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The Thor suture zone: From subduction to intraplate basin setting

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ABSTRACT

The crustal seismic velocity structure of northwestern Europe shows a low P-wave velocity zone (LVZ) in the lower crust along the Caledonian Thor suture zone (TSZ) that cannot be easily attributed to Avalonia or Baltica plates abutting the TSZ. The LVZ appears to correspond to a hitherto unrecognized crustal segment (accretionary complex) that separates Avalonia from Baltica, explaining well the absence of Avalonia further east. Consequently, the northern boundary of Avalonia is shifted ~150 km southward. Our interpretation, based on analysis of deep seismic profiles, places the LVZ in a consistent crustal domain interpretation. A comparison with present-day examples of the Kuril and Cascadia subduction zones suggests that the LVZ separating Avalonia from Baltica is composed of remnants of the Caledonian accretionary complex. If so, the present-day geometry probably originates from pre-Variscan extension and eduction during Devonian–Carboniferous backarc extension. The reinterpretation of deep crustal zonation provides a crustal framework in which the northern limit of Avalonia corresponds to the southern limit of the deep North German Basin and the northern limit of prolific gas reservoirs and late Mesozoic inversion structures.

INTRODUCTION

Basin analysis, including quantitative modeling of active basins, is critically dependent on a priori assumptions on deeper crustal and lithospheric structure and composition. This applies in particular to studies that aim at quantitative assessments of basin maturation (e.g., Van Wees et al., 2009), in-depth understanding of long-lived and repeatedly active fault zones and (upper) crustal segmentation (e.g., Cloetingh et al., 2010), and precise paleogeographic reconstructions (e.g., Torsvik et al., 2012). These all demand precise outlines of terranes and continents, their margin geometry, and accretion and postaccretion histories. This is quite challenging when the basement is currently in the middle of continents and covered by deep basins. In such settings, marked by limited direct observations, identification of crustal domains strongly relies on available seismic and potential field data. In the past decades significant progress has been made in the resolution and velocity interpretation of the deep crust from refraction and reflection seismic profiles, allowing the identification of deep crustal structures and their boundaries, such as the northwest European Caledonian suture zones (e.g., Barton, 1992; MONA LISA Working Group, 1997; Pharaoh, 1999; England, 2000; Fig. 1; Fig. DR1 in the GSA Data Repository[1]). Reflection seismic profiles in the southern North Sea and the North German Basin generally show poor resolution at deeper crustal levels due to the presence of evaporites, one of the reasons to record refraction seismic profiles (e.g., Rabbel et al., 1995; Krawczyk et al., 2008). In general, defining terranes on the basis of seismic velocities alone is not always trivial, as seismic velocity distributions can be affected by tectonic events following their amalgamation. Consequently, it is not always clear in how far current lower crustal velocities still represent a property of the original terranes. In the case of the Thor suture zone (TSZ), however, there is a systematic, consistent, and direct correlation between this structure and a low-velocity zone (LVZ) in the lower crust detected from a set of five parallel deep

[1]GSA Data Repository item 2016229, Figures DR1–DR5 (classic interpretation of tectonic setting, comparisons of classic and new interpretation, and extent of upper surface of LVZ), is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

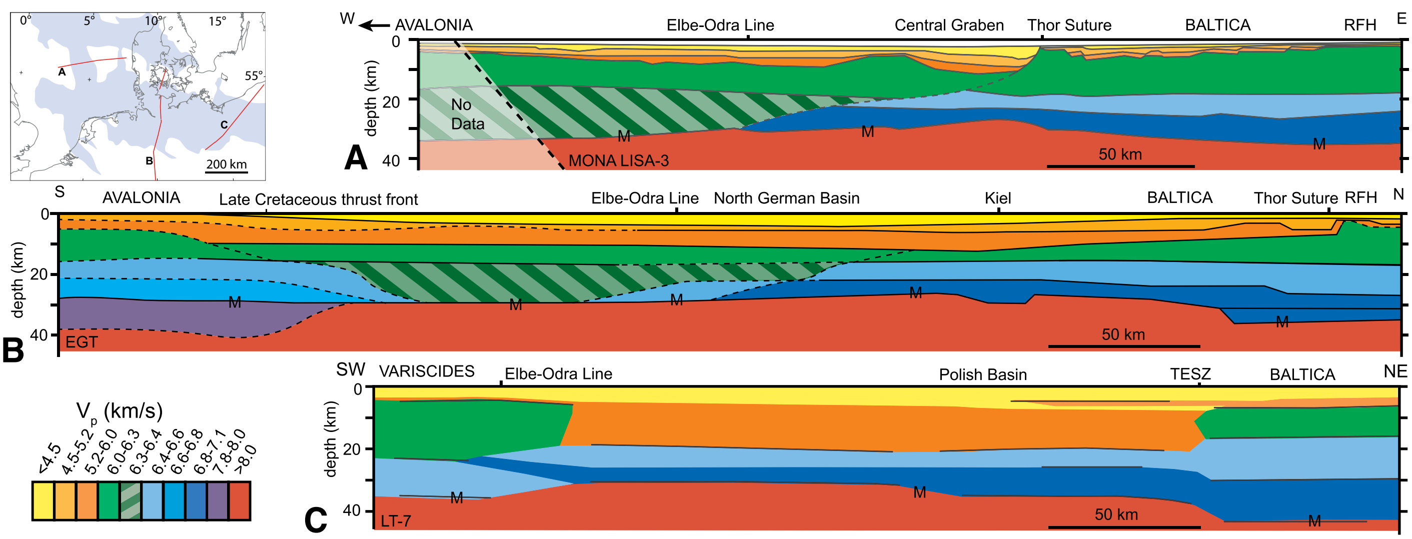

Figure 1. Three deep seismic refraction profiles across the Thor suture zone of northwestern Europe (locations in inset and in Fig. 2). Blue areas in inset mark location of main basins deeper than 1000 m. A: MONA LISA 3 (profile ML-3) across the North Sea Central Graben (modified from Lyngsie and Thybo, 2007). RFH—Ringkøbing-Fyn high; M—Moho. B: Combined European GeoTraverse subprofiles EUGEMI and EUGENO-S 1, showing relations between Thor suture zone, North German Basin, and northern Avalonian margin (modified from Aichroth et al., 1992; Thybo, 2001). C: LT-7 profile across Baltica margin, east of Rheic suture (from Guterch and Grad, 2006). TESZ—Trans-European suture zone.

seismic refraction lines (locations are given in Fig. 2 and Fig. DR1) that cannot be easily attributed to typical Avalonia or Baltica crustal signatures (e.g., MONA LISA Working Group, 1997; Thybo, 2001). This LVZ, located to the south of the Elbe-Odra line (EOL), has received little attention, contrary to the high-velocity lower crust of the Baltica margin north of the EOL (Fig. 1; Figs. DR2 and DR3) (e.g., Rabbel et al., 1995; Thybo, 2001; Krawczyk et al., 2008).

In this study we place the lower crustal LVZ in a consistent crustal domain interpretation. We propose that the LVZ corresponds to the existence of a hitherto unrecognized crustal segment that separates Avalonia from Baltica. Comparison with the active Kuril and Cascadia subduction zones and with the Rhodope metamorphic core complex yields an explanation for the LVZ and a scenario for the postsubduction history of the TSZ.

GEOLOGICAL SETTING

The TSZ separates Baltica from Avalonia and represents the northwestern segment of the Trans-European suture zone (TESZ). It formed during Ordovician–Silurian closure of the Thor Ocean–Tornquist Sea by southward subduction of Baltica under Avalonia, prior to the formation of Laurussia by closure of the Iapetus Ocean between Baltica-Avalonia and Laurentia. From the North Sea to the Polish Basin, the TSZ is deeply buried below basins with late Paleozoic–Holocene sedimentary thicknesses of up to ~15 km (e.g., Thybo, 2001; Doornenbal and Stevenson, 2010).

Crustal Architecture of TSZ and Adjacent Avalonia and Baltica from Seismic Data

North of the TSZ, the Ringkøbing-Fyn High shows a cratonic three-layer seismic crust that corresponds closely to Baltica with high lower crustal P-wave velocities (V_p 6.9–7.2 km/s; EUGENO-S Working Group, 1988; Thybo, 2001) (Fig. 1). The high-velocity lower crust continues southward, forming a wedge under the South Permian Basin until it thins out at the EOL (e.g., Thybo, 2001) (Fig. 1). It probably represents basement rocks of the thinned passive margin of Baltica. Well data (e.g., Ziegler, 1990; well locations in Fig. 2) show low-grade metasediments of Cambrian–Ordovician age with V_p ~5.2–6.0 km/s overlying the high-velocity lower crust (Fig. 1). Devonian–Carboniferous and younger rocks with V_p ~4.5–5.2 km/s overlie these rocks. The available deep seismic refraction lines that image the deep structure of the TSZ image the LVZ through low V_p 6.3–6.4 km/s in the lower crust from the North Sea Central Graben to the Rheic suture. This LVZ abuts and partly covers the high-velocity lower crust of Baltica. Therefore, and in accordance with regional tectonic models (e.g., Pharaoh, 1999), it is generally ascribed to Avalonia, although these velocities are uncommon in Phanerozoic lower crust (see Figs. DR2 and DR3 for the classic interpretation). High-pressure laboratory measurements indicate that these P-wave velocities of 6.3–6.4 km/s normally represent serpentinites or mid-crustal granites and gneisses instead (Christensen and Mooney, 1995).

To the west, the LISPB (Lithospheric Seismic Profile in Britain) profiles (e.g., Barton, 1992; Maguire et al., 2011) transect Avalonia from the Iapetus suture zone to the Rheic suture (see Fig. DR1 for location). A low-velocity lower crust as along the TSZ is absent. Instead, the Avalonian crust has a two-layer velocity structure with lower crustal velocities of V_p 6.6–6.9 km/s that are considered normal for a Phanerozoic crust. The European GeoTraverse (EGT) EUGEMI subprofile (Aichroth et al., 1992) (Fig. 2; Fig. DR3) and the NORDDEUTSCHLAND 1975/76 profile (Reichert, 1993) are the only profiles to document the transition from the LVZ to lower crustal velocities of 6.6–6.8 km/s of Avalonian crustal signature.

Located ~200 km east of the EGT EUGEMI profile, profile LT-7 (e.g., Guterch and Grad, 2006) images the crust east of the Rheic suture (Fig. 1). The Baltica margin is wider and layers are more tabular along profile LT-7, but its overall velocity structure is similar to the Baltica crust in the EGT profile. South of the high-velocity Baltica crust, a two-layer crust with lower crustal velocities V_p 6.4–6.6 km/s is typical of Variscan crust as imaged by other refraction profiles (e.g., Guterch and Grad, 2006). With both profiles located at either side of the Rheic suture, this suture appears to be the eastern limit of both Avalonia and the LVZ (Fig. 2).

Thor Suture LVZ as New Crustal Domain: Implications for the Northeastern Limit of Avalonia

The transition from the LVZ (V_p ~6.3–6.4 km/s) to normal (V_p ~6.6–6.8 km/s) P-wave velocities in the lower crust as imaged by the EGT EUGEMI (Fig. 1; Fig. DR3) and NORDDEUTSCHLAND 1975/76 profiles suggests that the LVZ along the TSZ is not typical for Avalonian crust as generally assumed. Instead, Avalonia most likely has a regular Phanerozoic velocity structure with a lower crustal P-wave velocity of 6.6–6.8 km/s as found to the west (e.g., Barton, 1992). Consequently, the LVZ forms a separate, 50–100-km-wide crustal domain that is characterized by a clearly different, abnormally low seismic velocity in the lower crust (V_p 6.3–6.4 km/s) and lower crustal velocity gradient from 6.3 to 6.4 km/s over ~10 km (Figs. 1 and 2; Figs. DR2–DR5). On the basis of the contrasting velocity structure, we place the eastern edge of Avalonia ~150 km further to the southwest and introduce the LVZ as separate crustal domain between Avalonia and Baltica (Fig. 2; Figs. DR2–DR5). The deep refraction profiles MONA LISA (profiles 1–3) image the LVZ but are too short to image the LVZ-Avalonia transition (e.g., Figs. 1 and 2; Fig. DR2). Therefore, we tentatively draw the westward continuation based on a supposed constant LVZ width (Fig. 2; Fig. DR5). In any case, this contact extends west of the North Sea Central Graben, which is entirely located on top of the Baltica margin (Figs. 1 and 2). The difference in deformation style across the Central Graben may be explained by noncylindrical extension and later deformation phases. Together with the recognition of the high-velocity zone as the Baltica margin (e.g., Lyngsie and Thybo, 2007), the introduction of the LVZ as a separate unit explains the previously noticed segmentation of Avalonia (e.g., Rabbel et al., 1995; Pharaoh, 1999).

The profiles located east of the EGT line image Variscan crust south of the Baltica

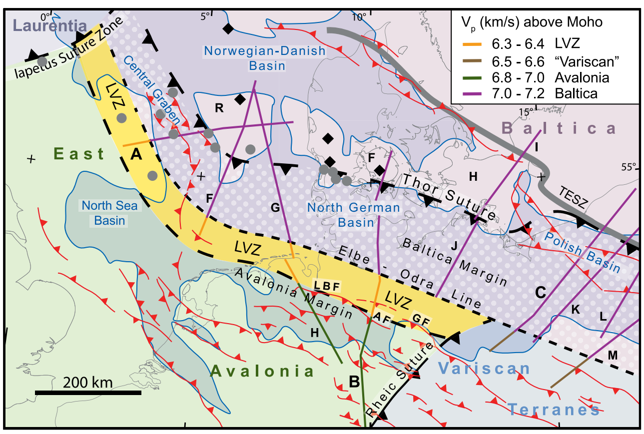

Figure 2. Revised map of present-day plate tectonic setting of West and Central Europe showing extent of main terranes at Moho level based on P-wave velocity (V_p) above the Moho. Avalonia and Baltica are separated by the low-velocity zone (LVZ). Dotted area is high V_p lower crust of the Baltica margin. The Rheic suture is the Avalonia eastern limit. Thrusts defining southern margin of the North German Basin (LBF—Leer-Bremen; AF—Allertal; GF—Gardelegen) coincide with the newly defined Avalonian margin. Thrust pattern is after Ziegler (1990) and Kley and Voigt (2008). Black diamonds and gray dots are wells with Baltica and Caledonian basement, respectively (from Ziegler, 1990). Blue solid outlines mark location of main basins deeper than 1000 m. RFH—Ringkøbing-Fyn High; TESZ—Trans-European suture zone. See Figure 1 for profiles A–C; names and references to other profiles are in Figure DR1 (see footnote 1).

remnant passive margin, indicating that the LVZ and Avalonia are absent between Variscan terranes and Baltica east of the Rheic suture (e.g., Guterch and Grad, 2006; Figs. 1 and 2). Here, the often assumed presence of Avalonia is largely based on sediments from boreholes that classically have been described as Avalonia derived (e.g., Pharaoh, 1999, and references therein). Alternatively, these sediments may be explained by eastward margin-parallel sediment transport beyond the limits of the Thor suture accretionary wedge, or they could derive from a distant Baltica source, as suggested for southern Norway (Slama and Pedersen, 2015).

Nature of the LVZ; Comparison with Velocity Structures in Active Tectonic Settings

Postulating the existence of a separate (lower crustal) unit characterized by low seismic velocities along a 400 Ma paleo–suture zone immediately raises the question of its nature and origin. At first sight it seems strange that rocks that are typically associated with these low seismic velocities, i.e., serpentinites, granites, or gneisses, would remain stable in the lower crust over 400 m.y. and maintain their low-velocity structure. Whereas anomalously high velocity layers in or below the continental crust are rather common (e.g., Thybo and Artemieva, 2013), anomalously low velocity zones such as along the Thor suture are rare. The well-documented present-day Cascadia and Kuril subduction zones (Fig. 3) provide examples of bodies with similar seismic velocities and velocity gradients at similar depths. A refraction profile across the Kuril subduction zone (Nakanishi et al., 2009) shows a triangular body of low velocities in front of the overriding plate that reaches to a depth of 30 km (Fig. 3). The Cascadia subduction zone contains a broad zone of low V_p (6.4–6.6 km/s) between 25 and 35 km depth in the subduction channel (Ramachandran et al., 2006) (Fig. 3A). Ramachandran et al. (2006) attributed the low velocities to trapped fluids, highly sheared lower crustal rocks, and/or underthrust accretionary rocks.

A body at the base of the Avalonian crust with V_p ~7.8 km/s, typical for underplating (Thybo and Artemieva, 2013), previously associated with late Variscan and Cenozoic magmatism, fits well with the relative position of underplating in both the Cascadia and Kuril subduction zones (Fig. 3). The geometric resemblance with the Kuril subduction zone is striking and in support of attributing the Avalonian underplates to the Caledonian magmatic arc.

Like the LVZ, the Rhodope metamorphic core complex (Greece) is located along a former suture and separates the hanging wall from the footwall plate. Kydonakis et al. (2015) proposed that the Rhodope complex results from extension by gravitational collapse of the accretionary complex. The following scenario

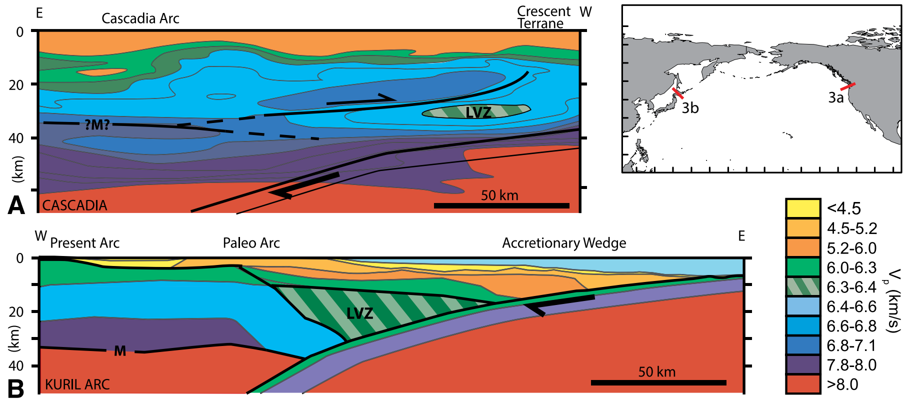

Figure 3. Examples of present-day active subduction zones containing bodies with similar seismic velocities and velocity gradients at depths similar to those of the Thor suture zone. LVZ—low-velocity zone; M—Moho. A: Cascadia (after Ramachandran et al., 2006). B: Kuril subduction zone (after Nakanishi et al., 2009).

for the development of the TSZ is based on the present-day geometries of the TSZ, the active Kuril subduction zone, and the Rhodope metamorphic core complex scenario (Kydonakis et al., 2015) The so-called soft docking of Avalonia and Baltica suggests that the Baltica continental margin has been barely subducted and that it was covered by the accretionary wedge (Fig. 4A), explaining the seismic images of thrusts below the northern margin of the North German Basin (e.g., Krawczyk et al., 2008). Slab break-off followed the end of southward subduction under Avalonia (Early Devonian; Fig. 4A). Subsequently, Baltica's subducted margin was exhumed by eduction (i.e., exhumation of subducted crustal material by extension along the suture; e.g., Andersen et al., 1991; Duretz et al., 2012; Fig. 4B) during the Late Devonian–early Carboniferous (ca. 370–330 Ma) phase of backarc extension of Avalonia (e.g., Ziegler, 1990). The space created between Avalonia and Baltica is filled by gravitational collapse of the former accretionary complex that is on the Baltica margin (possibly including material from the exhumed subduction channel) and by rising asthenosphere (Fig. 4B), in a manner similar to that inferred for the Rhodope metamorphic core complex (Kydonakis et al., 2015). Postextension thermal relaxation caused subsidence and burial of the TSZ and much of Avalonia since the late Carboniferous (ca. 330 Ma) (Fig. 4C). Subsidence and burial of the TSZ and plate margins continued during much of the Mesozoic and Cenozoic, aided by repeated tectonic reactivation and plume activity (Fig. 4D) (e.g., Ziegler, 1990; Doornenbal and Stevenson, 2010).

LVZ Physical Properties and Influence on Regional Tectonic Evolution

Lithospheric strength is highly sensitive to mantle strength that in turn is determined by Moho temperature and lithosphere thermal gradient. Along the Thor suture, the present-day

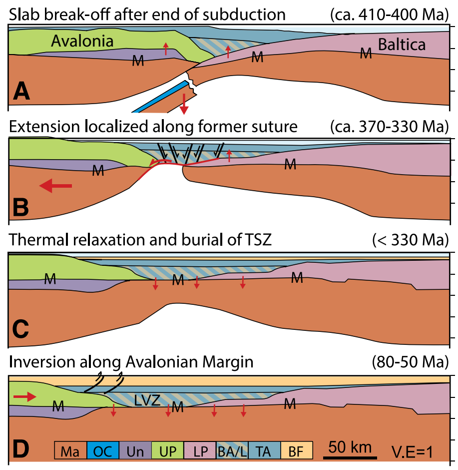

Figure 4. A–D: Proposed scenario for the temporal evolution of the Thor suture zone (TSZ) based on its present-day geometries and comparison with the Kuril subduction zone (Fig. 3B) and the Rhodope metamorphic core complex (Kydonakis et al., 2015). M—Moho, Ma—mantle, OC—oceanic crust, Un—underplated material, UP—upper plate, LP—lower plate, BA/L—base accretionary complex; LVZ—low-velocity zone; TA—top accretionary complex, BF—late Paleozoic–Cenozoic basin fill; V.E.—vertical exaggeration.

thermal gradient is relatively uniform (e.g., Cloetingh et al., 2010) and the LVZ is marked by a relatively shallow Moho depth. As a consequence, the (mantle) lithosphere of the LVZ is expected to be relatively strong compared to that of Avalonia. This explains a number of features that coincide with the Avalonia-LVZ contact. There are repeated concentrations of fault activity since at least the Permian–Carboniferous, including the important Cretaceous–Paleogene inversion (Figs. 2 and 4D) (e.g., Krawczyk et al., 2008). The Avalonia-LVZ contact also marks the transition from distributed deformation along a dominantly WNW-ESE–oriented fault network in Avalonia to deformation localized in a few major grabens along a NNE-SSW–oriented fault network above the LVZ and the Baltica margin (Fig. DR4). The boundary coincides with the northern limit of prolific gas provinces in the South Permian Basin (e.g., Doornenbal and Stevenson, 2010).

CONCLUSIONS

Based on our interpretation of seismic refraction data, regional fault networks, and basin inversion patterns (see the Data Repository), we present a revised crustal map of the TSZ. Four main crustal blocks can be recognized along the TSZ by their lower crustal seismic P-wave velocity: Baltica, Avalonia, Variscides, and an LVZ. We suggest that this LVZ, hitherto attributed to Avalonia, forms a 50–100-km-wide separate crustal unit between Avalonia and Baltica, characterized by its lower crustal low P-wave velocity (6.3–6.4 km/s) and low velocity gradient. South of the LVZ, the Avalonian lithosphere has a typical Phanerozoic velocity structure (lower crustal V_p ~6.6–6.8 km/s). It seems to be absent further east where Variscan crust is juxtaposed to Baltica's remnant passive margin. The northeastern margin of Avalonia coincides with the southern margin of the North German Basin. In the North Sea, the Avalonia margin is located west of the North Sea Central Graben, with an unknown exact position because deep seismic lines do not image the Avalonia-LVZ transition. Analogy with LVZs in active subduction zones suggests that the TSZ lower crustal LVZ is composed of remnants of the collapsed Caledonian accretionary complex. In this scenario, the present-day geometry originates from pre-Variscan extension-related eduction. A high-velocity body under the Avalonian margin shows a striking resemblance to underplated magmatism under the Cascadia and, notably, Kuril subduction zones.

The newly defined northern margin of Avalonia and TSZ are key elements in the reconstruction of Devonian–Carboniferous rifting of Avalonian lithosphere and for understanding long-lived tectonic segmentation.

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REFERENCES CITED

Aichroth, B., Prodehl, C., and Thybo, H., 1992, Crustal structure along the central segment of the EGT from seismic-refraction studies: Tectonophysics, v. 207, p. 43–64, doi:10.1016/0040-1951(92)90471-H.

Andersen, T.B., Jamtveit, B., Dewey, J.F., and Swensson, E., 1991, Subduction and eduction of continental crust: major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides: Terra Nova, v. 3, p. 303–310, doi:10.1111/j.1365-3121.1991.tb00148.x.

Barton, P.J., 1992, LISPB revisited: A new look under the Caledonides of northern Britain: Geophysical Journal International, v. 110, p. 371–391, doi:10.1111/j.1365-246X.1992.tb00881.x.

Christensen, N.I., and Mooney, W.D., 1995, Seismic velocity structure and composition of the continental crust: A global view: Journal of Geophysical Research, v. 100, p. 9761–9788, doi:10.1029/95JB00259.

Cloetingh, S., et al., 2010, Lithosphere tectonics and thermo-mechanical properties: An integrated modelling approach for enhanced geothermal systems exploration in Europe: Earth-Science Reviews, v. 102, p. 159–206, doi:10.1016/j.earscirev.2010.05.003.

Doornenbal, J.C., and Stevenson, A.G., eds., 2010, Petroleum geological atlas of the Southern Permian Basin area: Houten, Netherlands, EAGE Publications, 342 p.

Duretz, T., Gerya, T.V., Kaus, B.J.P., and Andersen, T.B., 2012, Thermomechanical modeling of slab eduction: Journal of Geophysical Research, v. 117, B08411, doi:10.1029/2012JB009137.

England, R.W., 2000, Deep structure of north west Europe from deep seismic profiling: The link between basement tectonics and basin development, *in* Mohriak, W., and Taiwani, M., eds., Atlantic rifts and continental margins: American Geophysical Union Geophysical Monograph 115, p. 57–83, doi:10.1029/GM115p0057.

EUGENO-S Working Group, 1988, Crustal structure and tectonic evolution of the transition between the Baltic Shield and the North German Caledonides (the EUGENO-S Project): Tectonophysics, v. 150, p. 253–348, doi:10.1016/0040-1951(88)90073-X.

Guterch, A., and Grad, M., 2006, Lithospheric structure of the TESZ in Poland based on modern seismic experiments: Geological Quarterly, v. 50, p. 23–32.

Kley, J., and Voigt, T., 2008, Late Cretaceous intraplate thrusting in central Europe: Effect of Africa-Iberia-Europe convergence, not Alpine collision: Geology, v. 36, p. 839–842, doi:10.1130/G24930A.1.

Krawczyk, C.M., McCann, T., Cocks, L.R.M., England, R., McBride, J., and Wybraniec, S., 2008, Caledonian tectonics, *in* McCann, T., ed., The geology of central Europe, Volume 1: Precambrian and Palaeozoic: London, Geological Society of London, p. 303–383, doi:10.1144/CEV1P.7.

Kydonakis, K., Brun, J.-P., and Sokoutis, D., 2015, North Aegean core complexes, the gravity spreading of a thrust wedge: Journal of Geophysical Research, v. 120, p. 595–616, doi:10.1002/2014JB011601.

Lyngsie, S.B., and Thybo, H., 2007, A new tectonic model for the Laurentia-Avalonia-Baltica sutures in the North Sea: A case study along MONA LISA profile 3: Tectonophysics, v. 429, p. 201–227, doi:10.1016/j.tecto.2006.09.017.

Maguire, P., England, R., and Hardwick, A., 2011, LISPB DELTA, a lithospheric seismic profile in Britain: Analysis and interpretation of the Wales and southern England section: Journal of the Geological Society [London], v. 168, p. 61–82, doi:10.1144/0016-76492010-030.

MONA LISA Working Group, 1997, MONA LISA—Deep seismic investigations of the lithosphere in the southeastern North Sea: Tectonophysics, v. 269, p. 1–19, doi:10.1016/S0040-1951(96)00111-4.

Nakanishi, A., et al., 2009, Crustal evolution of the southwestern Kuril Arc, Hokkaido Japan, deduced from seismic velocity and geochemical structure: Tectonophysics, v. 472, p. 105–123, doi:10.1016/j.tecto.2008.03.003.

Pharaoh, T.C., 1999, Palaeozoic terranes and their lithospheric boundaries within the Trans-European Suture Zone (TESZ): A review: Tectonophysics, v. 314, p. 17–41, doi:10.1016/S0040-1951(99)00235-8.

Rabbel, W., Förste, K., Schulze, A., Bittner, R., Röhl, J., and Reichert, J.C., 1995, A high velocity layer in the lower crust of the North German Basin: Terra Nova, v. 7, p. 327–337, doi:10.1111/j.1365-3121.1995.tb00802.x.

Ramachandran, K., Hyndman, R.D., and Brocher, T.M., 2006, Regional P-wave velocity structure of the Northern Cascadia subduction zone: Journal of Geophysical Research, v. 111, B12301, doi:10.1029/2005JB004108.

Reichert, J.C., 1993, Ein geophysikalischer Beitrag zur Erkundung der Tiefenstruktur des Nordwestdeutschen Beckens längs des refraktionsseismischen Profils NORDDEUTSCHLAND 1975/76: Geologisches Jahrbuch, v. 50, p. 87.

Slama, J., and Pedersen, R.B., 2015, Zircon provenance of SW Caledonian phyllites reveals a distant Timanian sediment source: Journal of the Geological Society [London], v. 172, p. 465–478, doi:10.1144/jgs2014-143.

Thybo, H., 2001, Crustal structure along the EGT profile across the Tornquist Fan interpreted from seismic, gravity and magnetic data: Tectonophysics, v. 334, p. 155–190, doi:10.1016/S0040-1951(01)00055-5.

Thybo, H., and Artemieva, I.M., 2013, Moho and magmatic underplating in continental lithosphere: Tectonophysics, v. 609, p. 605–619, doi:10.1016/j.tecto.2013.05.032.

Torsvik, T.H., et al., 2012, Phanerozoic polar wander, palaeogeography and dynamics: Earth-Science Reviews, v. 114, p. 325–368, doi:10.1016/j.earscirev.2012.06.007.

Van Wees, J.D., van Bergen, F., David, P., Nepveu, M., Beekman, F., Cloetingh, S., and Bonté, D., 2009, Probabilistic tectonic heat flow modeling for basin maturation: Assessment method and applications: Marine and Petroleum Geology, v. 26, p. 536–551, doi:10.1016/j.marpetgeo.2009.01.020.

Ziegler, P.A., 1990, Geological atlas of western and central Europe (second edition): Bath, U.K., Shell International Petroleum Mij. B.V., 238 p.

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