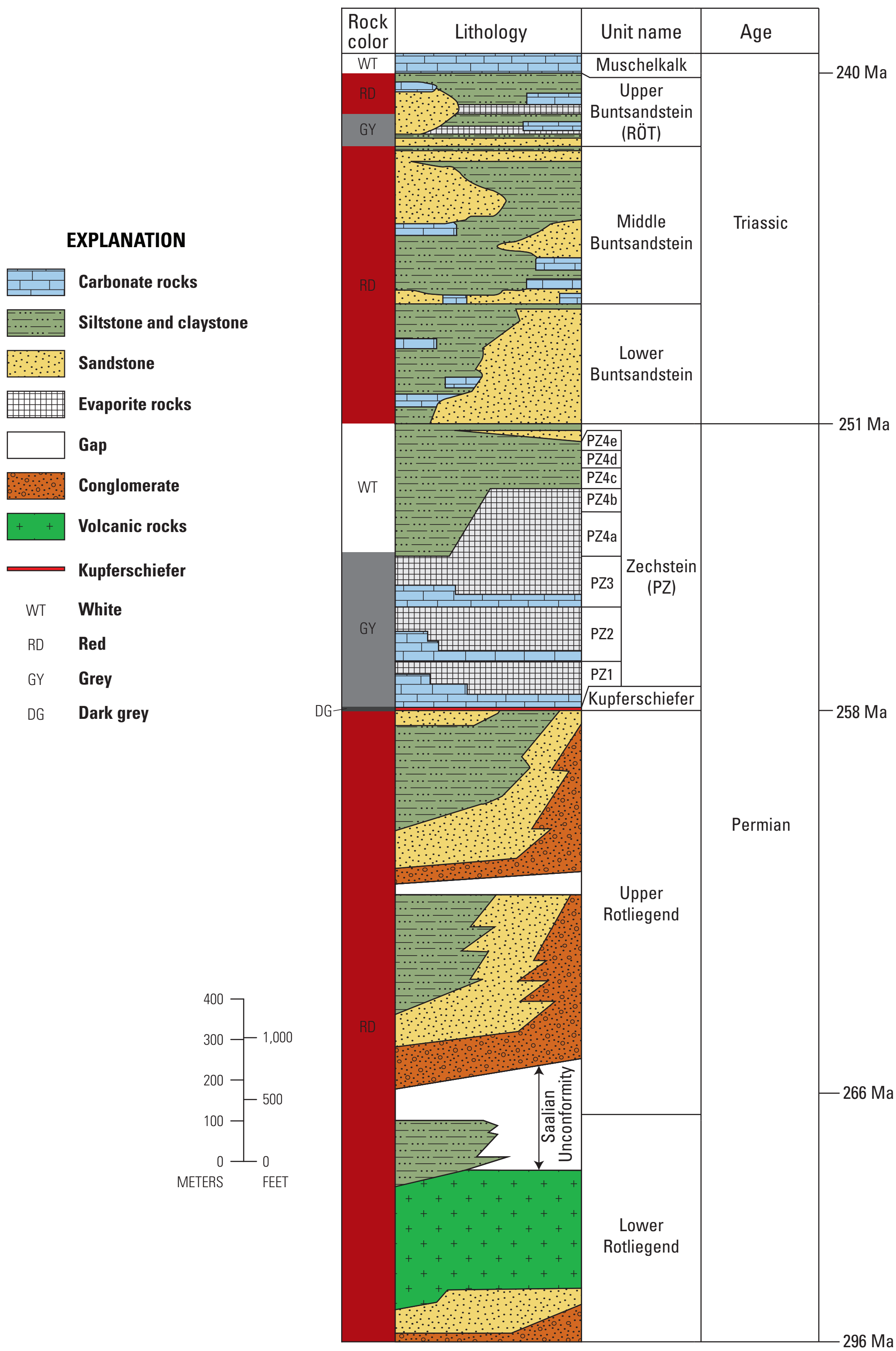


Figure 3. Composite lithostratigraphic column of Permian and Early Triassic rocks from the Polish part of the Southern Permian Basin. Modified from Nawrocki (1997). Ma, mega-annum (millions of years ago).

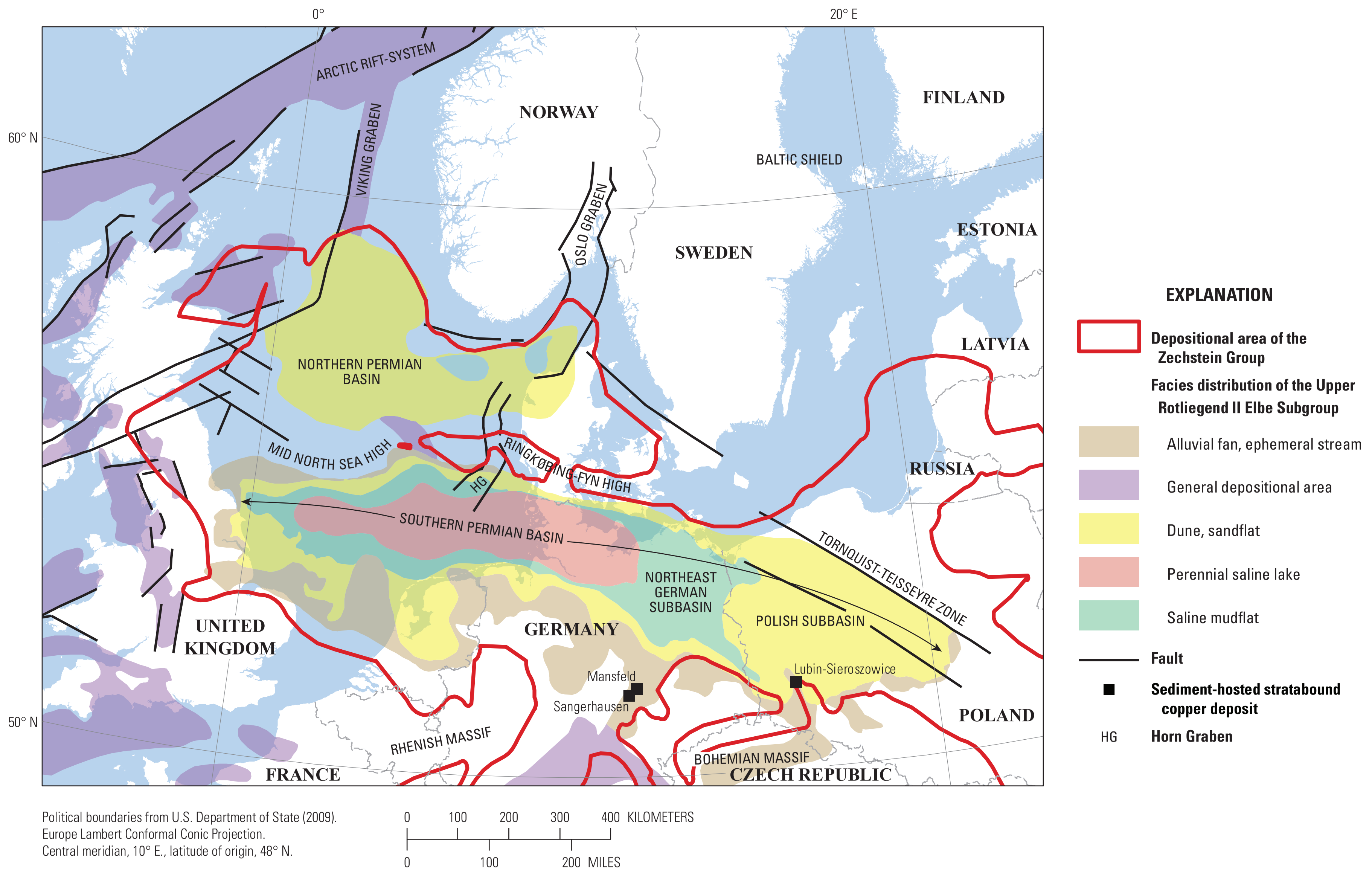


Figure 4. Map showing selected geologic and tectonic features related to the Northern and Southern Permian Basins in Europe. Information shown is modified from Littke and others (2008) and Stollhofen and others (2008).

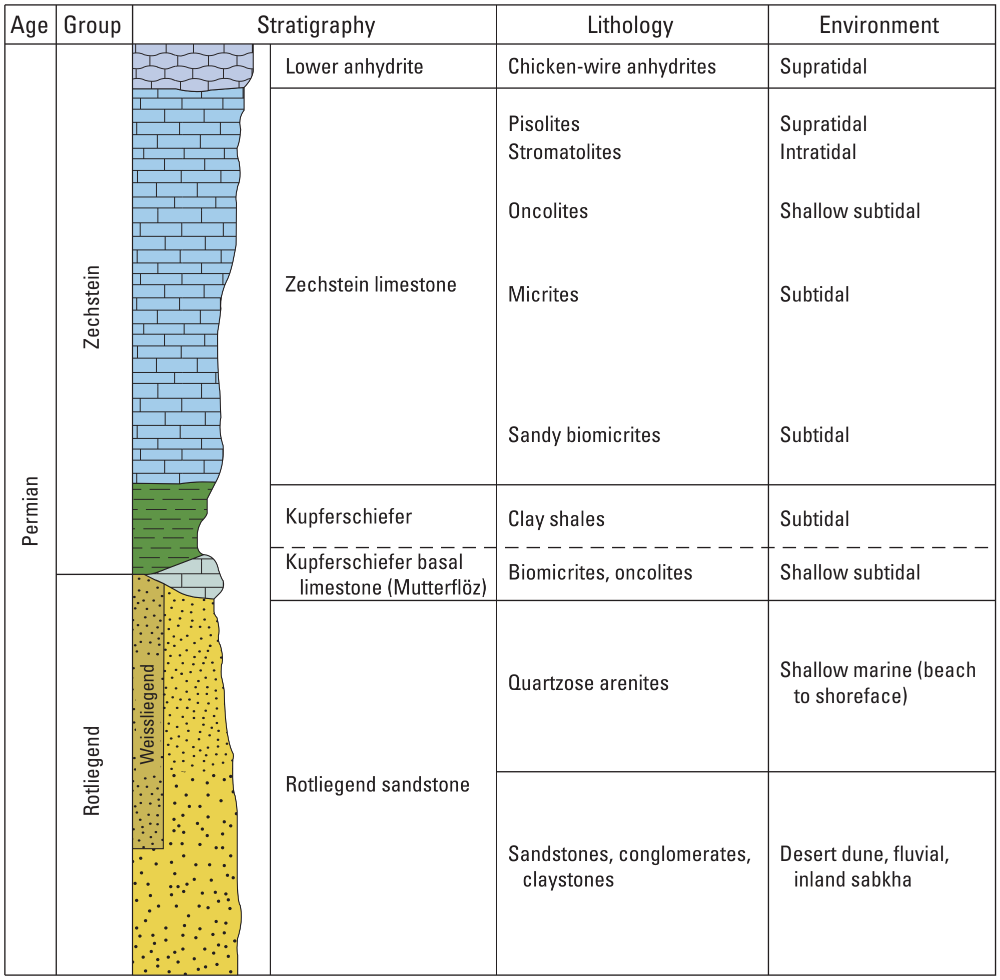


Figure 5. Generalized stratigraphic column of the basal Zechstein Group and underlying Upper Rotliegend Group in the Southern Permian Basin, Europe. Modified from Oszczepalski and Rydzewski (1987).

The Kupferschiefer is the first unit deposited after the transgression and forms the base of the Zechstein Group (fig. 5). The Zechstein Group is divided into cycles reflecting progressive evaporation and chemical precipitation in a giant saline basin (fig. 3; Peryt and others, 2010). Marine sediments (marls or limestone) form the base of each cycle and are overlain by layers of evaporites such as anhydrite and halite. Four evaporitic cycles (Z1-Werra, Z2-Stassfurt, Z3-Leine, and Z4-Aller) are found throughout the basin; younger cycles (Ohre-Z5, Friesland-Z6, and Fulda-Z7) are recognized in the axial parts of the Anglo-Dutch Basin (fig. 2) and Northeast German Subbasin (fig. 1; Geluk, 2005; Peryt and others, 2010).

The Kupferschiefer is an organic-rich unit usually less than a meter thick and consists of laminated black mudstones, marls, and carbonates that were deposited well below wave base in water depths of 200 m or more in depocenters (fig. 5; Ziegler, 1990; Paul, 2006; Stollhofen and others, 2008) and within storm wave base in the perilittoral zone (Oszczepalski and Rydzewski, 1987). The Kupferschiefer is one of the principal time markers in northwest European stratigraphy, having a Re-Os date of 257.3±1.6 Ma (Brauns and others, 2003), consistent with the occurrences of the Wuchiapingian-age conodont, *Mesogondolella britannica*, in Kupferschiefer equivalent strata in the southern North Sea (Stollhofen and others, 2008). Most of the Kupferschiefer was deposited under anoxic conditions in a stratified sea. Three cycles with varying carbonate and total organic carbon (TOC) contents can be traced throughout the basin (Paul, 2006). A fossiliferous carbonate bed, called the Mutterflöz in Germany, occurs on swells and marginal areas below the typical black shale facies (Paul, 2006). It is time equivalent with the lower part of the Kupferschiefer in basinal sites and therefore part of the Kupferschiefer. The Kupferschiefer is also known as the Marl Slate in the United Kingdom (Hirst and Dunham, 1963), the Coppershale Member of the Z1 (Werra) Formation in the Netherlands (Van Adrichem Boogaert and Kouwe, 1993–1997), łupek miedzionośny (an informal unit) in Poland (Marcinowski, 2004), the middle subformation of Murav’ev Formation in Russia (Zagorodnykh, 2000), and the Sasnava Series in Lithuania (Peryt and others, 2010).

Mesozoic rifting and latest Cretaceous and Paleocene basin inversion tectonics affected parts of the SPB. The structures observed today in the Northern and Southern Permian Basins evolved at four different times (Kley and others, 2008). The first is transtension in latest Carboniferous to Permian time (described above.). The second stage involves two discrete periods of extension in the Mesozoic, beginning in Early to Late Triassic time and subsequently in Late Jurassic to early Late Cretaceous time. The third stage involves contraction and inversion in latest Cretaceous to late Oligocene time related to the formation of the Alpine Orogen[6]. Some of the Mesozoic extensional fault systems were reactivated as reverse faults. In particular, many of the basement massifs that bound areas underlain by the Kupferschiefer were uplifted during the Alpine Orogeny. The fourth stage is the counterclockwise rotation of the major horizontal stress from a northeast-southwest to a northwest-southeast direction between the late Eocene and middle Miocene.

Mineralization

Large areas of the Kupferschiefer contain moderate concentrations of base and precious metals that are similar to other black shales and marls worldwide; however, high concentrations of copper, lead, zinc, silver, and other precious metals are found locally (Wedepohl and others, 1978, Vaughan and others, 1989; Oszczepalski and Rydzewski, 1997b; Rentzsch and Franzke, 1997; Paul, 2006). For example, copper concentrations higher than 3,000 parts per million (ppm) may occur in as much as one percent of the total area underlain by the Kupferschiefer (Wedepohl and others 1978).

Vaughan and others (1989) distinguish four styles of mineralization in the Kupferschiefer. The first is synsedimentary mineralization in which the average base-metal content is approximately 100 ppm. The second is early diagenetic mineralization, with sulfur derived from bacteriogenic processes and metals derived from immediately underlying rocks. The average base-metal content is about 2,000 ppm. The third is ore mineralization where the average base-metal concentration reaches approximately 3 percent. In these rocks, the ore minerals occur primarily as fine disseminations (less than 50 micrometers (µm) in diameter). Less common ore types include coarse-grained aggregates, lenses, streaks, and veinlets of sulfide minerals. The mineralization is late diagenetic and related to introduction of oxidized metal-rich brines at temperatures of approximately 130 degrees Celsius (ºC) (Jowett, 1986; Oszczepalski, 1989; Bechtel and Hoernes, 1993; Bechtel and others, 1996; Sun and others, 1995; Sun and Püttmann, 1997; Karnkowski, 1999; Bechtel and others, 2001; Blundell and others, 2003; Oszczepalski and others, 2002; and Speczik and others, 2003). Ore mineralization is generally restricted to those parts of the Kupferschiefer that are near the margins of Rotliegend basins. Sulfur isotope data indicates fixation of the metals by sulfur derived from bacterial reduction of sulfate. The fourth mineralization style associated with the Kupferschiefer is postdiagenetic, structure-controlled (Rücken-type) mineralization characterized by the presence of cobalt, nickel, and silver arsenide minerals. It appears to be genetically distinct from the other three types and is much younger, associated with Alpine-Carpathian tectonism (Wagner and Lorenz, 2002; Hitzman and others, 2005).

Sulfide mineralization found near the base of the Zechstein sequence is not restricted to the Kupferschiefer layer. Sulfide mineralization also occurs in clastic rocks underlying the Kupferschiefer (Zechstein conglomerate and Rotliegend strata) and in overlying Werra carbonate rocks (the Zechsteinkalk in Germany or wapień cechsztyński in Poland). In medieval times, only the Kupferschiefer shale bed itself was typically mined and the ore often averaged more than 5 percent copper (Paul, 2006). However, the zone of economic mineralization transgresses all three stratigraphic units at very low angles, allowing various rock types to be economically mined today. For example, in operating mines in Poland, approximately 12 percent of copper occurs in the Kupferschiefer, 57 percent in the underlying Rotliegend Group sandstone, and 31 percent in the overlying Zechstein Group limestone (KGHM (Copper Smelting-Mining Combine) Polska Miedź S.A. [KGHM], 2012). The thickness of the ore-bearing zone ranges from a few centimeters to 9 m in Germany (Rentzsch and Franzke, 1997) and locally exceeds 88 m in Poland (Oszczepalski and Rydzewski, 1997b). In the Lubin-Sieroszowice deposit, the thickness of the copper-rich sequence typically varies between 10 and 60 m; the maximum thickness is 25 m at Konrad and 10 m at Nowy Kościół (see fig. 1 for mine locations; Oszczepalski and Rydzewski, 1997b).

Mineral and Metal Zonation

In SSC deposits, ore minerals are distributed in patterns in and adjacent to ore bodies that can be used to infer the flow path of the metal-bearing solutions and the locations of the reaction front where mineral precipitation took place. For the Kupferschiefer, the change from oxidized (hematite-stable, organic-poor) to reduced (pyrite-stable, organic-rich) mineral assemblages shows where upwelling hematite-stable, oxidized copper-bearing brines interacted with the organic-rich host rocks. In this ore system, the Kupferschiefer bed is both the trap for the metals and the seal confining fluid flow.

For the Kupferschiefer, high-grade copper mineralization is always associated with barren, red-colored rocks found in the vicinity of the ore (fig. 6). The red-colored rocks were first observed in the "Fäule" layer near the base of the Zechstein Limestone; miners later referred to all barren, red-colored rocks of the Weissliegend, Kupferschiefer, and Zechsteinkalk as "Rote Fäule" (English translation "red rot"; Rentzsch, 1974; Jung and Knitzschke, 1976). The largest lateral extent of oxidized sedimentary rocks is observed within the Weissliegend Group sandstones, then within the Basal Limestone and Kupferschiefer, and limited in the overlying Zechstein Group limestone (Oszczepalski and Rydzewski, 1997b).

[6]The Alpine Orogen formed the Alps of Europe during the Eocene through Miocene Periods.

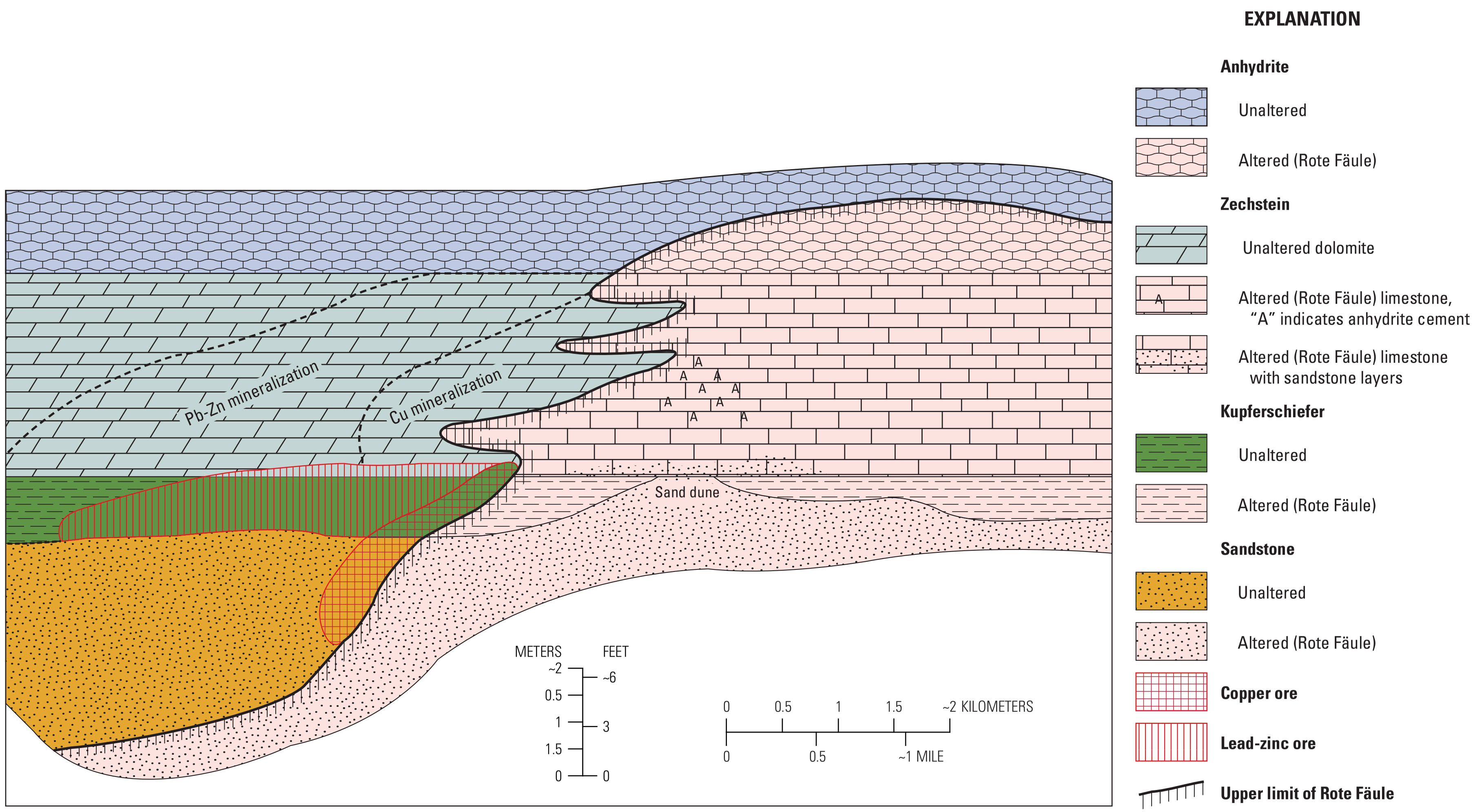


Figure 6. Schematic cross section showing the relation of Rote Fäule alteration facies to copper, lead, and zinc mineralization in the rocks in and adjacent to the Kupferschiefer in Poland and Germany. Modified from Vaughan and others (1989). Pb, lead; Zn, zinc; Cu, copper.

Freiesleben (1815) was the first to scientifically describe the Rote Fäule but did not recognize its relation to ore. Gillitzer (1936) was the first to suggest a causal relation between the presence of Rote Fäule alteration and the distribution of high-grade copper and distal lead-zinc mineralization in the Kupferschiefer. Since that time, locating the contact between the oxidized and reduced facies of the Kupferschiefer has been an important guide to the location of copper ore bodies (Rentzsch, 1974; Oszczepalski and Rydzewski, 1997b).

The red color of the rocks is caused by disseminated hematite and goethite and indicates alteration related to interaction of the oxidized ore fluids with sedimentary rocks (Oszczepalski, 1989; Püttmann and others, 1989; Vaughan and others, 1989). The transition from hematitic to sulfidic sedimentary rocks is characterized by a gradual change in color from reddish-brown, through grey with red spots or layers, to dark grey and black. This change in color is accompanied by an increase in the organic carbon content of the rocks. Organic carbon is depleted in the Rote Fäule relative to the original sulfidic, organic-rich sedimentary rocks. In the reaction zone, the oxide and sulfide minerals in the Kupferschiefer mineral system grade from (1) hematite with only scant traces of any sulfides (Rote Fäule); to (2) covellite with idaite, chalcopyrite, and trace magnetite; to (3) chalcocite with digenite, covellite, and pyrite; to (4) chalcocite with bornite, digenite, and pyrite; to (5) bornite with chalcocite, chalcopyrite, sphalerite, galena, and pyrite; to (6) bornite with chalcopyrite, pyrite, sphalerite, and galena; to (7) chalcopyrite and pyrite with sphalerite, galena, and tennantite; to (8) pyrite, sphalerite, galena, and chalcopyrite; to (9) pyrite, sphalerite, and galena with chalcopyrite; to (10) pyrite with only scant traces of any base-metal sulfides (Jung and Knitzschke, 1976). Paragenetic studies indicate that base-metal sulfide deposition postdated pyrite formation, that sulfur-poor minerals (such as chalcocite) progressively replaced sulfur-rich minerals (bornite, chalcopyrite), and that hematite replaced both the copper sulfides and pyrite (Oszczepalski, 1994).

The zoned distribution pattern of sulfide minerals gives rise to a zoned pattern of metal distribution ranging from a zone devoid of base metals (1 above), to a copper zone (2 through 6 above); to a lead zone (7 above); to zinc zone (8 above); and finally, to another zone nearly devoid of base metals (10 above) (fig. 7; Jung and Knitzschke, 1976; Oszczepalski and Rydzewski, 1997b). Ore grades of copper (typically greater than 1 percent) are developed only in zones that have chalcocite, covellite, or bornite as the predominant sulfide mineral.

Metal Surface Density

Metal surface density[7], usually in units of kilograms per square meter (kg/m^2), is commonly used to describe variation in the metal yield or content of the Kupferschiefer. This convention, which ignores the vertical dimension, is appropriate because (1) the ore bodies are stratabound in a gently dipping host unit with a large areal extent (the shape of the Kupferschiefer ore bodies can be approximated by a planar surface), and (2) the thicknesses of the ore bodies are insignificant compared to their areal extent (see Wellmer and others, 2008, p. 38, and Noble,1992, for discussions of resource estimation for stratiform ore bodies). Other terms that are synonymous with copper surface density (CSD) include "copper per unit area of lode" (Butler and Burbank, 1929); "Kupferinhalt je qm Flözfläche" [Copper content per square meter of surface seam] (Gillitzer, 1936); "kupferführung" [copper guide] (Eisentraut, 1939); "Kupfergehalt des Flözes" [copper content of the seam] (Richter, 1941; Kautzsch, 1942); "zasobność miedzi" [abundance of copper, or copper productivity] (Oszczepalski and Rydzewski, 1983); and "accumulation index" (Piestrzyński and Pieczonka, 2012).

Metal surface density can be calculated using the contained metal content of ore bodies and the surface projection of their area or by using information for profiles through the mineralized interval as sampled in outcrop, underground workings, or drill holes. Data from point locations (such as drill holes) can be contoured or gridded and used to estimate contained metal. Area multiplied by the estimated metal surface density for the area yields an estimate of the contained metal.

For profile data (such as drill holes), Oszczepalski and Rydzewski (1997b) define metal surface density as:

$$Q = 0.001MPC,$$

where

Q is the metal surface density (in kilograms per square meter) of a mineralized interval,
M is the thickness (in meters),
P is the average metal concentration (in grams per metric ton), and
C is the bulk density (in metric tons per cubic meter)

Metal surface density is calculated for continuously sampled profiles and weighted averages are used to calculate the metal surface density for the entire mineralized interval.

What are representative numbers for copper surface density in the Kupferschiefer region? Cutoff criteria for balance reserves[8] include grade cutoff of 0.7 percent copper, minimum copper equivalent[9] in sample composite of 0.7, and minimum yield (copper metal per unit area) of 50 kg/m^2 (Bartlett and others, 2013). Drill holes in sections through the Sieroszowice and Rudna Mines have CSD values ranging

[7]Surface density is the quantity per unit area of anything (such as mass or electricity) distributed over a surface (National Research Council Conference on Glossary of Terms in Nuclear Science and Technology, 1957; Neuendorf and others, 2005).

[8]In the mineral resource classification system used by former COMECON (Council for Mutual Economic Assistance) countries during the Soviet era, balance reserves are those that are economic (Jakubiak and Smakowski, 1994).

[9]Copper equivalent is Cu(%) + Ag(g/t)/100.

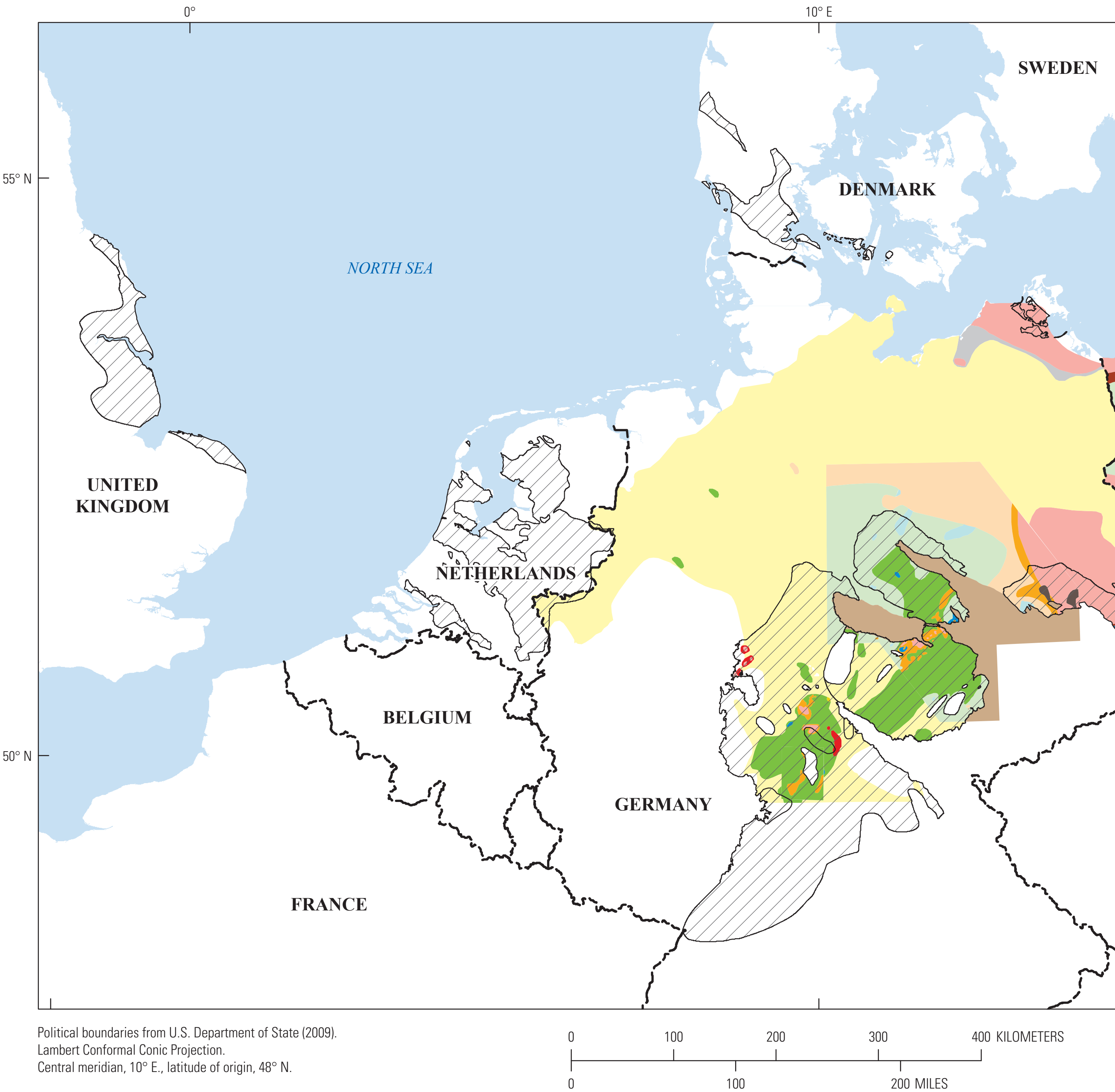
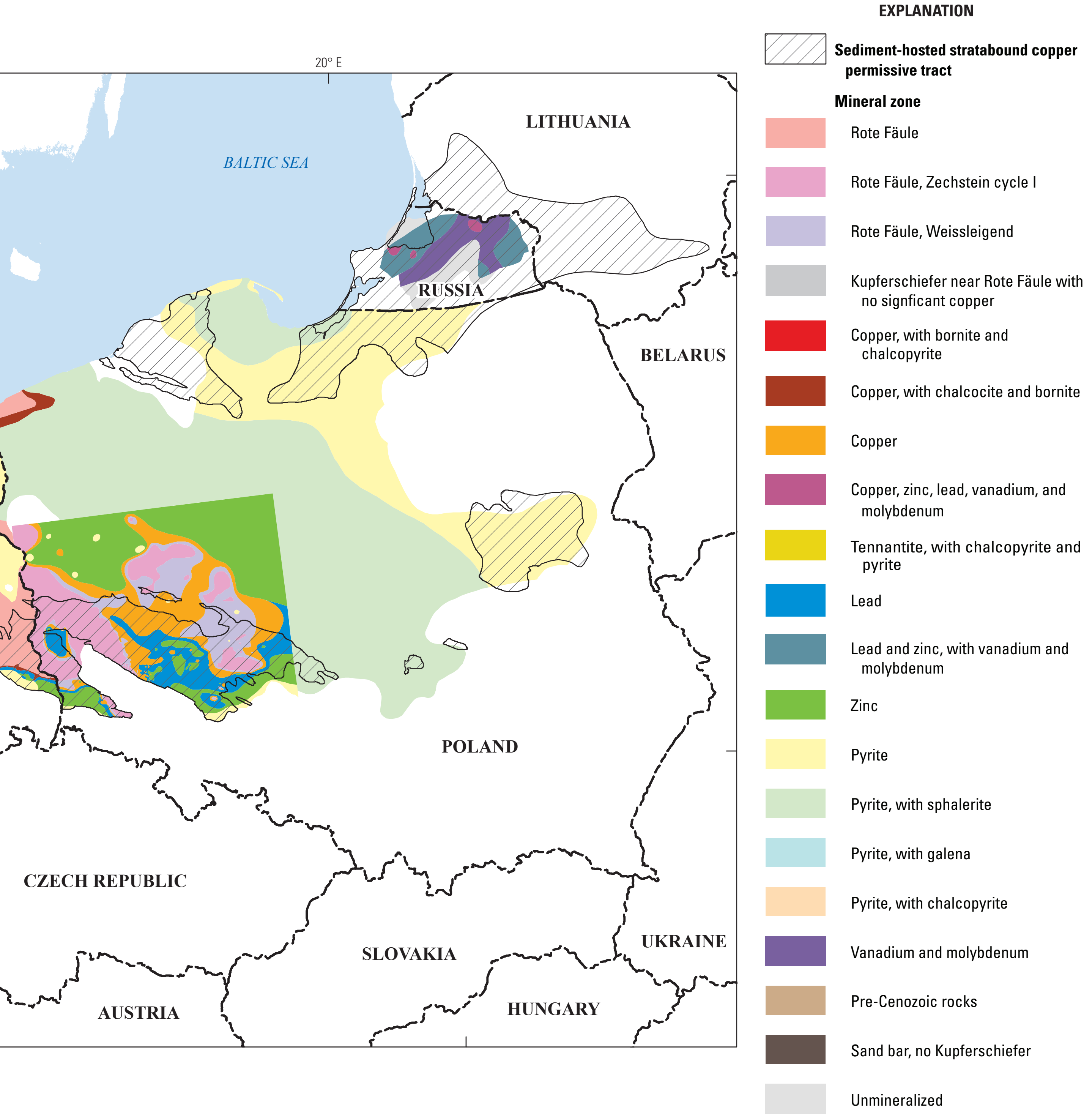


Figure 7. Map of the Southern Permian Basin, northern Europe, showing sulfide and oxide mineral zones developed in rocks near the base of the Zechstein Group. Compiled from Richter (1941), Schumacher and Schmidt (1985), Schmidt and others (1986), Schmidt (1987), Federal Institute for Geosciences and Natural Resources (1993), Oszczepalski and Rydzewski (1997a), Rentzsch and others (1997), Geological Office of the Saxony-Anhalt Mining Area (2000), Zagorodnykh (2000), Stedingk and Rentzsch (2003), Bavarian Geological State Office (2004a), and Oszczepalski and Speczik (2011).


EXPLANATION
Sediment-hosted stratabound copper permissive tract
Mineral zone
Rote Fäule
Rote Fäule, Zechstein cycle I
Rote Fäule, Weissliegend
Kupferschiefer near Rote Fäule with no signficant copper
Copper, with bornite and chalcopyrite
Copper, with chalcocite and bornite
Copper
Copper, zinc, lead, vanadium, and molybdenum
Tennantite, with chalcopyrite and pyrite
Lead
Lead and zinc, with vanadium and molybdenum
Zinc
Pyrite
Pyrite, with sphalerite
Pyrite, with galena
Pyrite, with chalcopyrite
Vanadium and molybdenum
Pre-Cenozoic rocks
Sand bar, no Kupferschiefer
Unmineralized
20° E
BALTIC SEA
LITHUANIA
RUSSIA
BELARUS
POLAND
CZECH REPUBLIC
SLOVAKIA
UKRAINE
AUSTRIA
HUNGARY

from 7 to 413 kg/m^2 (fig. 8; Pieczonka and others, 2001). Ore intercepts with copper surface-density values of 50 kg/m^2 are considered to be economic in Poland when there is a minimum of 1.7 percent copper in the "interval of the extracted wall" using a cutoff grade of 0.7 percent copper (Bartlett and others, 2013).[10] Oszczepalski and Speczik (2011) use a cutoff of 35 kg/m^2 to estimate prognostic (undiscovered) resources in Poland. The overall copper surface density for ore bodies in the Mansfeld and Sangerhausen areas is estimated to be 19.6 kg/m^2 (Knitzschke, 1995). Using surface area calculated with a geographic information system (GIS) and the contained copper of ore bodies, overall copper surface-density values for other reduced-facies-type deposits range from 60 to 260 kg/m^2 (table 1).

Regional Maps of Mineral and Metal Zones and Copper Surface Density

Regional mineral- and metal-zonation maps of mineral proportions and metal zones, as well as metal surface density, were compiled into a spatial (GIS) dataset to support the mineral resource assessment. The sources of information include metal surface-density maps for Germany based on 1,082 underground and surface exposures, as well as boreholes (Rentzsch and Franzke, 1997), and a corresponding mineral-zonation map, which shows about 270 drill-hole collar locations (Rentzsch and others, 1997). Ten thousand samples were used to delimit and calculate the metal contents of the Kupferschiefer ore zone on these maps. The mineralized interval is defined as the Kupferschiefer and the rocks in its hanging wall and footwall, provided they have metal values exceeding 0.1 percent copper, lead, or zinc. For Poland, the GIS incorporates the data in the metallogenic atlas of the Zechstein copper-bearing series, which is based on 774 boreholes and the chemical analyses of more than 50,000 samples (Oszczepalski and Rydzewski, 1997b). Metal surface density was calculated for continuously sampled profiles where the combined concentration of copper, lead, and zinc in individual samples is equal to or greater than 0.1 percent. The compilation also includes recent studies focused on southwestern Poland that are based on petrographic and analytical studies on more than 1,400 drill holes; only intervals with samples that contained in excess of 0.7 percent copper were used to calculate copper surface density (Oszczepalski and Speczik, 2011). In addition, the compilation incorporates small copper surface-density maps published by Schmidt and others (1986); Federal Institute for Geosciences and Natural Resources (1993); Geological Office of the Saxony-Anhalt Mining area (2000); Stedingk and Rentzsch (2003); Liedtke and Vasters (2008); and Volker Spieth (written commun., 2008).

Mineral-zonation maps based on the petrographic study of drill core show the zoned distribution of sulfide and oxide minerals in and near the Kupferschiefer (figs. 7 and 8). For example, Rentzsch and others (1997) describe 10 mineral associations, which they display on their map. Oszczepalski and Rydzewski (1997b) and Oszczepalski and Speczik (2011) map 8 and 6 mineral zones, respectively (table 2). These maps were also compiled in order to assess undiscovered resources.

To interpret the metal surface-density and mineral-zonation maps, GIS data that showed the surface extent of known ore bodies, the location of mineral occurrences, and mining leases and concession areas were compiled. Many of the known occurrences are either old mine workings or drill holes with mineralized intercepts. Spatial data files for metal surface density, mineral zones, ore bodies, leases and concessions, permissive tracts, and mineral occurrences are included with this report and are summarized in appendix B.

Mineralization Age

The accepted depositional age of the Kupferschiefer is from 260.4 to 258 Ma (Re-Os date; Menning and others, 2006; Słowakiewicz and others, 2009). Brauns and others (2003) reported a whole-rock and mineral-separate isochron from several samples from the Sangerhausen deposit that gives a Re-Os date of 257±1.6 Ma. The data presented by Brauns and others (2003) were based on one drill core from the Sangerhausen area and were obtained from unspecified sulfide minerals (Słowakiewicz and others, 2009). Nevertheless, Menning and others (2006) and many other authors accept the precise date reported by Brauns and others (2003) as a depositional age for the base of the Zechstein Group. Six samples of non-mineralized black shale from a Kupferschiefer section in the northern part of the Polish Zechstein Basin yield a Re-Os date of 247±20 Ma (Pašava and others, 2010). Pašava and others (2007) reported a Re-Os date of 240±3.8 Ma from mineralized, copper-rich Kupferschiefer whole-rock samples of the Lubin Mine. Pätzold and others (2002) obtained a Re-Os date of 204.3±0.5 Ma for copper-sulfide mineralization associated with the Kupferschiefer at Mansfeld. The younger ages at Lubin and Mansfeld are consistent with an epigenetic origin of the Kupferschiefer mineralization (fig. 9).

[10] Since 2012, the values used to define the deposit and its boundaries have changed to cut off of 0.5 percent copper, minimum copper equivalent in sample composite of 0.5, and minimum yield (copper metal per unit area) of 35 kg/m^2.

	Sieroszowice Mine		Rudna Mine			
Copper surface density, in kilograms per square meter	6.91	50.19	222.71	262.06	227.33	412.73
Borehole number	Sr 14-528	Sr 14-259	Po 1-671	Po 3-131	Po 18-912	Mo 25-626

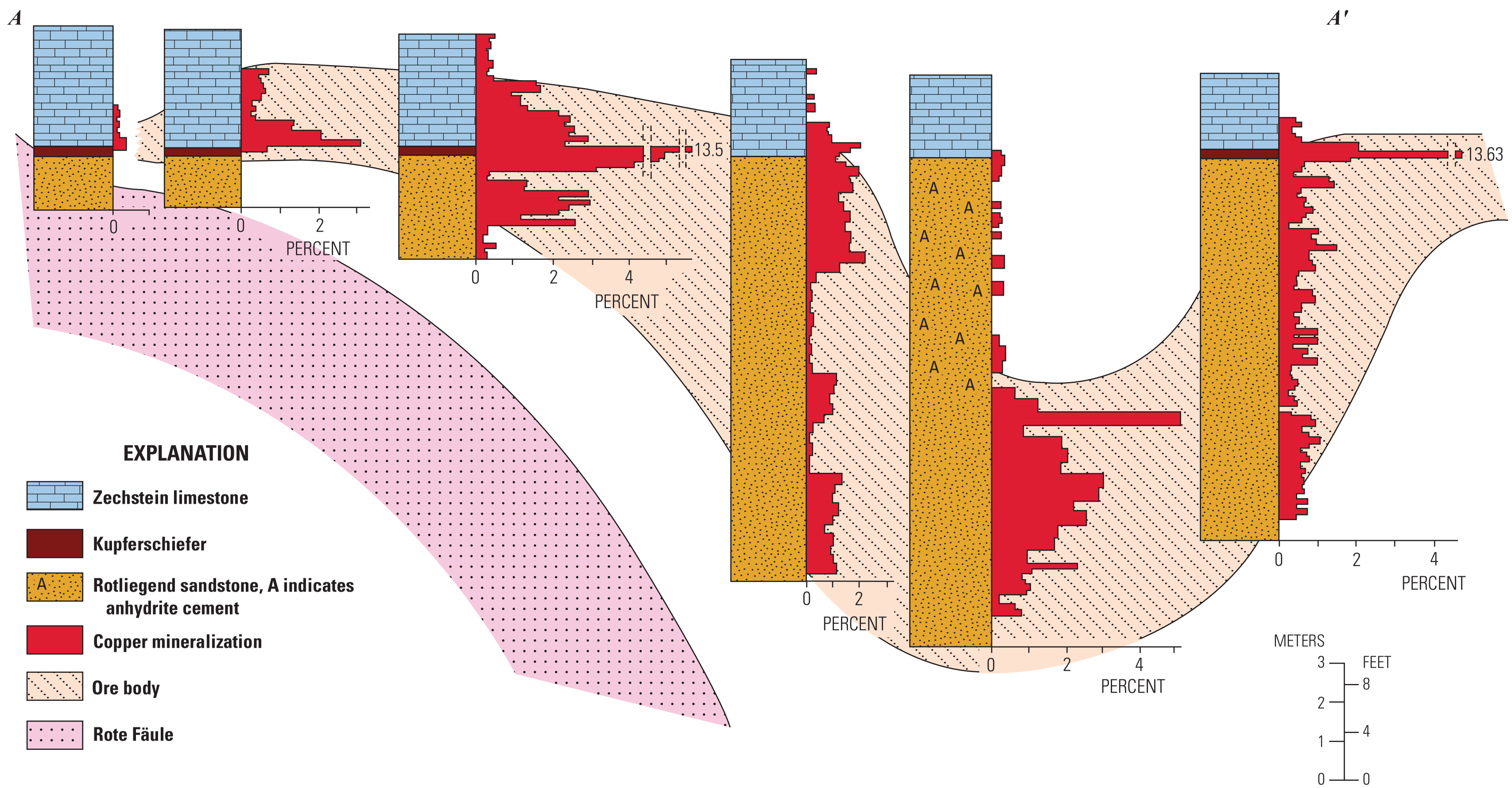


Figure 8. Stratigraphic columns through the Kupferschiefer in the Sieroszowice and Rudna Mine areas, Poland, showing rock type and histograms of copper content and the relation of mineralization to the Rote Fäule alteration facies. Line of section (*A–A′*) is shown on figure 26. Modified from Pieczonka and others (2001).

Table 1. Average copper surface density (CSD) values for selected flat-lying reduced-facies sediment-hosted stratabound copper deposits.

[km^2, square kilometers; kg/m^2, kilogram per meter squared]

Deposit name	Basin	Country	Ore body area (km^2)	Contained copper metal (metric tons)	CSD (kg/m^2)	Reference for contained copper
Spremberg	Southern Permian Basin	Germany	9.90	617,400	62	Kopp and others (2006)
Boleo	Santa Rosalia	Mexico	33.61	2,580,772	77	Dreisinger and others (2010)
Graustein	Southern Permian Basin	Germany	8.26	868,320	105	Kopp and others (2006)
Lubin-Sieroszowice	Southern Permian Basin	Poland	375.17	72,000,000	197	Kirkham and Broughton (2005); Polish Geological Institute–National Research Institute (2009a, b); Lattanzi and others (1997); Wodzicki and Piestrzyński (1994)
White Pine	Keweenawan	United States	32.25	8,256,000	256	Kirkham and others (1994)

Table 2. Correlation of mineral- and metal-zone mapping for the Kupferschiefer in the Southern Permian Basin, Germany and Poland.

[Pyrite includes marcasite; RF, Rote Fäule; Cu, copper; Pb, lead; Zn, zinc; Fe, iron]

Mineral-zone mapped			Metal type
Rentzsch, Franzke, and Friedrich (1997)	Oszczepalski and Rydzewski (1997a)	Oszczepalski and Speczik (2011)	
Hematite-type Rote Fäule facies (paragenesis 1)	Oxidized area (Rote Fäule)	Extent of the oxidized zone in the shale-carbonate Pz1 series; Extent of the oxidized zone in the White Sandstone (Weissliegend)	RF
Covellite-idaite-type (association 2); Chalcocite-type (association 3); Bornite-chalcocite-type (association 4); Bornite-type (association 5); Bornite-chalcopyrite-type (association 6); Chalcopyrite-(tennantite)-pyrite-type (association 7a)	Chalcocite-covellite mineralization; Chalcocite-bornite (chalcopyrite) mineralization	Copper-bearing zone	Cu
Chalcopyrite-galena-type (association 8a); galena-type (association 9a)	Galena-sphalerite-pyrite (chalcopyrite) mineralization	Lead-bearing zone	Pb
Chalcopyrite-sphalerite-type; (association 8b); sphalerite-type (association 9b)	Sphalerite-galena-pyrite (chalcopyrite) mineralization	Zinc-bearing zone	Zn
Pyrite-type (association 10) with chalcopyrite, galena, sphalerite, bornite, or chalcocite	Pyrite-chalcopyrite-sphalerite (galena) mineralization; Pyrite-sphalerite-galena (chalcopyrite) mineralization; Pyrite mineralization	Pyrite zone	Fe, (Cu), (Pb), or (Zn)

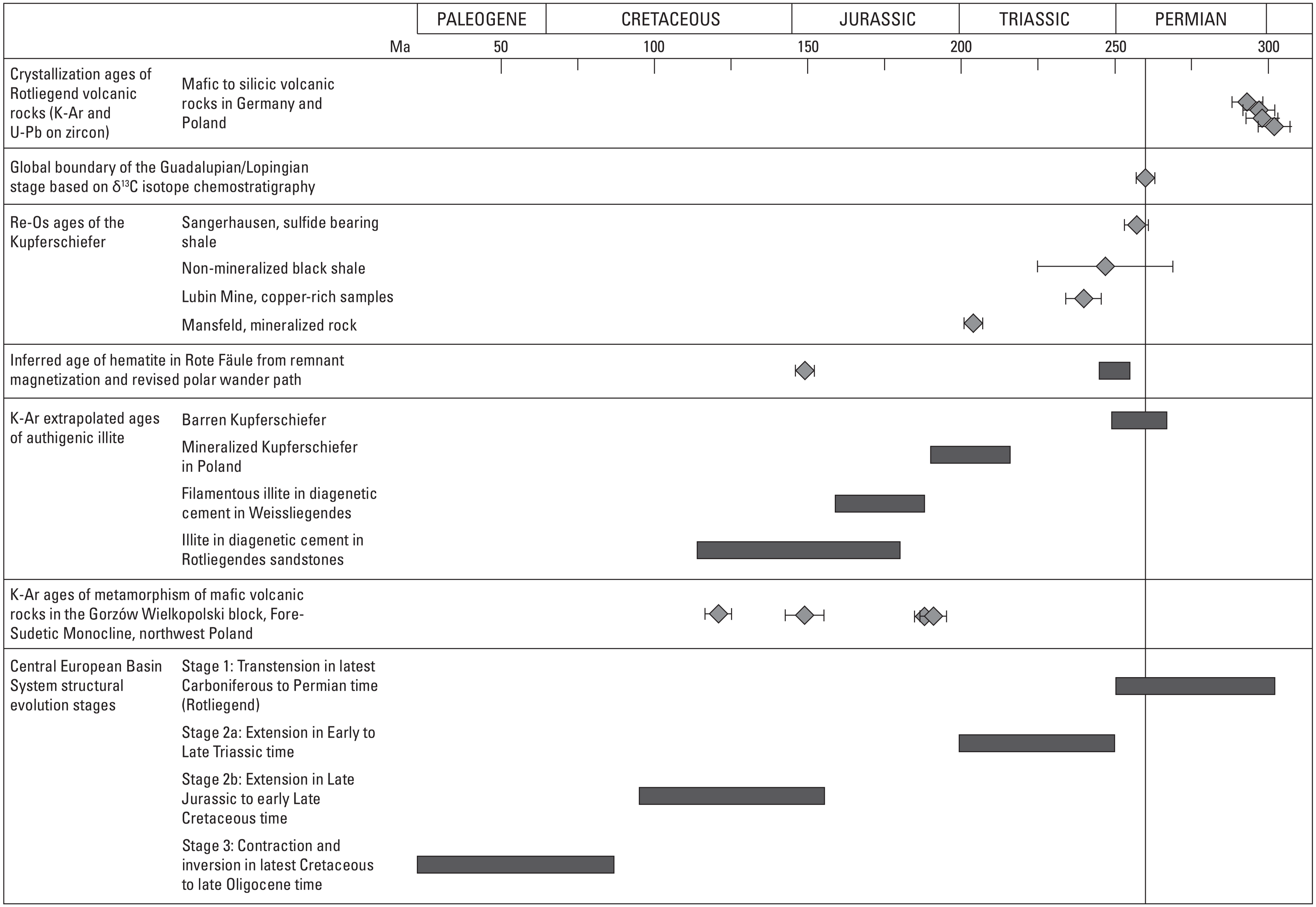


Figure 9. Chart illustrating age relations for the deposition and alteration of Rotliegend volcanic rocks and the Kupferschiefer in the Southern Permian Basin, northern Europe. Diamond and bars are radiometric ages with errors. Sources of information include Maliszewska and others (1998); Bechtel and others (1999); Nawrocki (2000); Michalik and Sawłowicz (2001); Pätzold and others (2002); Brauns and others (2003); Bylina (2006); Geißler and others (2008); Słowakiewicz and others (2009); Pašava and others (2010); and Symons and others (2011). Ma, mega-annum (millions of years ago); K-Ar, potassium-argon; U-Pb, uranium-lead; Re-Os, rhenium-osmium; δ13C, deviation of the carbon-13 to carbon-12 ratio with respect to Pee Dee Belemnite standard.

These ages can be compared with dates for alteration associated with the mineralization and with the Rote Fäule (fig. 9). Bechtel and others (1996) indirectly dated Kupferschiefer mineralization using K-Ar on illite from Kupferschiefer shale samples taken from barren pyrite zone, zinc-lead zone, copper-zinc-lead zone, copper zone, and Rote Fäule. Initial results indicated a Middle Triassic age. Bechtel and others (1999) refined the illite K-Ar ages using illite polytypes of probable diagenetic, authigenic origin from mineralized samples. Results varied from 216 to 190 Ma (Late Triassic to Early Jurassic). The paleomagnetic dating of Rote Fäule hematite initially yielded dates of 250 to 220 Ma, which were later refined to 255 to 245 Ma by Nawrocki (2000) based on improved polar wandering paths. Recent paleomagnetic age dating of pyrrhotite and magnetite mineralization at Sangerhausen has revealed late epigenetic ages of 149 or 53 Ma (Symons and others, 2011).

The various ages record a series of events distributed along the time-depth burial path for the Kupferschiefer, including mineralization and alteration (fig. 10). After deposition at 260 to 258 Ma, the Kupferschiefer was rapidly buried to depths of 1.5 km by 240 Ma (Middle Triassic). Rates of burial then apparently slowed until depths of 2.5 to 3 km were reached about 150 Ma (Upper Jurassic). This burial history is consistent with the extensional tectonic phases described by Kley and others (2008) for the SPB.

Mineral Resource Nomenclature

Scientific terminology for identified (discovered) mineral resources follows the usage proposed by Committee for Mineral Reserves and Reporting Standards (2006). “Mineral resources” are defined as concentrations or occurrences of material of economic interest in or on the Earth’s crust in such form, quality, and quantity that there exist reasonable prospects for eventual economic extraction. The location, quantity, grade, continuity, and other geological characteristics of a mineral resource are known, estimated, or interpreted from specific geological evidence, sampling, and other knowledge. The term “mineral reserve” is restricted to the economically mineable part of a mineral resource.

In this report, an “undiscovered mineral resource” estimate is considered to be mineralized rock that is likely to be present but for which location, grade, quality, and quantity are not constrained by specific geologic evidence. The estimates can refer to completely undiscovered deposits or to extensions of areas with known, drill-indicated resources. Some geologic information could be available for these extensions, but it is not sufficient to meet the requirements for defining (1) inferred mineral resources using the guidelines published by Committee for Mineral Reserves International Reporting Standards (2006) or (2) category C resources in the classification scheme used by many former COMECON (Sovet Ekonomicheskoy Vzaimopomoshchi [Council for Mutual Economic Assistance]) countries during the Soviet era (Diatchkov, 1994; Jakubiak and Smakowski, 1994; Henley and Young, 2009). The COMECON system has a prognostic or “P” category. Resources listed as prognostic are generally equivalent to undiscovered resources in the classification of mineral resources used by the USGS (U.S. Bureau of Mines and U.S. Geological Survey, 1976). Resources within the P1 category may be adjacent to and extend beyond the limits of drill-indicated resources (category C). Resources under the P2 category are estimated using geophysical and geochemical data (Diatchkov, 1994). In Poland, the prognostic resource categories P1 and P2 are referred to as D1 and D2 (Jakubiak and Smakowski, 1994).

Assessment Methodology Concepts

U.S. Geological Survey (USGS) mineral resource assessments address two basic questions: (1) where are undiscovered mineral resources likely to exist, and (2) how much undiscovered mineral resource could be present? Results are presented as maps and as a frequency distribution of in-place, undiscovered metal. We can make inferences about undiscovered mineral resource potential because natural accumulations of useful minerals or rocks (“mineral deposits”) can be classified into groups or “deposit types” that reflect processes of formation. Using the deposit-type paradigm, we can predict the geologic settings in which various types of deposits could be found, as well as anticipate the distribution and concentration of ore materials at the scale of the deposit.

The concepts of deposit type and ore genesis underlie geologically based mineral resource assessments. Two genetic concepts have been proposed for the origin of SSC deposits: (1) syngenesis, in which the mineralization developed simultaneously with the deposition of the sediments, and (2) diagenesis, in which the mineralization formed later than the deposition of the sediments during compaction and lithification. After decades of research, the diagenetic model of ore formation is now widely accepted and forms the basis for establishing assessment criteria.

The concept of a mineral system is used to translate theories of regional ore genesis into criteria that can be used in mineral resource assessment and exploration targeting studies (Wyborn and others, 1994; Knox-Robinson and Wyborn, 1997; Cox and others, 2003; Hronsky, 2004; Hitzman and others, 2005; Barnicoat, 2006; Hronsky and Groves, 2008; Blewett and others, 2010). For example, hydrothermal ore deposits can be understood by considering the source of the ore-forming fluid, its physical and chemical character, the mechanisms for dissolving and transporting ore-forming components, and the causes of precipitation from it (Skinner and Barton, 1973). Sites with appropriate combinations of structural, chemical, and physical conditions that force ore-mineral precipitation reactions are called ore traps (Reed, 1997). Variations of the source-transport-trap paradigm are used to define both petroleum and hydrothermal mineral-systems models

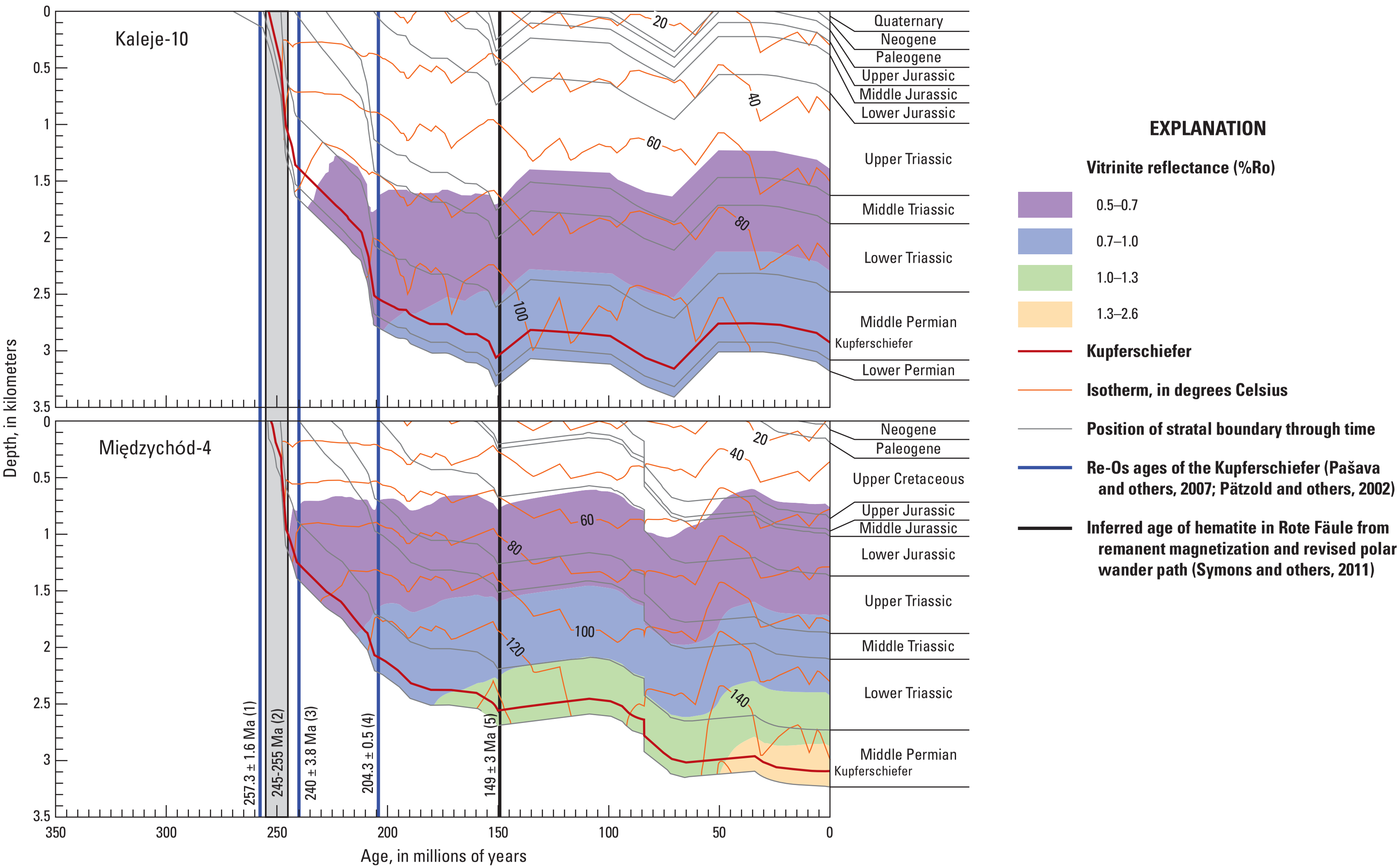


Figure 10. Illustration showing age of Kupferschiefer deposition, mineralization, and alteration on burial and modeled vitrinite-reflectance histories for the Kaleje-10 and Międzychód-4 boreholes, Poland. Burial history from Pletsch and others (2010) and Kupferschiefer-age information as given in figure 9. Numbers after the ages refer to source of information: (1) Brauns and others (2003), (2) Nawrocki (2000), (3) Pašava and others (2007a), (4) Pätzold and others (2002), and (5) Symons and others (2011). Ma, mega-annum (millions of years ago); Re-Os, rhenium-osmium.

(Magoon and Dow, 1994; Wyborn and others, 1994; Magoon and Schmoker, 2000).

The formation of SSC deposits requires a source of metals, a fluid that extracts and moves metals away from the source rocks, a pathway that allows the movement of these ore-bearing fluids, and a physical and redox chemical trap that fixes metals in an ore body (table 3; Taylor, 2000; Hitzman and others, 2005; Hayes and others, in press). The timing of the processes that control fluid generation, migration, storage, and preservation is crucial; if a single system component or process is missing or occurs out of order, the copper deposits cannot form (Magoon and Dow, 1994; Kreuzer and others, 2008; McCuaig and others, 2010).

Essential mineral-system components for assessing SSC deposits include (1) permeable red-bed rocks juxtaposed against strata that contain reductants (typically organic material and earliest diagenetic pyrite), (2) basin history that indicates that the rocks experienced burial diagenesis (depths of 1 to 5 km at temperatures ranging from 70 to 220 °C), and (3) subsurface water that is enriched in copper. The lithostratigraphic relations in the first component are used to delineate areas where reduced-facies-type copper mineralization could occur. The second component is necessary because sediment-hosted copper ore fluids will not develop unless the sediments undergo burial diagenesis. The third component is crucial—we use direct evidence for the presence of copper-bearing ore fluids to constrain the probable amounts of undiscovered copper resources because rocks with the appropriate lithostratigraphic relations can undergo burial diagenesis without developing subsurface water enriched in copper.

Mineral Resource Assessment—Delineating Permissive Tracts

Geographic areas are defined where undiscovered mineral resources could be present. These areas, or “permissive tracts,” represent the surface projection of that part of the Earth’s crust down to a specified depth where undiscovered mineral resources could be present. Areas are excluded from these tracts only on the basis of geology, knowledge about unsuccessful exploration, or the presence of barren overburden exceeding some specified thickness (Singer and Menzie, 2010). No areas are removed because of ownership or use of the land. The criteria used to select the permissive volume of rock, or assessment unit, are provided by descriptive mineral deposit and mineral-systems models.

Lithostratigraphy consistent with the reduced-facies deposit and mineral-system models is used to delineate the permissive tract. The tract is defined by the stratigraphic interval that separates a porous flow unit (reservoir-facies red beds of the Rotliegend) from the overlying ore trap and seal (the base of the Zechstein, which includes the ore trap, the Kupferschiefer, and regional sealing strata, the Kupferschiefer and the overlying evaporites). This stratigraphic interval is mapped to a depth of 2,500 m below the surface; the subsurface body (volume) vertically projected to the surface is the permissive tract. The assessment depth of 2,500 m was selected because it is a kilometer below the deepest mine workings on the Kupferschiefer; at this depth, the virgin rock temperatures are likely to be 80–90 ºC (Górecki, 2006). Based

Table 3. Various schemes to describe the components of mineral-ore systems that form sediment-hosted stratabound copper deposits.

Schemes for mineral-ore system			
Mineral system	**Sediment-hosted stratabound-copper mineral system**		
Wyborn and others (1994)	**Cox and others (2003)**	**Hitzman and others (2005)**	**Hayes and others (in press)**
• Sources of the mineralizing fluids and transporting ligands. • Sources of metals and other components. • Migration pathway. • Thermal gradient. • Energy source to physically mobilize sufficient quantities of fluid to transport economic amounts of metal. • A mechanical and structural focusing mechanism at the trap site. • A chemical and (or) physical cause for enriched mineral precipitation at the trap site.	• Oxidized source rocks that are hematite stable and contain ferromagnesian minerals or mafic rock fragments from which copper can be leached. • Source of brine to mobilize copper. • Source of reduced fluid to precipitate copper and form a deposit. • Conditions favorable for fluid mixing.	• Source(s) of metal and sulfur (sulfate or sulfide). • Source(s) of metal-transporting fluid. • Transport paths of these fluids. • Thermal or hydraulic pump to collect and drive the metal- and sulfate-transporting fluids. • Chemical and physical processes which resulted in precipitation (trapping) of the sulfides.	• Copper source rocks. • Liberation of copper from source rocks by a hot sedimentary brine. • Migration of this copper bearing brine. • Non-oxidized, typically pyrite-bearing host rocks. • Seal rocks. • Traps, both physical and chemical.

on current mining operations in South Africa, this is near the upper limit of virgin rock temperatures where current refrigeration technologies would permit underground mining.

Preliminary permissive tracts were created using GIS information from the Petroleum Geological Atlas of the Southern Permian Basin area (fig. 11; Doornenbal and Stevenson, 2010). Coarse-grained (reservoir-facies) rocks were selected for the lower and upper part of the Slochteren Formation (equivalent to the Rotliegend Group) and merged into a new spatial layer. The facies units included in the selection are: playa margin (coastal sand-belt of playa lake); erg margin (sand flats); erg (dunes); and fluvial plain. This spatial layer was then clipped to include only the areas where the Zechstein 1 cycle is present at depths less 2.5 km. The resulting polygons were smoothed and small holes were filled; small polygons (less than approximately 20 km^2) were deleted. The scale of the Petroleum Geological Atlas of the Southern Permian Basin area maps is 1:3,000,000 (Doornenbal and Stevenson, 2010); therefore, tract boundaries were refined using larger scale maps such as the 1:1,000,000-scale map of Germany (Federal Institute for Geosciences and Natural Resources, 1993) and the 1:400,000-scale map of Sachsen-Anhalt (Stedingk and Rentzsch, 2003).

The resulting polygons were grouped into seven assessment areas (tracts) for the purpose of this study (fig. 12):

- **150rfCu0001, Hercynian-Thüringian Basin** is located in central Germany in the states of Niedersachsen, Sachsen-Anhalt, and Thüringen. Mining began in the High Middle Ages[11] and two deposits were mined in the 20th century, Mansfeld and Sangerhausen. Two deposits, Feld Heldrungen (Thüringen) and Tiefscholle Osterhausen, have not been developed.
- **150rfCu0002, Hessian Depression** is located in south-central Germany in the states of Baden-Wurttemberg, Bayern, Hessen, Niedersachsen, Nordrhein-Westfalen, and Thüringen. Mining began in the Late Middle Ages[12] and one deposit was mined in the 20th century, Richelsdorf.
- **150rfCu0003, North Sea** includes part of northeastern England and most of the Netherlands. There is no history of mining, and there are no identified deposits for this tract.
- **150rfCu0004, Dolny Śląsk (Lower Silesia)** is located in southwestern Poland. Mining has continued since the Late Middle Ages and there are three deposits: Konrad-Grodziec-Wartowice, Lena-Nowy Kościół, and Lubin-Sieroszowice. Several mines are producing copper from Lubin-Sieroszowice, and geological studies have identified many areas prospective for undiscovered mineralization.
- **150rfCu0005, Spremberg-Wittenberg** is located in eastern Germany in the states of Brandenburg, Sachsen-Anhalt, and Sachsen. Two identified deposits, Graustein and Spremberg, are currently (2014) in the permitting process for development, and another site, Weisswasser, is being explored.
- **150rfCu0006, Baltic Basin** includes parts of eastern and northern Poland and extends into Russia and Lithuania. There is no history of mining, and no deposits have been identified.
- **150rfCu0007, Jutland Peninsula** includes parts of Denmark and Germany. There is no history of mining, and no deposits have been identified.

Some of the permissive tracts extend beyond the limits of the Southern Permian Basin area as specified in the Petroleum Geological Atlas (Doornenbal and Stevenson, 2010). The Hessian Depression tract was extended to the south using areas where the Zechstein intersected the Rotliegend as shown on 1:500,000-scale maps from Bavarian Geological State Office (2004a, b). A GIS layer showing the facies boundary from Rupf and Nitsch (2008) and the Zechstein rocks shown on the 1:1,000,000-scale map from Federal Institute for Geosciences and Natural Resources (1993) were also used for the southern boundary. The Baltic Basin tract was extended to the east using the extent of the Zechstein 1 cycle deposits dataset (Doornenbal and Stevenson, 2010) and the extent of Rotliegend rocks from Pokorski (1981). In the northeastern area, this tract was extended using the extent of the Zechstein 1 cycle deposits dataset from Doornenbal and Stevenson (2010). The Jutland Peninsula tract was extended to the north using the part of the Zechstein that is less than 2.5 km deep shown on a 1:750,000-scale structural-depth map of the Zechstein (Vejbæk and Britze, 1994).

Mineral Resource Assessment—Exploration History and Known Deposits

Central Germany—Permissive Tracts 150rfCu0001, Hercynian-Thüringian Basin and 150rfCu0002, Hessian Depression

Mining of the Kupferschiefer likely began in the High Middle Ages. Two miners from Goslar[13], Nappian and Neuke, are purported to have begun mining copper in Hettstedt in the Mansfeld area in about 1199 (fig. 13; Spangenberg, 1572;

[11] Approximately 1000–1299 C.E.

[12] Approximately 1300–1500 C.E.

[13] Goslar is a town near the Rammelsberg sedimentary exhalative lead-zinc-silver deposits. These deposits were mined as early as the Bronze Age and were more-or-less continuously mined from the 10th to the 20th centuries.

Jankowski 1995). Mining of the Kupferschiefer at Ilmenau is documented as early as 1216 (Schorn and others, 2012b). Mining of bituminous copper ores in central Europe is discussed by Albertus Magnus in Liber Mineralium, written about 1260 (Wyckoff, 1958).

By the Late Middle Ages, copper was being mined at several places along the margins of the Thüringian Basin and the Hessian Depression. Mining is documented as early as 1460 in the Richelsdorf Mountains (Walther and Lippert, 1986). In 1556, Georgius Agricola described mining and processing of ores and gave a brief description of the strata associated with the Mansfeld copper ores “For example, in those districts which lie at the foot of the Harz mountains, there are many different coloured strata, covering a copper *vena dilatata*.” Following a description of the overlying strata, he says “Beneath this, and last of all, lies the cupriferous stratum, black coloured and schistose, in which there sometimes glitter scales of gold-coloured pyrites in the very thin sheets, which, as I said elsewhere, often take the forms of various living things” (Hoover and Hoover, 1950, p. 127). Mining began in the area near Frankenberg about 1590 (Schorn and others, 2012a). Elsewhere, mines at Baumbach, Albungen, and Witzenhausen were also active.

Early production was from near-surface, secondarily enriched ores with copper and silver contents exceeding 1 percent and 10 ppm respectively (Walther and Lippert, 1986). Fires were set underground to fracture rocks and miners used hammers, chisels, and wedge hoes to excavate the ore (fig. 14*A*). The working face was about 50 to 60 centimeters (cm) high; miners lay on their sides to dig out the ore material (Spilker, 2010). Around 1500, mine workings penetrated the water table, which necessitated the construction of drainage tunnels. By 1571, there were 127 shafts worked by nearly 1,500 miners in the Mansfeld area (Stedingk, 2002). Mining was active at Korbach and Bieber in the 18th century (Walther and Lippert, 1986; Schorn and others, 2012a). By the end of the 18th century, mining reached depths of 130 m at Mansfeld (Walther and Lippert, 1986).

Ore was extracted from many small tunnels and shafts; the spoil piles from these workings are a unique feature of today’s landscape (fig. 14*B*). Google Earth™ imagery was used to map the distribution of the spoil piles that indicate the location of old mine shafts; mapping started near Eisleben in the Mansfeld area, where we are confident that the conical mounds are related to old mine sites on the Kupferschiefer. We reviewed imagery anywhere rocks near the base of the Zechstein are mapped. In the Mansfeld area, the distribution of the mounds is up dip of the drainage tunnels (German: stollen) that were constructed to drain groundwater from the mines (Jankowski, 1995; Geological Office of the Saxony-Anhalt Mining Area, [2000]). The distribution of these mounds clearly shows the concentration of mining activities in the Mansfeld and Sangerhausen areas, along the southern margin of the Harz, along the northern and southern flanks of the Thüringer Wald, along the northwestern margin of the Erzgebirge, and along the eastern margin of the Rheinisches Schiefergebirge (fig. 13).

The Industrial Revolution significantly increased ore production from the Kupferschiefer in central Germany (Stedingk, 2002; Krüger, 2006; Spilker, 2010). The first steam engine was put into operation in 1785; and iron hoist cables were first introduced in 1837. Dynamite was first used in 1870, and compressed air and pressurized-water drilling started in 1883. The diamond drill, invented about 1863 (Edson, 1926), was used in mineral exploration and mining to search for new deposits and to guide mine development beginning in 1889 (fig. 15; Spilker, 2010). The introduction of pneumatic tools increased the necessary working space in the mines to about 80 to 100 cm (Spilker, 2010). More than 20 ore production shafts were put into operation in the Mansfeld area in the 19th century (fig. 16; Geological Office of the Saxony-Anhalt Mining Area, 2000).

The late 18th and 19th centuries are also characterized by closures of mines that were intermittently mined since the Late Middle Ages (fig. 17)—Ilmenau in the late 1700s; Geismar, Schreufa, and Röddenau (near Frankenberg) about 1820; Leitmar in 1824; Albungen in 1849; and Hahausen shortly after 1862 (Walther and Lippert, 1986; Schorn and others, 2012a,b).

Beginning in the 1930s, the German government initiated mineral exploration programs with the intent of creating employment and securing strategic raw materials (Gillitzer, 1936; Piątek and others, 2004). Systematic mineral exploration in the Kupferschiefer was conducted in central Germany (fig. 17; Gillitzer, 1936; Richter, 1941; and Kautzsch, 1942) and in the region of Silesia (then a German province, now part of Poland) (fig. 12; Eisentraut, 1939). The geologists were clearly familiar with copper deposits that were mined intermittently from the Late Middle Ages and focused exploration efforts near these sites.

In central Germany, geologists conducted drilling programs that investigated (1) the area near Mansfeld, (2) the southern edge of the Harz between Sangerhausen and Walkenried, (3) the area around Kyffhaus and Bottendorf, (4) the northern and southern margins of the Thüringer Wald, (5) the area around the Richelsdorf Mountains, (6) areas north and northeast of the Harz (Wiederstadt, Wohlsdorf, and Golbitz), and (7) along the southern margin of the Flechtinger Höhenzug (figs. 13, 16, 17; Gillitzer, 1936; Richter, 1941; Kautzsch, 1942). Exploration results are illustrated with a variety of maps that are still in use today to identify areas with mineral potential. Maps show (1) the distribution of various sedimentary facies of the Rotliegend and the Kupferschiefer; (2) the distribution of the Rote Fäule; (3) the concentration of measured metal surface density for copper, lead, and zinc; and (4) metal facies with the relative proportion of copper, lead, and zinc. The exploration program identified mineral potential in the Richelsdorf Mountains (also called the Kurhessische copper ore field), the Sangerhausen area, and in the area of Silesia in what is now southwestern Poland. In most of the other areas that had been mined in central Germany during the 13th through 19th centuries, only low-grade copper mineralization was found in holes drilled down dip from the old mines. For example, one hole drilled near Bottendorf contained only tenths of a percent copper compared to copper grades of 2.5 to 2.8 percent in old mine workings (Gillitzer, 1936).

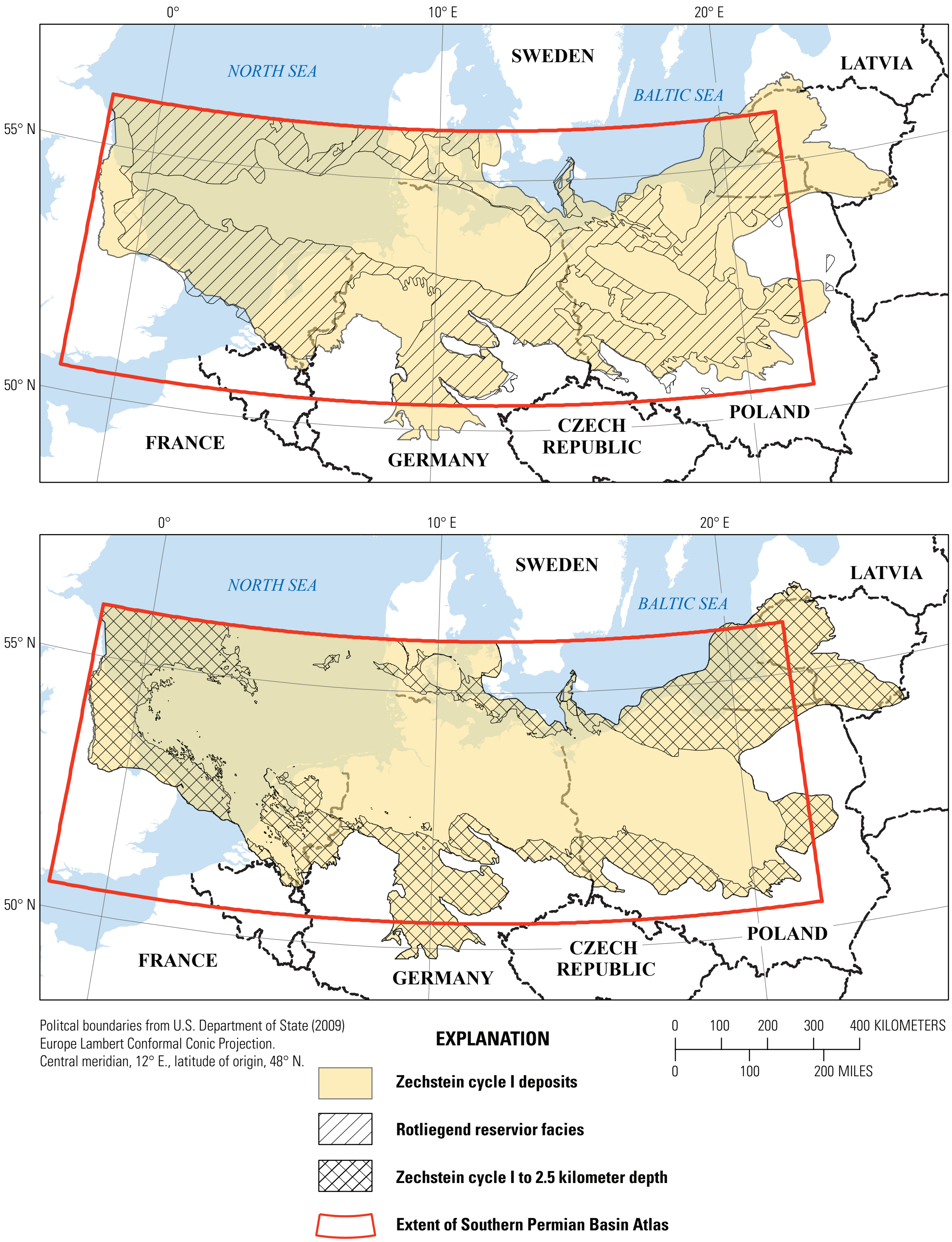


Figure 11. Maps showing how preliminary permissive tracts were delineated for reduced-facies sediment-hosted stratabound copper deposits in the Southern Permian Basin, northern Europe. The upper diagram shows the overlap between the sedimentary rocks of Zechstein Group cycle 1 (which includes the Kupferschiefer) and reservoir-facies red beds of the underlying Rotliegend Group. The lower map shows where the overlap occurs above a depth of 2.5 kilometers. The primary spatial datasets were published as part of the Petroleum Geological Atlas of the Southern Permian Basin area (Doornenbal and Stevenson, 2010).

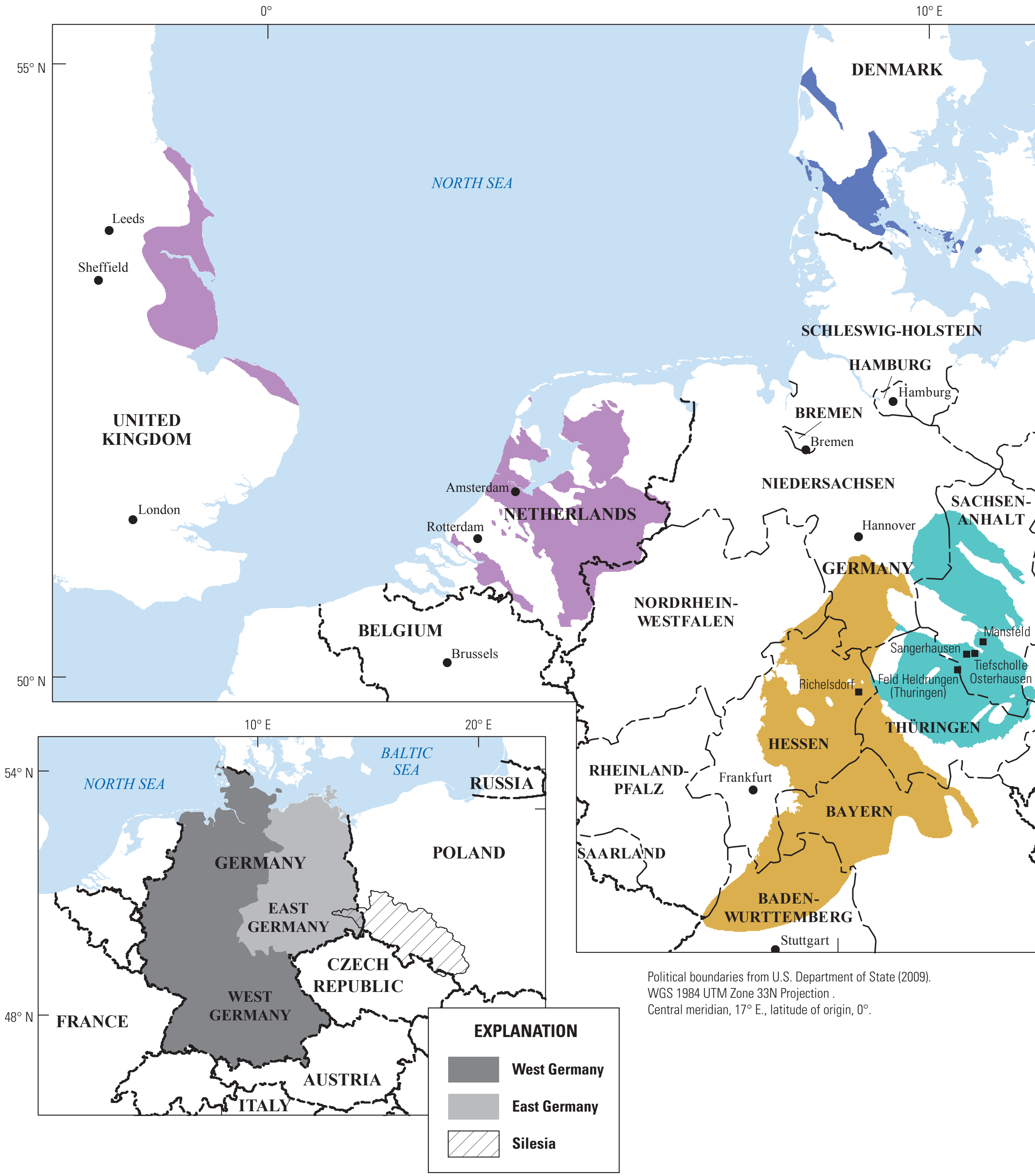
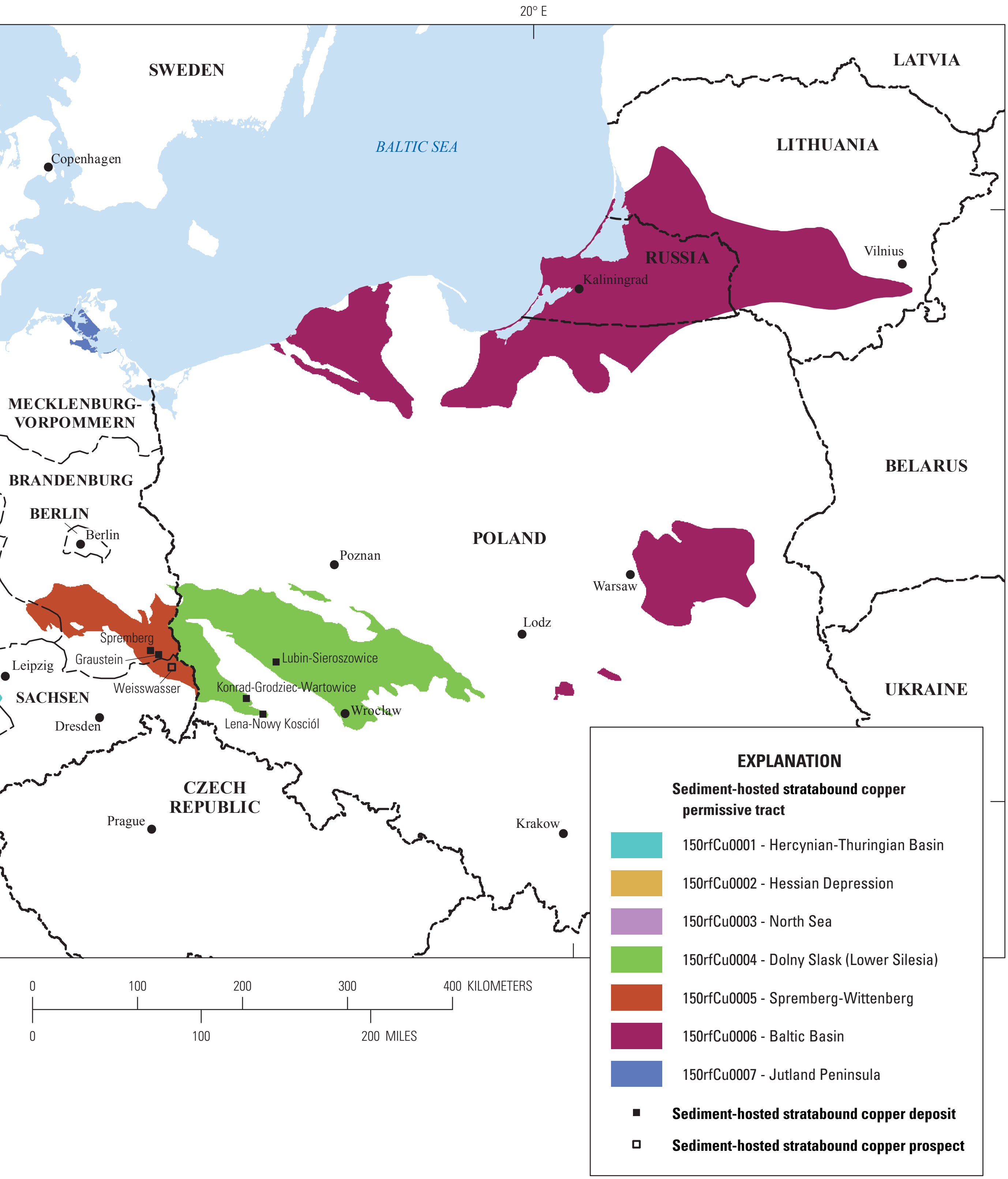
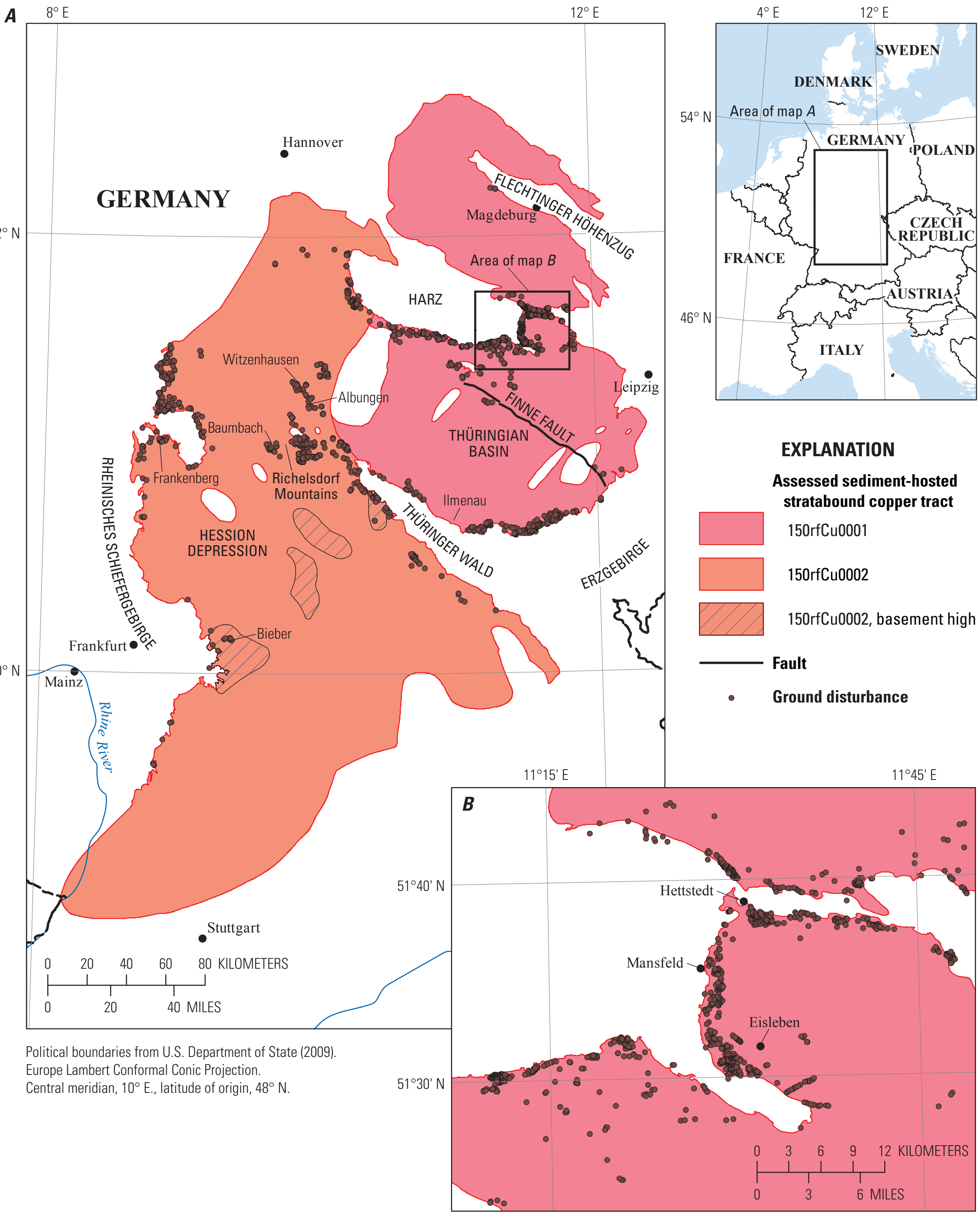


Figure 12. Map showing final permissive tracts delineated for reduced-facies sediment-hosted stratabound copper deposits in the Southern Permian Basin, northern Europe. Inset shows the location of the former East Germany and West Germany, as well as the province of Silesia.



20° E
SWEDEN
LATVIA
BALTIC SEA
LITHUANIA
Copenhagen
RUSSIA
Vilnius
Kaliningrad
MECKLENBURG-
VORPOMMERN
BRANDENBURG
BELARUS
BERLIN
Berlin
POLAND
Poznan
Warsaw
Lodz
Spremberg
Graustein
Lubin-Sieroszowice
Leipzig
Weisswasser
Konrad-Grodziec-Wartowice
UKRAINE
SACHSEN
Wroclaw
Dresden
Lena-Nowy Kosciól
CZECH
REPUBLIC
Prague
Krakow
0 100 200 300 400 KILOMETERS
0 100 200 MILES
EXPLANATION
Sediment-hosted stratabound copper permissive tract
150rfCu0001 - Hercynian-Thuringian Basin
150rfCu0002 - Hessian Depression
150rfCu0003 - North Sea
150rfCu0004 - Dolny Slask (Lower Silesia)
150rfCu0005 - Spremberg-Wittenberg
150rfCu0006 - Baltic Basin
150rfCu0007 - Jutland Peninsula
Sediment-hosted stratabound copper deposit
Sediment-hosted stratabound copper prospect



Political boundaries from U.S. Department of State (2009).
Europe Lambert Conformal Conic Projection.
Central meridian, 10° E., latitude of origin, 48° N.

Figure 13. Map of permissive tracts 150rfCu0001, Hercynian-Thüringian Basin, and 150rfCu0002, Hessian Depression, Germany, and ground disturbance features that likely represent waste heaps around pre-Industrial Revolution mine shafts. Map *A* shows the full extent of both tracts. Map *B* is an enlargement of tract 150rfCu0001, Hercynian-Thüringian Basin, showing the area around Mansfeld.

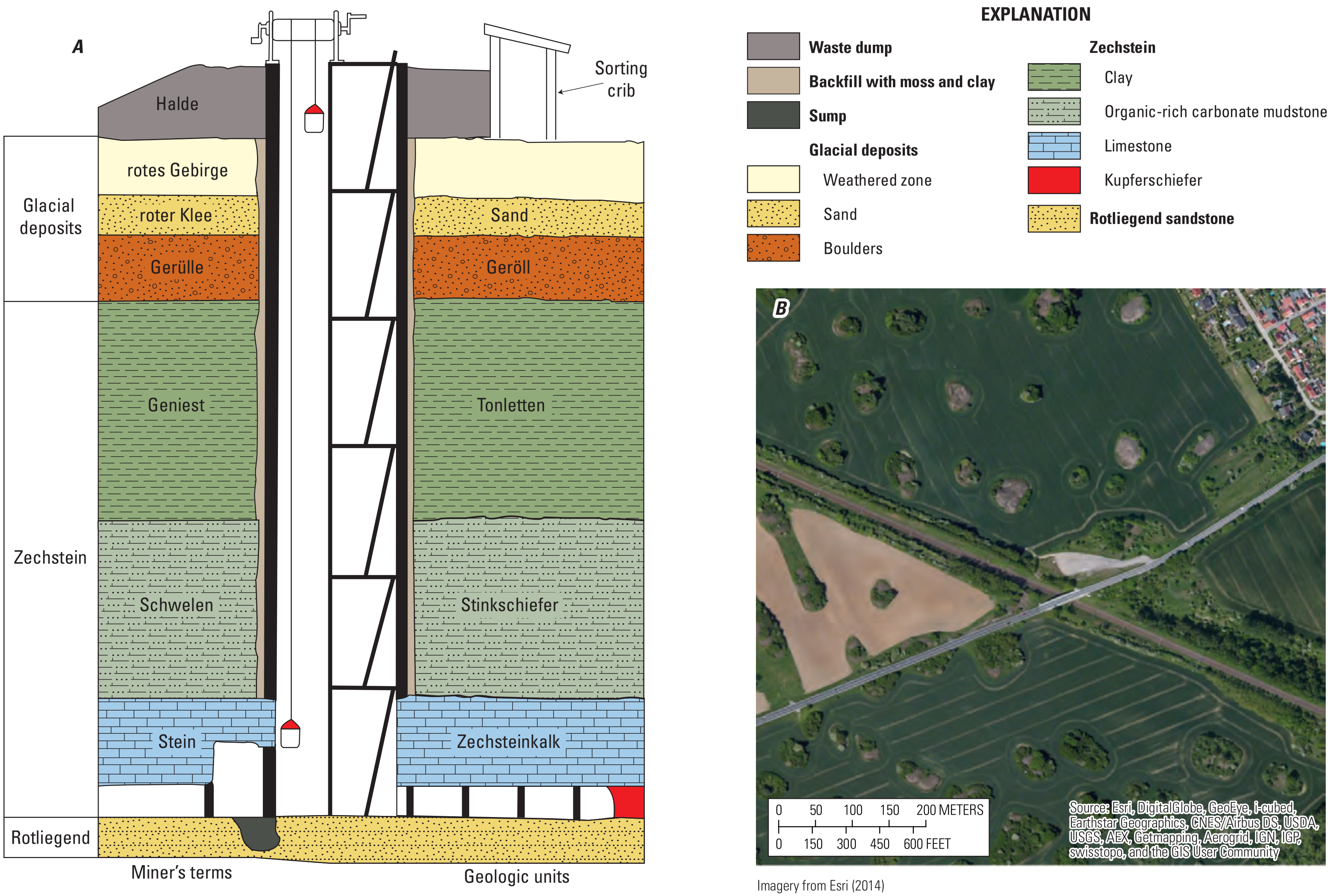


Figure 14. Illustration and satellite image showing pre-Industrial Revolution mine workings used to develop the Kupferschiefer in Germany. *A*, Schematic section showing mine workings used to develop the Kupferschiefer before the Industrial Revolution. Miners laid on their sides to excavate the ore-bearing material, which was moved on carts to the mineshaft and raised to the surface using buckets and winches. Ore was hand sorted and then transported by wagon to smelters. Waste material was deposited near the mineshaft, forming small earthen mounds which are still visible today. *B*, Image showing examples of these old mine sites as ground disturbance features such as shown on figure 13. Schematic section modified from Jankowski (1995).

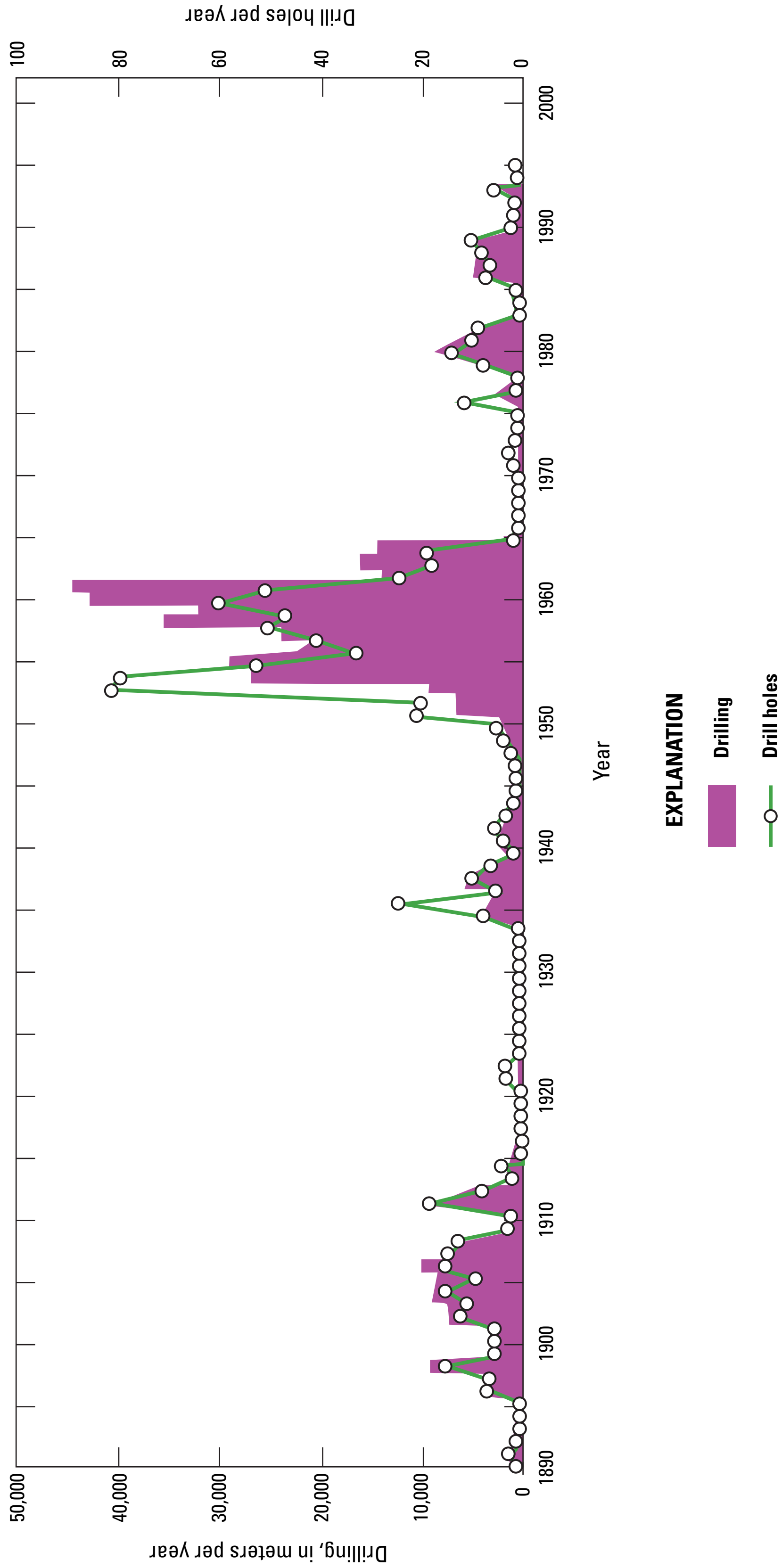


Figure 15. Graph showing the number of holes drilled and the meters drilled per year between 1890 and 1995 to explore for copper ore bodies and guide mine development in the Kupferschiefer in the Mansfeld and Sangerhausen areas, Germany. Modified from Spiker (2010).

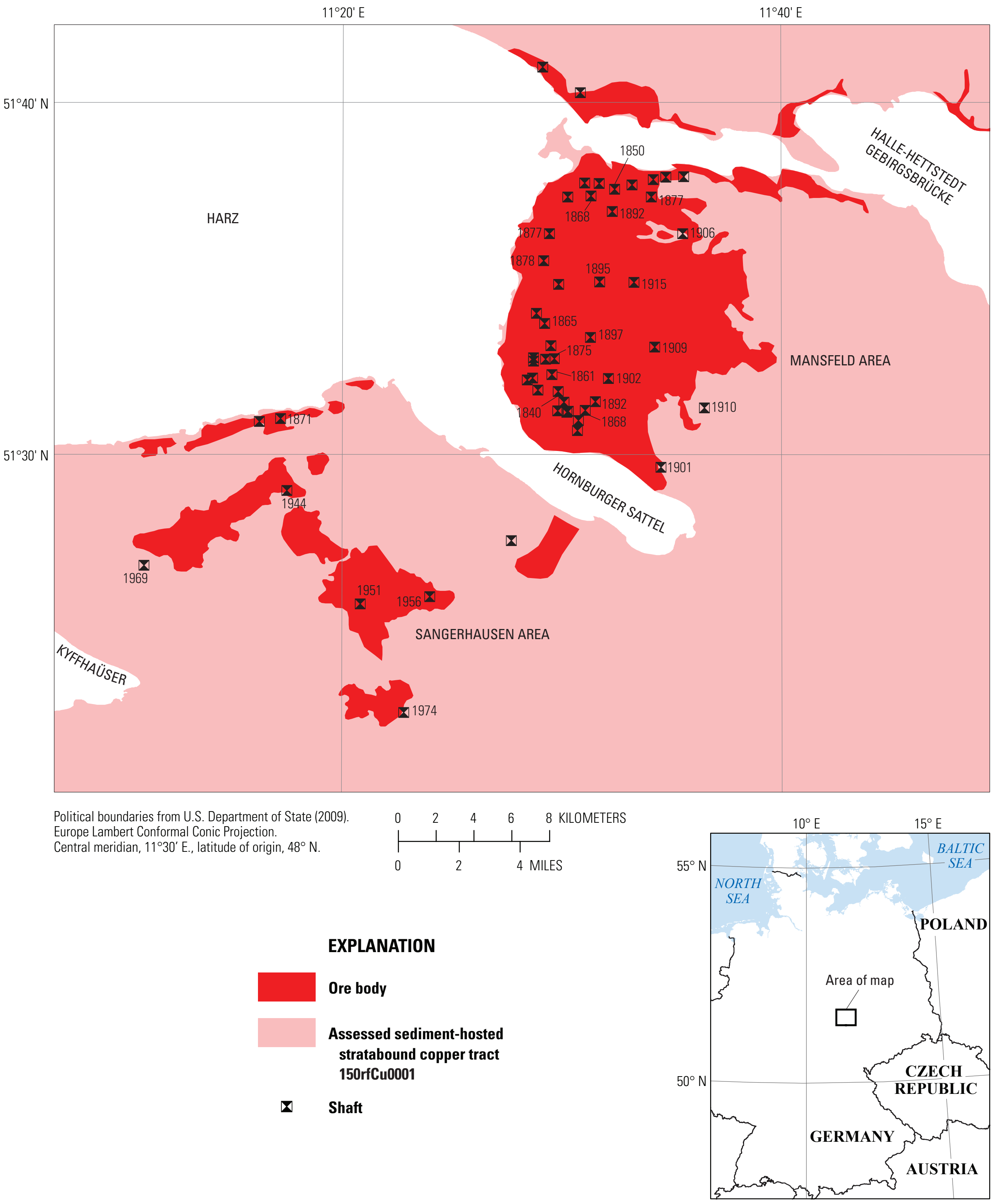


Figure 16. Map of the Mansfeld-Sangerhausen area, Germany, showing copper ore bodies in the Kupferschiefer; permissive tract 150rfCu0001, Hercynian-Thüringian Basin; and mine shafts. Mine shafts are labeled with the year the shaft was constructed, if known. Sources of information for the ore bodies include Geological Office of the Saxony-Anhalt Mining Area (2000) and Liedtke and Vasters (2008).

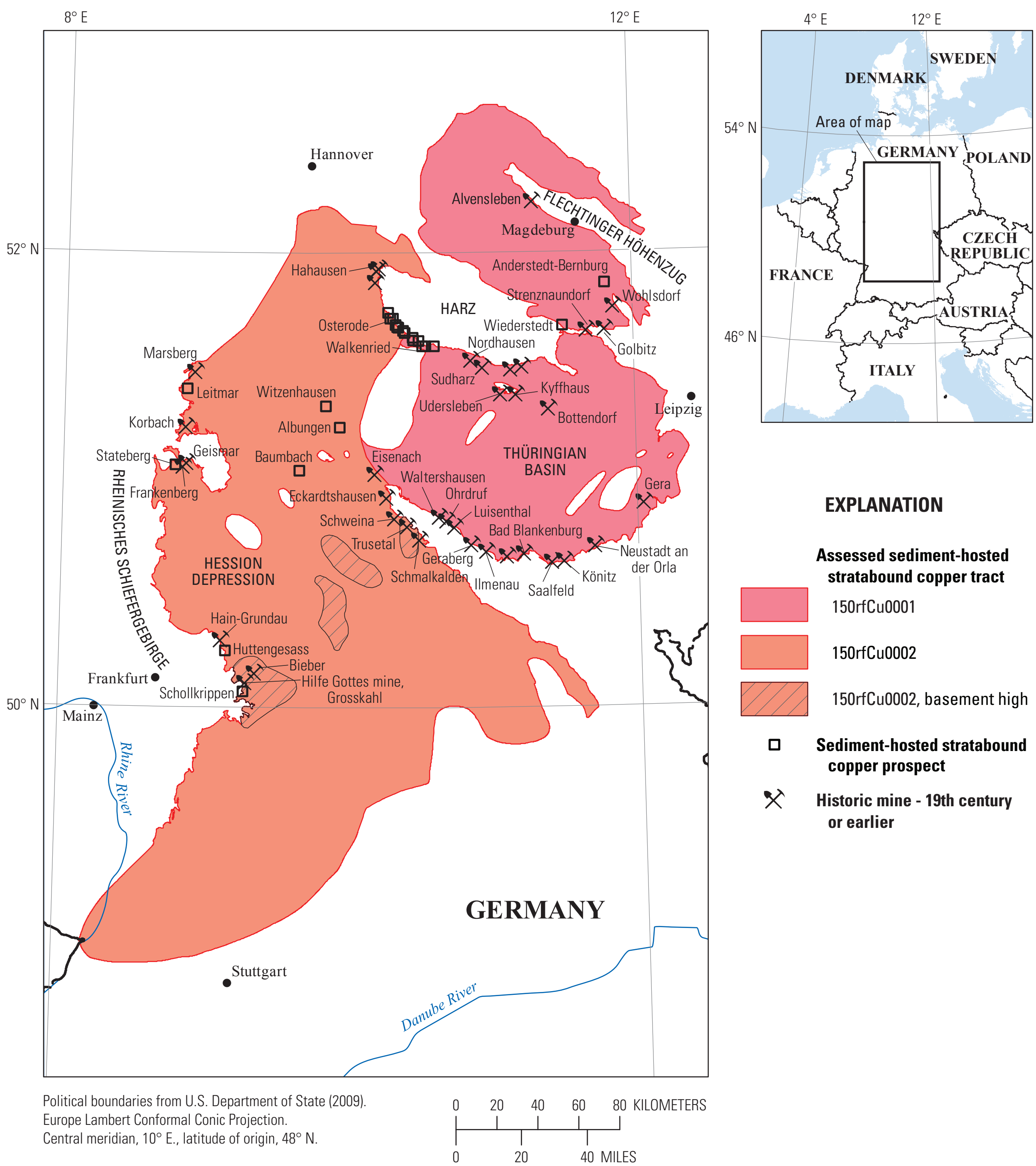


Figure 17. Map of permissive tracts 150rfCu0001, Hercynian-Thüringian Basin, and 150rfCu0002, Hessian Depression, Germany, showing sediment-hosted stratabound copper prospects and mine locations active through the early part of the 19th century.

The exploration program in the Richelsdorf area (fig. 18) began in the 1930s and continued until 1942. An in-situ resource of 42,000,000 metric tons (t) of ore with 0.99 percent copper and containing 400,000 t of copper was estimated (table 4). A mill and a copper smelter were constructed in Sontra, and mining began in 1939. From 1939 to 1945 and 1948 to 1954, 2,000,000 t of ore containing 15,300 t of copper and 7 t of silver were extracted. The mine closed in 1955 without exhausting the identified resources (Walther and Lippert, 1986).

In the Sangerhausen area, mineralized rock covering about 9 km^2 with an average thickness of 29.2 cm and a copper surface density of 16 kg/m^2 was delineated (Kautzsch, 1942). The Thomas-Münzer-Shaft was started in 1944, but no mining took place until after World War II.

Exploration and mining efforts halted in Germany during the course of World War II and did not resume until several years after the war ended. Resource depletion in the Mansfeld deposit was evident in the early 1940s. Around 1955, a reconnaissance survey was started between the Finne Fault and the Halle-Hettstedt Gebirgsbrücke that encompassed the Mansfeld and Sangerhausen areas (figs. 13 and 16). The work led to discovery of mineral resources at Sangerhausen, Tiefscholle Osterahausen, and Feld Heldrungen (figs. 16 and 19; Jung and Knitzschke, 1976). Development of the resources at Sangerhausen began in the early 1950s. Mining continued until 1969 at Mansfeld to a depth of 995 m and 1990 at Sangerhausen to a depth of 950 m (Geological Office of the Saxony-Anhalt Mining Area, [2000]; Spilker, 2010).

From about 1200 to 1990, about 109 million metric tons (Mt) of ore containing 2.6 Mt copper and 14,000 metric tons silver were produced from deposits in the region of Mansfeld and Sangerhausen (tract 150rfCu0001, Hercynian-Thüringian Basin) (table 4; fig. 20; Knitzschke, 1995). About 35.4 Mt of ore containing 860,000 t copper, 105,000 t lead, 100,000 t zinc, and 4,700 t silver remain at Sangerhausen, Tiefscholle Osterhausen, and Feld Heldrungen (Knitzschke, 1995; Stedingk and Rentzsch 2003; Liedtke and Vasters, 2008). The deposits at Tiefscholle Osterhausen and Feld Heldrungen have not been mined.

The exploration work conducted by geologists from 1946 to 1989 in East Germany (fig. 12) was not limited to the Mansfeld and Sangerhausen area; these geologists investigated the metal distribution of the basal Zechstein over an area of 159,000 km^2 where the Kupferschiefer occurs in Germany (Rentzsch and Franzke, 1997). The results are illustrated as a series of maps based on 1,082 underground and surface exposures, as well as 200 boreholes. A total of 10,000 samples were used to delimit and calculate the metal contents of the Kupferschiefer (Rentzsch and Franzke, 1997; Stedingk and Rentzsch, 2003). Copper surface density and metal zoning in permissive tracts 150rfCu0001 and 150rfCu0002 are shown on figures 21 and 22.

In West Germany (fig. 12), beginning in 1978 and continuing through 1987, St. Joe Explorations GmbH and various joint venture partners conducted an exploration program focused on the Lower Zechstein strata. In two areas, Richelsdorf (Ronshausen-Rotenburg-Sontra) in the State of Hessen (Hesse) and Spessart-Rhön, in the State of Bayern (Bavaria), 60 holes were drilled to depths between 150 and 780 m (fig. 19; Schmidt and others, 1986).

In the Richelsdorf area, St. Joe geologists found a Rote Fäule zone in several widespread drill holes (Schmidt and others, 1986). Near the village of Ronshausen, exploration work delineated geological resources of 8 Mt of ore containing 2.1 percent copper and 25 grams per metric ton (g/t) silver over a mining height of 2 m in the southern part of the Richelsdorf area (Südmulde) (Schumacher and Schmidt, 1985; Liedtke and Vasters, 2008). However, no significant results were obtained in the northern part of the Richelsdorf area (Nordmulde) or in the area between Bad Hersfeld and Fulda (fig. 19).

Exploration of the Spessart-Rhön area by St. Joe delineated a copper anomaly covering more than 200 km^2 (figs. 21 and 22). This anomaly is divided into three areas: (1) Fulda (North Rhön) with maximum grades of 1.08 percent copper and 70 ppm silver over 2 m minimum thickness, (2) Spessart-Rhön with maximum grades of 0.4 percent copper and 73 ppm silver over 2 m minimum thickness in the southwest and maximum copper contents of 0.73 percent and 19 ppm silver over 2 m minimum thickness in the northeast, and (3) Spessart-Rhön East (fig. 19; Schumacher and Schmidt, 1985; Schmidt and others, 1986; Liedtke and Vasters, 2008).

Recent summaries of exploration activity in Germany do not describe ongoing projects in tracts 150rfCu0001, Hercynian-Thüringian Basin, or 150rfCu0002, Hessian Depression (Seifert and Gutzmer, 2012; Wellmer, 2012). Many of the historic mine sites here are now parks or museums (Ließmann, 2010).

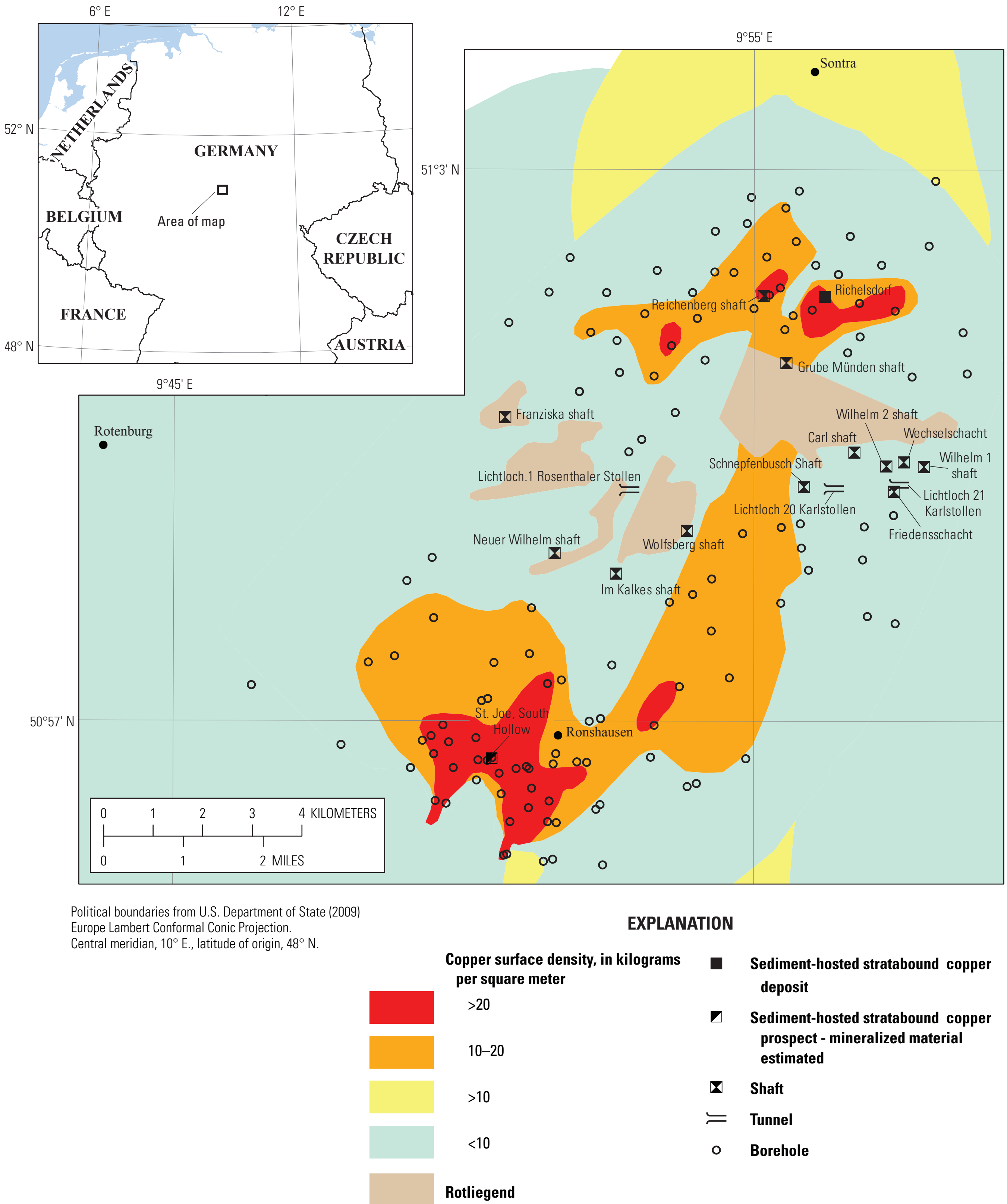


Figure 18. Map of the Richelsdorf area, Germany, showing copper surface density, deposits, occurrences, shafts, tunnels, and boreholes. Sources of information include Schmidt and others (1986), Federal Institute for Geosciences and Natural Resources (1993), Rentzsch and others (1997), Rentzsch and Franzke (1997), and Liedtke and Vasters (2008). >, greater than; <, less than.

Table 4. Reduced-facies sediment-hosted stratabound copper deposits associated with the Kupferschiefer in the Southern Permian Basin, Germany and Poland.

[n.d., no data; km², square kilometers; Mt, million metric tons; %, percent; g/t, grams per metric ton; >, greater than]

Deposit name	Mines	Tract name	Country	Latitude	Longitude	Ore body area (km²)	Ore (Mt)	Copper grade (%)	Silver grade (g/t)	Contained copper metal (Mt)	Reference
Feld Heldrungen (Thüringen)	n.d.	Hercynian-Thuringian Basin	Germany	51.2949	11.2522	20.26	10.0	3.00	128	0.300	Knitzschke (1995); Lidtke and Vasters (2008)
Mansfeld	Many shafts	Hercynian-Thuringian Basin	Germany	51.553	11.58	173.14	80.8	2.49	137.6	2.01	Knitzschke (1995); Liedtke and Vasters (2008)
Sangerhausen	Many shafts	Hercynian-Thuringian Basin	Germany	51.434	11.361	54.38	28.1	2.20	110.2	0.619	Knitzschke (1995); Liedtke and Vasters (2008)
Tiefscholle Osterhausen	n.d.	Hercynian-Thuringian Basin	Germany	51.4494	11.4808	5.24	6.60	1.89	92	0.125	Knitzschke (1995); Liedtke and Vasters (2008)
Richelsdorf	Many shafts	Hessian Depression	Germany	51.027	9.937	n.d.	42.0	0.99	25.0	0.416	Cox and others (2003); Liedtke and Vasters (2008)
Konrad-Grodziec-Wartowice	Konrad; Lubichów	Dolny Śląsk (Lower Silesia)	Poland	51.217	15.685	>67	131	1.25	53.0	1.640	Błądek and others (2005); Oszczepalski and Speczik (2011)
Lena-Nowy Kościół	Lena; Leszczyna; Nowy Kościół	Dolny Śląsk (Lower Silesia)	Poland	51.081	15.912	>38	32.0	0.68	43.0	0.216	Błądek and others (2005); Oszczepalski and Speczik (2011)
Lubin-Sieroszowice	Bytom Odrzanski; Gaworzyce; Glogow Gleboki-Przemyslowy; Lubin; Malomice; Polkowice; Radwanice Zachod; Retkow; Rudna; Sieroszowice	Dolny Śląsk (Lower Silesia)	Poland	51.528	16.091	>432.04	3.61	1.99	56.5	71.9	Kirkham and Broughton (2005); Polish Geological Institute (2009 a, b); Lattanzi and others (1997); Wodzicki and Piestrzyński (1994)
Graustein	n.d.	Spremberg-Wittenberg	Germany	51.5726	14.4737	8.25	53.6	1.62	n.d.	0.868	Kopp and others (2006); Liedtke and Vasters (2008)
Spremberg	n.d.	Spremberg-Wittenberg	Germany	51.6051	14.3611	9.89	44.1	1.40	n.d.	0.617	Kopp and others (2006); Liedtke and Vasters (2008)

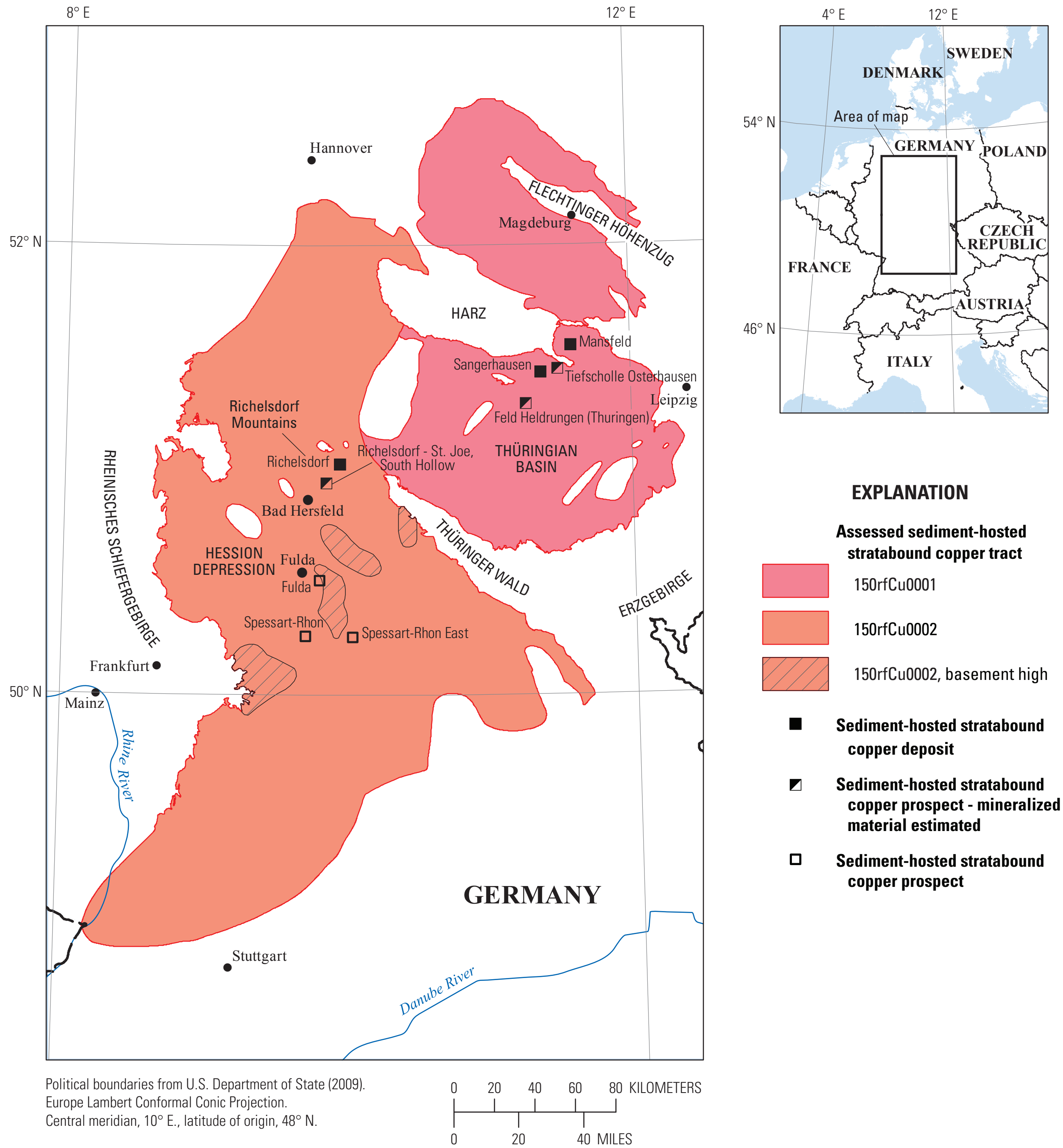


Figure 19. Map of permissive tracts 150rfCu0001, Hercynian-Thüringian Basin, and 150rfCu0002, Hessian Depression, Germany, with the location of deposits and occurrences that were important in the 20th century.

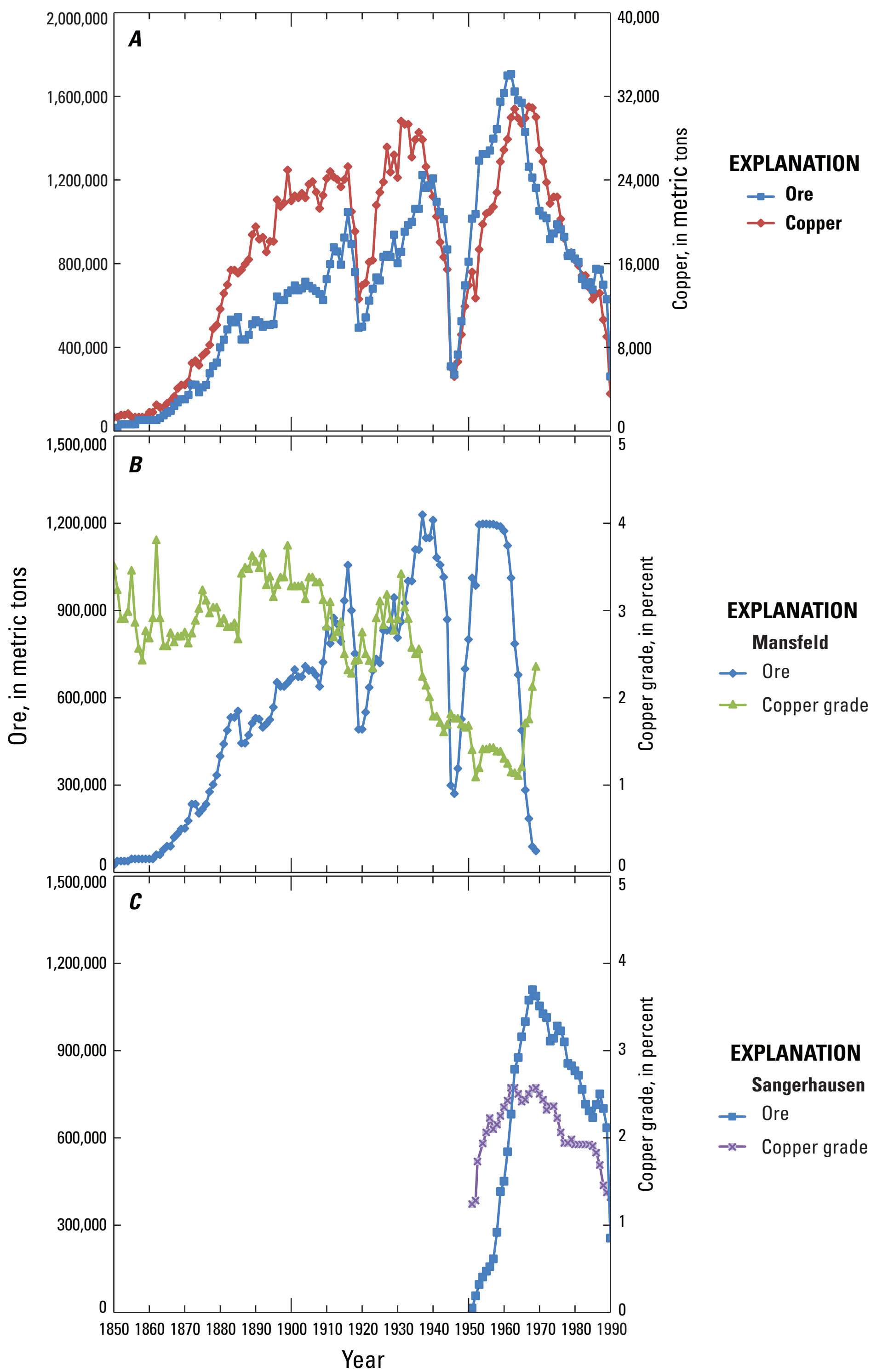


Figure 20. Graphs showing copper ore, production, and grade from 1850 to 1990 for the Mansfeld-Sangerhausen area, Germany. *A*, Copper ore and production for the Mansfeld-Sangerhausen area; *B*, copper ore and grade from the Mansfeld area; and *C*, copper ore and grade from the Sangerhausen area. Modified from Spilker (2010).

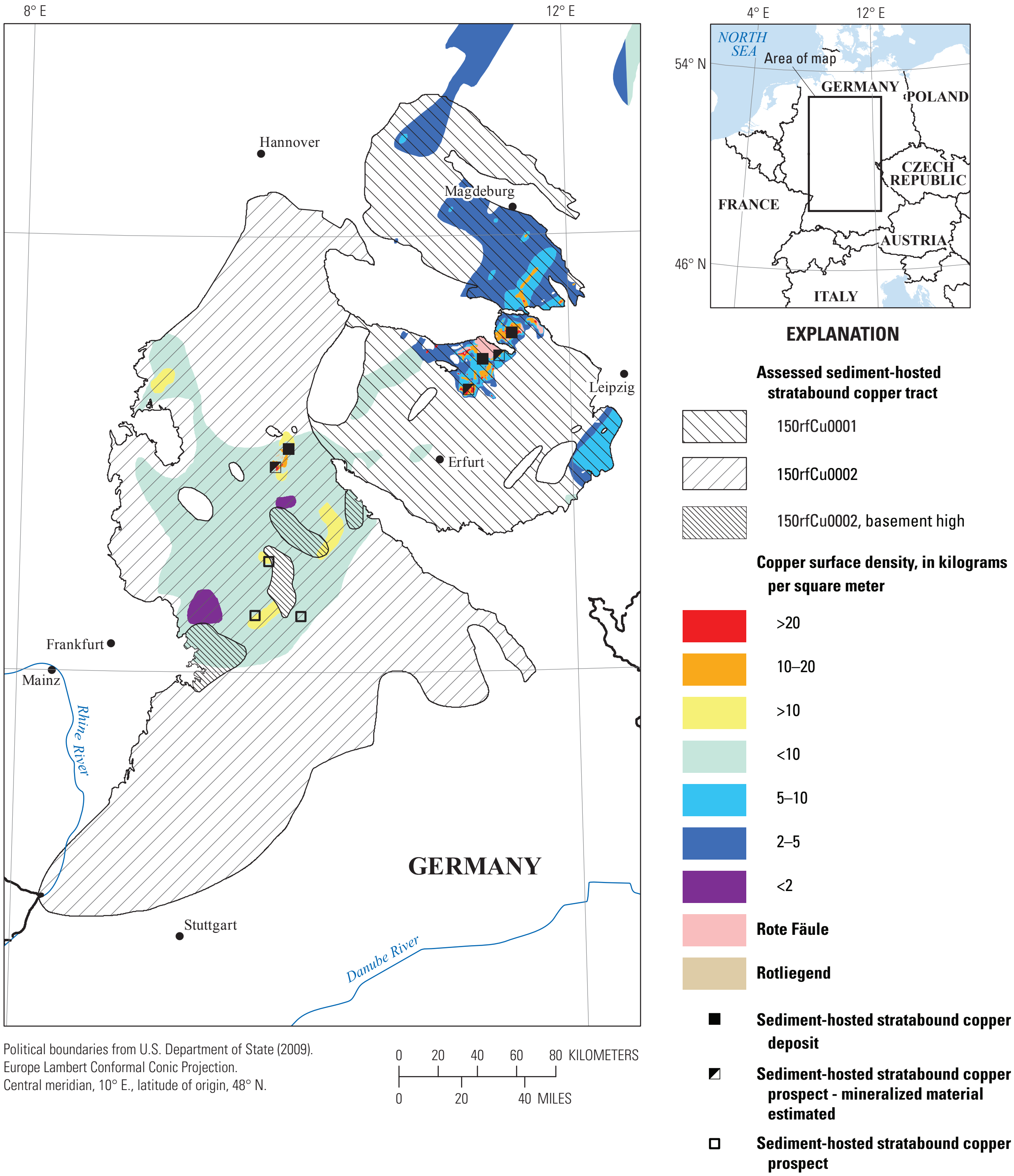


Figure 21. Map of the Hercynian-Thüringian and Hessian Depression Basin areas, Germany, showing copper surface density; permissive tracts 150rfCu0001, Hercynian-Thüringian Basin, and 150rfCu0002, Hessian Depression; deposits; and occurrences. Sources of information for copper surface density include Schmidt and others (1986); Federal Institute for Geosciences and Natural Resources (1993); Rentzsch and Franzke (1997); Rentzsch and others (1997); Geological Office of the Saxony-Anhalt Mining Area (2000); Stedingk and Rentzsch (2003); and Liedtke and Vasters (2008).

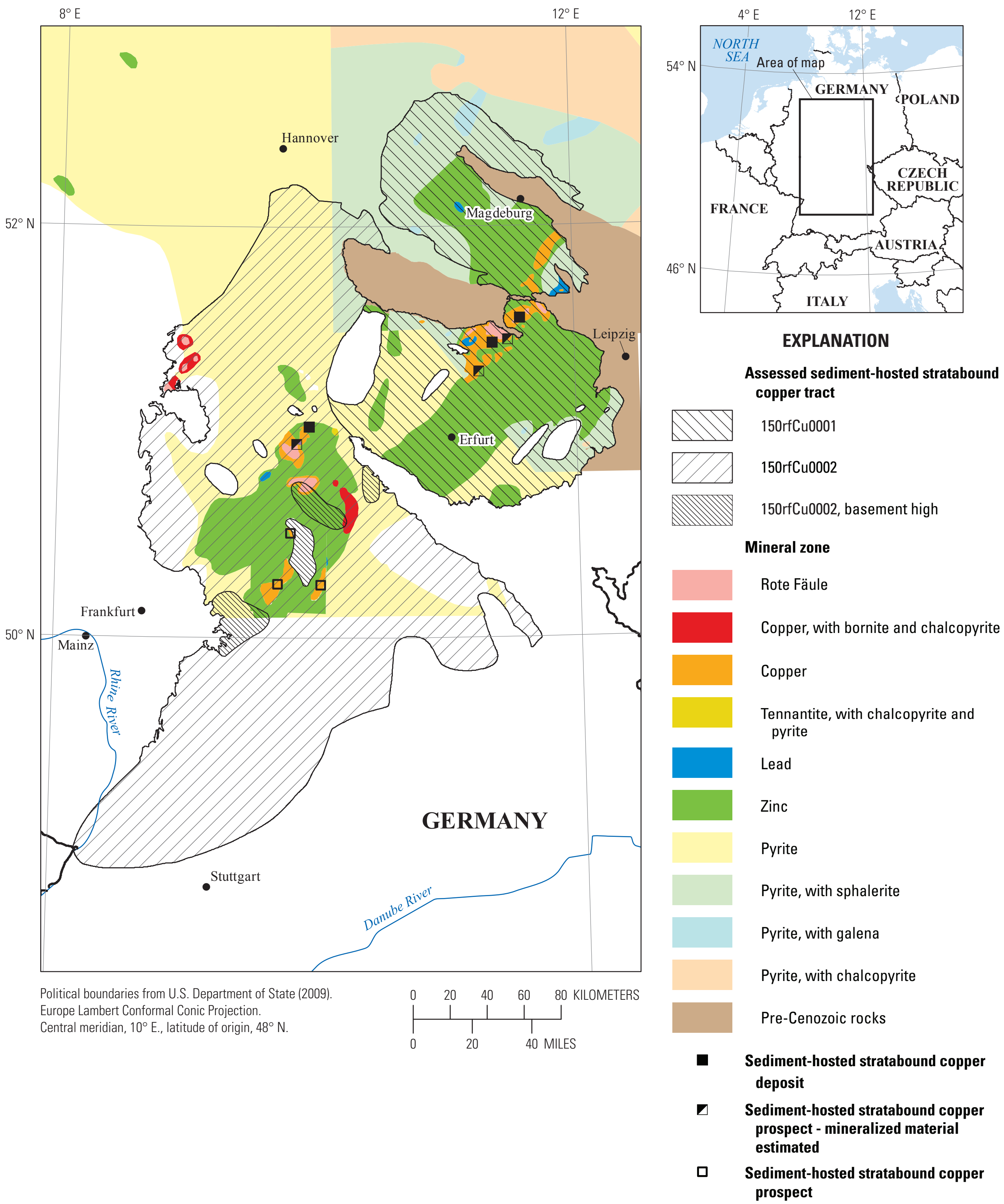


Figure 22. Map of the Hercynian-Thüringian and Hessian Depression areas, Germany, showing mineral zones; permissive tracts 150rfCu0001, Hercynian-Thüringian Basin, and 150rfCu0002, Hessian Depression; deposits; and occurrences. Sources of information for mineral zones include Richter (1941), Schumacher and Schmidt (1985), Schmidt and others (1986), Schmidt (1987), Federal Institute for Geosciences and Natural Resources (1993), Rentzsch and others (1997), Geological Office of the Saxony-Anhalt Mining Area (2000), Stedingk and Rentzsch (2003), and Bavarian Geological State Office (2004a).

Southwestern Poland and Adjoining Areas in Germany—Permissive Tracts 150rfCu0004, Dolny Śląsk (Lower Silesia), and 150rfCu0005, Spremberg-Wittenberg

In southwestern Poland, in the area of Silesia (fig. 23; tract150rfCu0004, Dolny Śląsk (Lower Silesia)), the earliest mining of the Kupferschiefer may date from the 13th century at Leszczyna (fig. 24; German: Haasel), when Saxon miners from Mansfeld introduced metallurgical practices that could extract metal from the ores (Piątek and others, 2004). The first written documentation of copper mining at Leszczyna is from 1360. Mining took place intermittently throughout the 14th to 18th centuries; however, the largest production came from a mine near Leszczyna called "Stilles Glück" or "Ciche Szczęście" (Kobylańska and Madziarz, 2012). From 1866 to 1883, approximately 85,000 t of copper-enriched marl was mined, and 1,100 t copper and 3,437 kg of silver were produced (Eisentraut, 1939). Average grades were 1.3 percent copper and 40 g/t silver. In the late 19th and early 20th centuries, copper occurrences in the basal Zechstein Group were also described at Grzędy (German: Konradswaldau), Biegoszów (German: Hundorf), and Nowy Kościół (German: Neukirch) (Beyschlag and others, 1916).[14]

In the 1930s, most of Silesia was part of the German empire; Zechstein exposures in the eastern part of the North Sudetic Syncline were examined by German geologists in the 1930s (fig. 24; Eisentraut, 1939). Exploration focused on the Leszczyna and Nowy Kościół occurrences near Złotoryja (German: Goldberg) and an area approximately 30 km to the northwest near Bolesławiec (German: Bunzlau) (Eisentraut, 1939; Błądek and others, 2005). In the area south of Złotoryja, construction began on a mine near Wilków (German: Wolfsdorf), which after World War II became the Lena Mine (table 4). The mine operated from 1950 to 1973 and produced 14,468,129 t of ore at 0.55 percent copper. In the area southeast of Bolesławiec, construction began on shafts that ultimately, after the war, became the Konrad Mine. Lubichów produced approximately 2,000,000 t of ore containing 0.68 percent copper before it was merged with the Konrad Mine in 1976; Konrad produced 37,914,702 t of ore with 0.78 percent copper before mining ceased in 1989 (table 4).[15]

[14]Maps and text in Beyschlag and others (1916) and Eisentraut (1939) use German names for settled areas in Silesia. Modern maps of the region use Polish names. German names are given in parentheses to help interpret information in these older reports.

[15] For sediment-hosted stratabound copper deposits, it is common to have multiple mines on a deposit. The Lena and Nowy Kościół deposits are contiguous; therefore, tonnage and grade are aggregated in table 4. The production numbers reported in this paragraph are from individual mines on the deposit.

Beginning in 1952, the Polish Geological Institute–National Research Institute (PGI) in Warsaw, under the direction of Jan Wyżykowski, conducted research and exploration in the Fore-Sudetic Monocline (figs. 23 and 25). In 1957, ore-grade material was discovered in the Sieroszowice region at a depth of 600 m; in this area, Triassic and older rocks, including the deposit, are concealed beneath hundreds of meters of Tertiary and Quaternary alluvium (fig. 25). In 1959, Jan Wyżykowski and team announced resources of 1,360,000,000 t of ore containing 19,300,000 t of copper in the Lubin-Sieroszowice area based on the results of 24 holes (Błądek and others, 2005). The ore deposit is so large that several mines are currently needed to develop it—Lubin (in production 1958), Rudna (in production 1974), and Polkowice-Sieroszowice (Polkowice in 1968 and Sieroszowice in 1980) (fig. 26; table 5). Another mine, Głogów Głęboki Przemysłowy, is in the pre-production stage (KGHM, 2012).

From 1958 to 2009, KGHM mines produced 14,800,000 t of copper from about a billion metric tons of ore (fig. 27; USBM and USGS data from Minerals Yearbooks). The amount of metal produced reflects losses in metallurgical recovery, dilution, mining operations, and pillars. Using loss information in Lattanzi and others (1997), we estimate that the premining resource for the material that was mined was approximately 1,400 Mt of ore containing about 1.83 percent copper and 26 Mt of contained copper. As of December 31, 2011, KGHM reports measured and indicated mineral resources of 1,500 Mt of ore with 1.97 percent copper and 59 g/t silver (KGHM, 2012). These remaining resources contain 29,485,000 t of copper and 88,298 t of silver and the deposit is open at depth. After accounting for dilution and losses that occur during mining, reserves are estimated to be 1,181,032,000 t of ore with 1.58 percent copper and 48 g/t silver (KGHM, 2012). The production and remaining resource information suggest an ore body that contained about 2,900 Mt of ore containing more than 55 Mt of copper. If the resource estimates for Bytom Odrzanski, Gaworzyce, Radwanice-Zachod, and Retchow are added to early, published numbers of tonnage and grade (Wodzicki and Piestrzyński, 1994), the estimated premining size of the deposit is 3,600 Mt of ore with approximately 72 Mt of copper (table 4). With the available information, we cannot explain the discrepancy between the estimates of the original size of the deposit. Regardless, either estimate indicates that the Lubin-Sieroszowice area contains a supergiant deposit using the criteria of Singer (1995).

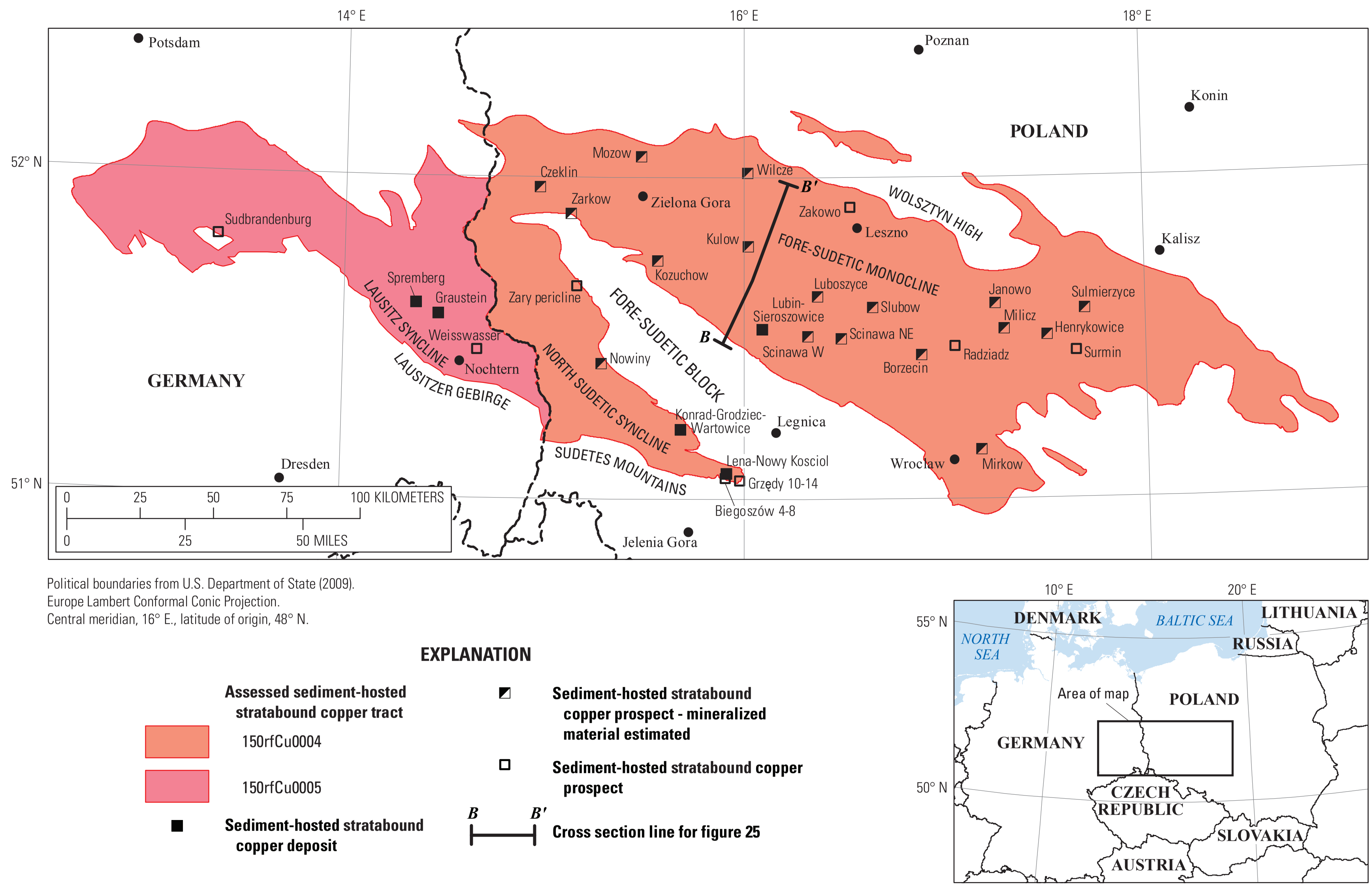


Figure 23. Map showing permissive tracts 150rfCu0004, Dolny Śląsk (Lower Silesia), Poland, and 150rfCu0005, Spremberg-Wittenberg, Germany; deposits; and occurrences.

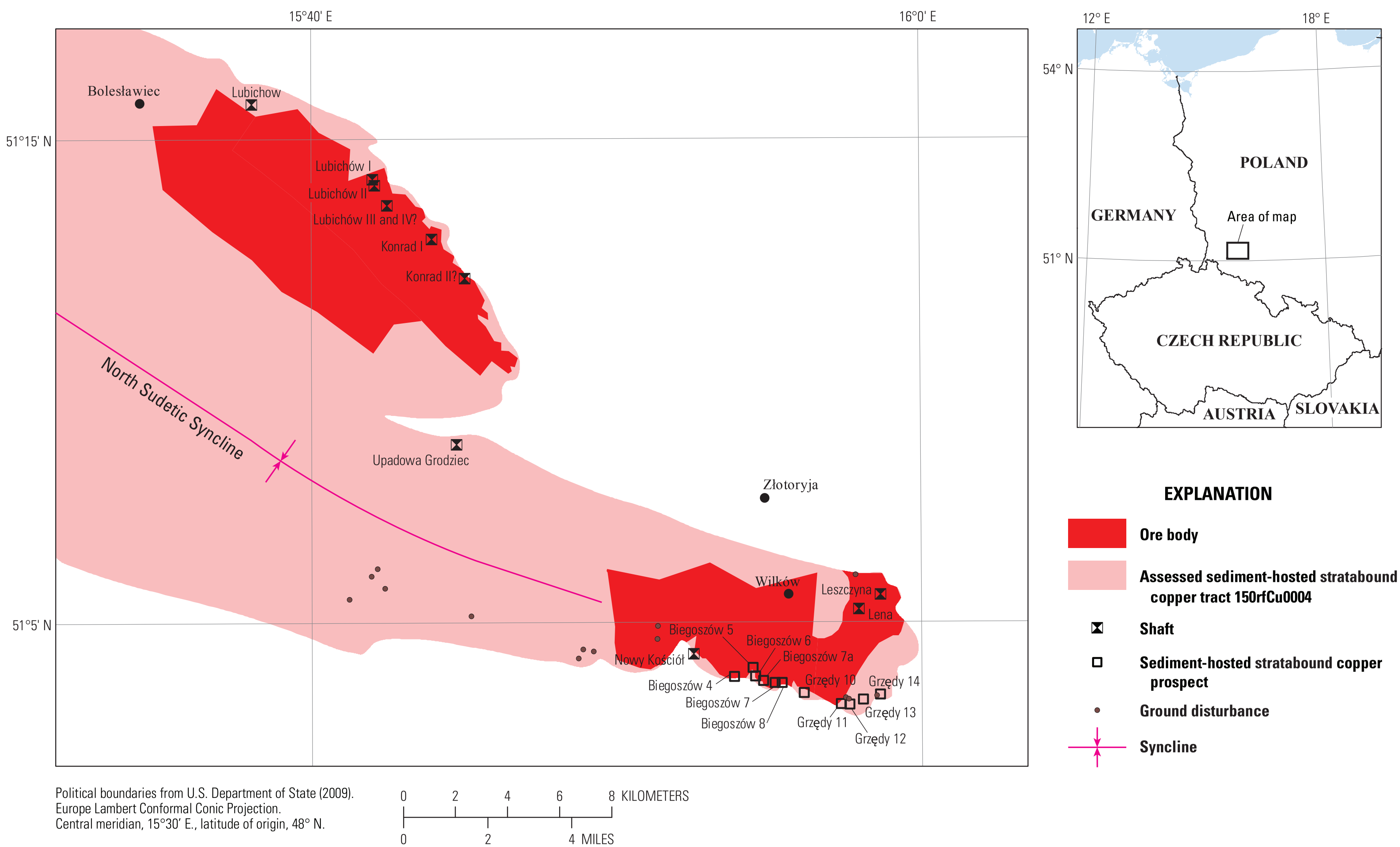


Figure 24. Map of the North Sudetic Syncline in Poland showing the location of the permissive tract 150rfCu0004, Dolny Śląsk (Lower Silesia), Poland; ore bodies; mine shafts; prospects; and ground disturbances. Information sources include Eisentraut (1939), Błądek and others (2005), Bońda and Siekiera (2009), and Kobylańska and Madriarz (2012).

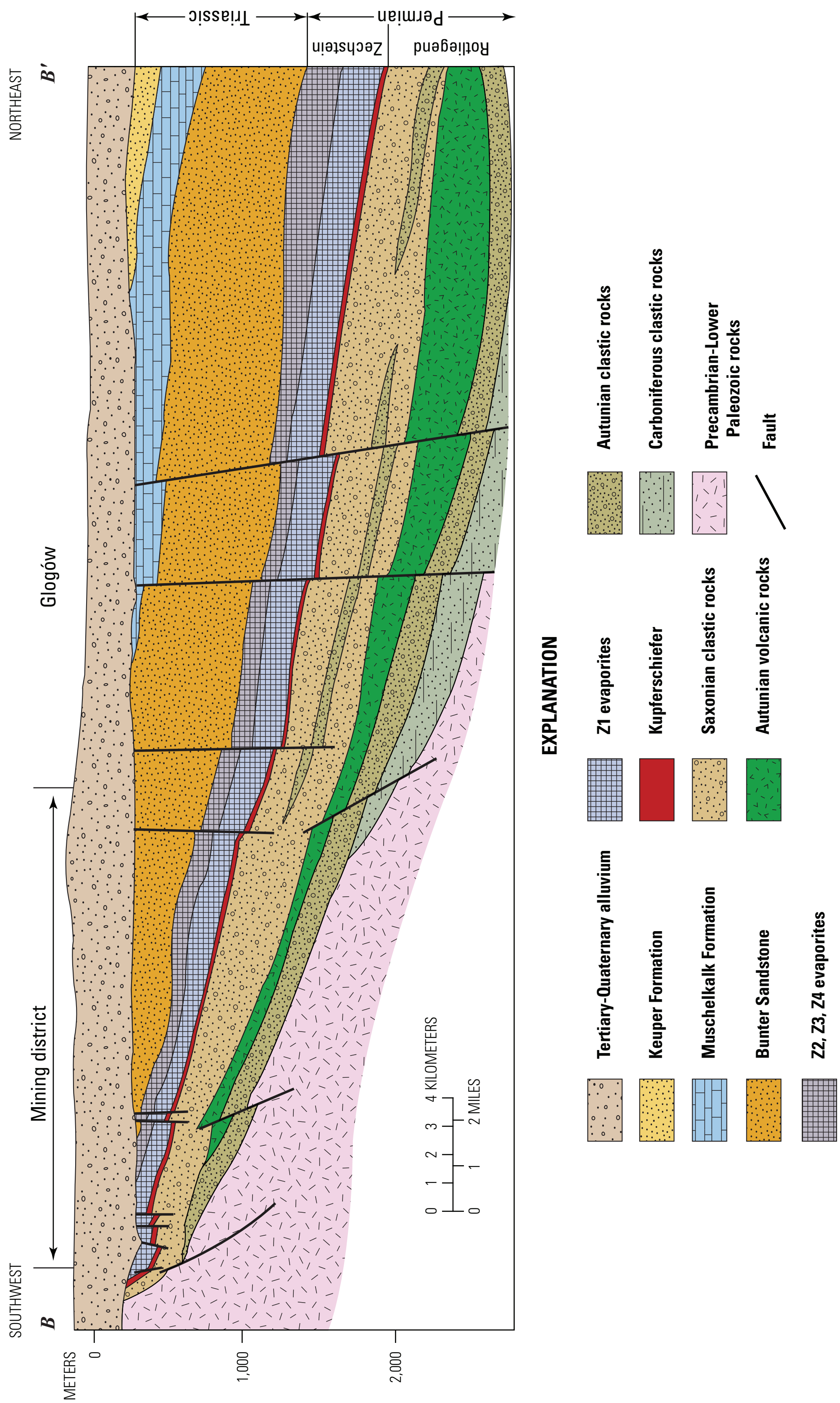
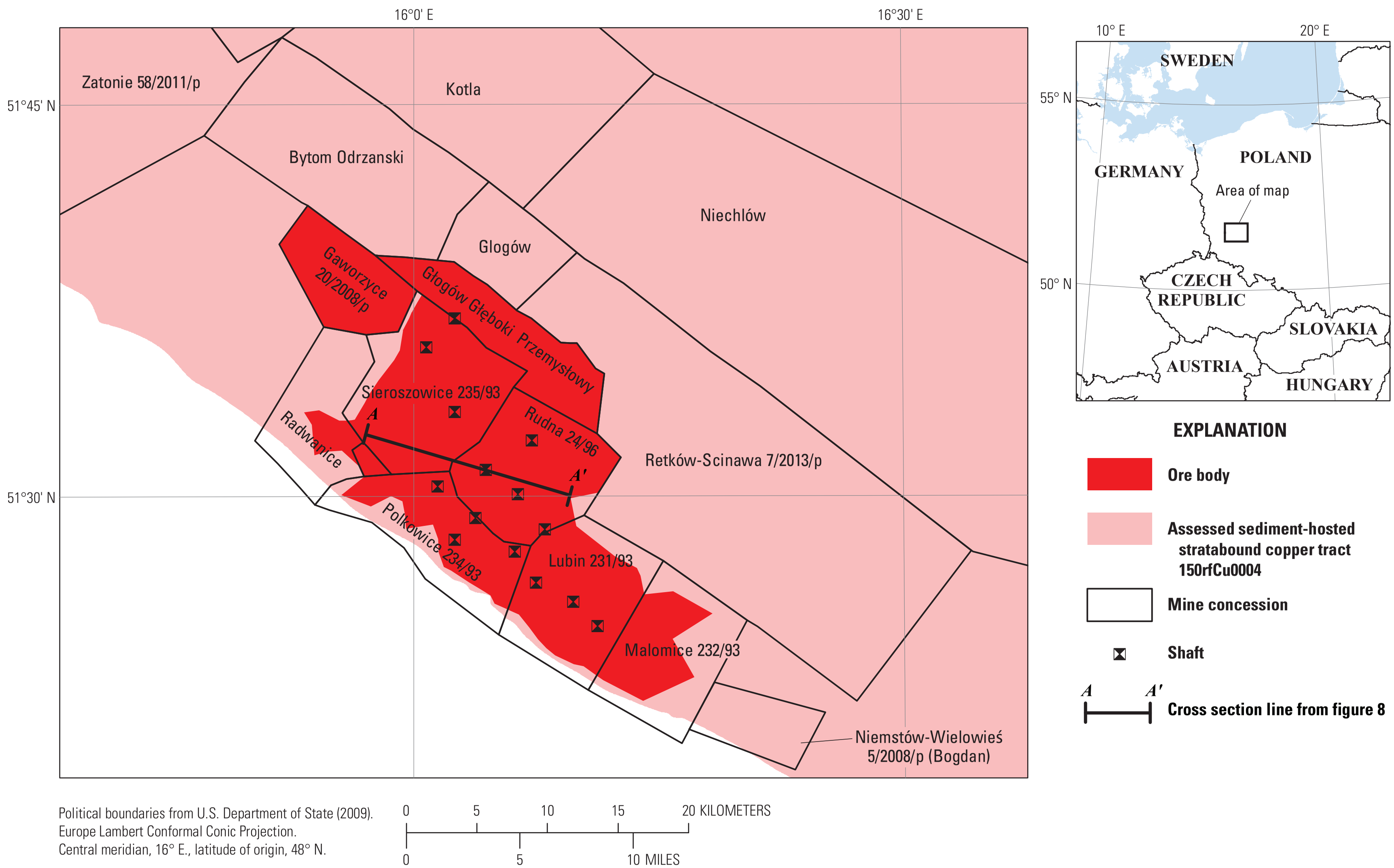


Figure 25. Cross section through the Lubin-Sieroszowice mining area, Fore Sudetic Monocline, Poland. Line of section is shown on figure 23. Modified from Pieczonka and others (2001).



Political boundaries from U.S. Department of State (2009).
Europe Lambert Conformal Conic Projection.
Central meridian, 16° E., latitude of origin, 48° N.

Figure 26. Map of the Lubin-Sieroszowice mining area, Poland, showing the ore body; permissive tract 150rfCu0004, Dolny Śląsk (Lower Silesia); mine concessions; and shafts. Sources of information include Bońda and Siekiera (2009) and Oszczepalski and Speczik (2011).

Table 5. Technical information for the mines developing copper deposits in the Fore-Sudetic Monocline, Southern Permian Basin, Poland.

[P, Polkowice; S, Sieroszowice; n.d., no data; %, percent; g/t, grams per metric ton; m, meter; m/ºC, meters per degrees Celsius; ºC/100 m, degrees Celsius per 100 meters; ºC, degrees Celsius]

Mine	Mining areas	Average copper grade (%)	Average silver grade (g/t)	Mining depths (m)	Average geothermal step (m/ºC)	Average geothermal gradient (ºC/100 m)	Virgin rock temperature, Upper Permian strata (ºC)
Lubin	Lubin I and Małomice I	1.0	42	480–890	38.0	3.0	21.7 to 36.5
Polkowice-Sieroszowice	Polkowice II, Sieroszowice I; and Radwanice Wschód	1.85	44	676–1,084	P: 36.1 S: 40.9	P: 3.0 S: 2.8	P: 27.5 to 35.0 S: 27.2 to 48.7
Rudna	Rudna I and Rudna II	1.65	46	920–1,170	39.8	2.5	34.5 to 47.7
Głogów Głęboki-Przemysłowy	Głogów Głęboki-Przemysłowy	1.90	61	1,200–1,400	n.d.	n.d.	47.8

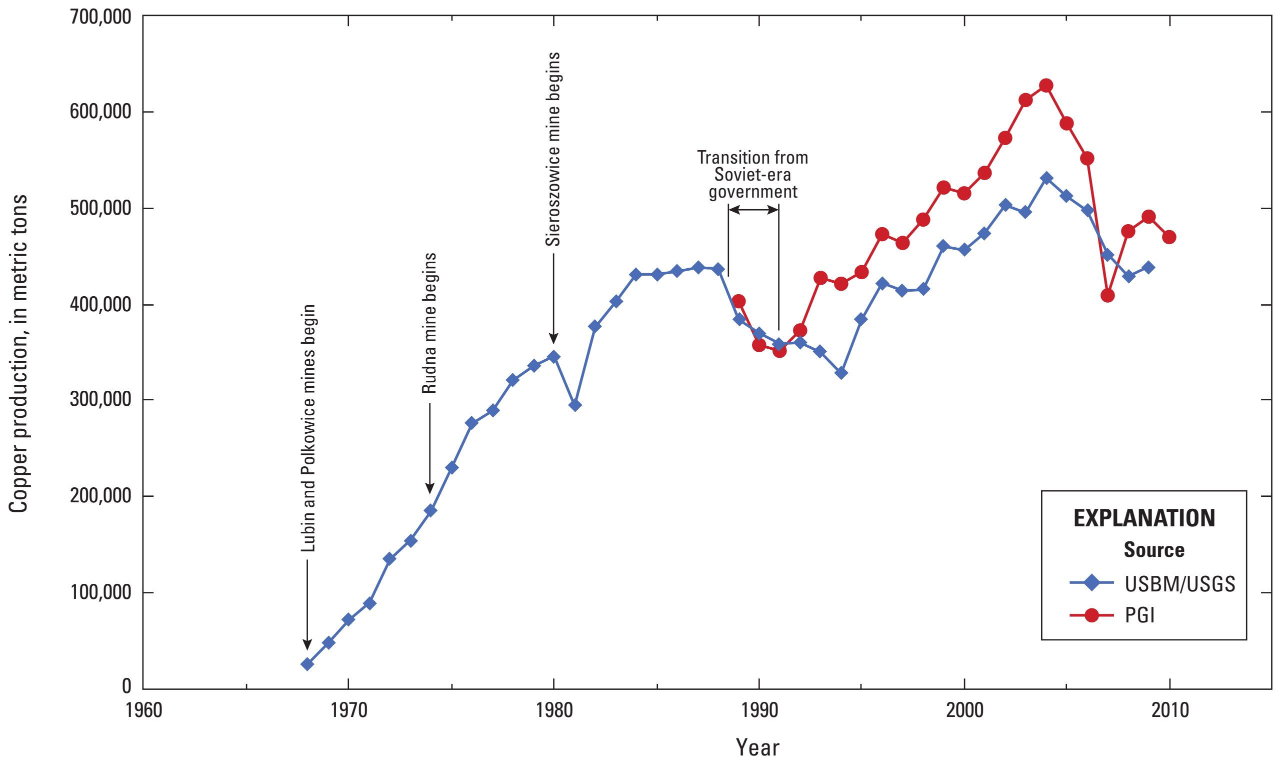


Figure 27. Graph showing copper production from the Lubin-Sieroszowice mining area, Poland, from 1958 to 2010. Data from the U.S. Bureau of Mines (USBM) and U.S. Geological Survey (USGS) Minerals Yearbooks, as well as Polish Geological Institute–National Research Institute (PGI) (2009b).

In the 1980s, PGI used a computer database to study the grade of mineralization and distribution of metals in the basal part of the Zechstein Formation in Poland. The database contains results of chemical analyses of rock samples for copper, lead, zinc, silver, nickel, cobalt, vanadium, and molybdenum and information on lithostratigraphic units. In 1995, the database contained data from 774 boreholes with chemical analyses of more than 50,000 samples. In 1997, a metallogenic atlas of the Zechstein was published (Oszczepalski and Rydzewski, 1997b); the database is continually supplemented and new versions of maps have been subsequently released (figs. 28 and 29; Oszczepalski and Speczik 2011, 2012). This information has been used to document the potential for copper and silver in SSC mineralization in Poland; 15 prospects above the depth of 2,000 m are forecast to have prognostic resources[16] containing 69.54 Mt of copper. Below 2,000 m, another six prospects are thought to contain an additional 186.4 Mt of copper (fig. 30; Oszczepalski and Speczik 2011, 2012).

As of August 1, 2013, more than 20 concessions for prospecting and exploration have been awarded by the Polish Ministry of the Environment (Ministerstwo Środowiska, MOS) and another 12 applications are pending (Ministry of the Environment, Republic of Poland, 2013a, b) (fig. 30). Concessions largely cover areas recently identified as prospective with prognostic resource estimates (Oszczepalski and Speczik, 2011, 2012). Exploration information was found for five of the concessions.

KGHM is conducting exploration on two of the concessions (KGHM, 2012; Bartlett and others, 2013). For the Radwanice-Gaworzyce Project, 19 drill holes are planned with the objective of assessing the possibility of exploiting the copper deposit on MOS concessions Gaworzyce 20/2008/p and Radwanice 13/2009/p. For the Grodziecka Syncline Project (MOS concession Synklina Grodziecka 23/2009/p), 15 or more drill holes are planned in order to increase the mineral inventory and the confidence level of the resource estimate.

Balamara Resources Limited has drilled three holes on its Bogdan Project (MOS concession Niemstów-Wielowieś 5/2208/p) with the following results (Balamara Resources Limited, 2013):

- Hole B1: 2 m at 2.39 percent lead, 0.42 percent copper, and 18.9 g/t silver from 284 to 286 m
- Hole B2: 1 m at 2.05 percent lead, 0.28 percent copper, and 10.6 g/t silver from 371.4 m
- Hole B4: Upper lead zone with 6 m at 0.73 percent lead and 4.6 g/t silver from 343 m; and lower copper zone with 8.5 m at 0.36 percent copper and 11.6 g/t silver from 349.5 m.

[16]Prognostic resources are equivalent to undiscovered resources as used by the USGS. They do not have enough information to be formally classified as mineral inventory using either the COMECON or CRIRSCO (Committee for Mineral Reserves International Reporting Standards) systems.

In the Lausitzer area in the German States of Brandenburg and Saxony (fig. 23; tract 150rfCu0005, Spremberg-Wittenberg), geophysical exploration by East German scientists in the 1950s located a seismic high that subsequent drilling showed to be a covered, pre-Tertiary northwest- to southeast-trending fault-bounded anticline superimposed on the westward extension of the North Sudetic Syncline in Poland. Early drill results showed that the Zechstein and the Kupferschiefer are present (Kölbel, 1958). Between 1953 and 1981, the structure was investigated by geophysical surveys and more than 120 drill holes, culminating in the discovery of the Spremberg and Graustein copper deposits (fig. 23; Kopp and others, 2006). The deposits occur on the north and northeast flank of the structure and underlie an area that extends for about 14 km in a northwest-southeast direction with a width of 2 to 3 km. The Spremberg and Graustein deposits occur at depths ranging from 400 to 1,650 m below the surface (Knitzschke and Vulpius, 2007)

The first resource estimates were based on work conducted between 1958 and 1964 and were revised based on supplementary drilling done between 1971 and 1974. Based on the new resource estimate, an investment decision was made to develop the Spremberg and Graustein deposits, with start of production scheduled for 1990. However, work was suspended on the project in August 1980 (Knitzschke and Vulpius, 2007).

In 2007, KSL Kupferschiefer Lausitz GmbH [KSL] was established to reassess the Spremberg and Graustein deposits. From 2008 to 2010, KSL reevaluated the existing data and drilling and then completed a program of three drill holes and four drill-hole deflections.[17] In 2011, a seismic survey was conducted around the Spremberg ore deposit, and an authorization was granted to KSL for the mining rights of the Spremberg and Graustein deposits (KSL, 2011). Currently, the Graustein deposit has 53.6 Mt of ore containing 868,320 metric tons of copper; the Spremberg deposit has 44.1 Mt of ore containing 617,000 metric tons of copper (table 4). The company is currently (2014) working on obtaining a regional planning permit (KSL, 2013).

KGHM is also conducting exploration in the Lausitzer area between Weisswasser and Nochten in Germany at a site where previous studies indicated ore mineralization in a single drill hole (fig. 23; Bachowski and others, 2007; KGHM, 2012). KGHM has completed four holes to test the mineral potential of this area (Gazeta Polska Codziennie, 2013). The mineralization occurs at depths ranging from 1,250 to 1,350 m (Legnica, 2012).

[17]A wedge-shaped piece of metal is used to deflect the drill bit so that another hole can be drilled through an ore body. The cost of deflecting is much less than drilling a new hole.

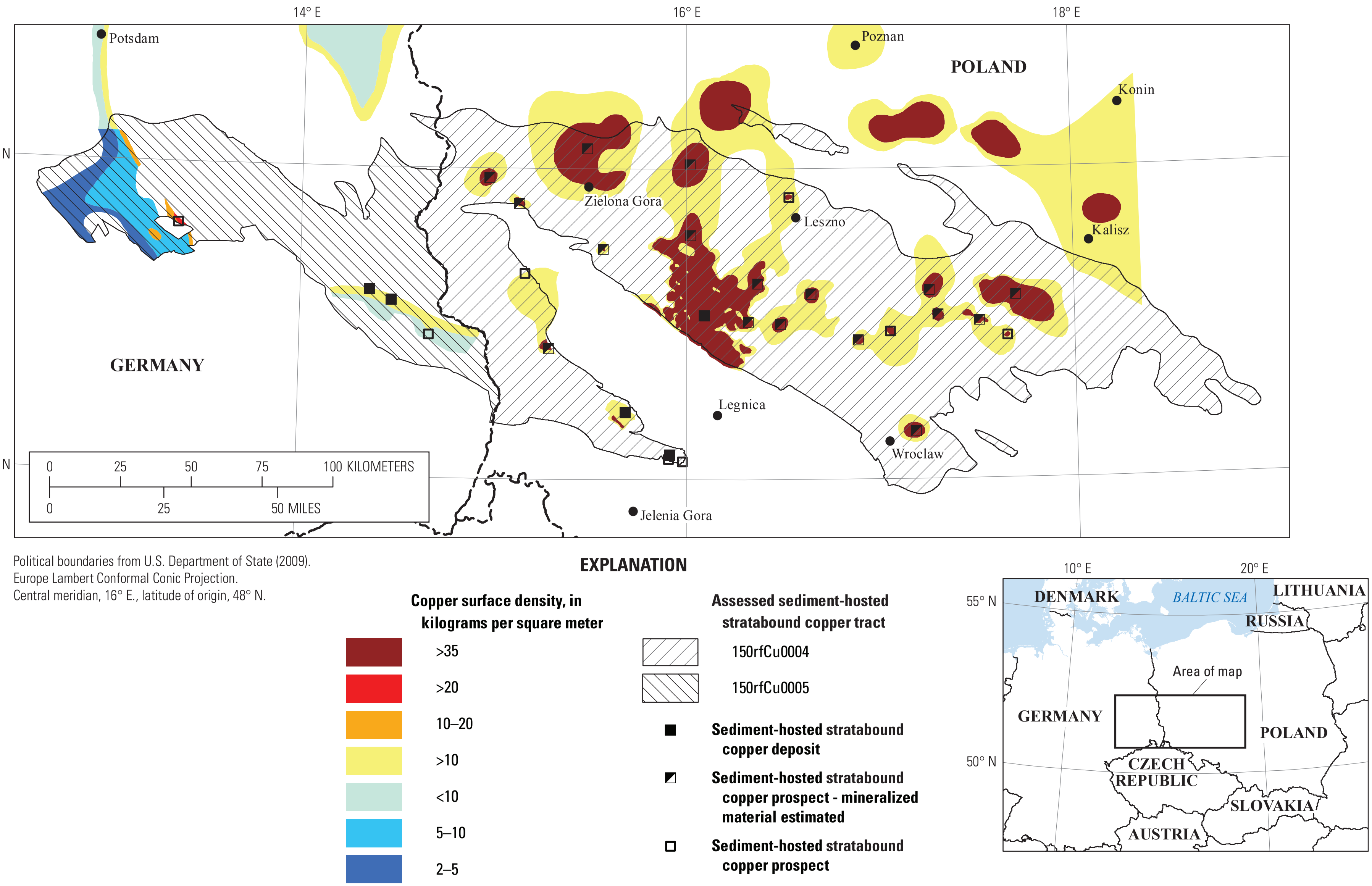


Figure 28. Map of the Lower Silesia and Spremberg-Wittenberg areas, Poland and Germany, showing copper surface density; permissive tracts 150rfCu0004, Dolny Śląsk (Lower Silesia), Poland, and 150rfCu0005, Spremberg-Wittenberg, Germany; deposits; and occurrences. Sources for copper surface density include Rentzsch and Franzke (1997), Stedingk and Rentzsch (2003), Liedtke and Vasters (2008), and Oszczepalski and Speczik (2011). >, greater than; <, less than.

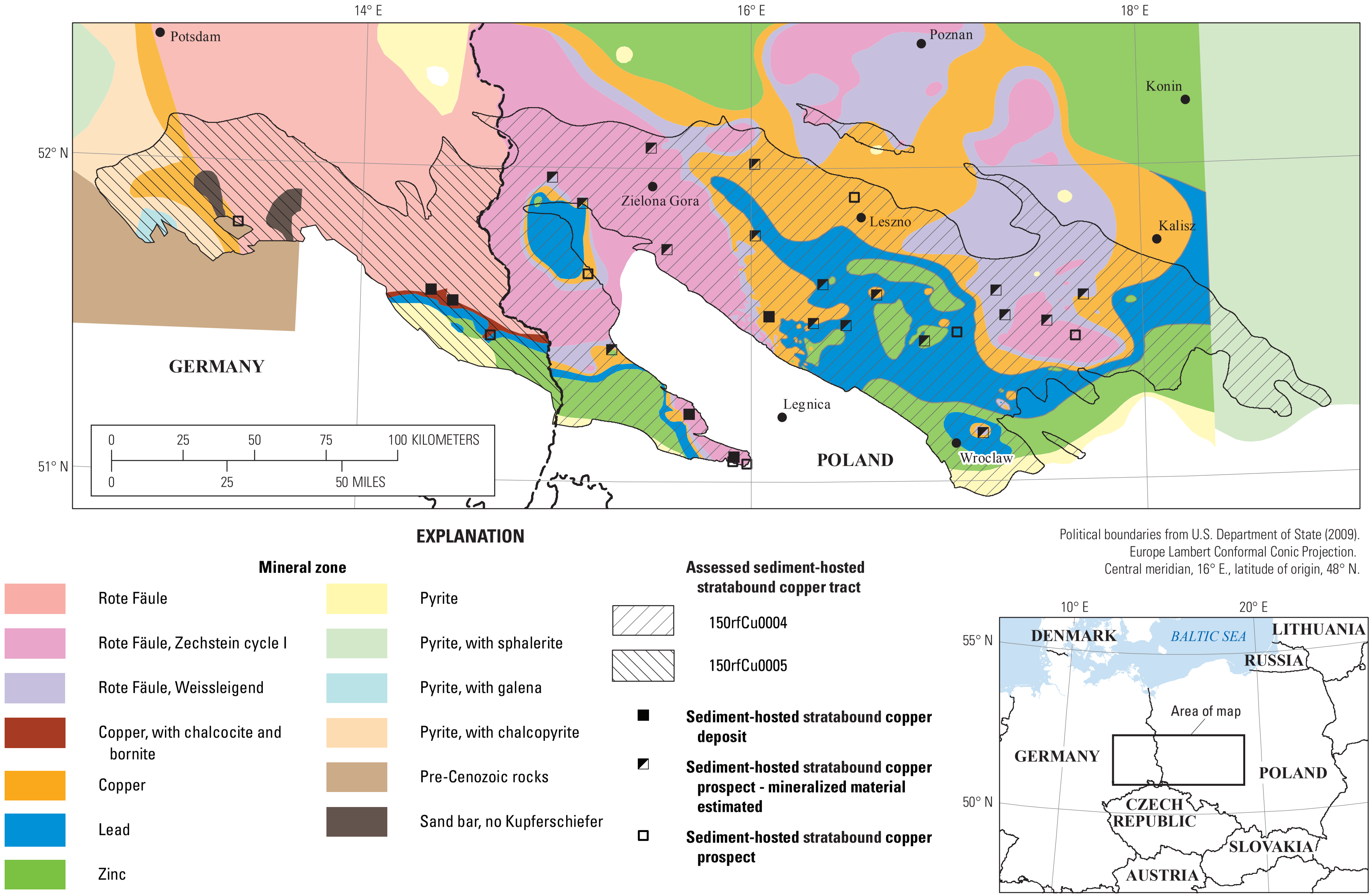


Figure 29. Map of the Lower Silesia and Spremberg-Wittenberg areas, Poland and Germany, showing mineral zones; permissive tracts 150rfCu0004, Dolny Śląsk (Lower Silesia), Poland, and 150rfCu0005, Spremberg-Wittenberg, Germany; deposits; and occurrences. Sources for mineral zones include Federal Institute for Geosciences and Natural Resources (1993), Oszczepalski and Rydzewski (1997a), Rentzsch and others (1997), Stedingk and Rentzsch (2003), Bavarian Geological State Office (2004a), and Oszczepalski and Speczik (2011).

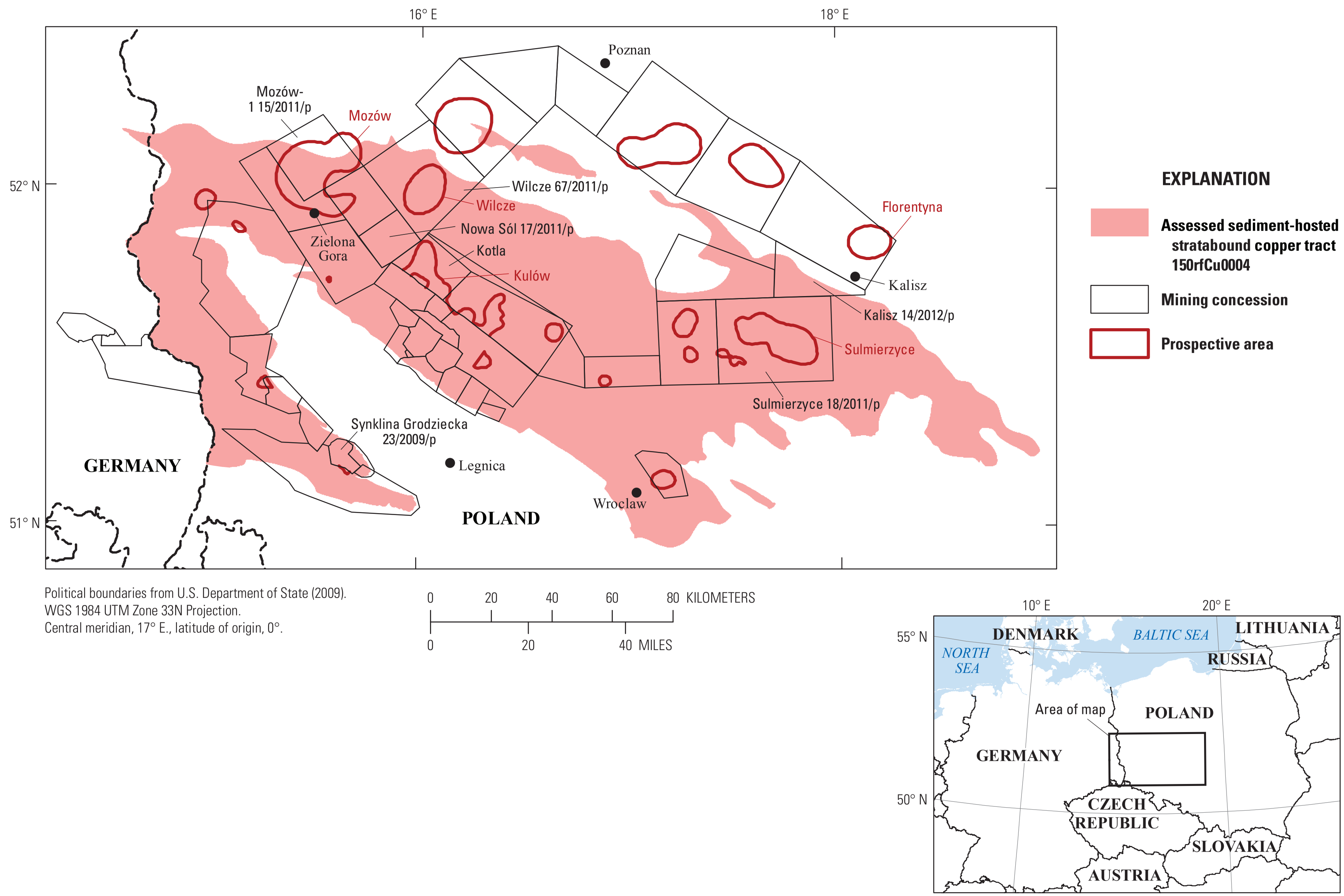


Figure 30. Map of southwest Poland showing permissive tract 150rfCu0004, Dolny Śląsk (Lower Silesia), prospective areas (Oszczepalski and Speczik, 2012), and mining exploration concessions for copper (Bońda and Siekiera, 2009; Bartlett and others, 2013; and Ministry of the Environment, Republic of Poland, 2013a, b, and c).

Northeast England and the Netherlands—Permissive Tract 150rfCu0003, North Sea

The stratigraphic equivalents of the Kupferschiefer occur over reservoir-facies Rotliegend Group rocks in England and the Netherlands and make up tract 150rfCu0003 (fig. 31). The Marl Slate, a bituminous dolomitic siltstone, is the equivalent of the Kupferschiefer Formation in England (Hirst and Dunham, 1963; Turner and others, 1978; Haslam, 1982). It is black to dark gray and ranges in thickness from 0.2 to 3.9 m, with an average thickness of 1.33 meters (Hirst and Dunham, 1963). Sulfide minerals occur mainly as disseminated framboidal pyrite and also as lenses of pyrite, chalcopyrite, galena, sphalerite, and rarer sulfides (Love, 1962; Turner and others, 1978). In the Netherlands, the Coppershale Member of the Z1 (Werra) Formation is the equivalent of the Kupferschiefer (Van Adrichem Boogert and Kouwe, 1993–97).

Concentrations of copper, lead, and zinc are not known to reach economic levels in the Marl Slate of northeast England or the United Kingdom (U.K.) sector of the Southern North Sea Basin (table 6; Hirst and Dunham, 1963; Haslam, 1982). During 1960–1961, boreholes were drilled by the [U.K.] National Coal Board to investigate an extension of the Durham Coalfield (Carbonaceous Coal Measures[18]) concealed beneath the Permian Magnesian Limestone (fig. 32; Hirst and Dunham, 1963). Unweathered Marl Slate was sampled from six localities. The average copper contents of the shale interval in cores ranged from 69 to 310 ppm, with individual samples ranging from 13 to 754 ppm. The metal content of the Marl Slate was also investigated in nine wells in the United Kingdom sector of the Southern North Sea Basin (Haslam, 1982). In most wells, thickness of the slate ranged from 7.6 cm to 1.8 m. Of the 17 samples, 12 contain 100 ppm copper or less. Copper contents were higher in two wells with condensed sections of the Marl Slate: 3,000 ppm in well 49/20-1, where the slate was 7.6 cm thick and 7,000 ppm in well 48/12-2 where the slate was 30 cm thick.

Rocks equivalent to the Kupferschiefer (the Coppershale Member of the Werra Formation of the Netherlands) were deposited in most of the Netherlands, with the exception of the southern on-shore area (Geluk, 2005). For the part of the permissive tract in the Netherlands, the depth of the Coppershale Member is greater than 1,000 m. We did not find information on the metal contents or the sulfide mineralogy of the shale in this area.

[18]The Coal Measures is a lithostratigraphic term used in the U.K. for the coal-bearing part of the Upper Carboniferous System. The Coal Measures Group consists of the Upper Coal Measures Formation, the Middle Coal Measures Formation, and the Lower Coal Measures Formation.

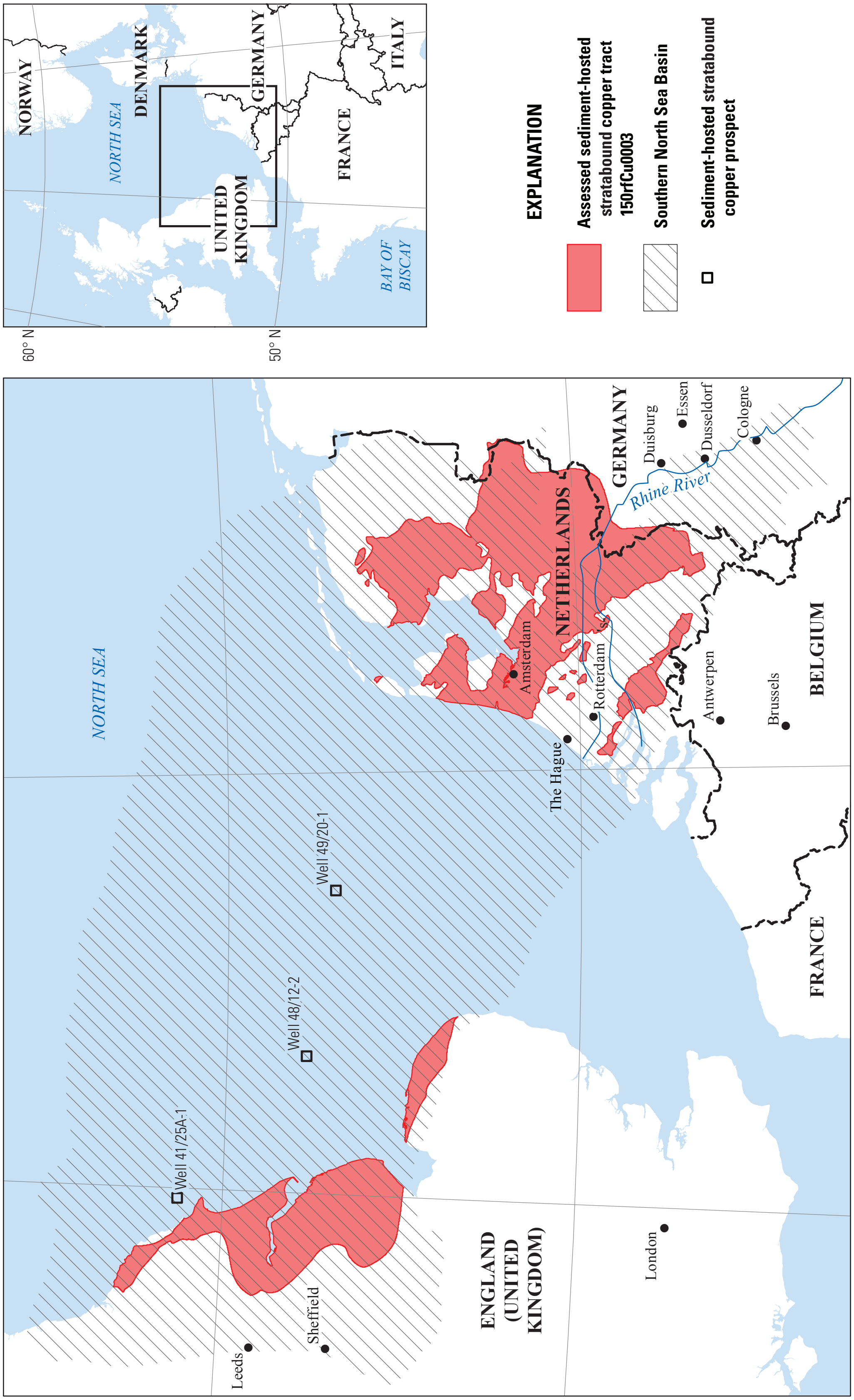
Lithuania, Poland, and Russia—Permissive Tract 150rfCu0006, Baltic Basin

Permissive tract 150rfCu0006, Baltic Basin consists of three areas where the Kupferschiefer (or stratigraphic correlative units) overlies reservoir-facies Rotliegend red beds in north-central Poland (west of Gdansk), northeastern Poland-Lithuania-Russia (east of Gdansk to Vilnius), and eastern Poland (east of Warsaw) (fig. 33). Permissive strata of all three areas are east of the Tornquist-Teisseyre Zone and overlie the Baltic Shield, beyond the zone of Variscan deformation (fig. 1). For the areas west of Gdansk and east of Warsaw, studies of drill core show that the sulfide minerals of the Zechstein rocks are dominated by pyrite, indicating the absence of hydrothermal, diagenetic copper mineralization (Oszczepalski and Rydzewski, 1997b).

The largest permissive area extends from northeastern Poland through the Kaliningrad Oblast[19] of Russia, and into Lithuania. These rocks occur in the far northeasternmost part of the Southern Permian Basin in Lithuania. At the time of deposition, this area had a restricted connection with the main part of the basin resulting in the deposition of a condensed section of Zechstein rocks. Evaporite horizons, which form a seal in most of the Southern Permian Basin, are commonly thin or absent, although some carbonate units are thicker than those in more basinward locations (Peryt and others, 2010). The Sasnava Series (the Z1 Kupferschiefer equivalent in Lithuania) is usually 0.4 to 1.7 m thick (maximum 15 m) and consists of calcareous, sandy and bituminous shales. Local increases in metal concentrations (mainly of copper, lead, and zinc) are not economically important (Oszczepalski and Rydzewski, 1997b; Peryt and others, 2010).

The Middle Subformation of the Murav'ev Formation has been drilled in Kaliningrad Oblast. It is the stratigraphic equivalent of the Lithuanian Sasnava Formation and the European Kupferschiefer (table 7; Zagorodnykh, 2000). The unit is no more than 3 m thick and consists of dark gray and black silty-carbonate rocks with high organic carbon content. Sulfide minerals are unevenly disseminated in these rocks. Where the subformation has been sampled in 25 drill holes, copper contents are less than 80 ppm; three holes have copper contents of 800, 1,500, and 3,000 ppm. These same intervals have lead and zinc contents of 3,000, 10,000, and 7,000 and 200, 800, and 15,000 ppm, respectively. Metal concentrations and mineralogy do not indicate the presence of a significant copper-mineralizing ore system (fig. 34).

[19]Oblast is an administrative territorial division within Russia and other former Soviet republics.



Political boundaries from U.S. Department of State (2009).
Europe Lambert Conformal Conic Projection.
Central meridian, 3° E., latitude of origin, 48° N.

Figure 31. Map of the southern North Sea area showing permissive tract 150rfCu0003, North Sea; Southern North Sea Basin; and sediment-hosted copper prospects.

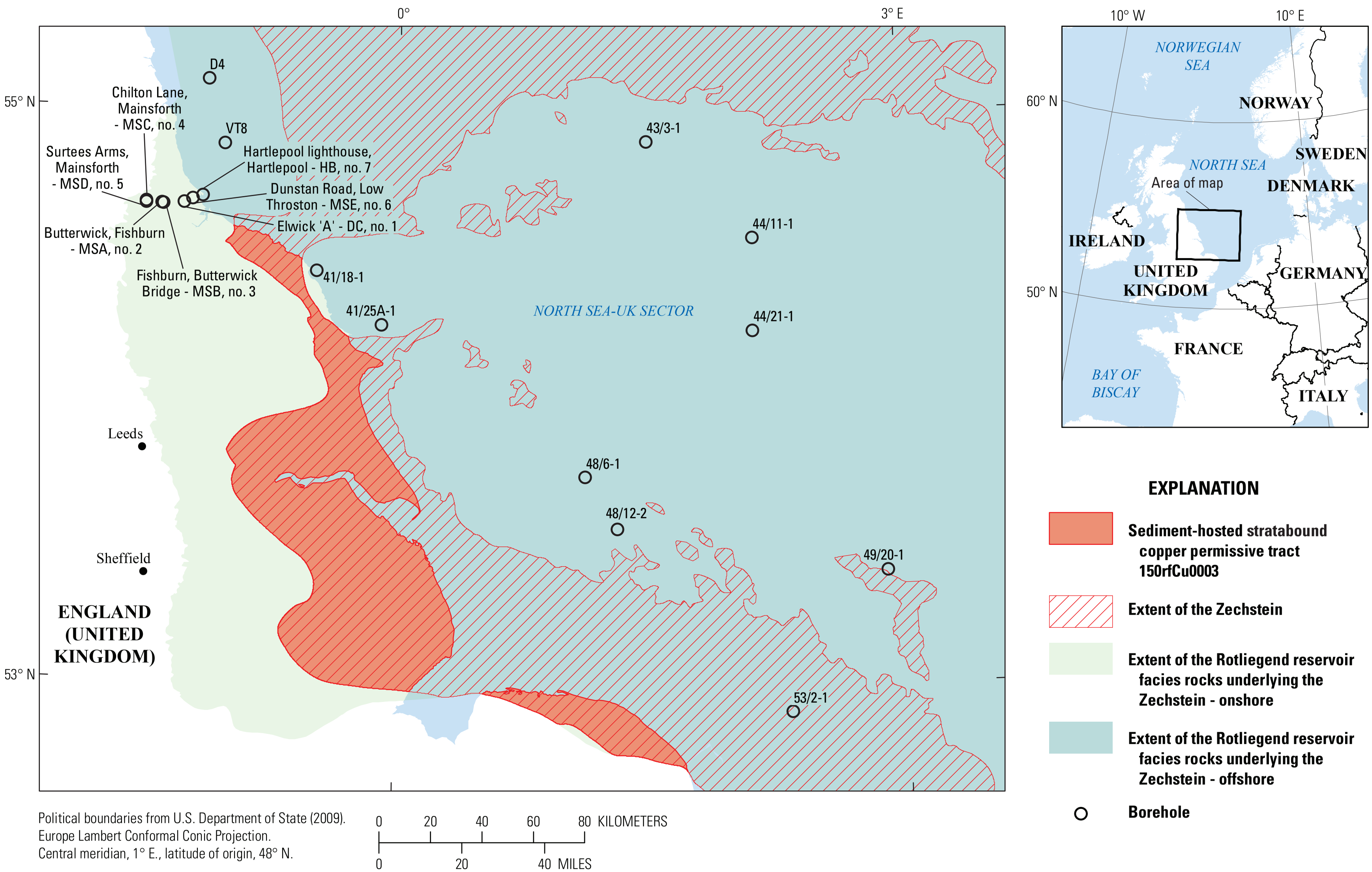


Figure 32. Map of northeast England and the North Sea-United Kingdom (U.K.) sector showing permissive tract 150rfCu0003, North Sea; extent of the Zechstein; Rotliegend reservoir facies rocks underlying the Zechstein; and holes drilled to investigate the metal content of the Marl Slate (equivalent to the Kupferschiefer). Sources of information for drill data include Hirst and Dunham (1963), Turner and others (1978), Haslam (1982), and Sweeney and others (1987).

Table 6. Data from drill core intersecting the Marl Slate in permissive tract 150rfCu0003, North Sea, Southern Permian Basin, United Kingdom.

[n.d., no data; m, meter; ppm, parts per million]

Borehole name	Sample thickness (m)	Kupferschiefer depth interval (m)	Kupferschiefer thickness (m)	Number of samples	High copper (ppm)	Low copper (ppm)	Average copper (ppm)	Reference
				Onshore				
Butterwick, Fishburn	0.4953	103.7–104.2	0.4953	21	188	59	91	Hirst and Dunham (1963)
Chilton Lane, Mainsforth	1.016	n.d.–78.6	n.d.	7	57	13	43	Hirst and Dunham (1963)
Dunstan Road, Low Throston	0.254	200.736–200.99	0.254	10	156	49	84	Hirst and Dunham (1963)
Elwick 'A'	0.0508	n.d.–166.7	n.d.	n.d.	n.d.	n.d.	n.d.	Hirst and Dunham (1963)
Fishburn, Butterwick Bridge	0.1905	100.8–101.0	0.1905	21	754	139	310	Hirst and Dunham (1963)
Hartlepool lighthouse, Hartlepool	0.0508	n.d.–260.9	n.d.	8	43	37	39	Hirst and Dunham (1963)
Surtees Arms, Mainsforth	2.3622	59.5–61.9	2.3622	20	141	43	69	Hirst and Dunham (1963)
				Offshore				
D4	n.d.	n.d.	1.15	36	440	20	94	Turner and others (1978); Sweeney and others (1987)
VT8	n.d.	n.d.	1.44	144	900	200	656	Turner and Magaritz (1986); Sweeney and others (1987)
41/18-1	n.d.	1,612.39–1,613.0	0.6096	3	340	38	141	Haslam (1982)
41/25A-1	n.d.	1,722.12–1,723.34	1.2192	3	750	28	279	Haslam (1982)
43/3-1	n.d.	2,962.6–2,964.4	1.8288	40 (drill cuttings)	64	24	37	Haslam (1982)
44/11-1	n.d.	3,401.26–3,402.48	1.2192	5	200	28	93	Haslam (1982)
44/21-1	n.d.	3,862.12–3,863.03	0.9144	1	16	16	16	Haslam (1982)
48/12-2	n.d.	n.d.	0.3048	3	7,000	84	4,100	Haslam (1982)
48/6-1	n.d.	2,652.06–2,652.67	0.6096	3	130	25	51	Haslam (1982)
49/20-1	n.d.	2,410.36–2,410.4362	0.0762	1	3,000	3,000	3,000	Haslam (1982)
53/2-1	n.d.	1,906.219–1,918.411	2.192	2	100	78	89	Haslam (1982)

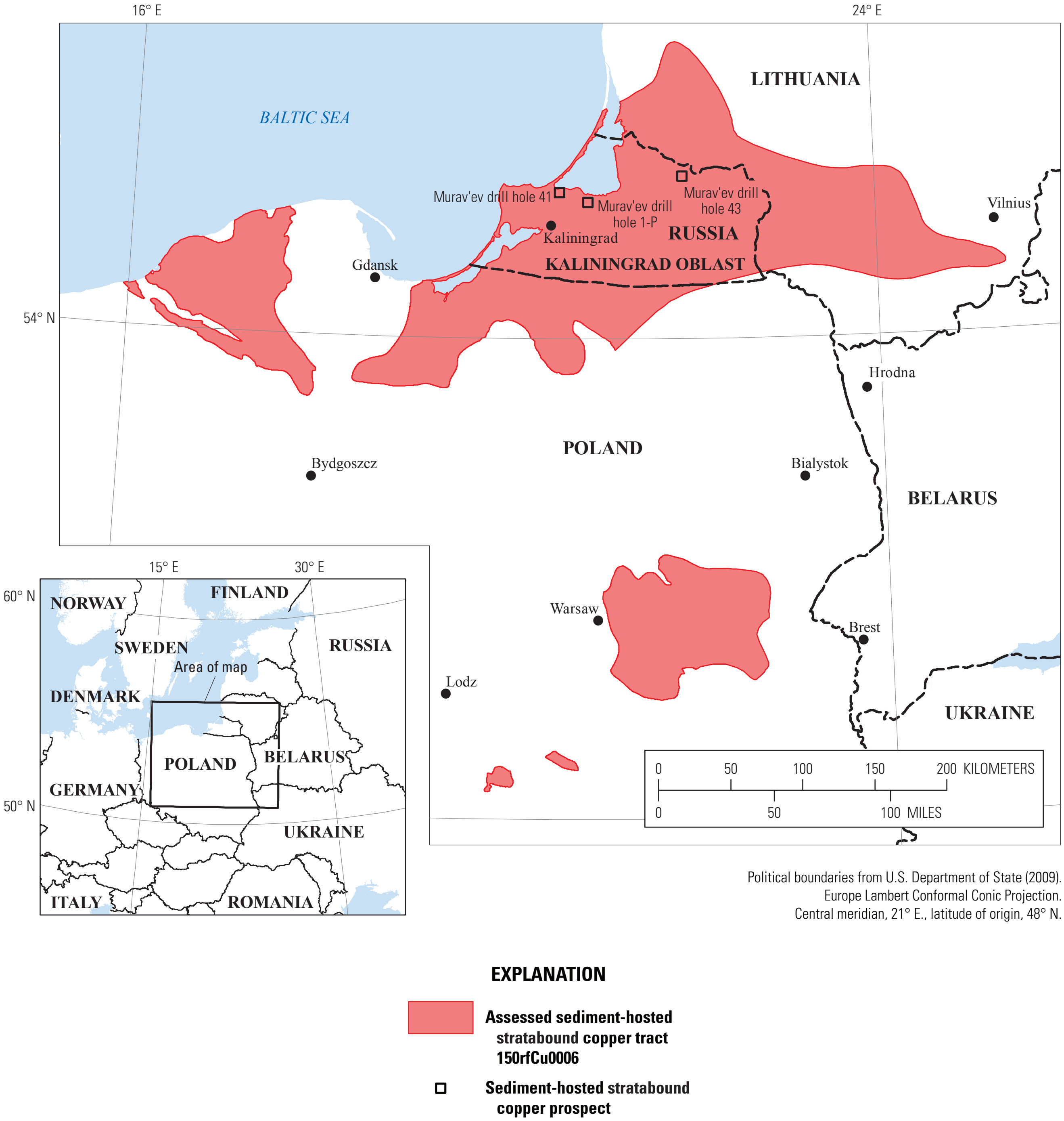


Figure 33. Map of the southeastern Baltic Sea area showing permissive tract 150rfCu0006, Baltic Basin, and sediment-hosted stratabound copper prospects.

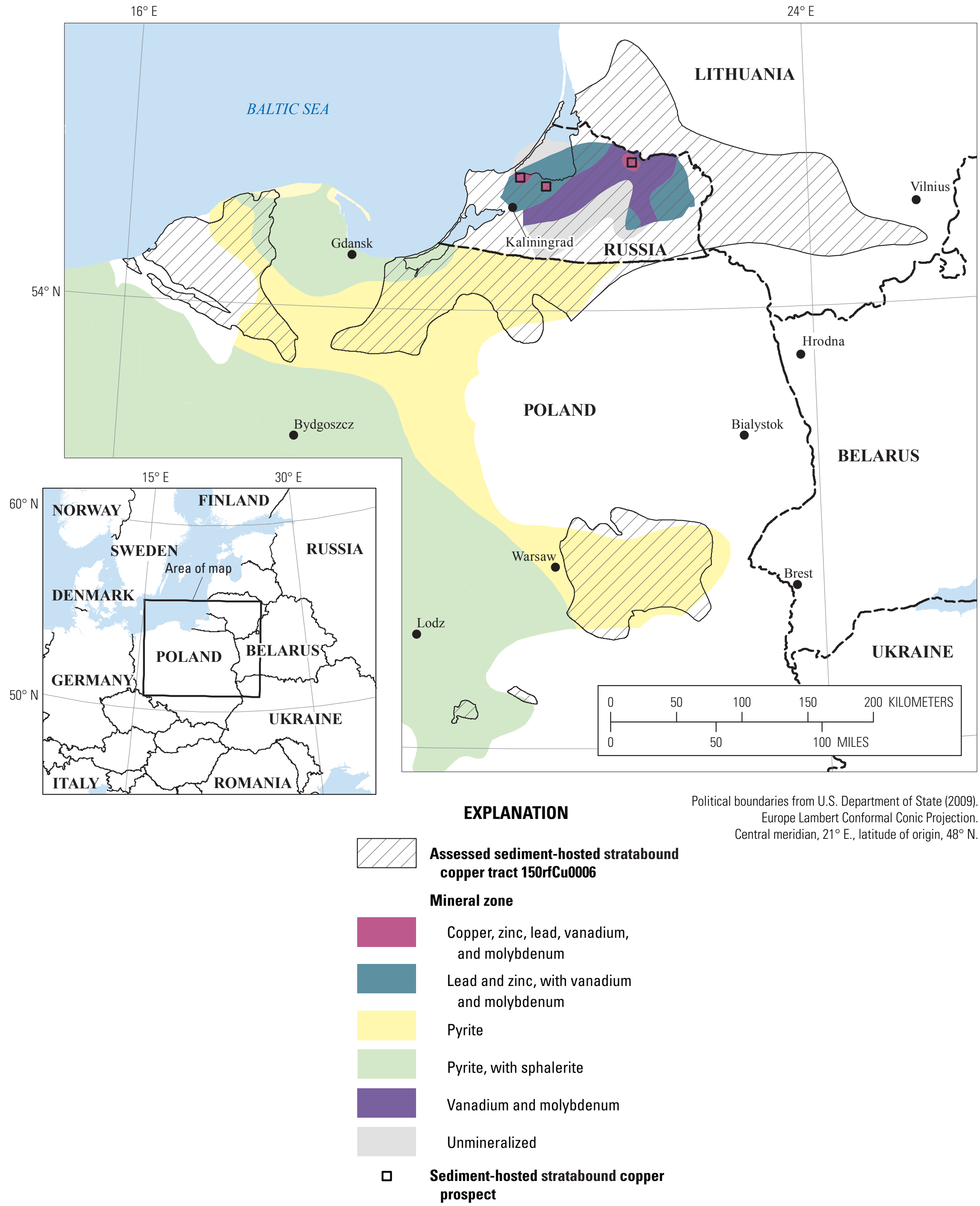


Figure 34. Map of the southeastern Baltic Sea area showing mineral zones; permissive tract 150rfCu0006, Baltic Basin; and prospects. Sources of information include Oszczepalski and Rydzewski (1997a), Zagorodnykh (2000), and Oszczepalski and Speczik (2011).

Table 7. Analyses of core samples from the Middle subformation of the Murav'ev Formation (correlative with the Kupferschiefer; Zagorodnykh, 2000) in permissive tract 150rfCu0006, Baltic Basin, Southern Permian Basin, Russia.

[m, meter; ppm, parts per million; Cu, copper; Pb, lead; Zn, zinc; V, vanadium; Mo, molybdenum; Co, cobalt; Ni, nickel; >, greater than]

Borehole number	Depth interval (m)	Cu (ppm)	Pb (ppm)	Zn (ppm)	V (ppm)	Mo (ppm)	Co (ppm)	Ni (ppm)
1-C	2,934.0–937.0	40	80	100	250	100	50	80
2-C	848.5–848.8	50	1,000	100	400	60	80	100
3-C	1,023.0	50	80	60	100	30	40	80
20	1,012.5	40	500	2,000	500	100	40	100
21	1,005.0–1,007.0	40	60	15	800	100	80	100
17	771.0–773.0	40	300	1,500	500	100	60	80
23	923.0–925.0	50	80	200	200	50	30	80
27	337.0–840.0	50	2,000	600	250	300	150	100
28	1,041.0–1,042.3	50	60	50	250	50	40	80
32	767.0–769.0	60	6,500	4,000	5,000	320	80	150
33	778.5–780.0	60	1,500	300	1,800	100	120	150
36	692.0–693.0	50	100	50	1,700	300	60	100
37	709.0–710.0	50	60	150	1,800	100	75	130
41	1,021.5–1,022.8	800	3,000	200	250	100	50	60
43	687.0–688.5	1,500	10,000	800	2,000	>300	700	500
46	1,047.0–1,049.0	70	700	1,500	1,000	>300	50	200
50	925.5–926.0	40	30	60	100	30	40	80
1-P	1,044.5–1,045.5	3,000	7,000	15,000	3,000	>300	300	300
2-P	1,051.0–1,052.0	60	5,000	6,000	1,200	400	200	30
5-Nem	686.2–687.2	40	25	40	>1,000	300	50	100
7-Nem	725.6–726.6	40	20	30	>1,000	250	50	10
11-W.S.	716.0–717.0	80	3,500	7,000	7,800	490	60	220
6-Gus	887.0–888.5	60	150	1,500	500	150	50	100
3-N.G.	797.3–799.0	50	40	40	500	100	50	100
4-N.G.	795.0–795.5	30	200	2000	120	40	20	60

Denmark, Germany, and Poland—Permissive Tract 150rfCu0007, Jutland Peninsula

Permissive tract 150rfCu0007 occurs where the Kupferschiefer overlies Rotliegend rocks in the Jutland Peninsula area (fig. 35). Along the southwestern flank of the Ringkøbing-Fyn-Mon structural high, south-dipping Rotliegend and basal Zechstein beds pinch out by onlap against basement rocks, forming the northern boundary of the permissive tract (fig. 36: Z1 onlap pinchout) (Clausen and Pedersen, 1999). The southwestern margin of the permissive tract is delimited where the south-dipping basal Zechstein Group rocks are more than 2.5 km below the surface (fig. 36, greater than 2.5 km deep). On the Jutland Peninsula, tract boundaries north of the Brande Trough are also defined where north-dipping permissive rocks are at depths of 2,500 m below the surface. This tract has a generally favorable paleotopographic setting where the Kupferschiefer and subjacent Rotliegend onlap on local basement-rock highs (similar to those found in the Spessart-Rhön and Richelsdorf areas of southwestern Germany). However, the basal Zechstein rocks are buried everywhere by at least 1.3 km of younger sedimentary rocks.

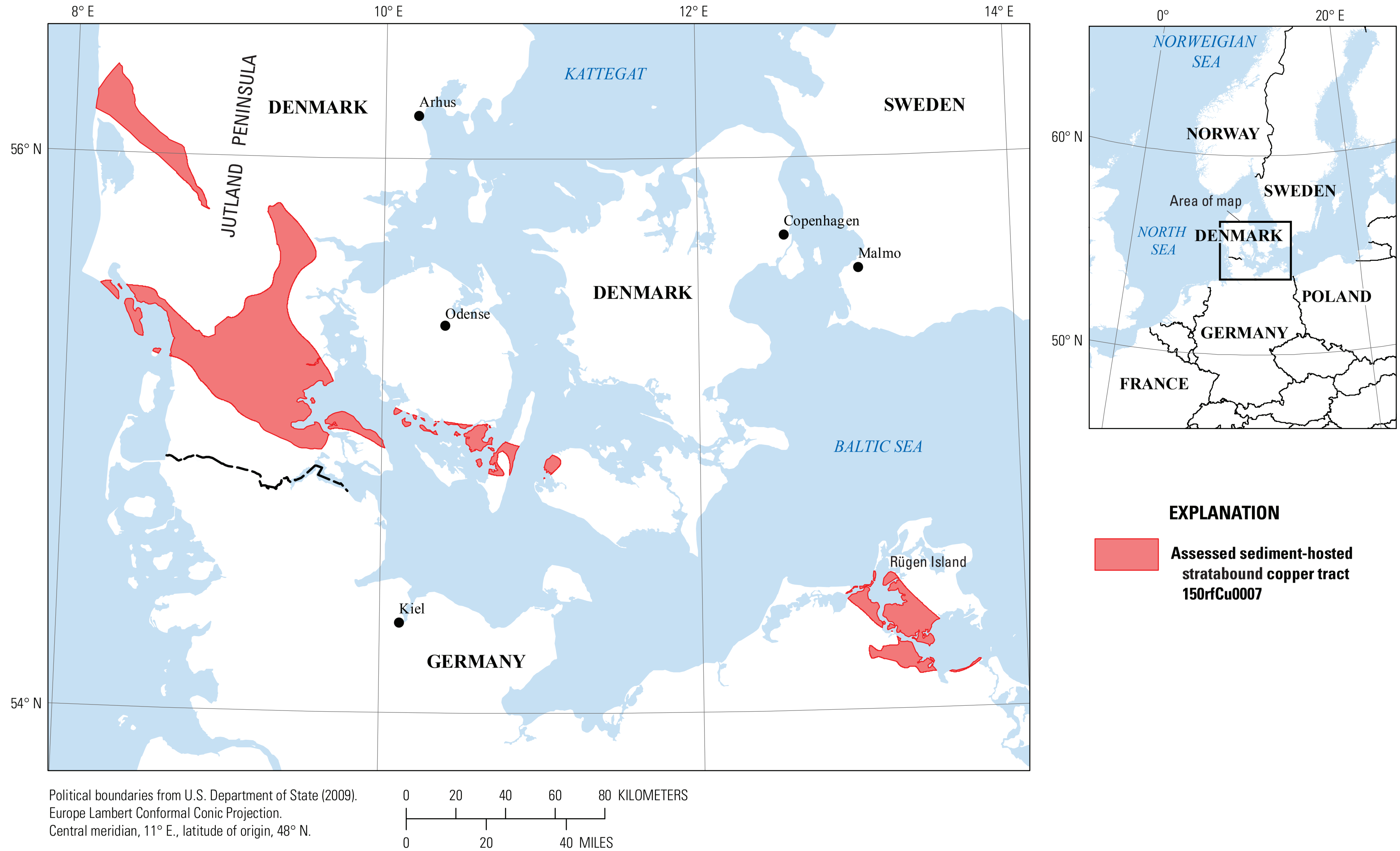


Figure 35. Map of the Jutland Peninsula area, Demark and Germany showing the permissive tract 150rfCu0007, Jutland Peninsula.

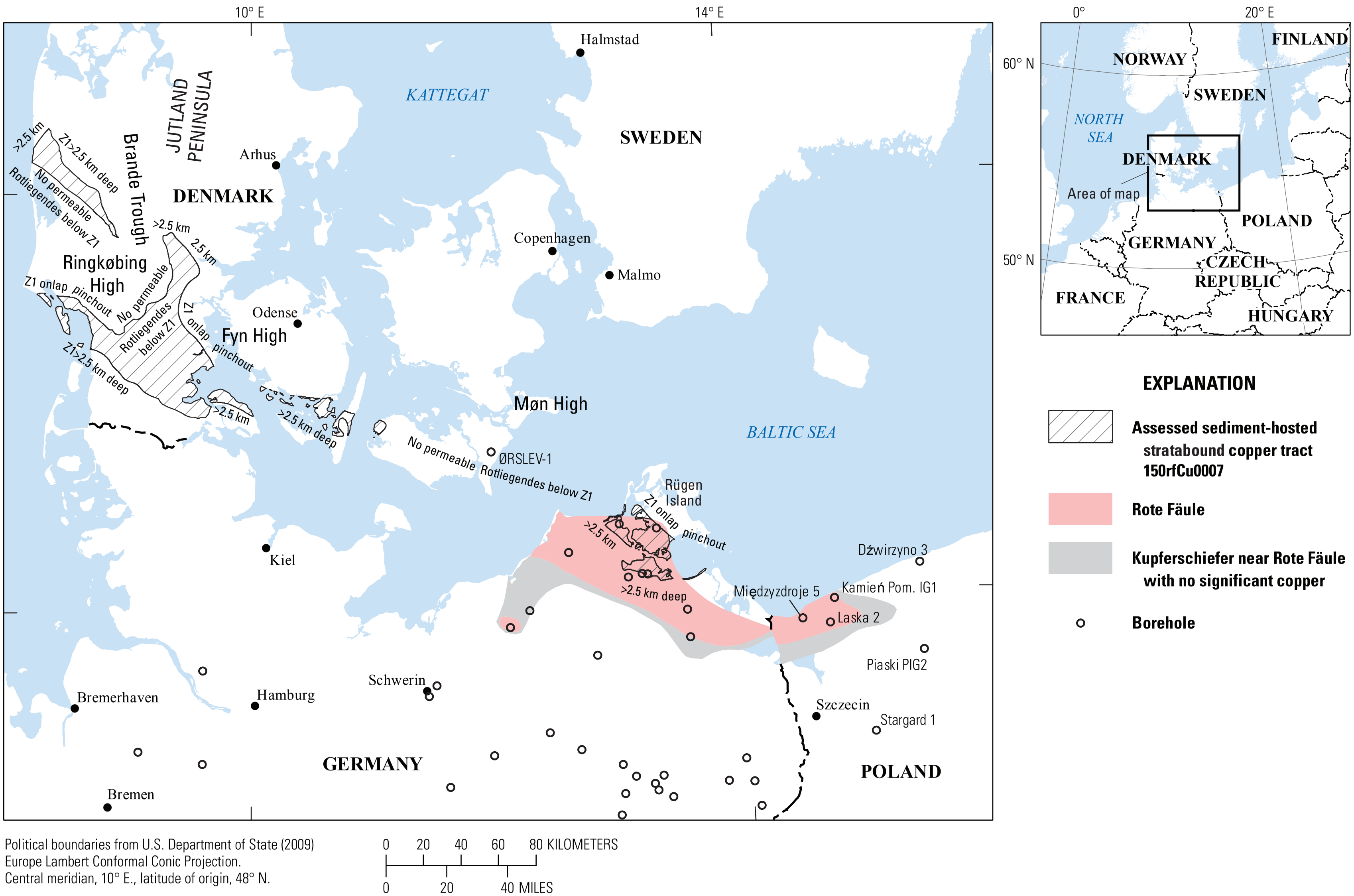


Figure 36. Map of the Jutland Peninsula area Demark, Germany, and Poland, showing mineral zones; permissive tract 150rfCu0007, Jutland Peninsula; and boreholes. Sources of information for mineral zones include Federal Institute for Geosciences and Natural Resources (1993), Oszczepalski and Rydzewski (1997a), Rentzsch and others (1997), and Bavarian Geological State Office (2004a). Z1, Zechstein Group cycle 1; >, greater than; km, kilometers.

Rentzsch and others (1997) show an area of Rote Fäule that has altered the host sequence extending southwestward into northeastern mainland Germany from a Kupferschiefer onlap pinch out against basement rocks in the subsurface of Rügen Island (fig. 36). However, the mineral-zonation map shows no significant copper enrichment adjacent to it. Oszczepalski and Rydzewski (1997b) report copper surface density of 1 to 5 kg/m^2 in samples from Polish holes, Międzyzdroje 5 and Laska 2, associated with the continuation of the Rote Fäule zone in northwestern Poland (fig. 36). Rote Fäule alteration of the host interval was probably produced by oxidizing brine analogous with the copper-mineralizing brines of economic Kupferschiefer-related deposits. However, copper concentrations in 10 holes along the 190-km length of the Rote Fäule boundary are only slightly above background values. Nevertheless, the Rügen Island Rote Fäule zone is taken as a favorable indicator for the entire Jutland Peninsula tract despite the low copper values.

About 18 wells drilled for hydrocarbon exploration likely penetrated the Kupferschiefer horizon in tract 150rfCu0007 (Vejbaek and Britze, 1994). However, there are no analyses of metal or organic content of Zechstein rocks in these holes (Bo Møller Stensgaard, Geological Survey of Denmark and Greenland, written commun., 2010).

Mineral Resource Assessment—Probable Amounts of Undiscovered Copper

For this report, “undiscovered mineral resources” could be present where location, grade, quality, and quantity of mineralized material are not constrained by specific geologic evidence. Two different methods are used to assess undiscovered mineral resources. The first approach, the three-part form of assessment, estimates the number of undiscovered deposits to constrain undiscovered resources; this approach has been widely used in USGS mineral resource assessments since the 1970s (Singer and Menzie, 2010). A second approach, Gaussian Geostatistical Simulation, uses geostatistical methods and simulation techniques to estimate undiscovered mineral resources from drill data in incompletely explored extensions of SSC deposits in permissive tract 150rfCu0004, Dolny Śląsk (Lower Silesia).

Three-Part Form of Assessment

In the three-part form of assessment (Singer, 1993; Singer and Menzie, 2010), probabilistic distributions of the amount of in-situ metal are used to express the amount of undiscovered mineral resource. To estimate undiscovered resources, numbers of undiscovered deposits of a given type are estimated at various quantile levels for the permissive tracts. Using Monte Carlo simulations, these undiscovered deposit estimates are combined with tonnage and grade models to derive a probability distribution for the amounts of commodities and rock that could be present in undiscovered deposits.

The amounts of undiscovered resources are derived from (1) models for grades and tonnages of undiscovered deposits of the same type in geologically similar settings and (2) probabilistic estimates of the number of undiscovered deposits of each type that are predicted to exist in the delineated tracts. About 170 well-explored deposits were used to construct several SSC grade and tonnage models (Zientek, Hayes, and Taylor, 2013). The grade and tonnage model used for this assessment is the model for reduced-facies-nonbrecciated deposits. It is based on 50 deposits; summary statistics are given in table 8. Median and mean values for ore tonnage are 34 and 180 Mt and for copper grades are 1.5 and 1.6 percent, respectively.

The distribution of undiscovered deposits is estimated by expert panels of geologists at several probability percentiles. From these percentile values, a default probability distribution for the undiscovered deposits is chosen that is approximately in the middle of all possible choices (Root and others, 1992). Monte Carlo simulation is used to combine grade and tonnage models with the probability distribution of undiscovered deposits to obtain the estimated probability distributions of undiscovered metals in each tract (Root and others, 1996; Bawiec and Spanski, 2012; Duval, 2012).

Table 8. Summary statistics for the reduced-facies-nonbrecciated sediment-hosted stratabound copper deposit model of Zientek, Hayes, and Taylor (2013).

[n.d., no data]

Value	Number of deposits	Mean	Quantile 5th	Quantile 10th	Quantile 25th	Median	Quantile 75th	Quantile 90th	Quantile 95th
Ore (million metric tons)	50	180	1.1	1.6	6.2	34	97	550	730
Copper grade (percent)	50	1.6	0.8	0.9	1.0	1.5	2.1	2.5	2.8
Silver grade (grams per metric ton)	19	33	2.4	5.0	10	17	45	110	140
Cobalt grade (percent)	9	0.1	n.d.	n.d.	0.03	0.1	0.1	0.3	0.3
Contained copper metal (million metric tons)	50	3.5	0.016	0.023	0.1	0.46	1.4	10	19

Criteria for Assessing Mineral Potential

For the Kupferschiefer permissive tracts, several criteria were considered when assessing the potential for undiscovered copper resources (table 9). Tracts where Permian-Carboniferous volcanic rocks are absent do not have significant mineral occurrences (fig. 37); similarly, no significant mineral occurrences are reported in tracts underlain by rocks of the Carboniferous Coal Measures or crystalline basement on the northeast side of the Tornquist-Teisseyre zone (fig. 38). Tracts underlain by Rotliegend depocenters have mineral occurrences, whereas tracts away from known depocenters have no mineral occurrences. In tracts where mineral occurrences are known, maps of metal surface density and mineral zoning strongly influenced estimates of mineral potential.

Sources of Metal

The presence of source rocks for copper is one criterion that can be used to evaluate the permissive tracts. The high amounts of base metals in the ore deposits must be derived from underlying strata, most probably the Rotliegend volcanic rocks and continental clastic rocks (fig. 37; Wedepohl, 1964; Marowsky, 1969; Harańczyk, 1986; Jowett, 1986; Speczik and others, 1986; Oszczepalski, 1989). Burial metamorphism of mafic volcanic rocks could produce copper-bearing fluids by dehydration and metal leaching of the fragmental, amygdaloidal, or fractured parts of the flows (Borg, 1991; Brown, 2006). For example, geothermal fluids derived from Permo-Carboniferous volcanic rocks and basal Rotliegend conglomerates in a deep well in the Northeast German Subbasin have a pH value of 6.2, an oxidation/reduction potential Eh value of 50 millivolts (mV), and relatively high values of copper, zinc, iron, lead, and manganese—9, 65, 200, 100–225, and 230 milligrams per liter (mg/L), respectively (Wolfgramm and others, 2003). Red beds are known to contain labile[20] detrital minerals, such as biotite, hornblende, and magnetite, which are known to contain trace amounts of copper (Walker, 1989; Core and others, 2005). Postdepositional alteration of these minerals could release copper to be dissolved in groundwater or adsorbed onto simultaneously forming smectite and poorly crystallized ferric hydroxides (Rose, 1976; Rose and others, 1986; Walker, 1989; Rose and Bianchi-Mosquera, 1993). The adsorbed copper could be liberated by later diagenetic alteration that accompanies aging and burial of red beds (Walker, 1989). Red beds are present in each tract; however, Rotliegend volcanic rocks are not known from the North Sea and Baltic Basin tracts (150rfCu0003 and 150rfCu0006).

Ore Fluids

Another criterion used to evaluate permissive tracts is whether a copper-rich ore fluid is likely to have been present. The metal-bearing fluids for SSC deposits are thought to be low-temperature, oxidized (hematite-stable), chloride-rich, subsurface sedimentary brines. The mineral reactions associated with ore formation occurred at depths of 2 to 3 km in sedimentary basins. Gangue mineral assemblages associated with ore deposition in SSC mineral deposits are the same as those that occur in the transition from mechanical to chemical compaction during the diagenetic evolution of a basin (Burst, 1969; Boles, 1982; Hower and others, 1976; Surdam and Crossey, 1987; Hayes and others, 1989; Surdam and others, 1989; Morad and others, 2000; Worden and Burley, 2003; van de Kamp, 2008).

Copper has limited solubility in most surface and subsurface water (Rittenhouse and others, 1969; Rickard, 1970; Kharaka and others, 1987; Saunders and Swann, 1990; Donat and Bruland, 1995; Gallup, 1998) suggesting that transport of significant amounts of copper by surface or subsurface waters is likely uncommon (Rose, 1976; Rose and others, 1986). However, studies of solution and mineral equilibria show that copper and sulfur (as sulfate) are readily transported in aqueous fluids that are near neutral in pH, chloride-rich, and oxidized (in the stability field of hematite) (Garrels and Christ, 1965; Rose, 1976).

Elevated concentration of chlorine in subsurface waters is not unusual. More than 50 percent of the world's basinal waters are more saline than seawater (greater than 35,000 mg/L) and more than 70 percent of oil field waters are either saline (10,000 to 50,000 mg/L) or brines (greater than 50,000 mg/L) (Warren, 2006). The crucial process in ore formation appears to be developing and maintaining an oxidized fluid at depth. Most subsurface oil field brines have relatively low redox potentials (Collins, 1975), with the oxidation state buffered by the presence of organic material. Also, the field for maximum solubility of copper in aqueous solutions is at higher Eh than most oil field brines.

The elevated Eh required for the transport of copper indicates the ore fluids had contact with the atmosphere. Brown (2009) suggests the origin of oxidized ore fluids is oxygen-rich meteoric water driven by topographic recharge in highlands adjacent to the intracratonic rift basins hosting the deposits. However, for this assessment, we propose that the oxidized subsurface waters are the result of brine reflux.[21] This refluxed connate brine could be stored in adjacent continental strata (such as fluvial or aeolian sediments) as well as in a marine host (Warren, 2006). This proposal implies that areas will be more prospective if the brine reflux is retained in the continental strata until it is released later during burial diagenesis and reacts with reduced strata. Studies of diagenetic processes show that diagenetic fluids from rocks lower in the basin can flush potential ore fluids from Rotliegend rocks.

The Rotliegend sandstones have distinctive suites of authigenic minerals that can be related to multiple fluid

[20]Labile refers to rocks and minerals that are mechanically or chemically unstable (Neuendorf and others, 2005).

[21]Brine reflux occurs when ponded or concentrating holomictic brines atop the floor of an evaporitic seaway or lake become dense enough to displace underlying pore fluids and so percolate into the underlying succession (Warren, 2006).

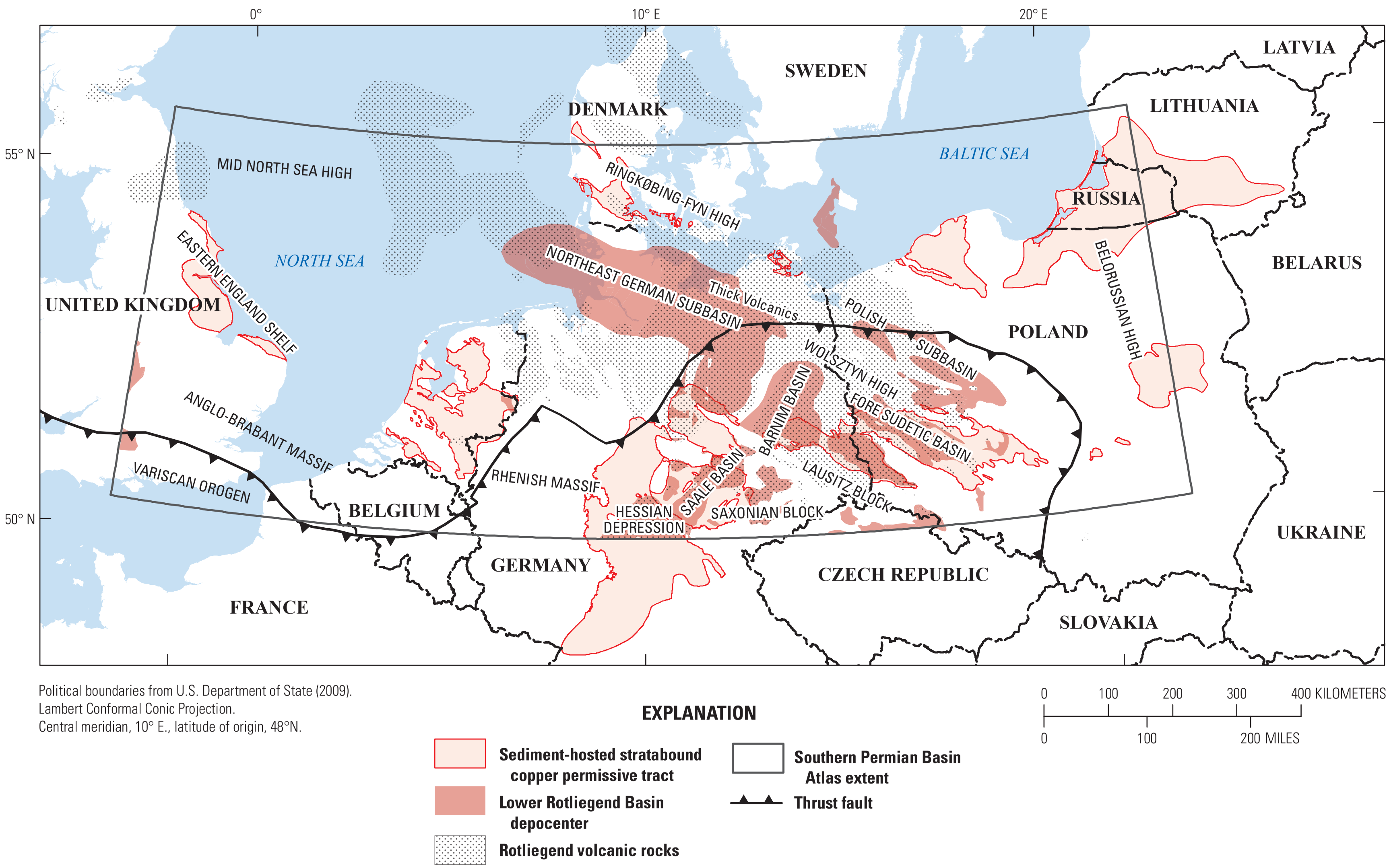


Figure 37. Map of northern Europe showing the distribution of the Kupferschiefer permissive tracts in relation to Rotliegend depocenters and areas of Rotliegend volcanic rocks. Rotliegend features from Pharaoh and others (2010).

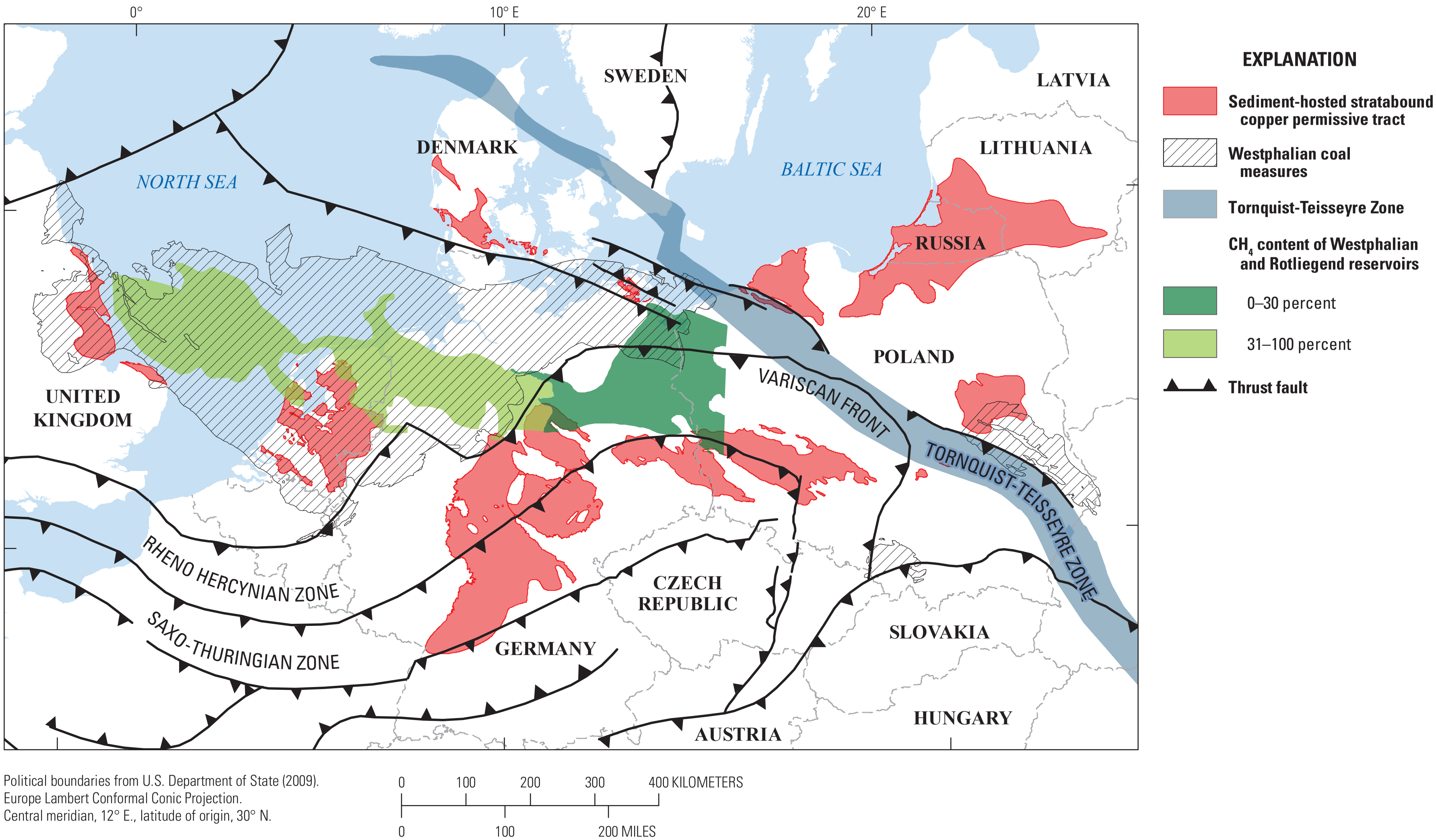


Figure 38. Map of northern Europe showing the relation of permissive tracts, basement rock terranes, and the composition of natural gas in Rotliegend reservoirs. The southern part of the Southern Permian Basin overlies the Rheno-Hercynian and Saxo-Thüringian zones of the Variscan Orogen. The northwestern part of the basin overlies rocks deposited in the Variscan foreland basin, including large areas of Westphalian coal-bearing deposits, which are the source rocks for natural gas in overlying reservoir-facies Rotliegend red beds. The methane (CH_4) content of natural gas in Rotliegend reservoirs is distinctly higher where the Rotliegend overlies Westphalian deposits. Information on map from Maystrenko and others (2008) and Kombrink and others (2010).

Table 9. Selected criteria used to evaluate reduced-facies sediment-hosted stratabound copper tracts for mineral potential in the Southern Permian Basin, Europe.

Assessment areas with aquifer or reservoir facies red beds overlain by Kupferschiefer	Possible sources of copper	Rotliegend depocenter	Pre-Permian basement type	Rote Fäule, copper occurrences, and (or) copper zone mapped	Country(ies)
Not assessed quantitatively					
150rfCu0003, North Sea	Subaerial volcanic rocks—None Red beds—Rotliegend	None	Westphalia coal measure	None	Netherlands, United Kingdom
150rfCu0006, Baltic Basin	Subaerial volcanic rocks—None Red beds—Rotliegend	None	Baltica craton and Westphalian coal measures	None	Lithuania, Poland, Russia
150rfCu0007, Jutland Peninsula	Subaerial volcanic rocks—Rotliegend Red beds—Rotliegend	None	Westphalian coal measure and Baltica craton	Rote Fäule is mapped only near Rügen Island, Germany, but copper is not enriched in adjacent rocks	Denmark, Germany
Assessed quantitatively					
150rfCu0002, Hessian Depression	Subaerial volcanic rocks—Rotliegend Red beds—Rotliegend	Saale Basin	Variscan crystalline basement	Elongated area with elevated zinc	Germany
150rfCu0001, Hercynian-Thuringian Basin	Subaerial volcanic rocks—Rotliegend Red beds—Rotliegend	Saale Basin	Variscan crystalline basement	Several prospective areas with copper-rich margins along areas of Rote Fäule; numerous basement highs	Germany
150rfCu0005, Spremberg-Wittenberg	Subaerial volcanic rocks—Rotliegend Red beds—Rotliegend	Barnum and North Sudetic Basins	Variscan crystalline basement	Two prospective areas where copper-rich margins are present along a large area of Rote Fäule	Germany
150rfCu0004, Dolny Śląsk (Lower Silesia)	Subaerial volcanic rocks—Rotliegend Red beds—Rotliegend	North Sudetic and Fore-Sudetic Basins	Variscan crystalline basement	Many prospective areas defined by copper-rich zones adjacent to Rote Fäule and areas with copper surface density greater than 35 kilograms per square meter	Poland

sources and migration events (Gaupp and others, 1993; Schöner and others, 2008). The fluids include waters associated with the deposition of the Rotliegend sediments, as well as waters derived from underlying and overlying sedimentary units. The waters from outside the Rotliegend sandstones have profoundly affected the diagenetic mineral suites that are developed.

Where the Rotliegend sandstones are not affected by other fluids, early formed cements reflecting early to shallow burial diagenetic processes are preserved down to maximum burial depths (Schöner and Gaupp, 2005; Schöner and others, 2008). Near-surface fluids in the Rotliegend sediments were oxidizing meteoric waters. Soon after deposition, diagenetic processes included precipitation of hematite on the surfaces of detrital grains, adhesion of detrital clays to grains as grain coatings, and formation of minor clay minerals that form bridges across pore space in the sediments (pore-bridging clay) and clay minerals that form a matrix that fill pore space (Hillier and others, 1996; Amthor and Okkerman, 1998; Maliszewska and others, 1998).

In northwest Europe where the Rotliegend is underlain by Carboniferous Coal Measures and the top seal is formed by basal Zechstein anhydrites and salt, the diagenetic mineral suites of Rotliegend sandstones record the infiltration of acidic, reducing pore fluids derived from the decomposition of organic matter during burial of Carboniferous source rocks; this is reflected by the methane-enriched natural gas compositions in areas underlain by Westphalian coal measures (fig. 38; Luders and others, 2005; Schöner and Gaupp, 2005; Schöner and others, 2008; Gaupp and Okkerman, 2011). Permissive tracts underlain by Westphalian Coal Measures (150rfCu0003, North Sea) are not considered prospective because the diagenetic fluids moving through the Rotliegend beds appear to have had a reduced composition. This is consistent with early observations that the highest concentrations of metal are limited to the southern edge of the Southern Permian Basin (SPB), where Rotliegend beds lie on Variscan crust (Richter, 1941; Rentzsch and Franzke, 1997).

Fluid Flow

The prospectivity for a mineral deposit is greater if geologic elements that allow, focus, and then impede fluid movement can be identified. A flow system for transport of copper from source rocks to host rocks by sedimentary brines must have existed for all SSC-type deposits. The brines are thought to move upward toward a hydrologic seal. One process that could cause the upward and lateral movement of the pore fluids towards and in the more permeable layers is the increase in the pressure gradient above the hydrostatic gradient (Muchez and Sintubin, 2002). Other processes could include tectonically induced and gravity-driven groundwater flow; therefore, various types of flow systems and hydrologic drivers can act as transport paths, but aquifers, at the time of mineralization, would have been confined so that brines migrated stratigraphically upward. Transport and (or) migration of copper must occur under artesian heads (by confined aquifer flow), because in almost all cases where it has been possible to determine, the zoning and paragenesis indicate that copper-rich, hematite-stable brines have entered the host rocks from below. Synsedimentary and postdepositional faults were probably crucial for many systems in providing focused cross-stratal fluid flow (Blundell and others, 2003; Hitzman and others, 2005).

Most reduced-facies copper deposits appear to have formed on basin edges or where irregularities in the geometry of the basin focused fluid flow through the red-bed package and upward into the host beds. Such focusing could be due to thinning of the red-bed sequence on a basin margin, faults, permeability contrasts within specific sedimentary units, and paleotopography within the basin itself (for example, basement highs, and anticlines).

For the Kupferschiefer, numerous authors have noted the relation between mineralization and structure. In particular, Rentzsch and Franzke (1997) observed a spatial relation between metal-bearing Zechstein and lower Permian structural basins, such as the Saale Basin. Permissive tracts that overlie Rotliegend basins are considered much more prospective than those that do not.

Estimate of the Number of Undiscovered Deposits

In January 2010, numbers of undiscovered deposits were estimated by an expert panel (appendix A). After a discussion of the geology of the area and the deposit models, assessment team members made separate, subjective estimates of the numbers of undiscovered deposits. Estimators were asked for the least number of deposits of a given type that they believed could be present at three specified levels of certainty (90 percent, 50 percent, and 10 percent). For example, on the basis of all available data, a team member might estimate that there is a 90-percent chance of 1 or more, a 50-percent chance of 5 or more, and a 10-percent chance of 10 or more undiscovered deposits occurring in a given permissive tract. Each person made initial estimates without sharing their results until everyone was finished; then the results were compiled and discussed. This discussion is crucial because it almost always reveals information or insight not held by all of the panelists. As a result of the discussion, the individual scores were adjusted and a single estimate was selected for the simulation process for each tract. The final estimate of undiscovered deposits reflects both uncertainty in what could exist and the favorability of the tract (Singer, 1993). Preliminary assessment results were presented to an internal USGS review panel. In addition to hearing presentations, this review panel had access to all available data and could address technical questions to the assessment team. The panel evaluated the assessment and provided written comments that were addressed during the preparation of this report.

Final team estimates of the numbers of undiscovered deposits in each assessed tract are summarized in table 10, together with statistics that describe mean expected numbers of undiscovered deposits, the standard deviation and coefficient of variation within the estimate, and the number of known deposits. Within the Dolny Śląsk (Lower Silesia) tract (150rfCu0004), with 3 known deposits, a mean of 28 undiscovered reduced-facies deposits was predicted to a depth of 2.5 km. Within the Hessian depression tract (150rfCu0002), having 1 known deposit, a mean of 4 undiscovered deposits was estimated. A mean of 3 undiscovered deposits was predicted in the Spremberg-Wittenburg tract (150rfCu0005), which contains 2 known deposits. Finally, a mean of 1 undiscovered deposit was estimated for the Hercynian-Thüringian Basin tract (150rfCu0001), with 4 known deposits.

Three of the areas with permissive rocks were not assessed quantitatively even though the lithostratigraphic setting characteristic of reduced-facies copper deposits is present. These areas do not overlie Rotliegend depocenters, and the only potential copper sources for these tracts are the Rotliegend red beds; Permian volcanic rocks are not mapped in these assessment areas. The North Sea tract (150rfCu0003) overlies part of the Variscan foreland basin that contains extensive Westphalian coal deposits. Expulsion of reduced fluids from these Carboniferous rocks could have flushed the Rotliegend reservoir and displaced any fluids that could have been capable of carrying copper in solution. Mineral-zonation maps for the area northeast of the Tornquist-Teisseyre Zone do not show evidence for interaction of the Kupferschiefer with oxidized ore fluids (tract 150rfCu0006, Baltic Basin). However, one of these three tracts deserves some attention. The permissive tract in the Jutland Peninsula area (150rfCu0007) has a Rote Fäule zone indicating that oxidizing brine migrated and altered the host interval. However, the data are not sufficient to say that the brine contained important amounts of copper.

Probabilistic Assessment Simulation Results

Probable amounts of undiscovered resources for the tracts were estimated by combining consensus estimates for numbers of undiscovered deposits with the SSC models (Zientek, Hayes, and Taylor, 2013) using the EMINERS program (Root and others, 1992; Duval, 2012). Simulation results are reported at selected quantile levels, together with the mean expected amount of metal, the probability of the mean, and the probability of no deposits being present. The amount of metal reported at each quantile represents the least amount of metal expected. Results of the Monte Carlo simulation are shown as cumulative frequency plots (fig. 39) and summarized in table 11.

All of the assessed tracts contain known mineral deposits with identified resources. With the exception of tract 150rfCu0001, Hercynian-Thuringian Basin, the assessed tracts have more estimated undiscovered deposits than known deposits. However, by far the largest amount of undiscovered copper is likely in tract 150rfCu0004, Dolny Śląsk (Lower Silesia).

Table 10. Undiscovered deposit estimates, deposit numbers, and tract area for the Kupferschiefer in the Southern Permian Basin, Germany and Poland.

[N_{XX}, Estimated number of deposits associated with the xxth percentile; N_{und}, expected number of undiscovered deposits; s, standard deviation; C_v%, coefficient of variance; N_{known}, number of known deposits in the tract that are included in the grade and tonnage model; N_{total}, total of expected number of deposits plus known deposits; tract area, area of permissive tract in square kilometers. N_{und}, s, and C_v% are calculated using a regression equation (Singer and Menzie, 2005)]

Tract	Consensus undiscovered deposit estimates					Summary statistics					Tract area (km²)
	N_{90}	N_{50}	N_{10}	N_{05}	N_{01}	N_{und}	s	C_v%	N_{known}	N_{total}	
150rfCu0002, Hessian Depression	1	3	10	10	10	4.4	3.4	77	1	5.4	38,200
150rfCu0001, Hercynian-Thuringian Basin	0	0	3	7	10	1.3	2.4	190	4	5.3	18,300
150rfCu0004, Dolny Śląsk (Lower Silesia)	12	25	50	50	50	28	14	50	3	31	18,700
150rfCu0005, Spremberg-Wittenberg	1	3	6	6	6	3.2	1.9	58	2	5.2	6,100

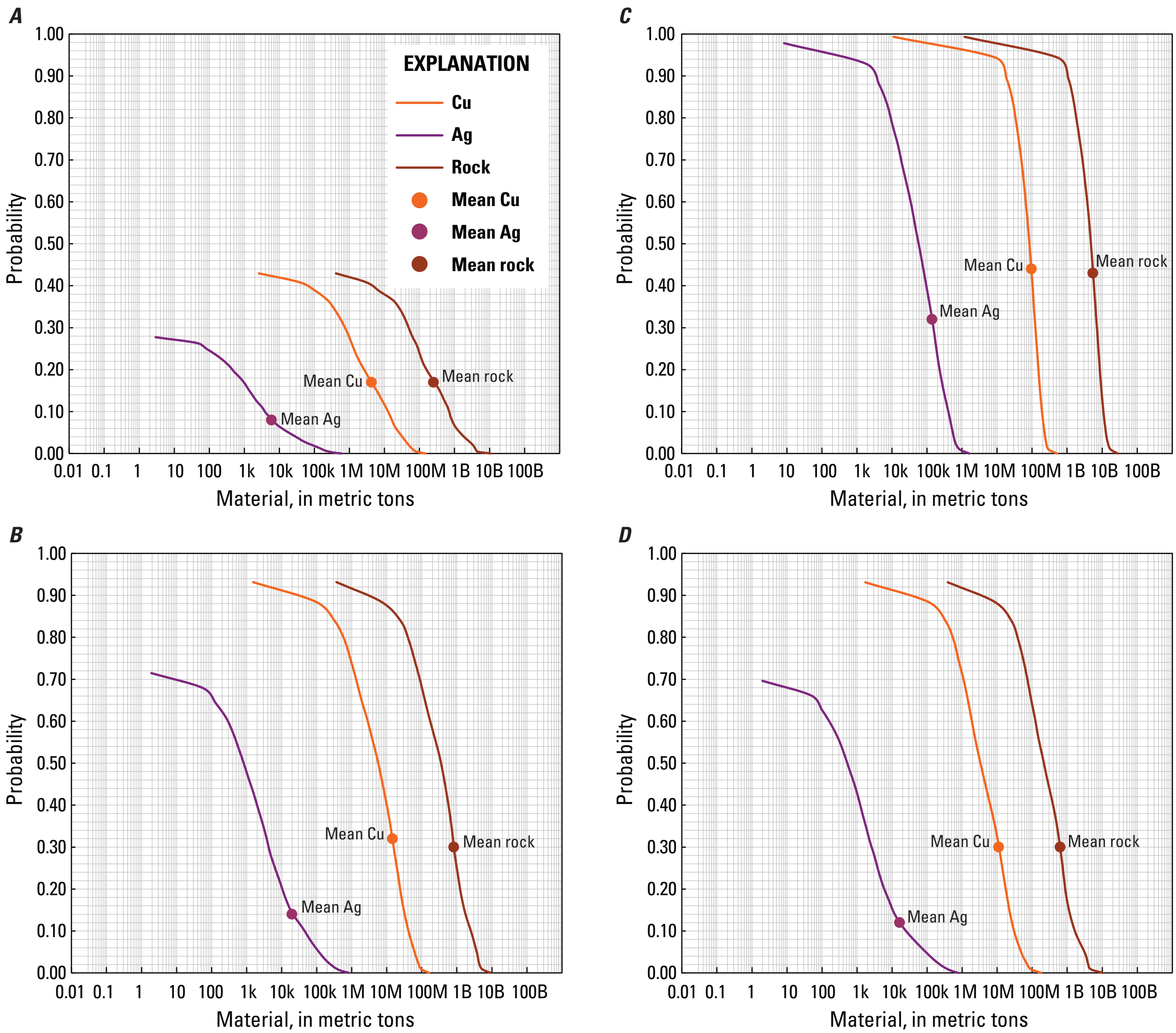


Figure 39. Cumulative frequency distribution plots showing the results of Monte Carlo computer simulation of undiscovered silver and copper resources for tracts in Germany and Poland—(*A*) 150rfCu0001, Hercynian-Thüringian Basin; (*B*) 150rfCu0002, Hessian Depression; (*C*) 150rfCu0004, Dolny Śląsk (Lower Silesia); and (*D*) 150rfCu0005, Spremberg-Wittenberg. Ag, silver; Cu, copper; k, thousand; M, million; B, billion.

Table 11. Results of Monte Carlo simulations of undiscovered resources for the Kupferschiefer in the Southern Permian Basin, Germany and Poland.

Tract name	Probability of at least the indicated amount						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Undiscovered resources of copper, in metric tons								
150rfCu0001, Hercynian-Thuringian Basin	0	0	0	13,000,000	25,000,000	4,200,000	0.17	0.57
150rfCu0002, Hessian Depression	0	60,000	5,700,000	42,000,000	62,000,000	15,000,000	0.32	0.07
150rfCu0004, Dolny Śląsk (Lower Silesia)	7,200,000	17,000,000	84,000,000	190,000,000	230,000,000	96,000,000	0.44	0.01
150rfCu0005, Spremberg-Wittenberg	0	65,000	3,300,000	30,000,000	48,000,000	11,000,000	0.30	0.07
Undiscovered resources of silver, in metric tons								
150rfCu0001, Hercynian-Thuringian Basin	0	0	0	3,900	18,000	6,000	0.08	0.72
150rfCu0002, Hessian Depression	0	0	830	44,000	110,000	20,000	0.14	0.29
150rfCu0004, Dolny Śląsk (Lower Silesia)	780	3,300	58,000	410,000	550,000	140,000	0.32	0.02
150rfCu0005, Spremberg-Wittenberg	0	0	510	26,000	94,000	16,000	0.12	0.30
Rock in undiscovered deposits, in million metric tons								
150rfCu0001, Hercynian-Thuringian Basin	0	0	0	700	1,400	250	0.17	0.57
150rfCu0002, Hessian Depression	0	5	360	2,500	3,700	820	0.30	0.07
150rfCu0004, Dolny Śląsk (Lower Silesia)	450	1,000	4,800	11,000	13,000	5,500	0.43	0.01
150rfCu0005, Spremberg-Wittenberg	0	5	220	1,600	3,100	630	0.30	0.07

Gaussian Geostatistical Simulation

Under the classification system used in Poland, mineral resource categories have specific guidelines for sampling density (for example, Jakubiak and Smakowski, 1994). For stratiform deposits such as hard coal, sapropel, and bituminous shale, the minimum distance between observation points is 3 to 4 km for the resource to be in the C2 category, which is roughly equivalent to inferred resources in the CRIRSCO standards (Committee for Mineral Reserves International Reporting Standards, 2006). KGHM drills copper deposits on a 0.5- to 1.5-km grid, to obtain the degree of confidence required for the C1 category (table 12; Bartlett and others, 2013). The data for known resources of SSC deposits in table 4 meet these sampling requirements.

Drill data exist for areas outside of the area where the sampling density is sufficient to formally assign resources to categories C2 or higher. In this situation, probabilistic estimates can be made for undiscovered mineral resources in incompletely explored extensions of large, stratabound deposits if appropriate data are available to calculate metal surface density.

For this study, geostatistical simulation techniques are used to probabilistically estimate the amount of undiscovered metal in Poland, where copper surface density (CSD) information is available for drill holes. Copper surface-density data are available for continuously sampled profiles for about 1,500 drill holes throughout the country, including more than 640 drill holes within mine lease areas (Oszczepalski and Speczik, 2011, 2012). Drill-hole locations and CSD information were derived from unpublished maps provided by PGI and the published metallogenic atlas (Oszczepalski and Rydzewski, 1997b).

A variety of techniques can be used to create a continuous (predictive) surface of metal density from point values (for example, drill holes). In the 1930s, contour maps, likely drawn by hand, were used to represent the metal-density surface. Recently, both deterministic and geostatistical interpolation

Table 12. Definitions of mineral resource categories as used by Kombinat Górniczo-Hutniczy Miedzi Polska Miedź S.A. (KGHM) in the Legnica-Głogów Copper Belt Area, Southern Permian Basin, Poland.

[Information on drilling grid for category C2 and the definition of category D from Jakubiak and Smakowski (1994); CRIRSCO, Committee for Mineral Reserves International Reporting Standards (2006); km, kilometers]

Category	Confidence	Continuity	Corresponding CRIRSCO category	Drilling grid
B	High	The quantity and quality of information confirms the continuity of the geological body and its borders	Measured mineral resources	Requires mining development
C1	High	The data points are, however, too scarce to confirm the continuity of the geological body	Indicated mineral resources	1.5 by 1.5 km
C2	Low	The geological indications and evidence of which have not been verified	Inferred mineral resources	3 by 3 km
D1-D2	Very low	The estimate is based on indirect indications, showings, and isolated sampling. D1 and D2 are equivalent to categories P1 and P2, prognostic resources, as used in the former Soviet Union	Not defined as a resource category	

tools have been used to represent metal surface-density surfaces. Deterministic interpolation techniques create surfaces from measured points, based on either the extent of similarity or the degree of smoothing. Geostatistical interpolation techniques (kriging) use the statistical properties of the measured points when creating the surface. For example, PGI has used both deterministic (inverse distance weighted) and geostatistical (kriging) techniques. These techniques are locally accurate and produce a smooth surface appropriate for visualizing trends.

Uncertainty is a characteristic of undiscovered resource estimation, and forecasts should be accompanied by measures of uncertainty. Simulation techniques assess uncertainty by generating many model realizations that represent a range of plausible possibilities that honor the known data and their spatial variability (Vann and others, 2002; Esri, 2013a, b). Any individual simulation is a poorer estimate than kriging. However, averaging a set of simulations can yield a good estimate that tends toward the prediction generated using kriging.

Gaussian Geostatistical Simulations is a tool in the Geostatistical Extension for ArcGIS version 10 (Esri, 2013a, b, c). The tool uses Gaussian geostatistical simulation (GGS), which is based on the multivariate Gaussian random function model. The parameters of the conditional distribution function are straightforward to infer and the mean and variance are estimated by kriging (Vann and others, 2002). The Gaussian Geostatistical Simulations tool in ArcGIS accepts any simple kriging model as input. In ArcGIS, GGSs work by creating a grid of randomly assigned values drawn from a standard normal distribution. The covariance model (from the semivariogram specified in the input simple kriging layer) is then applied to the raster, ensuring that raster values conform to the spatial structure found in the input dataset. The resulting raster constitutes one unconditional realization, and many more realizations can be produced using subsequent rasters of normally distributed values (Esri, 2013a, b, c).

A workflow for GGS involves preparing the data, developing a simple kriging model, running the simulation to create the realizations, and postprocessing the results (Esri, 2013a, b, c). To use this simulation technique, the data, or a transformation of the data, is assumed to have a Gaussian (normal) distribution. Copper surface-density values were positively skewed; therefore, the copper surface-density data were log transformed to approximate a normal distribution. In addition, declustering[22] was done to obtain a representative histogram from clustered data. Drill holes are concentrated in the mine lease areas and were randomly sampled so that the density of holes in the GGS simulation was similar to that of the rest of the study area.

A simple kriged surface was generated using the ArcGIS Geostatistical Extension. The technique also assumes that the data are stationary; that is, the mean, variance, and spatial structure (semivariogram) do not change over the spatial domain of the data (Esri, 2013a, b, c). When creating the input surface, a first-order trend removal was performed on the data to ensure that the mean is stationary over the spatial domain. Next, a normal-score transformation, was applied to the log-transformed copper surface-density data. An iterative process was used to model the semivariogram and covariance. Lag size and the number of lags were varied and the resulting prediction errors were examined. After a number of trials, a semivariogram was selected (fig. 40) and an input surface was created to use in the simulation (fig. 41).

[22]Declustering is a process applied to data that have been preferentially sampled with higher densities of points in some areas so that the sample of points properly reflects the histogram of the whole population.

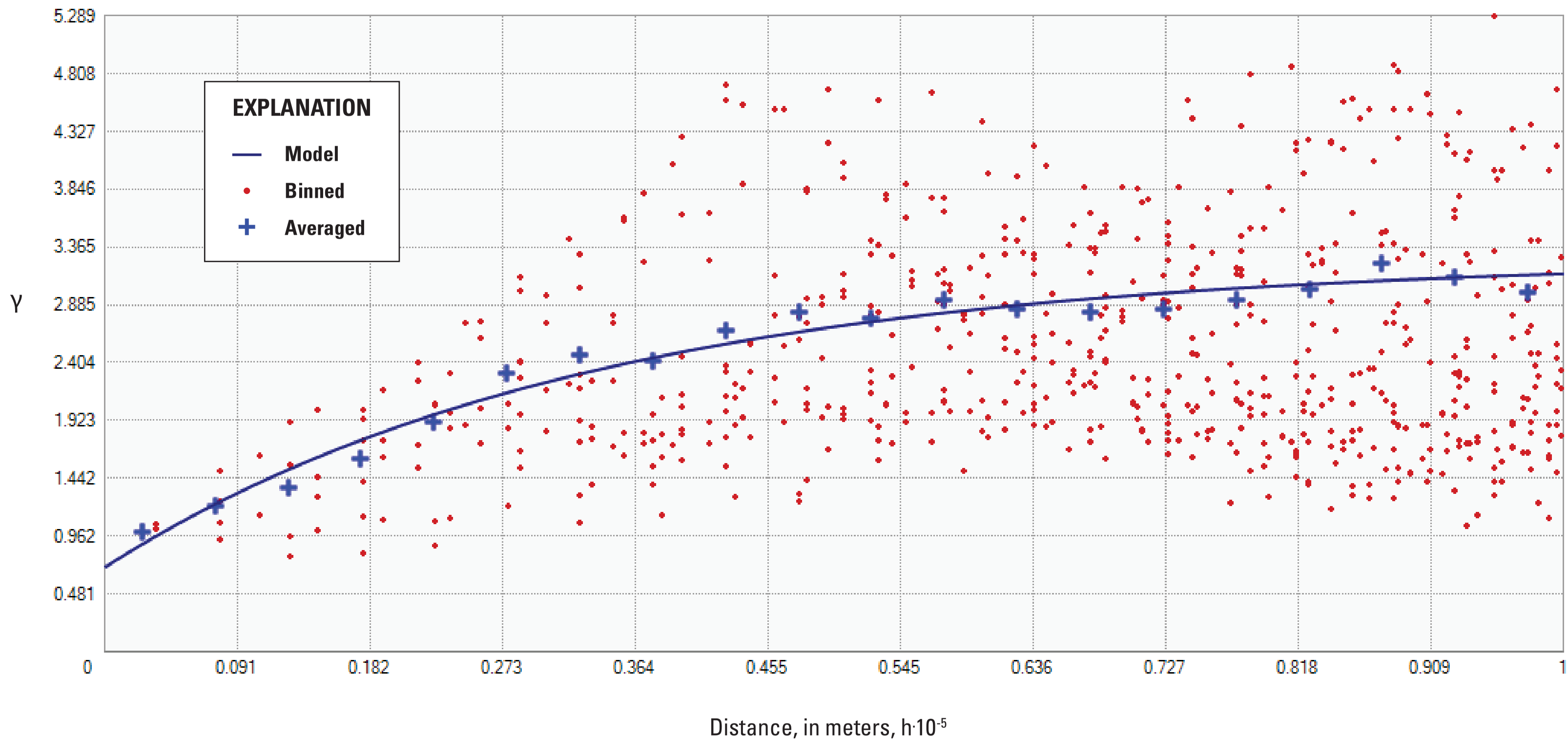


Figure 40. Graph illustrating the observed semivariogram and model used for Gaussian geostatistical simulation modeling of copper surface density in Poland. The y-axis is γ, the semivariogram value; h on the x axis is the distance vector between 2 points. An exponential model with a nugget of 0.70332, a value of 2.5627 for the sill, and a range of 99,128 was used to fit the observed data. The nugget is the value where the semivariogram model intercepts the y-axis. The nugget effect can be related to measurement errors and (or) spatial sources of variation at distances smaller than the sampling interval. The range is the distance where the model first flattens out; samples closers than the range are spatially autocorrelated, whereas locations farther apart are not. The value that the semivariogram model attains at the range (the value on the y-axis) is called the sill. Description of the range, sill, and nugget from Esri (2013).

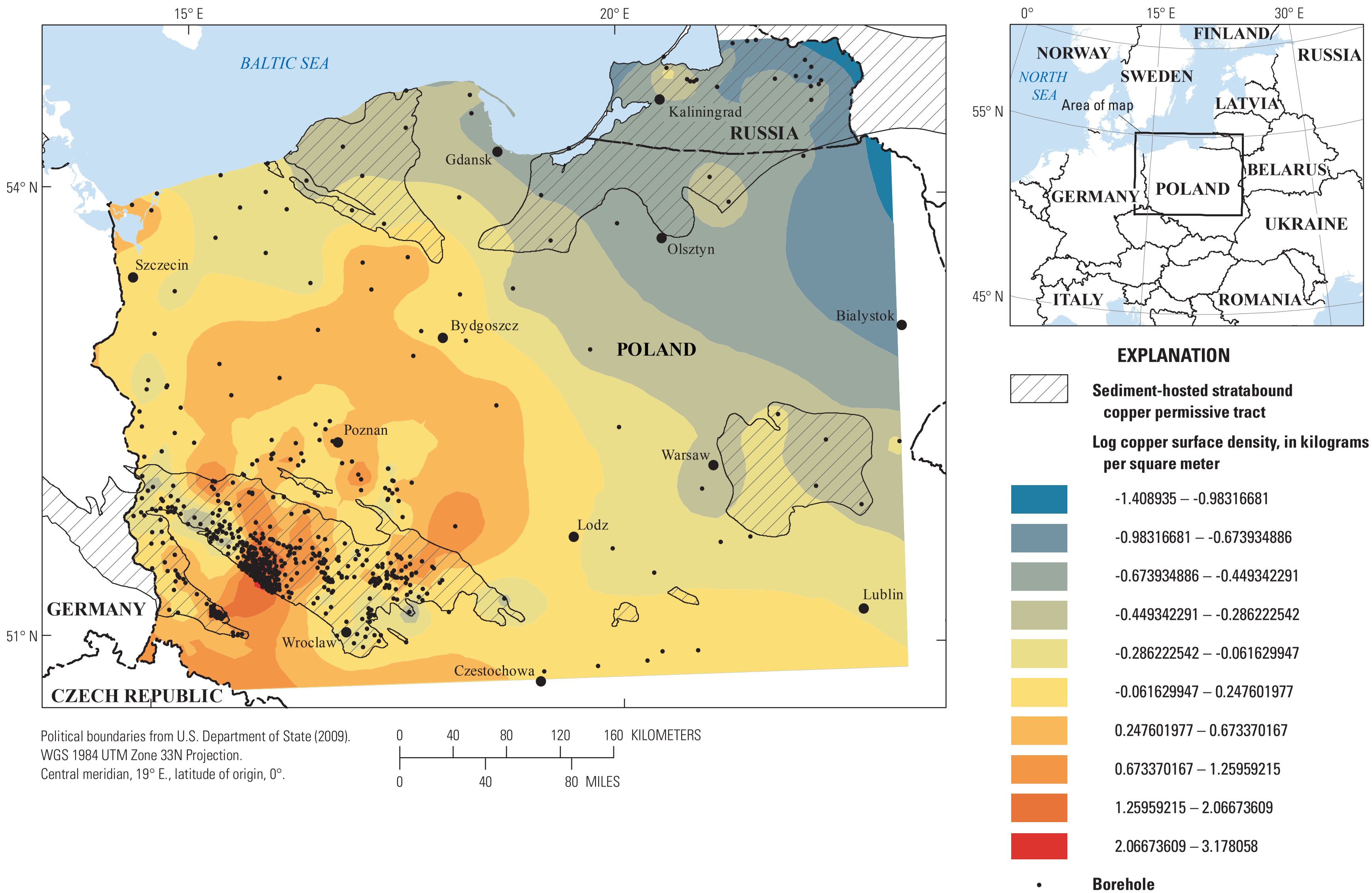


Figure 41. Map of Poland showing permissive tracts, boreholes, and copper surface-density grid used in Gaussian geostatistical simulation modeling.

The simulation consisted of 100 realizations. The input data used to fit the semivariogram was also used to condition the realizations; this ensures that the simulated values honor the input data values and that, on average, the kriged predictions are replicated (Esri, 2013a, b, c). The output cell size was set to 1,000 m. The permissive tract for the study area served as a bounding polygon that limited the extent of the analysis. The permissive tract included polygons for those areas with identified mineral inventory so that simulation results could be tabulated separately for those areas. All the bounded unconditional rasters were saved.

An additional raster was also created that specified the percentage of simulated values that exceeded a threshold for each cell (fig. 42). In this study, the threshold value was set to 1.544, which corresponds to a copper surface-density value of 35 kg/m^2. This is the cutoff value used by PGI when they estimated prognostic copper resources of the same area. Realizations were checked to confirm that the output values, their spatial patterns, and locations were reasonable.

Using polygons that subdivide the permissive tract into areas inside and outside of mine concession areas, the attribute values for log(copper surface density), raster name, and polygon number are extracted for each raster and output to a single table. The table is imported into statistical software and the contained copper associated with each cell is computed using copper surface density and cell area. Cells with copper surface density less than 35 kg/m^2 are excluded from the analysis and summary tables are created that sum the contained copper within each polygon for each of the realizations. Summary statistics are then calculated for each polygon (table 13).

Our estimate of the contained copper resource for the Lubin-Sieroszowice Mine area is about 72 Mt. This includes the published mineral inventory and an estimate of the amount of copper that has been produced. Median and mean contained copper estimated from the simulation is 83 and 82 million tons, respectively. The 90th and 10th quantiles are 69 and 94 Mt. The mean and median values from the simulation are within 15 percent of what is thought to be present from published mineral inventory and production data.

Simulation results indicate a mean value of 63 Mt of undiscovered copper in the tract, outside the mine lease areas. This compares with a mean estimate of 96 Mt estimated using the three-part form of assessment. The mean simulation results are lower but the form of the distribution is different. For example, at the 95th percentile, the simulation indicates at least 27 Mt may be present compared to only 7.6 million tons for the estimate from the three-part form of assessment.

The probability threshold map (fig. 42) shows a zone of mineralization extending from the current mine lease areas northward into the Kotla, Nowa Sól 17/2011/p, and Wilcze 67/2011/p concessions and includes the Kulów and Wilcze prospective areas of Oszczepalski and Speczik (2012) (fig. 30). A second area of mineralization north of the city of Zielona Gora, covered by the Mozów-1 15/2011/p concession, corresponds to the Mozów prospective area of Oszczepalski and Speczik (2012) (fig. 30). A third area of mineralization occurs southwest of the city of Kalisz and underlies the Sulmierzyce 18/2011/p and Kalisz 14/2012/p concessions (fig. 30). It indicates a broad zone of mineralization that occurs in this tract and extends to the northeast into rocks that are below our assessment depth 2.5 km; it corresponds to the Sulmierzyce and Florentyna prospective areas of Oszczepalski and Speczik (2012) (fig. 30).

Discussion

The Kupferschiefer deposits in Germany are world famous. In 800 years of mining, about 2.6 Mt of copper were produced from these deposits; geologic research on these deposits played a significant role in the scientific debates on the genesis of sediment-hosted stratabound copper (SSC) deposits. The tracts associated with the deposits in central Germany (150rfCu0001, Hercynian-Thuringian Basin and 150rfCu0002, Hessian Depression) have been well explored; less than one Mt of copper remains in identified deposits. The USGS Global Mineral Resource Assessment Team forecasts that copper remains to be discovered in parts of the tract that are likely below 1 km depth (table 11).

Assessments by PGI and this study forecast large amounts of undiscovered copper in the Kupferschiefer in the Fore-Sudetic Monocline in Poland and Lausitz Syncline in Germany (150rfCu0004, Dolny Śląsk (Lower Silesia) and 150rfCu0005, Spremberg-Wittenberg; table 14). Since 1958, about 15 Mt of copper have been produced, and there is a remaining resource of about 30 Mt of copper. The sum of mean estimates of the amount of undiscovered copper in tracts 150rfCu0004, Dolny Śląsk (Lower Silesia), and 150rfCu0005, Spremberg-Wittenberg, using the 3-part form of assessment to depths of 2.5 km are about 110 Mt (table 15). Most of the undiscovered resource in southwestern Poland will be below depths of 1.5 km, where virgin rock temperatures will exceed 50 ºC. Development of these resources will require sophisticated mining methods requiring refrigeration and additional ground support that will add to the mining costs. In-situ leaching could possibly be used to extract copper from the more porous and permeable Rotliegend strata in deep ore bodies. However, this would require development of new technologies.

To aggregate the probabilistic assessment results from the 4 tracts in Germany and Poland into a single, probabilistic estimate, the degree of association or dependency between these geologically based permissive tracts must be considered (Schuenemeyer, 2003, 2005; Schuenemeyer and others, 2011). Dependencies between probabilistic distributions do not affect the mean of the distributions. Therefore, the mean of an aggregated distribution is the sum of the means of the individual distributions. Geologic dependencies between tracts can affect the spread or uncertainty of the aggregated probability distribution. Independence between tracts implies that the occurrence of one event (such as a deposit) in a tract

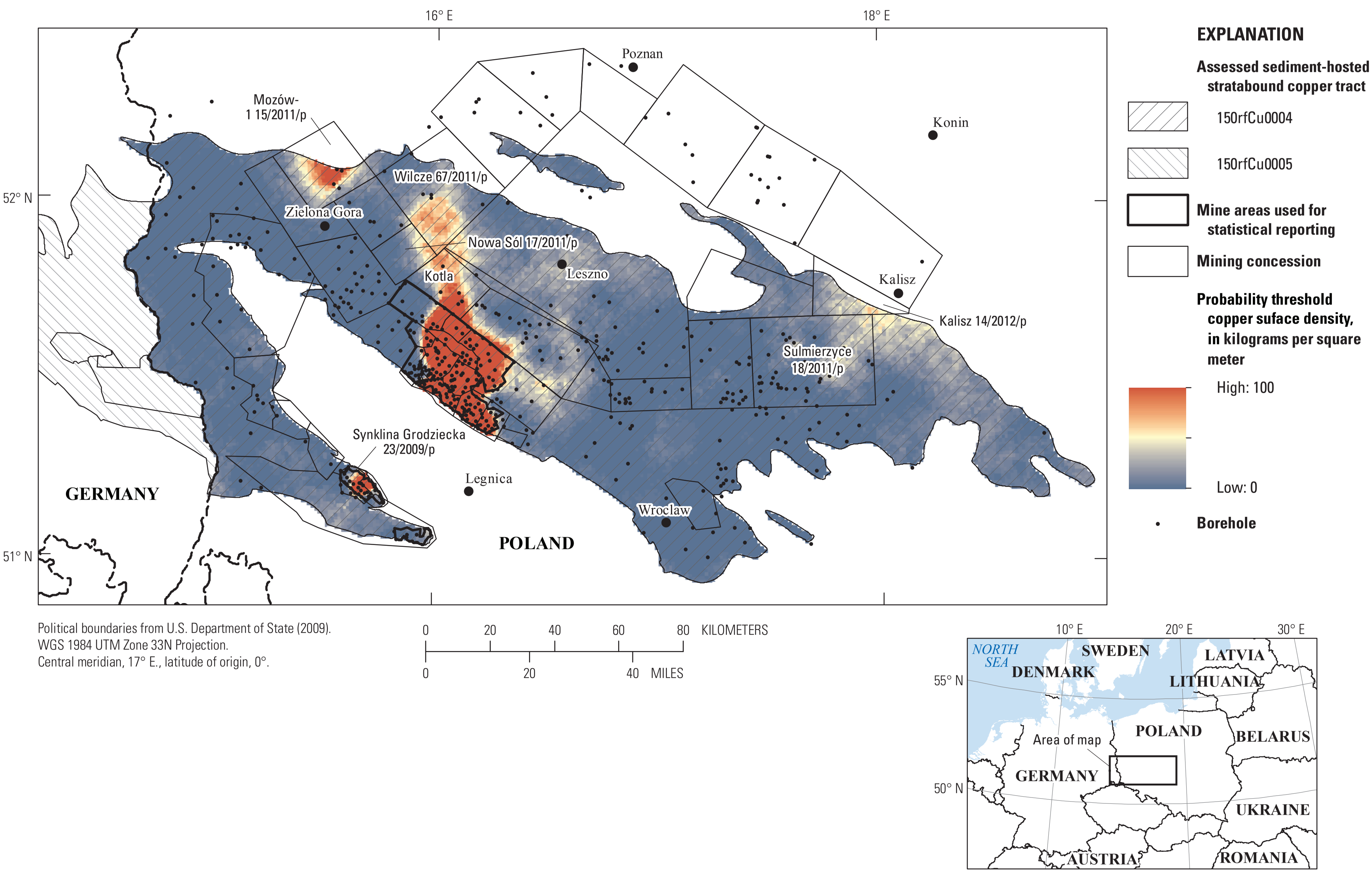


Figure 42. Map showing where the probability that copper surface density (CSD) will exceed a threshold of 35 kilograms per square meter (kg/m²) in tract 150rfCu0004, Dolny Śląsk (Lower Silesia), Poland; the location of mine areas used for statistical reporting; boreholes that were used in the model; and mining and exploration concessions for copper. Information on map from Bońda and Siekiera (2009), Bartlett and others (2013), and Ministry of the Environment, Republic of Poland (2013a, b, and c).

Table 13. Selected results of Gaussian geostatistical simulation summarized by features in permissive tract 150rfCu0004, Dolny Śląsk (Lower Silesia), Poland.

[All results are contained copper, in metric tons. Identified copper is production plus remaining resources from table 2. Q, quantile; n.d., no data]

Area	Identified copper	Mean	Median (Q 50)	Q 95	Q 90	Q 75	Q 25	Q 10	Q 05
Undiscovered resources									
Most of permissive tract, excluding mining areas	n.d.	62,000,000	57,000,000	27,000,000	31,000,000	44,000,000	79,000,000	93,000,000	110,000,000
Small tract outlier to the north	n.d.	540,000	240,000	37,000	41,000	89,000	660,000	1,600,000	2,300,000
Small tract outlier, east of Wroclaw	n.d.	190,000	190,000	37,000	37,000	37,000	340,000	340,000	340,000
Identified resources in permissive tract									
Lubin-Sieroszowice mining area	72,000,000	82,000,000	83,000,000	66,000,000	69,000,000	76,000,000	89,000,000	94,000,000	98,000,000
Konrad-Wartowice mining area	1,600,000	1,900,000	1,600,000	210,000	350,000	840,000	2,800,000	3,900,000	4,800,000
Nowy Kosciol-Lena mining area	220,000	380,000	240,000	37,000	50,000	83,000	620,000	1,100,000	1,400,000

makes it neither more nor less probable that the other event (deposit) occurs in another tract. For dependence, events, such as number of deposits, in one tract predict the events in a second. An assumption of independence between tracts will yield uncertainty estimates that are unrealistically small if the predicted events (deposits) are not independent. Conversely, an assumption of total dependence will yield estimates of uncertainty that often are unrealistically large if the predicted events (deposits) are dependent.

We use the algorithm presented by Schuenemeyer and others (2011) in which user-specified estimates of correlation between tracts are used to aggregate uncertainty where some degree of dependence between tracts is likely and can be estimated. For this study, dependency relations among tracts are based on shared components in ore-forming systems. For example, the permissive tracts may or may not share the same sources of copper and oxidized brines, reservoir-facies host rocks, and stratigraphic and (or) structural traps.

In total, the mean aggregated estimate of undiscovered copper in all four assessed tracts is 130 Mt (table 16 and fig. 43). The estimated median is about 120 Mt. The values of the other percentiles depend on assumptions made about dependence among tracts (Schuenemeyer and others, 2011). Assuming partial correlation, the tracts could contain as little as 14 Mt of copper at the 95th quantile or as much as 270 Mt at the 5th quantile.

The data available for Poland made it possible to compare undiscovered resource estimates made by the PGI and the USGS using different methods. The PGI used deterministic interpolation methods to estimate 69.5 Mt of copper to a depth of 2,000 m (Oszczepalski and Speczik, 2011, 2012). The mean values obtained by the USGS to a depth of 2,500 m were 62 and 97 Mt, using Gaussian geostatistical simulation and the three-part form of assessment, respectively. The results are remarkably similar. The main difference is that the USGS methods give some estimate of the uncertainty associated with

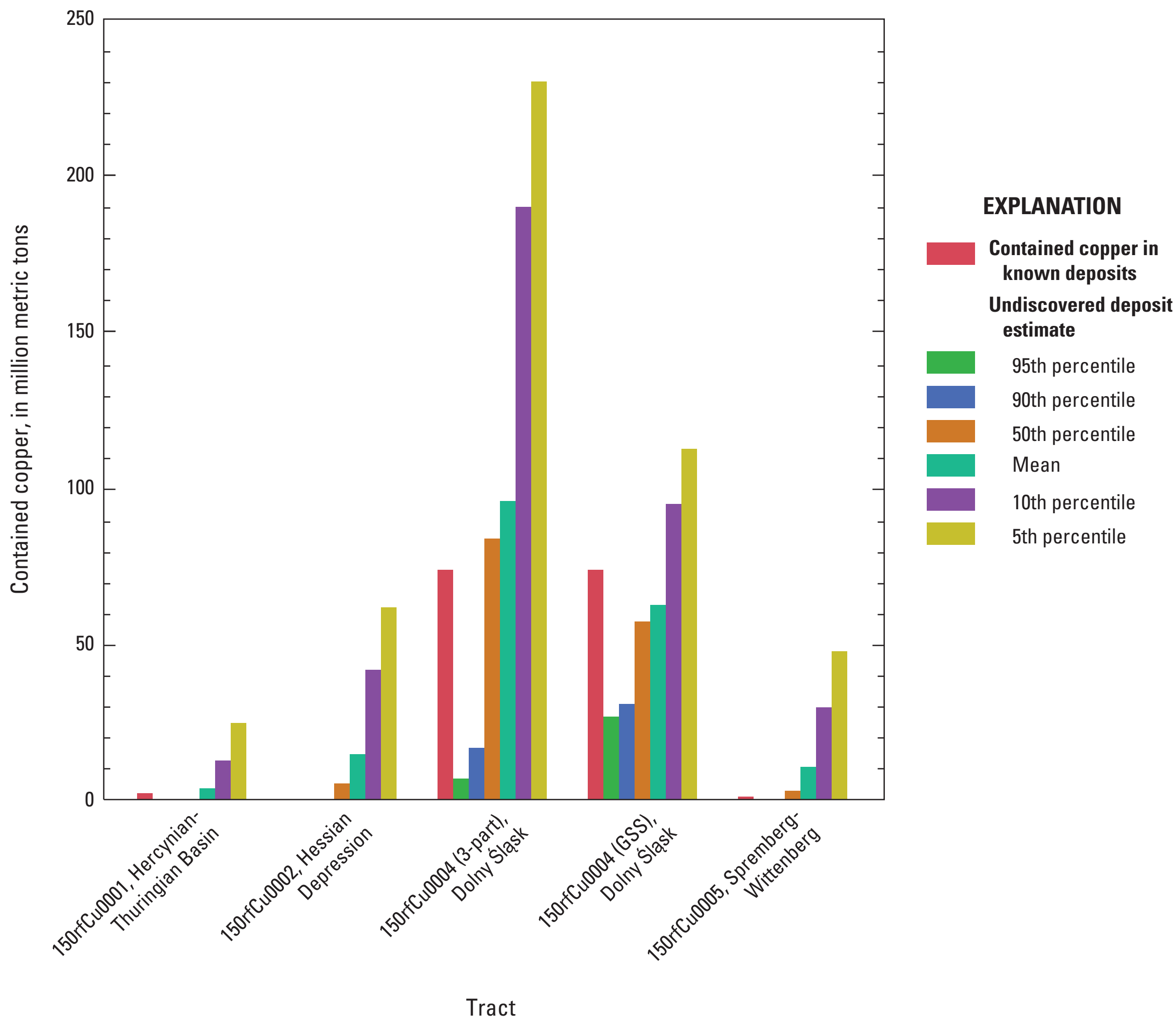


Figure 43. Histograms comparing probabilistic estimates of undiscovered copper for the Kupferschiefer reduced-facies copper permissive tracts—Germany and Poland.

Table 14. Selected simulation results of undiscovered copper resources obtained using the three-part form of assessment and Gaussian geostatistical simulation for permissive tract 150rfCu0004, Dolny Śląsk (Lower Silesia), Poland.

[GGS, Gaussian geostatistical simulation; n.d., no data]

Tract name	Probability of at least the indicated amount of copper (metric tons)						Probability of	
	0.95	0.9	0.5	0.1	0.05	Mean	Mean or greater	None
Dolny Śląsk (Lower Silesia), GGS results	27,000,000	31,000,000	57,000,000	93,000,000	110,000,000	62,000,000	n.d.	n.d.
Dolny Śląsk (Lower Silesia), three-part assessment results	7,600,000	18,000,000	84,000,000	190,000,000	230,000,000	97,000,000	0.43	0.01

Table 15. Selected simulation results of undiscovered copper resources compared with known resources, Southern Permian Basin, Germany and Poland.

[GGS, Gaussian geostatistical simulation; km², square kilometers]

Tract name	Country	Known deposits	Tract area (km²)	Known copper resources (metric tons)	Mean estimate of undiscovered copper resources (metric tons)	Median estimate of undiscovered copper resources (metric tons)
150rfCu0001, Hercynian-Thuringian Basin	Germany	Mansfeld; Sangerhausen	18,300	2,600,000	5,500,000	500,000
150rfCu0002, Hessian Depression	Germany	Richelsdorf	38,200	420,000	15,000,000	6,000,000
150rfCu0004, Dolny Śląsk (Lower Silesia), three-part assessment results	Poland	Konrad-Grodziec-Wartowice; Lena-Nowy Kosciol; Lubin-Sieroszowice	18,700	74,000,000	97,000,000	84,000,000
150rfCu0004, Dolny Śląsk (Lower Silesia), GGS results					62,000,000	57,000,000
150rfCu0005, Spremberg-Wittenberg	Germany	Graustein; Spremberg	6,100	1,500,000	12,000,000	4,700,000

Table 16. Aggregated assessment results for tracts permissive for reduced-facies-type sediment-hosted stratabound copper deposits in the Southern Permian Basin, Europe.

[The three-part form of assessment results for the tracts were used in the computation. All results are contained copper, in metric tons. Q, quantile]

Aggregation assumption	Mean	Q 95	Q 90	Q 75	Median	Q 25	Q 10	Q 5
Total dependence	130,000,000	11,000,000	25,000,000	58,000,000	110,000,000	180,000,000	250,000,000	300,000,000
Partial correlation	130,000,000	14,000,000	30,000,000	64,000,000	120,000,000	180,000,000	240,000,000	270,000,000
Complete independence	120,000,000	16,000,000	31,000,000	65,000,000	120,000,000	170,000,000	230,000,000	270,000,000

the estimate. The USGS assessment could not have been done without the data provided by PGI.

Miners and scientists are emphatic about the association of copper ore with the contact between oxidized (Rote Fäule) and reduced facies rocks of the Kupferschiefer. This association leads some scientists to propose that the largest areas underlain by Rote Fäule alteration are associated with the largest ore deposits (fig. 44). Unfortunately, this is not always true. The mineral-zonation map shows a large area of Rote Fäule facies that extend from Germany into Poland (fig. 8). The large deposits in Poland concentrated along the eastern margin of the altered region (150rfCu0004, Dolny Śląsk (Lower Silesia)), but the western side, in Germany, has narrow zones of copper enrichment (tract 150rfCu0005, Spremberg-Wittenberg). The large area of Rote Fäule underlying the coastal areas of northern Germany and northwestern Poland (tract 150rfCu0007, Jutland Peninsula) also has insignificant zones of copper enrichment. The Rote Fäule area along the German-Polish border overlies different Rotliegend basins—the Barnim Basin to the west and the North Sudetic and Fore-Sudetic Basins to the east. Perhaps the difference in copper enrichment may be related to different copper source rocks and evolutionary paths for these basins. The area of Rote Fäule overlying the Barnim Basin is also characterized by the presence of numerous salt diapirs, whereas few are mapped in the area overlying the North Sudetic and Fore-Sudetic Basins. Perhaps the integrity of the trap and seal needed to form copper deposits was adversely affected by salt tectonics. Understanding the relation between the size of areas of Rote Fäule and the distribution of world-class deposits is warranted and could be highly valuable.

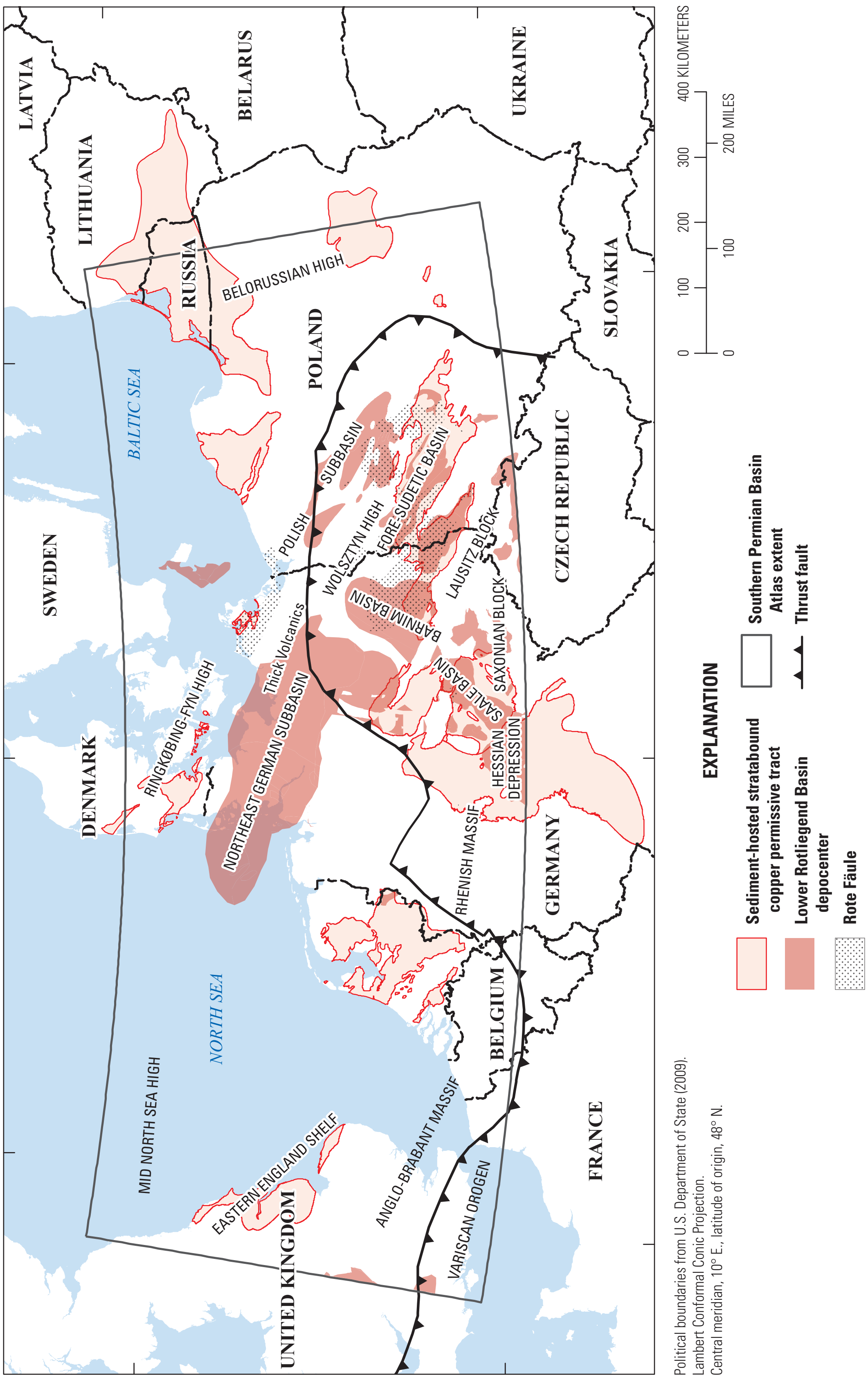


Figure 44. Map of northern Europe showing the distribution of the Kupferschiefer permissive tracts in relation to Rotliegend depocenters and areas where the rocks near the base of the Zechstein Group are affected by Rote Fäule alteration. Rotliegend features from Pharaoh and others (2010). Rote Fäule sources are given in figure 10.

Most of the literature on the three-part form of assessment emphasizes that the primary source of information for delineating tracts is a geologic map. Mineral occurrence information, classified by deposit type, is used to infer the spatial extent of ore-forming processes (Singer and Menzie, 2010). If we had had no more information than this, we would not have been able to complete an assessment of undiscovered copper associated with the Kupferschiefer. We required maps that showed the distribution of the base of Zechstein in the subsurface along with maps of the facies of the underlying Rotliegend Group. Isodepth maps were needed to constrain the down-dip extent of permissive rocks. To estimate undiscovered resources we needed to know the spatial extent of known deposits and the possible extent of mineralizing systems, which could only be inferred from drill data and derivative maps. Published atlases by Ziegler (1990), Heeremans and Faleide (2004), Heeremans and others (2004), and Doornenbal and Stevenson (2010) and unpublished information provided by PGI provided most of the information needed for the assessment.

Considerations for Users of this Assessment

This mineral resource assessment provides maps that show where undiscovered deposits may exist and gives estimates of how much resource might be present in these areas; however, it does not specifically address the likelihood of future development. This study does not evaluate how much of the undiscovered resource is likely to be found, how much it would cost to find, and, if found, what part would be economic under various conditions. Current research on economic filters is providing some tools that can be used to estimate how much of an undiscovered mineral resource may be economic (Robinson and Menzie, 2012), but this technique has not been applied to results of this study.

Permissive tracts are based on geology, irrespective of current land-use conditions. Therefore, tracts may include lands that already have been developed for other uses or have been withdrawn from mineral development as protected areas. The tracts are intended to be displayed at a scale of 1:1,000,000, even though higher resolution information was used in the compilations.

USGS Global Mineral Resource Assessment products represent a synthesis of current, readily available information. This assessment is based on the deposit models, maps, and data represented in this report. Different datasets would result in a different assessment.

Acknowledgments

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Appendix A. Short Biographies of the Assessment Team

James D. Bliss is a research geologist with the U.S. Geological Survey (USGS) in Tucson, Arizona. His research focuses on mineral deposit modeling and mineral resource assessment methodology.

Gregor Borg is Full Professor for Petrology and Economic Geology at Martin-Luther-Universität at Halle-Wittenberg, Germany. He has conducted research on sediment-hosted stratabound copper deposits in the Kalahari Copperbelt in southern Africa and the Kupferschiefer in Germany.

Stephen E. Box is a research geologist with the USGS in Spokane, Washington. He received his degrees in geology from Fort Lewis College and the University of California, Santa Cruz. He is a structural geologist and served on the assessment panel.

Paul D. Denning is a GIS specialist/physical science technician with the USGS in Denver, Colorado.

Timothy S. Hayes is a research geologist with the USGS in Tucson, Arizona. He received degrees in geology from the South Dakota School of Mines and Stanford University. He is an economic geologist with expertise in sediment-hosted stratabound copper deposits, particularly those in the Belt Basin of Montana; in Permian rocks in Oklahoma; and in the Ablah Group, Saudi Arabia. He served on the assessment panel.

Sławomir Oszczepalski is an Associated Professor with the Polish Geological Institute–National Research Institute in Warsaw, Poland. He has conducted research on the Kupferschiefer in Poland since the mid-1980s and has published dozens of peer-reviewed papers on this topic.

Heather L. Parks is a geologist working for the USGS in Spokane, Washington. She received her degree in geology from Eastern Washington University and is a GIS specialist.

Volker Spieth is a geologist and executive manager with KSL Kupferschiefer Lausitz GmbH, Germany. He has owned and operated his own exploration and project management consultancy company for 25 years. His team discovered the Rhonshausen Kupferschiefer deposit in Germany.

Cliff D. Taylor is a research geologist with the USGS in Denver, Colorado. He received a doctorate in geology from the Colorado School of Mines. He is an economic geologist with expertise in volcanogenic massive sulfide deposits and served on the assessment panel.

Michael L. Zientek is a research geologist with the USGS in Spokane, Washington. He received his degrees in geology from the University of Texas and Stanford University. He is an economic geologist with expertise in magmatic ore deposits and mineral resource assessment and served on the assessment panel.

Appendix B. Description of Spatial Data Files

By Heather L. Parks and Michael L. Zientek

Introduction

Eight spatial databases provide data for use in an assessment of undiscovered sediment-hosted copper resources in the Southern Permian Basin (SPB) of Europe. The spatial databases are presented as Esri shapefiles (.shp), which contain spatial and descriptive data for deposits and prospects, permissive tracts, mine shafts and tunnels, ore bodies, mineral zones, copper surface density, mine concessions, and ground disturbance sites. Also included are .xml metadata files, an Excel file of references cited, and a brief descriptive ASCII text file. This information can be downloaded from the USGS Web site as zipped file **GIS_SIR2010-5090-U.zip**. These databases can be queried in a geographic information system (GIS) to portray the distribution, geologic setting, and resource potential of copper deposits and to model grade and resource tonnage in the region.

Sedimentary Copper Deposits and Prospects, Southern Permian Basin of Europe (Kupferschiefer_deposits_prospects.shp)

This dataset includes points that represent sedimentary copper deposits and prospects associated with sedimentary rocks in the SPB of Europe. Its purpose is to document the locations of deposits and prospects that will be used as part of the process to estimate undiscovered mineral resource endowments.

This dataset was created by combining preexisting deposit and prospect point files (about 25 percent of the records) and by manually digitizing points from georeferenced maps (the remaining 75 percent). A deposit and prospect point file from Cox and others (2003) and a deposit and prospect point file from Kirkham and others (2003) were combined into one file. Duplicate entries were removed and the attribute table was normalized into a table structure similar to Cox and others (2003) (table B1). The points were compared against georeferenced geologic and mineral occurrence maps to verify the positional accuracy of each point. Point locations were corrected using the highest resolution data available. For example, a 1:100,000-scale map took precedence over a 1:1,000,000-scale map for the site location. The points were attributed using information derived from georeferenced maps and reports. Attribute fields and field definitions are shown in table B1.

Permissive Tracts for Reduced-Facies-Type Copper Deposits, Southern Permian Basin of Europe (Kupferschiefer_permissive_tracts.shp)

This dataset includes polygons that represent permissive tracts for reduced-facies-type copper deposits in the SPB of Europe. Its purpose is to delineate where undiscovered reduced-facies-type copper deposits could occur within the upper 2 km of the Earth's crust.

Process steps for the creation of the tracts are discussed in the "Mineral Resource Assessment—Delineating Permissive Tracts" section of this report. Attribute fields and field definitions are shown in table B2.

Sedimentary Copper Mine Shafts and Tunnels, Southern Permian Basin of Europe (Kupferschiefer_shafts_tunnels.shp)

This dataset includes points that represent sedimentary copper mine shafts and tunnels associated with sedimentary rocks in the SPB of Europe. Its purpose is to document the locations of mine shafts and tunnels that will be used as part of the process to estimate undiscovered mineral resource endowments.

This shapefile was created by manually digitizing shafts and tunnels shown on georeferenced maps and Google Earth™. The shafts and tunnels are attributed with information shown in table B3, which was derived from the maps and reports listed in the field Ref_short.

Surface Extent of Reduced-Facies-Type Copper Ore Bodies, Southern Permian Basin of Europe (Kupferschiefer_orebodies.shp)

This dataset includes polygons that represent the surface extent of reduced-facies-type copper ore bodies in the SPB of Europe. Its purpose is to document the spatial extent of mineralized rock in reduced-facies-type copper deposits and significant prospects and to constrain estimates of mineral resource endowment.

This shapefile was created by manually digitizing the ore bodies shown on georeferenced maps. The ore bodies are attributed with information shown in table B4, which was derived from the maps and reports listed in the field Ref_short.

Table B1. Definitions of user-defined attribute fields in the shapefile Kupferschiefer_deposits_prospects.shp.

[m, meter; ppm, parts per million; PGI, Polish Geological Institute–National Research Institute]

Field name	Description
Coded_ID	Coded, unique identifier assigned to permissive tract within which the site is located.
Tract_name	Name of permissive tract in which the site is located.
Group_name	Group name for sites that have been grouped together for aggregation/modeling purposes.
Name	Name of site.
Name_other	Other names used for the site.
Includes	Names of deposits that have been combined with the primary deposit as a result of the 500-m aggregation rule used for calculating grades and tonnages.
Type	Mineral deposit type.
Subtype	Sediment-hosted copper subtype.
SiteStatus	Deposit, prospect, prospect—mineralized material estimated or historic mine. Deposit if the site has grade and tonnage. Prospect if no grade and tonnage values provided. Prospect—mineralized material estimated if it has resources forecasted by PGI.
SiteStat2	Status of the site, including miscellaneous comments regarding the sites status.
Latitude	Latitude in decimal degrees; −90.00000 to 90.00000. Negative south of the equator.
Longitude	Longitude in decimal degrees; −180.00000 to 180.00000. Negative west of the Greenwich meridian.
Code_cntry	Country code (Singer and others, 2008).
Country	Country in which the site is located.
State_Prov	State or province in which the site is located.
Age_Ma	Age in millions of years before present. Age is average for geologic era, period, or epoch listed.
Age_range	Age of host rock in standard divisions of geologic time.
Comm_major	Major commodities in decreasing order of economic importance.
Tonnage_Mt	Ore tonnage in millions of metric tons; −9999 indicates no data.
Cu_pct	Average copper grade in weight percent; −9999 indicates no data.
Ag_g_t	Average silver grade in ppm (=grams per ton); −9999 indicates no data.
Con_Cu_t	Million metric tons of contained Copper; −9999 indicates no data.
Comments	Miscellaneous comments.
HostRocks	Simplified lithologic description of host rocks.
Unit	Geologic unit in which site is located.
Footwall	Rock types of foot wall rocks.
Hangwall	Rock types of hanging wall rocks.
Mineralogy	Ore and gangue minerals in approximate order of abundance.
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying file, “GIS_references.xlsx.”

Table B2. Definitions of user-defined attribute fields in the shapefile Kupferschiefer_permissive_tracts.shp.

Field name	Description
Coded_ID	Coded, unique identifier assigned to permissive tract.
Tract_name	Informal name of permissive tract.
Unregcode	Three-digit United Nations code for the region that underlies most of the permissive tract.
Country	Country(ies) in which the permissive tract is located.
Commodity	Primary commodity being assessed.
Dep_type	Deposit type being assessed.
GT_model	Grade-tonnage model used for the undiscovered deposit estimate.
Geology	Geologic feature assessed.
Age	Age of the assessed geologic feature.
Asmt_date	Year assessment was conducted.
Asmt_depth	Maximum depth beneath the Earth's surface used for the assessment, in kilometers.
Est_levels	The set of percentile (probability) levels at which undiscovered deposit estimates were made; −9999 indicates no data.
N90	Estimated number of deposits associated with the 90th percentile (90-percent chance of at least the indicated number of deposits); −9999 indicates no data.
N50	Estimated number of deposits associated with the 50th percentile (50-percent chance of at least the indicated number of deposits); −9999 indicates no data.
N10	Estimated number of deposits associated with the 10th percentile (10-percent chance of at least the indicated number of deposits); –9999 indicates no data.
N05	Estimated number of deposits associated with the 5th percentile (5-percent chance of at least the indicated number of deposits); −9999 indicates no data.
N01	Estimated number of deposits associated with the 1st percentile (1-percent chance of at least the indicated number of deposits); −9999 indicates no data.
N_expected	Expected (mean) number of deposits. N_Expected = (0.233×N90) + (0.4×N50) + (0.225×N10) + (0.045×N05) + (0.03×N01); −9999 indicates no data.
s	Standard deviation. s = 0.121 − (0.237×N90) − (0.093×N50) + (0.183×N10) + (0.073×N05) + (0.123×N01); -9999 indicates no data.
Cv_percent	Coefficient of variance, in percent. Cv = (s/N_Expected) × 100; −9999 indicates no data.
N_known	Number of known deposits in the tract; −9999 indicates no data.
N_total	Total number of deposits. N_total = N_Expected + N_Known; −9999 indicates no data.
Area_km^2	Area of permissive tract, in square kilometers.
DepDensity	Deposit density (total number of deposits per square kilometer). DepDensity = N_total/Area_km2; −9999 indicates no data.
DepDen10E5	Deposit density per 100,000 square kilometers. DepDen10E5 = DepDensity × 100,000; −9999 indicates no data.
Estimators	Names of people on the estimation team.
Schwelle	Name of basement high area.

Table B3. Definitions of user-defined attribute fields in the shapefile Kupferschiefer_shafts_tunnels.shp.

Field name	Description
Coded_ID	Coded, unique identifier assigned to permissive tract within which the site is located.
Tract_name	Name of permissive tract in which the site is located.
Name	Name of site.
Feature	Type of feature.
Latitude	Latitude in decimal degrees; −90.00000 to 90.00000. Negative south of the equator.
Longitude	Longitude in decimal degrees; −180.00000 to 180.00000. Negative west of the Greenwich meridian.
Country	Country in which the site is located.
State_Prov	State or province in which the site is located.
Comm_major	Major commodities in decreasing order of economic importance.
Comments	Miscellaneous comments.
HostRocks	Simplified lithologic description of host rocks.
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying file, “GIS_references.xlsx.”

Table B4. Definitions of user-defined attribute fields in the shapefile Kupferschiefer_orebodies.shp.

Field name	Description
Name	Name of the ore body.
Area_km2	Area of the surface extent of the ore body in square kilometers.
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying file, GIS_references.xlsx.”

Mineral Zones, Southern Permian Basin of Europe (Kupferschiefer_mineral_zones.shp)

This dataset includes polygons that represent mineral zonation in the SPB of Europe. Its purpose is to document the spatial extent of epithermal mineralizing systems.

This shapefile was created by manually digitizing areas of mineralization from georeferenced maps. The polygons are attributed with information shown in table B5, which was derived from the maps and reports listed in the field Ref_short.

Copper Surface Density, Southern Permian Basin of Europe (Kupferschiefer_Cu_surface_density.shp)

This dataset includes polygons that represent copper surface density in the SPB of Europe. Its purpose is to document the spatial extent of copper mineralization.

This shapefile was created by manually digitizing areas with elevated copper surface-density amounts. The polygons are attributed with information shown in table B6, which was derived from the maps and reports listed in the field Ref_short.

Mine Concessions, Southern Permian Basin of Europe (Kupferschiefer_mine_concessions.shp)

This dataset includes polygons that represent mine concessions of the SPB of Europe. Its purpose is to document the locations of mine concession properties.

This shapefile was created by manually digitizing the mine concession areas using georeferenced maps. The polygons are attributed with information shown in table B7, which was derived from the maps listed in the field Ref_short.

Ground-Disturbance Sites, Southern Permian Basin of Europe (Kupferschiefer_ground_disturbance.shp)

This dataset includes points that represent ground-disturbance sites in the SPB of Europe. Its purpose is to document the locations of ground-disturbance features that likely represent waste heaps around pre-Industrial Revolution mine shafts.

This shapefile was created by manually digitizing the ground-disturbance sites from Google Earth™. Attribute fields and field definitions are shown in table B8.

Table B5. Definitions of user-defined attribute fields in the shapefile Kupferschiefer_mineral_zones.shp.

Field name	Description
Orig_descr	Information associated with the mineral zone, in the original language.
Engl_descr	Information associated with the mineral zone, translated into English if needed.
Zone1	Minerals and elements found in the zone.
Zone2	Abbreviation of minerals and elements found in the zone.
Area_km2	Area of mineral zone in square kilometers.
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying file, “GIS_references.xlsx.”

Table B6. Definitions of user-defined attribute fields in the shapefile Kupferschiefer_Cu_surface_density.shp.

Field name	Description
CuSurfDens	Copper surface density in kilograms per square meter.
Assoc_dep	Name of sediment-hosted copper deposit associated with copper surface density polygon.
Area_km2	Area of copper surface density polygon in square kilometers.
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying file, “GIS_references.xlsx.”

Table B7. Definitions of user-defined attribute fields in the shapefile Kupferschiefer_mine_concessions.shp.

Field name	Description
Name	Name of mine concession.
Status	Status of the concession—accepted or pending.
Company	Name of mining company holding the concession.
Area_km2	Area of mine concession polygon in square kilometers.
Ref_short	Short reference; abbreviated citation for reference; full reference is provided in accompanying file, “GIS_references.xlsx.”

Table B8. Definitions of user-defined attribute fields in the shapefile Kupferschiefer_ground_disturbance.shp.

Field name	Description
Latitude	Latitude in decimal degrees; –90.00000 to 90.00000. Negative south of the equator.
Longitude	Longitude in decimal degrees; –180.00000 to 180.00000. Negative west of the Greenwich meridian.

Probability Threshold Simulation Results for Copper Surface Density, Southern Permian Basin of Europe (csdprblty)

This dataset is an outcome from Gaussian statistical simulation of copper surface-density values and shows the probability that a value in a given cell exceeds 35 kg/m^2. The probability threshold results are used to show the spatial variation of copper mineralization that meets minimum cut-off grades.

This dataset was created using a two-part process. The first process step created a krig surface using the Esri Geostatistical Wizard in the Geostatistical Analyst tool/extension from borehole point data. The second step used the Gaussian Geostatistical Simulations tool in ArcToolbox to generate many copper surface-density surfaces that are consistent with the semivariogram of the krig surface and the threshold dataset. The text of this report discusses the process in further detail under the "Gaussian Geostatistical Simulation" section.

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