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Fold/cleavage relationships as indicator for late Variscan sinistral transpression at the Rheno-Hercynian–Saxo-Thuringian boundary zone, Central European Variscides

Tobias Stephan [a,*], Uwe Kroner [a], Torsten Hahn [b], Peter Hallas [a], Thomas Heuse [c]

[a] Geologisches Institut, TU Bergakademie Freiberg, B. v. Cotta Str. 2, 09599 Freiberg, Germany
[b] Bayerisches Landesamt für Umwelt, Dienststelle Hof, Hans-Högn-Straße 12, 95030 Hof/Saale, Germany
[c] Thüringer Landesanstalt für Umwelt und Geologie (TLUG), Göschwitzer Straße 41, 07745 Jena, Germany

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ABSTRACT

The boundary between the Rheno-Hercynian and the Saxo-Thuringian zones of the European Variscides is characterized by a NE–SW striking late orogenic fold-and-thrust belt affecting the intervening Rheic suture. Classical models used the first-order strike of this zone as an indicator for perpendicular plate convergence, i.e. NW–SE. We present structural data from both sides of the suture, focusing on fold–cleavage relationships. The statistical analysis reveals an orientation maximum of the youngest cleavage that deviates from the strike of the fold-and-thrust belt by c. 22°. The presence of clockwise transection of the folds by the cleavage (up to −16°) indicates pervasive sinistral transpression. Three types of fold–cleavage relationships are observed: NE trending folds (I) with or (II) without a transecting cleavage, and (III) non-transected ENE trending folds. We explain the occurrence of different fold–cleavage types by strain partitioning due to NNW convergence obliquely to pre-existent NE trending mechanical anisotropies. In terms of plate tectonics we propose that the classical boundary of the Rheno-Hercynian and the Saxo-Thuringian Zone represents an initial transform plate boundary that was finally affected by sinistral transpression.

1. Introduction

The classical zonation of the Central European Variscides by Kossmat (1927) is based on the striking differences in terms of Palaeozoic lithologies within the Saxo-Thuringian Zone and the Rheno-Hercynian Zone (Fig. 1a). The boundary between these zones is interpreted as a suture separating continental crust of different plates (Behr et al., 1984; Matte, 1986). The Rheno-Hercynian Zone as part of Laurussia (Lefort and Van der Voo, 1981) and the Peri-Gondwana shelf of the Saxo-Thuringian Zone were initially separated by the Rheic Ocean (Cocks and Fortey, 1982). The Rheic Ocean was opened after the termination of the Cadomian orogeny (700–540 Ma; Linnemann et al., 2007) and was closed during the formation of Western Pangaea (400–250 Ma; Kroner and Romer, 2013). In Europe, the Rheic suture can be traced from the Mid-German Crystalline Zone (Zeh and Gerdes, 2010), the Lizard ophiolite in southern Britain (Nutman et al., 2001), around the Iberian–Armorican arc to the Beja-Acebuches ophiolite and the Pulo do Lobo suture of southern Iberia (Quesada et al., 1994; Braid et al., 2010). To the east, in the Bohemian Massif the Rheic suture is represented by the Sleza ophiolite in the Northern Sudetes (Kryza and Pin, 2010), and may extend to the Moravo-Silesian Zone. Remnants of the Rheic Ocean are exposed in the Cambrian Vesser rift complex, the Saxo-Thuringian Zone (Kemnitz et al., 2002) and in different slices within the Mid-German Crystalline Zone, which contains relics of a Silurian island arc and Late Devonian to Early Carboniferous magmatic rocks (Zeh and Gerdes, 2010).

Compared to the highly arcuate trend of the Rheic suture of the European Variscides, the boundary of the Rheno-Hercynian and Saxo-Thuringian Zone, i.e. the Mid-German Crystalline Zone, has a linear NE–SW orientation (Fig. 1a). The dominant structural feature of this area is a late Variscan fold-and-thrust belt with predominantly NW and SE vergent folds in the Rheno-Hercynian Zone and the Saxo-Thuringian Zone, respectively (Fig. 1c). Balanced cross-sections of the Rheno-Hercynian Zone (Oncken et al., 1999) and the Saxo-Thuringian Zone (Schäfer et al., 2000) led to the introduction of the doubly-vergent orogenic wedge model with a Rheno-Hercynian pro-wedge and a Saxo-Thuringian retro-wedge (Schäfer et al., 2000), assuming prolonged NW–SE directed shortening, i.e. strictly perpendicular to the strike of the orogenic wedge. However, in contrast to the large-scale cylindrical architecture of the fold-and-thrust belt predicted in these models, detailed structural observations and palaeostress analyses in the Rheno-Hercynian Zone reveal locally varying shortening directions and oblique strain geometries to the dominant NE strike of the major structures (e.g. Oncken, 1988; Fielitz, 1992; Jacob and Franzke, 1992; Klügel, 1997).

* Corresponding author. Tel.: + 49 3731 393748.
E-mail address: Tobias.Stephan@geo.tu-freiberg.de (T. Stephan).

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Moreover, assuming that the proposed NW–SE shortening for this fold-and-thrust belt did not occur before Late Visean times (Ahrendt et al., 1983), the structural complexity of the Mid-German Crystalline Zone, requires earlier increments of deformation. Although there are no constraints for NW–SE convergence during early to mid-Variscan subduction/accretion tectonics preserved in the core of the orogenic wedge, there is ample evidence for Devonian strike-slip along NE–SW trending faults (Krohe, 1992). This early Variscan deformation at the Saxo-Thuringian–Rheno-Hercynian boundary should have influenced the strain geometry of the subsequent formation of the fold-and-thrust belt (e.g. Krohe, 1992; Willner et al., 2000; Kroner et al., 2007).

The purpose of this study is to test the cylindrical orogenic wedge model of the boundary between the Rheno-Hercynian and the Saxo-Thuringian Zone by examining synorogenic sedimentary rocks of the Selke Valley in the Harz Mountains (pro-wedge area), as well as the Teuschnitz Synform and pre-orogenic units in the Schwarzburg Antiform (both retro-wedge area, Fig. 1a). Our structural investigation provides a large data set that is sufficient for a statistically valid analysis, demonstrating that the late Variscan strain increments, i.e. the fold/cleavage relationships, are compatible with a doubly-vergent but oblique orogenic wedge. The pervasive final deformation is related to NNW–SSE directed shortening under formation of a transecting cleavage (sensu Johnson, 1991; Treagus and Treagus, 1992; Jones and Tanner, 1995), providing a strong argument for regional sinistral transpression. We interpret the non-cylindrical architecture of the belt to reflect the final reactivation of a large scale NE–SW oriented mechanical anisotropy formed prior to the late Variscan shortening.

2. Geological setting

The Saxo-Thuringian–Rheno-Hercynian orogenic wedge comprises three structural units: (i) the Rheno-Hercynian pro-wedge in the NW, (ii) the Mid-German Crystalline Zone within the core and (iii) the Saxo-Thuringian retro-wedge in the SE. Faunal data show that the Rheno-Hercynian Zone displays affinities to Avalonia, hence Laurussia, whereas the Saxo-Thuringian Zone is a part of Gondwana (e.g. Franke, 2000; Romer et al., 2011).

2.1. The pro-wedge area: the Rheno-Hercynian Zone

The Rheno-Hercynian Zone is exposed in the Ardennes, the Rhenish Massif, the Harz Mountains and the Flechtingen Rise (Fig. 1a). From the SE to the NW, allochthonous and (para)-autochthonous units of the Rheno-Hercynian Zone can be distinguished. As a part of the external fold-and-thrust belt of the Variscides the para-autochthonous units are characterized by neritic shelf sedimentary rocks of Laurussia (Huckriede et al., 2004). Widespread bimodal intracontinental magmatism indicates that the Rheno-Hercynian shelf remained under NW–SE extension from the Devonian until the Early Carboniferous (Timmermann, 2008). The age of subsequent folding and low-grade metamorphism of the Rheno-Hercynian Zone decreases from c. 330 Ma in the SE to c. 300 Ma in the NW (K-Ar and Rb-Sr white mica ages; Ahrendt et al., 1983).

In the Rhenish Massif, structural data and strain analysis of the Taunus and the Northern Phyllite Shear Zone (Fig. 1a) reveal oblate strain geometries (Klügel, 1997) related to sinistral transpression during NNW directed shortening as the latest strain increment. K/Ar dating of synkinematic mica yields an age of 323 ± 4 Ma, which is interpreted as the timing of this late Variscan deformation stage. The latest strain increments of the Monschau Shear Zone along the SE-limb of the Stavelot-Venn Anticlinorium (Fig. 1a) provide additional evidence for sinistral transpression (Fielitz, 1992). Similar orientations of the structures as found in the Taunus Mts. indicate a coeval deformational event (Klügel, 1997). Furthermore, palaeostress analysis of the Rhenish Massif by Oncken (1988) yields Early Carboniferous N–S shortening directions.

Allochthonous units in the Harz Mountains form a duplex-like structure sandwiched between the Gießen-Harz nappe and the para-autochthonous rocks (Fig. 1c). The duplex consists of Silurian to Carboniferous, non-metamorphic to low-grade metamorphic metasedimentary rocks with Laurussian and since the Middle Devonian additional Gondwanan provenances (Oczlon, 1994; Huckriede et al., 2004). The Wippra Zone (Fig. 2a) shows greenschist-grade metamorphism and separates the allochthonous units in the northwest from the Mid-German Crystalline Zone in the SE along an out-of-sequence thrust. NNW and SSE dipping reverse faults characterize the youngest Variscan structures in this zone (Jacob and Franzke, 1992). The intensively folded Tanne Zone (Fig. 2a) consists of low-grade, Late Tournaisian–Early Visean metagreywackes and slates (Lippert, 1999).

2.2. The core of the wedge: the Mid-German Crystalline Zone

The Mid-German Crystalline Zone consists of medium to high-grade gneisses and granitic rocks (Zeh and Will, 2010) that separate the low-grade metasedimentary rocks and volcanic rocks of the Northern Phyllite Zone in the north from the low to medium-grade rocks of the Saxo-Thuringian Zone in the south (Fig. 1).

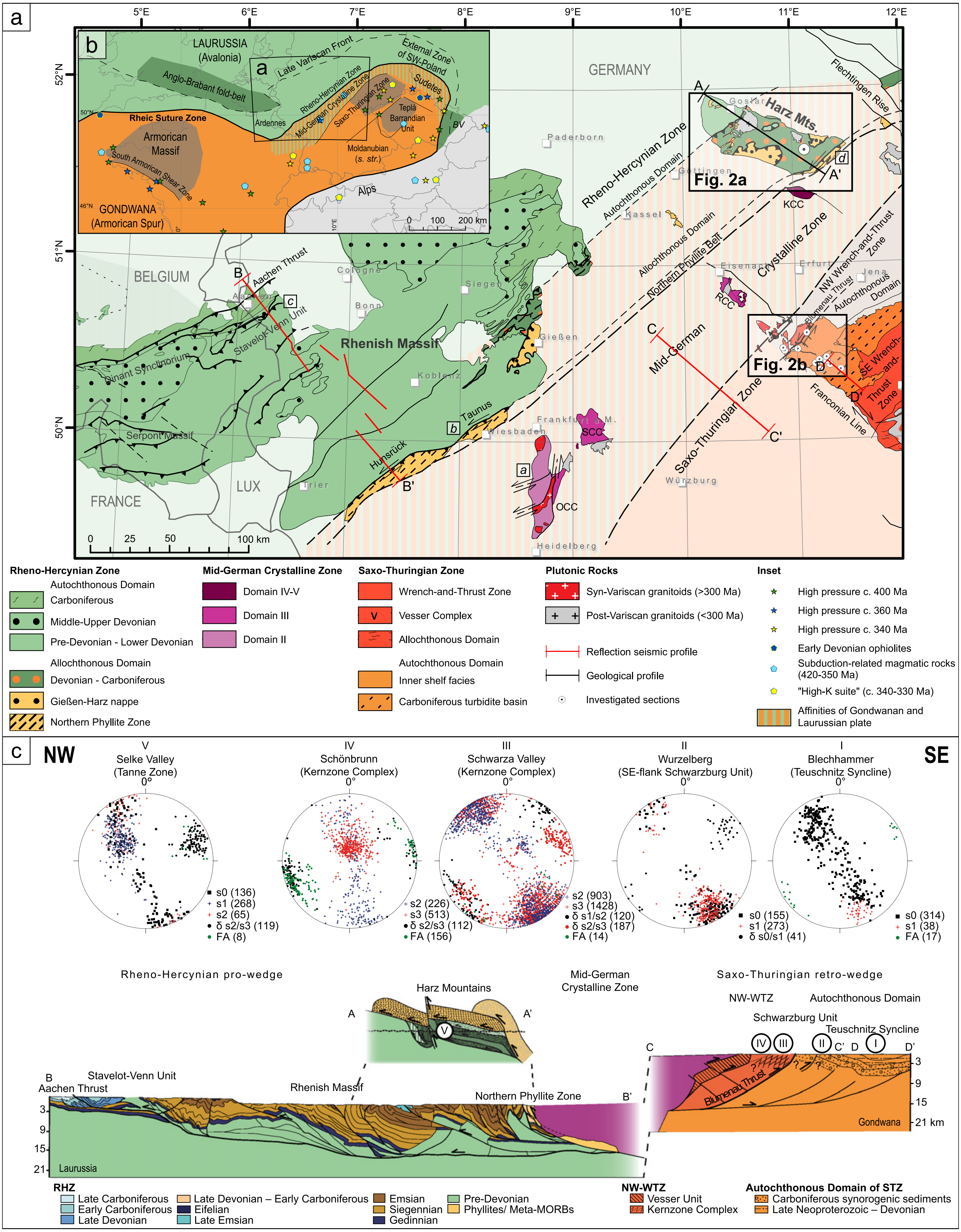
Within the Mid-German Crystalline Zone gently NE or SW plunging mineral stretching lineations are a common feature occurring both in the Ruhla Crystalline Complex (Wunderlich, 1989), and in the Kyffhäuser Crystalline Complex (Zeh and Wunderlich, 2003; Franzke et al., 2007). In the Odenwald Crystalline Complex NE trending strike-slip tectonics influenced the intervening Rheic suture zone, as indicated by NE striking sinistral shear zones with subhorizontal stretching lineations (Krohe, 1991, 1992). According to Krohe (1992), the associated divergent strike shear deformation occurred shortly after the eclogite-facies metamorphism within the Böllstein Odenwald (357 ± 6 Ma, Lu–Hf garnet–whole rock; Will, 2001a; Scherer et al., 2002) and lasted until 335 Ma. Ductile deformation structures agree with the palaeostress analysis (Flöttmann and Oncken, 1992; Will, 2001b) revealing c. N–S compression within the Odenwald, Ruhla Crystalline Complex and the Palatinate Forest. However, the deformation of the Mid-German Crystalline Zone is older than the folding and thrusting within the Rheno-Hercynian and Saxo-Thuringian Zone (330–300 Ma). Hence, the rigid rocks of the Mid-German Crystalline Zone were almost unaffected by the late Variscan deformation and exhumed by forming a crustal-scale pop-up structure within the axial uplift zone of the orogenic wedge.

2.3. The retro-wedge area: the Saxo-Thuringian Zone

The retro-wedge area comprises the Autochthonous Domain and the NW Wrench-and-Thrust Zone (sensu Kroner et al., 2007) of the Saxo-Thuringian Zone (Fig. 1a). The exposed part of the retro-wedge area in Thuringia (Germany) is called the Schwarzburg Unit (Fig. 2b). The unit comprises a nearly continuous sedimentary sequence from the Late Precambrian to the Early Carboniferous. It records the geological history of Gondwana that ranges from (i) the Cadomian basement (650–550 Ma), (ii) the Cambro-Ordovician rift-and-drift setting, (iii) the subsequent Silurian to Middle Devonian marine shelf sedimentation at the southern margin of the Rheic Ocean, and (iv) the inner shelf facies of the passive continental shelf along the northern spur of Gondwana. The structure of the Schwarzburg Unit is classically interpreted as a SE vergent anticline ("Schwarzburg Anticline") because of lithological similarities on both sides of the core of the antiformal structure (Schäfer et al., 2000; Bankwitz and Bankwitz, 2003).

2.3.1. The NW Wrench-and-Thrust Zone

The core of the Schwarzburg Unit (Kernzone Complex) constitutes a tectonic mélange which comprises Neoproterozoic (c. 600 Ma) low-



a
5°E
6°E
7°E
8°E
9°E
10°E
11°E
12°E
52°N
51°N
50°N
b
LAURUSSIA
(Avalonia)
Anglo-Brabant fold-belt
Late Variscan Front
External Zone of SW-Poland
Rheno-Hercynian Zone
Mid-German Crystalline Zone
Saxo-Thuringian Zone
Sudetes
Tepla Barrandian Unit
Ardennes
Rheic Suture Zone
Armorican Massif
South Armorican Shear Zone
Moldanubian (s. str.)
BV
Alps
GONDWANA
(Armorican Spur)
0 100 200 km
GERMANY
Flechtingen Rise
Harz Mts.
Goslar
Fig. 2a
Paderborn
Göttingen
Kassel
KCC
Rheno-Hercynian Zone
Autochthonous Domain
Allochthonous Domain
Northern Phyllite Belt
Crystalline Zone
Eisenach
Erfurt
Jena
NW Wrench-and-Thrust Zone
Blumenau Thrust
Autochthonous Domain
RCC
Fig. 2b
SE Wrench-and-Thrust Zone
Franconian Line
BELGIUM
Aachen Thrust
Aachen
Cologne
Bonn
Siegen
Stavelot-Venn Unit
Dinant Synclinorium
Rhenish Massif
Gießen
Koblenz
Mid-German
Saxo-Thuringian Zone
Taunus
Frankfurt a.M.
Wiesbaden
SCC
Serpont Massif
Hunsrück
OCC
Würzburg
LUX
Trier
FRANCE
Heidelberg
0 25 50 100 km
A
A'
B
B'
C
C'
D
D'
Rheno-Hercynian Zone
Autochthonous Domain
Carboniferous
Middle-Upper Devonian
Pre-Devonian - Lower Devonian
Allochthonous Domain
Devonian - Carboniferous
Gießen-Harz nappe
Northern Phyllite Zone
Mid-German Crystalline Zone
Domain IV-V
Domain III
Domain II
Saxo-Thuringian Zone
Wrench-and-Thrust Zone
Vesser Complex
Allochthonous Domain
Autochthonous Domain
Inner shelf facies
Carboniferous turbidite basin
Plutonic Rocks
Syn-Variscan granitoids (>300 Ma)
Post-Variscan granitoids (<300 Ma)
Reflection seismic profile
Geological profile
Investigated sections
Inset
High pressure c. 400 Ma
High pressure c. 360 Ma
High pressure c. 340 Ma
Early Devonian ophiolites
Subduction-related magmatic rocks (420-350 Ma)
"High-K suite" (c. 340-330 Ma)
Affinities of Gondwanan and Laurussian plate
c
NW
SE
V Selke Valley (Tanne Zone)
IV Schönbrunn (Kernzone Complex)
III Schwarza Valley (Kernzone Complex)
II Wurzelberg (SE-flank Schwarzburg Unit)
I Blechhammer (Teuschnitz Syncline)
s0 (136)
s1 (268)
s2 (65)
δ s2/s3 (119)
FA (8)
s2 (226)
s3 (513)
δ s2/s3 (112)
FA (156)
s2 (903)
s3 (1428)
δ s1/s2 (120)
δ s2/s3 (187)
FA (14)
s0 (155)
s1 (273)
δ s0/s1 (41)
s0 (314)
s1 (38)
FA (17)
Rheno-Hercynian pro-wedge
Harz Mountains
Mid-German Crystalline Zone
Saxo-Thuringian retro-wedge
NW-WTZ
Autochthonous Domain
Schwarzburg Unit
Teuschnitz Syncline
Stavelot-Venn Unit
Aachen Thrust
Rhenish Massif
Northern Phyllite Zone
Blumenau Thrust
Laurussia
Gondwana
3
9
15
21 km
RHZ
Late Carboniferous
Early Carboniferous
Late Devonian
Late Devonian – Early Carboniferous
Eifelian
Late Emsian
Emsian
Siegennian
Gedinnian
Pre-Devonian
Phyllites/ Meta-MORBs
NW-WTZ
Vesser Unit
Kernzone Complex
Autochthonous Domain of STZ
Carboniferous synorogenic sediments
Late Neoproterozoic – Devonian

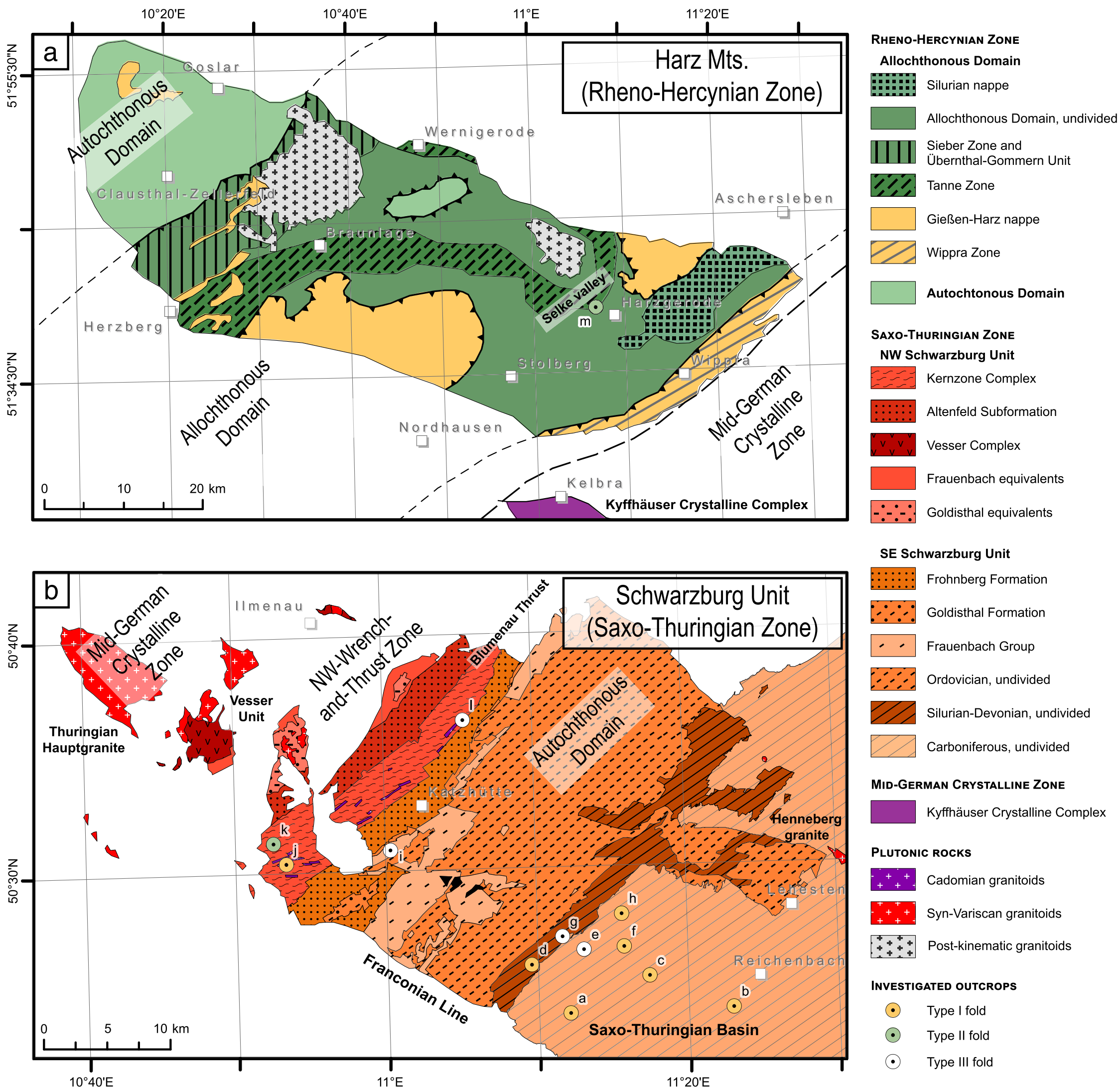


Fig. 2. Geological map of the (a) Harz Mts. and (b) Schwarzburg Unit. Note the heterogeneous distribution of the different fold types. Location of the maps is displayed in Fig. 1a.

grade greywackes and phyllites (c. 0.45 GPa at c. 350–375 °C; Schäfer, 1997) and metagranitoids of Cambro-Ordovician age (Linnemann et al., 1999; Linnemann et al., 2000; Kemnitz et al., 2002; Linnemann et al., 2014). The phyllites and greywackes show a complex structural fabric that is interpreted as a remnant of a Neoproterozoic fold-and-thrust belt which represents the Cadomian basement that was overprinted by the Variscan orogeny (Schäfer et al., 2000; Bankwitz and Bankwitz, 2003; Linnemann et al., 2007).

To the NW of the Kernzone Complex the Altenfeld Subformation comprises low-grade Ediacaran (c. 570 Ma) metagreywackes, slates and MORB-type volcanic rocks (Heuse, 1989; Heuse et al., 2001; Linnemann et al., 2014). According to Linnemann et al. (2007) the Altenfeld Subformation was deposited in a Cadomian back-arc. The Blumenau Thrust separates the Kernzone Complex in the hanging wall from the Frohnberg Formation in the SE.

2.3.2. The Autochthonous Domain of the Saxo-Thuringian Zone

The SE part of the Schwarzburg Unit consists of an almost continuous sedimentary succession that ranges from the Late Neoproterozoic to the Early Carboniferous (Fig. 2b). The Frohnberg Formation in the footwall of the Blumenau Thrust comprises metagreywackes and metapelites which were deposited at an active continental margin (Kemnitz et al., 2002) at c. 540 Ma (Linnemann et al., 2014) and consists of detritus from a continental magmatic arc (Linnemann and Romer, 2002). The Frohnberg Formation was affected by very low-grade metamorphism (0.32–0.38 GPa at c. 350–375 °C; Schäfer, 1997) at 334 Ma

Fig. 1. a) Simplified geological map of the Rheic suture zone separating the Saxo-Thuringian Zone (Gondwana plate) from the Rheno-Hercynian Zone (Laurussia plate). Note the linear NE–SW structural trend in this area compared with the generally highly arcuate shape of the Rheic suture zone of the Variscides of Central and Western Europe. Saxo-Thuringian Zone modified after Kroner et al. (2007); Rheno-Hercynian Zone modified after Huckriede et al. (2004) and Oncken et al. (1999); domains of the Mid-German Crystalline Zone sensu Zeh and Will (2010); Units I–IV of the Odenwald sensu Krohe (1992); sense of oblique thrusts from: a — Krohe (1992), b — Klügel (1997), c — Fielitz (1992), d — Jacob and Franzke (1992). Letters on cross-sections refer to Fig. 1b. Abbreviations: HG — Henneberg Granite, KCC — Kyffhäuser Crystalline Complex, RCC — Ruhla Crystalline Complex, THG — Thüringer Hauptgranit, VU — Vesser Unit. b) Overview of Central European Variscides. Modified after Kroner and Romer (2013). Abbreviations: BV — Bruno-Vistulian Unit. c) Orogenic wedge model for the boundary of the Saxo-Thuringian and the Rheno-Hercynian Zone. The location of the cross-section is displayed in Fig. 1a. A–A′ Schematic cross-section after Huckriede et al. (2004). B–B′ Balanced cross-section of pro-wedge area after Oncken et al. (1999). C–C′, D–D′ Balanced cross-section of the retro-wedge area modified after Schäfer et al. (2000). Note that the pro-wedge–retro-wedge model (Schäfer et al., 2000) is based on the assumption of a cylindrical architecture for the fold-and-thrust belt of the Rheno-Hercynian–Saxo-Thuringian boundary. Schmidt nets (lower hemisphere) of the investigated areas (I–V) and their position in the particular zones of the orogenic wedge. Abbreviations: s0 — bedding, s1 — first foliation, s2 — second foliation, s3 — third foliation, δ — intersection of foliations, FA — fold axes.

(Franke and Stein, 2000). The non-metamorphic sedimentary rocks of the overlying Goldisthal Formation comprise conglomerates, coarse-grained sandstones, slates and tuffitic layers. Dating of magmatic zircons within a tuffitic layer at the base of the Goldisthal Formation gives the maximum age of sedimentation at c. 486 Ma (Linnemann et al., 2007).

The overlying Early Ordovician to Middle Devonian sedimentary successions record an undisturbed shelf sedimentation (inner shelf facies of the Saxo-Thuringian Zone) at the northern periphery of Gondwana (Nance et al., 2010). In the Early Carboniferous the erosion of the exhumed allochthonous Saxo-Thuringian HP-units in the Erzgebirge led to the basinal deposition of distal to increasingly proximal synorogenic sediments until c. 334 Ma within the so-called Saxo-Thuringian Basin (Hahn et al., 2010). During the Variscan orogeny the Saxo-Thuringian Basin was affected by folding, thrusting and very low-grade metamorphism (<300 °C, 0.1–0.15 GPa; Schäfer et al., 2000). According to Hahn et al. (2010), the maximum age of the Late Variscan folding and thrusting is 334 Ma. The intrusion of the undeformed Henneberg Granite at c. 299 Ma (Loth et al., 1997) postdates the metamorphism and folding of the Autochthonous Domain of the Saxo-Thuringian Zone (Fig. 2b).

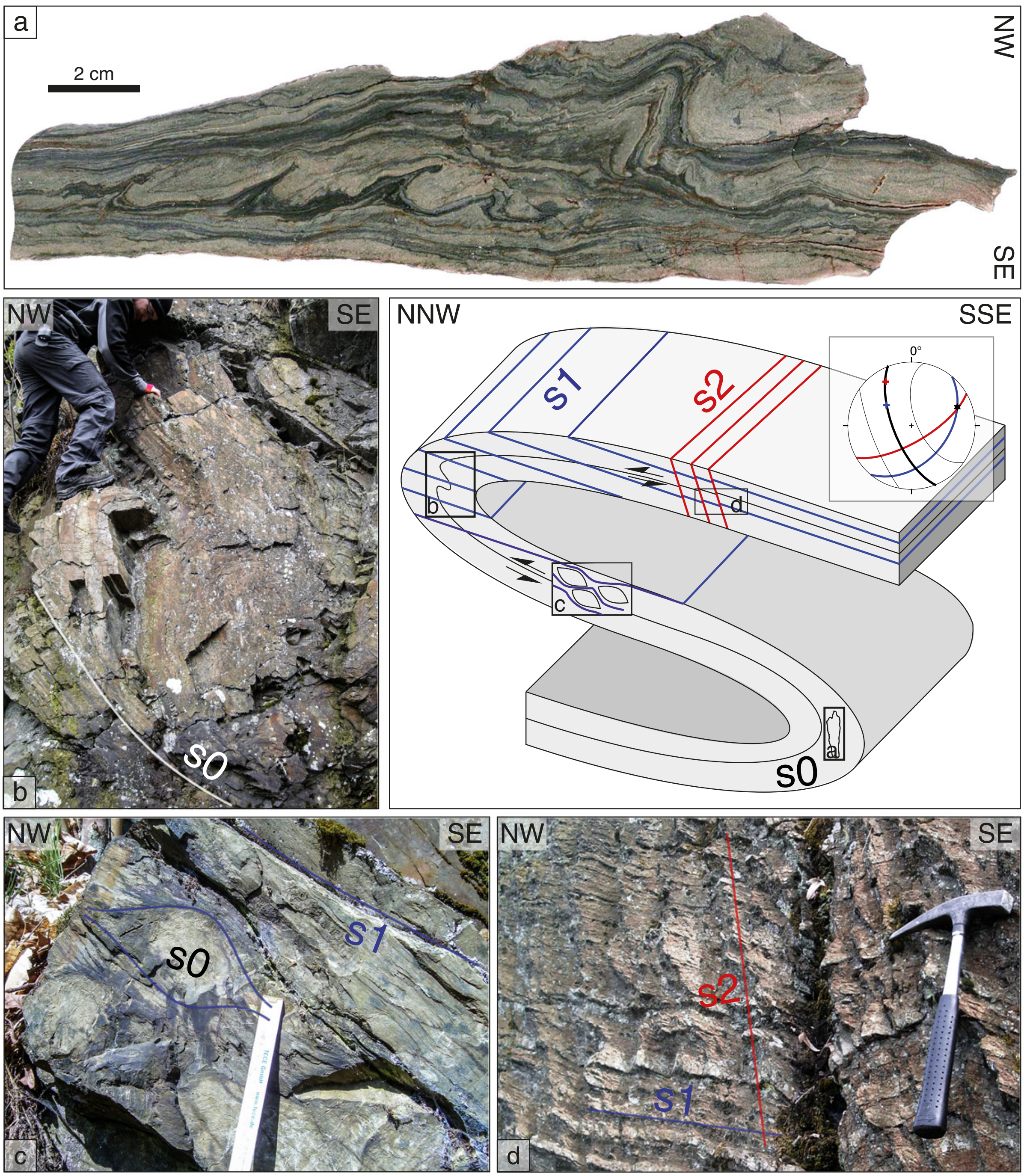


Fig. 3. Structures of synorogenic sedimentary rocks of the Tanne Zone (Harz Mountains, allochthonous unit of the Rheno-Hercynian Zone). a) Soft-sediment folds and flame marks are preserved inside the hinge area of the first-order fold. b) Parasitic folds in the hinge area of the first order fold. c) s1 foliation of pervasively deformed slates is deflected by asymmetric clasts of competent greywackes, indicating top-to-NW tectonic transport. d) Intersection of the flat lying main foliation (s1) and the steeply inclined s2 foliation.

3. Tectonics of the studied units

3.1. The Rheno-Hercynian pro-wedge: Tanne Zone

The rocks of the Selke Valley (Fig. 3) display NW vergent and recumbent folding of synorogenic siliciclastic rocks. The folding of the greywacke and pelite layers (s0) is associated with the formation of the first foliation, the main foliation s1. In the limbs of the first-order fold, the s1-foliation is sub-parallel to the bedding. The folding and formation of the foliation has resulted in the partial obliteration of sedimentary structures (Fig. 3b), but bedding is locally preserved in quartzitic clasts that deflect the s1-cleavage (Fig. 3c). Synsedimentary structures (e.g. convolute bedding) are exclusively observed in the hinge area of the first-order folds where s1 crosscuts the bedding (Fig. 3a). The youngest, pervasive cleavage (s2) dips steeply to the SSE and crosscuts the main foliation and the folded bedding (Fig. 3d).

3.2. The Saxo-Thuringian retro-wedge: autochthonous domain

The Autochthonous Domain is characterized by open, (S)SE vergent folds. The youngest foliation s1 crosscuts the bedding (s0) and dips steeply to the (N)NW. Structural data throughout the synorogenic, Lower Carboniferous metasedimentary rocks of the Teuschnitz Syncline and the Ordovician–Devonian metasedimentary rocks of the SE part of the Schwarzburg Unit reveal that the entire Autochthonous Domain was only affected by a single Variscan deformation event.

Metapelites of the Neoproterozoic Frohnberg Formation comprise alternating sericite and quartz-rich layers that are very low-grade to non-metamorphic. We observe no change in the orientation of the s1-foliation traversing the contact of the low-grade Neoproterozoic Frohnberg Formation and the non-metamorphic Late Cambrian Goldisthal Formation. This indicates a common formation of the s1 foliation and excludes a Cadomian origin for the s1 foliation in the

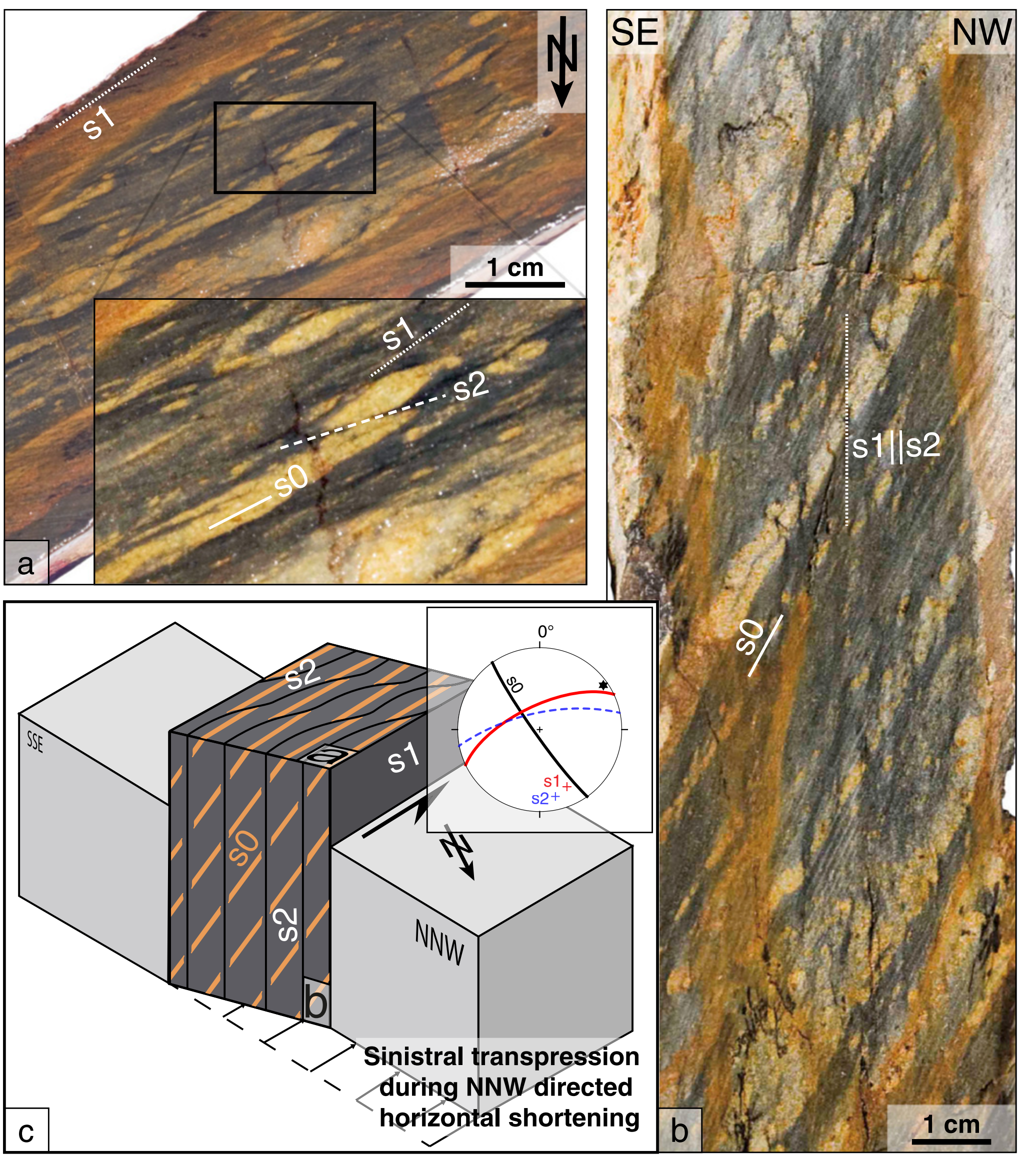


Fig. 4. Deformed Late Cambrian siliciclastic rocks of the Autochthonous Domain of the Saxo-Thuringian Zone (outcrop at the Wurzelberg, SE of the Blumenau Thrust). a) Sinistral shearing of quartzitic layers is synkinematic with respect to the formation of the s2 foliation in slaty domains (horizontal yz-section, i.e. parallel to fold axis and perpendicular to main foliation). b) NW–SE section (xz), i.e. perpendicular to fold axis and main foliation. c) Explanation of the structure invoking sinistral transpression during NNW directed horizontal shortening; 3D-sketch modified after Sanderson and Marchini (1984). Note that s1 and s2 are cogenetic.

Frohnberg Formation as it was argued by Bankwitz and Bankwitz (2003).

Within the Late Cambrian Goldisthal Formation we observe that in the XZ-plane of the finite strain ellipsoid the bedding is subparallel to the steeply dipping s1 foliation. However, in the YZ-plane the s1-foliation is sinistrally displaced by a cogenetic foliation s2, which dips steeply to the SSE (Fig. 4).

3.3. The Saxo-Thuringian retro-wedge: NW Wrench-and-Thrust Zone

Traversing the Blumenau Thrust towards the northwest, the metamorphic grade and structural style change abruptly. The Kernzone Complex comprises phyllites and metagreywackes containing abundant quartz-segregations. Phyllite domains contain the mineral assemblage Qtz + Ser + Chl + Fsp ± Grt, indicating a greenschist-facies metamorphic grade (Bankwitz and Bankwitz, 2003). Feldspar is strongly sericitized.

In contrast to the Autochthonous Domain, the highly deformed rocks of the Kernzone Complex host at least three foliations partially obliterating the bedding (s0). The oldest foliation (s1) is axial-planar to the tight isoclinal folding of the bedding (Fig. 5b, c). Quartz segregations are exclusively observed in the Kernzone Complex and are oriented parallel to the s1 foliation (Fig. 5b, c).

The s2 foliation represents the most distinctive structure in most outcrops and is characterized by alternating phyllitic and quartzitic layers. The quartzitic layers consist of fine to coarse-grained quartz, whereas the phyllitic layers comprise fine-grained chlorite and sericite. In the phyllosilicate-rich layers boudinaged segregations indicate s2-parallel extension (Fig. 5d). Segregations within the quartz-rich layers occur as tightly folded quartz-veins, with folding axial-planar to s2 (Fig. 5d). The alternation of quartzitic and phyllitic layers was formerly

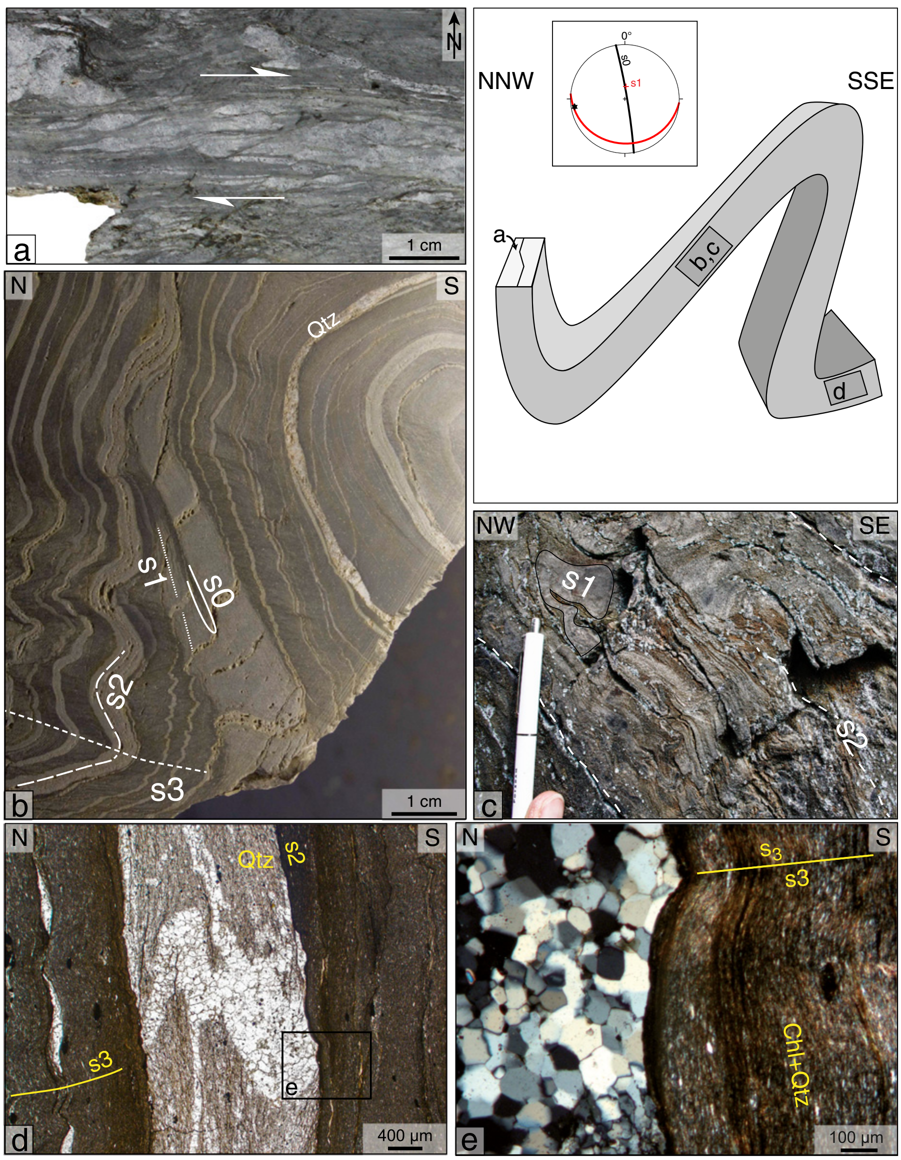
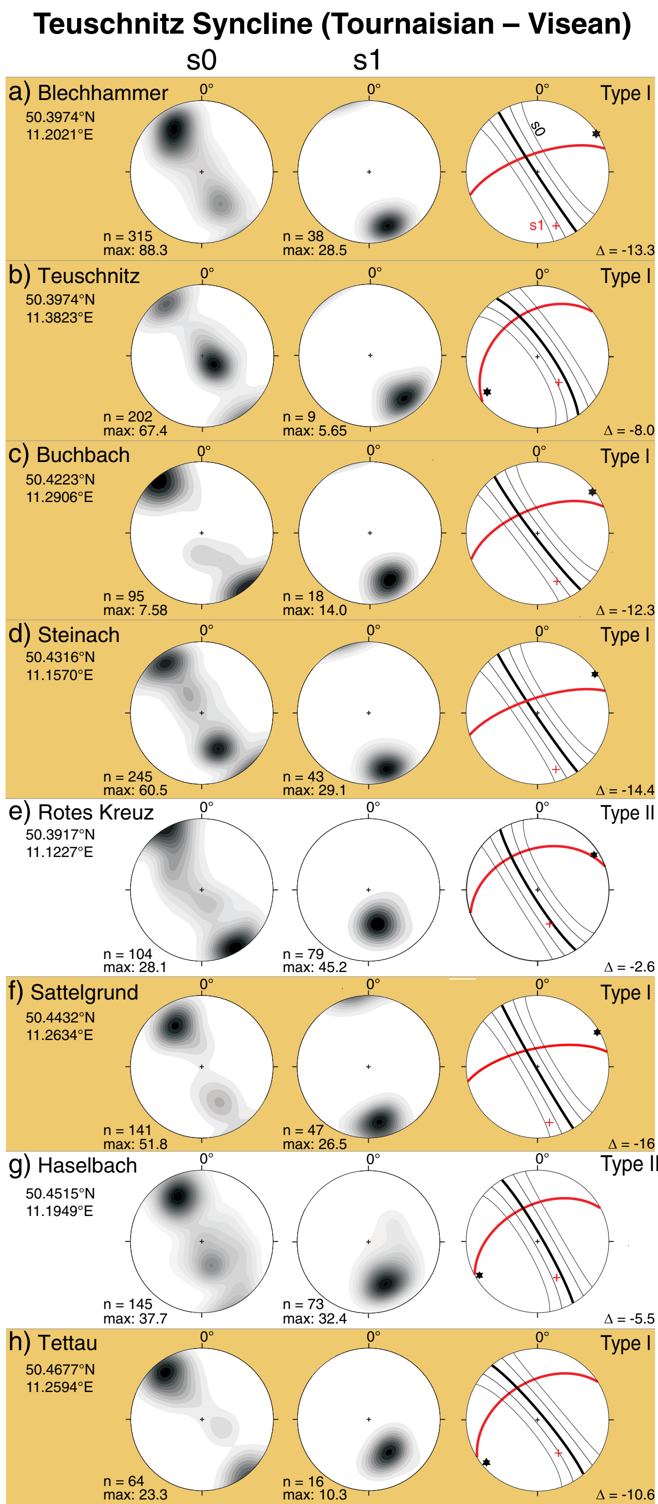


Fig. 5. Structures of the Kernzone Complex (NW Wrench-and-Thrust Zone of the Saxo-Thuringian Zone). a) Dextral shearing parallel s2 indicates initial subhorizontal simple shear with a NE trending X-axis of the incremental strain ellipsoid. b) Bedding (s0) is preserved in relic fold hinges (s1) and is crosscut by the related axial plane parallel s1 foliation. The main foliation s2 intersects both s0 and s1. The competence contrast results in deflection of s2. Final folding led to the formation of s3 and pressure solution along s2. Note the occurrence of quartz segregations which were temporally emplaced between the formation of s2 and s3. c) Relic fold hinges reveal disharmonic folding of s1 prior to the formation of s2. d) Shearing parallel s2 indicated by tightly folded quartz-veins within quartzitic layers. Note the s2-parallel extension as portrayed by the quartz boudins within the phyllitic layers (photomicrograph, plane-polarized light). e) Detail of d. Pressure solution during the formation of s3. Note the sharp contact between the polygonal quartz and the pressure solution seam (photomicrograph, cross-polarized light).

interpreted as bedding. However, the s2 foliation resembles a turbiditc layering, the observation of the oblique s1 foliation implies a metamorphic origin for the layering, i.e. pseudo-bedding in terms of Simpson (1985). The s2 foliation crosscuts s0 and s1 features, resulting in a partial obliteration of these structures (Fig. 5b). We interpret the s2 foliation to have formed due to quartz pressure solution precipitation resulting in a spaced foliation. The youngest deformation is represented by the crenulation of the s2 foliation and pressure-solution creep along s2, resulting in the formation of the s3 foliation (Fig. 5d, e). This final deformation leads to SE or SSE vergent folding of the s2 foliation (Fig. 5b).



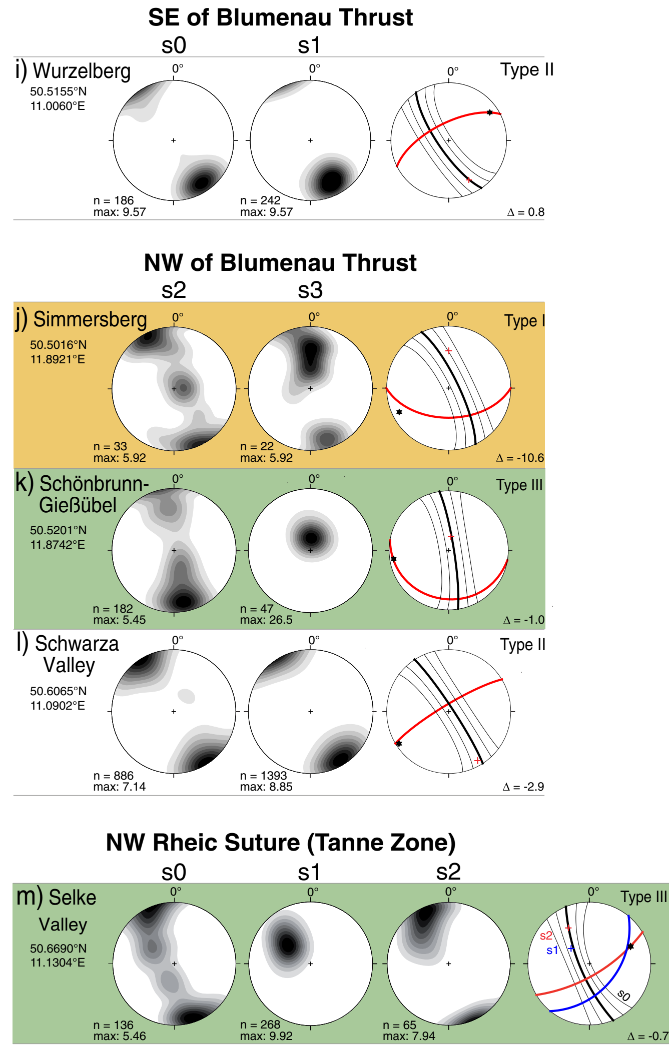


Fig. 6. Stereographic projections (equal area, lower hemisphere) of the late orogenic ductile strain increments of different zones of the Rheno-Hercynian–Saxo-Thuringian orogenic wedge. Yellow background: type I folds (transecting cleavage domains displaying NNW–SSE shortening). Green background: type II folds (non-transecting, fold axial parallel cleavage domains displaying NNW–SSE shortening). White background: type III folds (non-transecting, fold axial parallel cleavage domains displaying NW–SE shortening). a–h) Synorogenic sedimentary rocks of the Teuschnitz Syncline of the Saxo-Thuringian Basin (Tournaisian–Visean). i) Schwarzburg Unit southeast of the Blumenau Thrust (Autochthonous Domain of the Saxo-Thuringian Zone). j–l) Schwarzburg Unit northwest of the Blumenau Thrust, Kernzone Complex of the Schwarzburg Unit (NW Wrench-and-Thrust Zone of the Saxo-Thuringian Zone). m) Synorogenic sedimentary rocks of the Tanne Zone (Allochthonous Domain of the Rheno-Hercynian Zone). Location of investigated sections in Figs. 1 and 2. Left column: density distribution of the planes of the late Variscan folds. Middle column: density distribution of the youngest cleavage. Right column: Pi-circle (black great circle), Pi-girdle (black small circles ±20° and 10°) and Pi-pole (black star) refer to the girdle distribution of the left column; red great circle and red cross refer to the point maximum of the middle column; in Fig. 6m: blue and red great circles/crosses refer to s1 and s2, respectively. Schmidt nets: n — number of measurements; max: — multiples of uniform distribution (MUD); density distribution parameter: calculation — cosine sums, cosine exponent — 20.

In the NW of the Kernzone Complex, the metagreywackes and metapelites of the Altenfeld Subformation are characterized by the lack of quartz segregations, a distinctive feature in comparison with the Kernzone Complex. The metasedimentary rocks underwent a lower greenschist-facies metamorphism, as suggested on the mineral paragenesis of Qtz + Chl + Bt + Ser ± Fsp. We observe a subtle transition from steep, (N)NW or (S)SE dipping s3-foliation in the Kernzone Complex towards shallow, SE dipping foliation planes in the Altenfeld Subformation. The foliation obliquely cuts bedding structures while older strain increments are absent (like s2 and s1 of the Kernzone Complex). The lower grade of metamorphism and the lack of older strain increments without any sharp transition between the Kernzone Complex and the Altenfeld Subformation imply a structural boundary. We suggest that the Altenfeld Subformation represents the structural upper part of the Kernzone Complex, later juxtaposed due to a NW dipping normal fault.

3.4. Late Variscan fold–cleavage relationships

Because the poles of the folded foliation planes lie on a girdle with a 80–90% level of confidence (Fig. 6), the Rheno-Hercynian–Saxo-Thuringian boundary zone is characterized by (sub-) cylindrical folding. Regarding fold–cleavage relationships, the structural observations and the statistical analysis of the dihedral angle (Δ) between the mean cleavage plane and the normal to the fold plane girdle (i.e. fold axis, represented by the Pi-pole in Fig. 6) disclose three different fold–cleavage geometries:

- *Type I*: NE striking fold axial planes are crosscut by a clockwise transecting cleavage at an angle $\Delta < -7°$. The strike of the transecting cleavage is ENE (Fig. 6a–d, f, h, j).
- *Type II*: Folds with an axial plane parallel (non-transecting to slightly transecting) cleavage, which strikes NE–SW (Fig. 6e, g, i, l). The dihedral angle is $-7° < \Delta < -1°$. Small-scale sinistral strike-slip faults are observed as a second foliation displacing the main foliation (Fig. 3).
- *Type III*: Folds with an axial plane parallel (non-transecting) cleavage, which strikes ENE (Fig. 6k, m). The dihedral angle is $-1° < \Delta < 1°$.

The existence of three different fold–cleavage types suggests kinematic partitioning of a triclinic bulk strain into simple shear, i.e. transpressional (types I and II) and pure shear dominated deformations (type III). However, the statistical analysis of all the youngest cleavage planes reveals a dominant ENE strike of the cleavage (Fig. 7a). Because the only consistent feature of the three fold–cleavage types is the strike of the youngest cleavage, it can be used as an indicator for the XY plane of the last deformation increment (Sanderson and Marchini, 1984; Soper, 1986; Treagus and Treagus, 1992), i.e. late Variscan shortening is oriented NNW–SSE. The lack of a mineral stretching lineation corroborates a bulk oblate strain, a characteristic feature of many transpression zones (Sanderson and Marchini, 1984; Dewey et al., 1998).

The transecting cleavage (sensu Treagus and Treagus, 1992) as the latest ductile strain increment in type I folds provides further evidence for transpression. The sense of axial plane transection is used as an indicator for the sense of transpression. Clockwise-rotation ($\Delta < 0°$) of the transecting cleavage with respect to the fold axial plane of type I indicates sinistral transpression (Fig. 7b). Type II is characterized by non- to slightly clockwise transected folds that trend NW–SE (Fig. 7b). To maintain strain compatibility with NNW–SSE shortening, we propose strain partitioning within this fold type, i.e. strike-slip deformation accompanying the folding. At the Wurzelberg small-scale sinistral strike-slip faults are preserved as a second foliation displacing the cogenetic main foliation (Fig. 3). Type III is represented by ENE striking non-transected folds. Because the cleavage and the folding are perpendicular to the shortening direction, this type represents pure shear folding. The partitioning into different fold–cleavage types during uniform NNW–SSE shortening indicates the presence of mechanical anisotropies within the transpressional types I and II. These anisotropies should be oriented oblique to the shortening

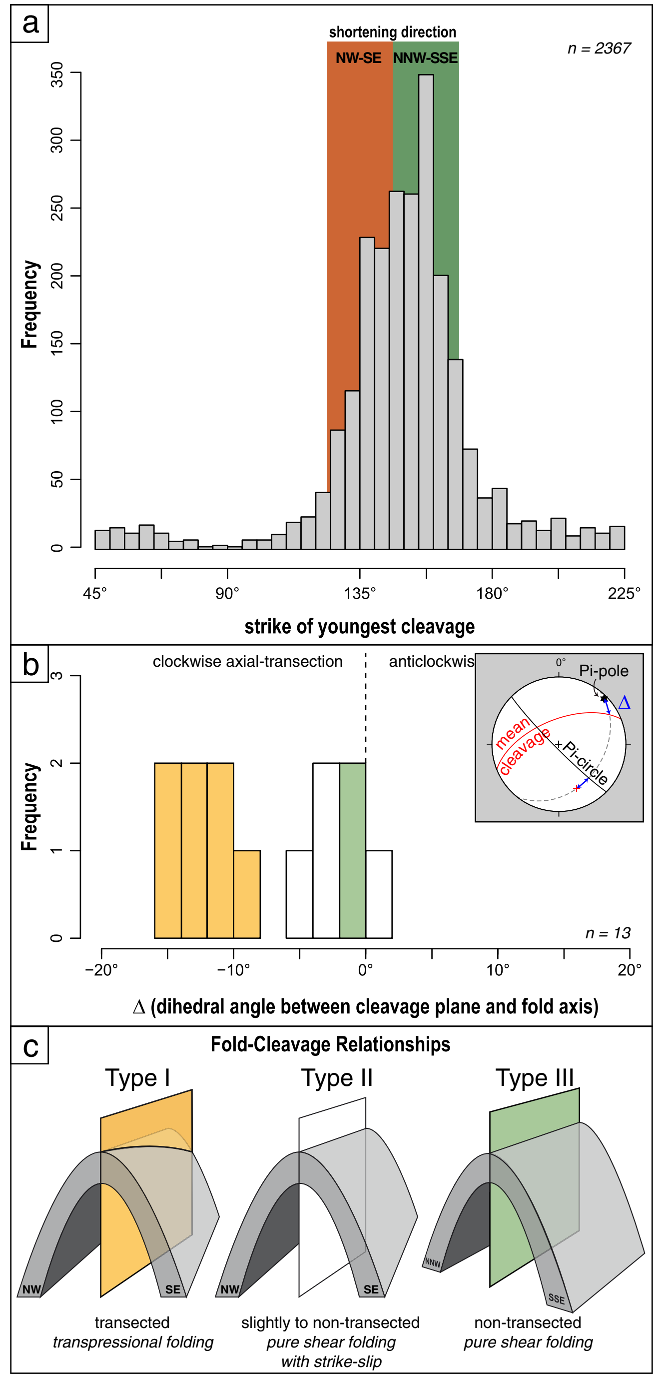


Fig. 7. Statistical analysis of the latest orogenic ductile strain increments of the Rheno-Hercynian–Saxo-Thuringian boundary zone. a) Histogram of the strike direction of the youngest cleavage (n = 2367, 5° classes). Shortening direction is perpendicular to the strike of the cleavage, i.e. perpendicular to the XY-plane of the finite strain. Note that orientation maxima of the youngest cleavage indicates NNW–SSE shortening. b) Histogram of the dihedral angle (Δ) between the mean cleavage plane and the fold axis (2° classes). Δ is determined for each investigated region (n = 13, see Fig. 6) bases on single measurements of n = 2367 foliation and n = 2734 bedding planes. Sense of axial-transection: anticlockwise: $\Delta > 0°$, clockwise: $\Delta < 0°$. The bimodal distribution reflects the fold classification (Fig. 6): $-1° < \Delta < 1°$ folds with axial plane parallel cleavage (type II), $-7° < \Delta < -1°$ slightly cleavage-transected folds (type III), see Fig. 6), $\Delta < -7°$ cleavage-transected folds (type I). Note that all fold types plot in the clockwise axial plane transection field, indicating sinistral transpression. The inset displays the determination of Δ in the equal area projection, lower hemisphere. c) Graphical sketches of the relationships of first-order fold and youngest cleavage (types I–III).

direction (Jones and Tanner, 1995) and thus sub-parallel to the fold axes, i.e. NE–SW.

4. Discussion

4.1. Regional relevance of the late Variscan sinistral transpression

In polyphase deformed regions, the finite strain may be the expression of different deformational episodes. In the Saxo-Thuringian Zone, particularly in the Schwarzburg Unit, there is ample evidence for the overprint of older structures by younger deformation events. Because the superposition precludes that the geometry of the finite strain of any deformed sample is the exclusive result of a single deformation event, 3D-strain analysis is not sufficient to demonstrate transpression. Nevertheless, the youngest fold–cleavage relationship, i.e. the transecting cleavage, constitutes the latest strain increment of each investigated rock unit and gives evidence for transpression (Treagus and Treagus, 1981; Soper, 1986). The negative dihedral angles (up to −16°) in the pro- and the retro-wedge represent a feature that affected the entire Rheno-Hercynian–Saxo-Thuringian orogenic wedge. It reveals that the orogenic wedge was formed under sinistral transpression during NNW–SSE directed shortening (Figs. 6 and 7). Pressure-solution creep accompanied the formation of the youngest cleavage, indicating upper crustal deformation conditions.

The regional significance of late Variscan NNW–SSE convergence (Fig. 8) is underlined by consistent results obtained from palaeostress field measurements in the Teplá-Barrandian Unit (Pitra et al., 1999) and in the Moldanubian Zone (Büttner, 2007). The coeval activity of NW trending dextral shear zones, e.g. the Elbe Shear Zone (Nasdala et al., 1999) and the Pfahl Shear Zone (Siebel et al., 2004), is in agreement with general NNW–SSE directed shortening. We suggest that both strike-slip systems (dextral NW trending, and sinistral NE trending systems) developed as a conjugate set in the late Variscan event.

Because Late Carboniferous sinistral transpression during NNW shortening is also reported from several parts of the Rhenish Massif (Oncken, 1988; Fielitz, 1992; Klügel, 1997) and the Harz Mountains (Jacob and Franzke, 1992), we propose that this style of deformation acted along the entire NE trending segment of the Rheic suture zone during the late Variscan event. It is important to note that there is no evidence for sinistral transpression at the western continuation of the Late Carboniferous fold-and-thrust belt. In the Ardennes the strike of the orogenic belt changes progressively from NE–SW to NW–SE (Fig. 1a). The regional thrusting direction is NNW–SSE and caused local dextral transpression (Lacquement et al., 2005; Jacques et al., 2014).

In the westernmost continuation of the suture, i.e. the SW Irish and British Variscides, dextral transpressional deformation along WNW trending structures has also been documented (Sanderson, 1984; Gayer and Nemcok, 1994; Gayer et al., 1998; Bresser and Walter, 1999). Along NNE striking faults in NW England Woodcock and Rickards (2003) documented sinistral transpression during NNW–SSE shortening in the Late Carboniferous.

In conclusion, NNW–SSE shortening is the common late Variscan deformation on both sides of the Rheic suture in West and Central Europe. The sense of transpression correlates with the trend of the suture: sinistral transpression occurs along NE trending segments of the suture, whereas dextral transpression is documented along NW trending segments (Fig. 8). It is worth noting that transpression is a result of the reactivation of pre-existing, mechanical anisotropies that are obliquely oriented to the shortening direction (Jones and Tanner, 1995). The fact that these anisotropies run parallel to the trend of the suture, both the anisotropies and the shape of the suture are a result of an earlier Variscan event (Fig. 9).

4.2. Evidence for early Variscan deformation

Although the Schwarzburg Unit comprises similar lithologies on both sides of the core of the antiformal structure, the NW and the SE parts contain different metamorphic overprints (Schäfer, 1997; Schäfer et al., 2000) and structural styles. The entire SE part of the Schwarzburg Unit (i.e. the Autochthonous Domain of the Saxo-Thuringian Zone) is only affected by the late Variscan deformation that began at 334 Ma. However, the Kernzone Complex at the NE part of the Schwarzburg Unit hosts several older strain increments (Fig. 4) which are absent in the adjacent Frohnberg Formation at the SE part.

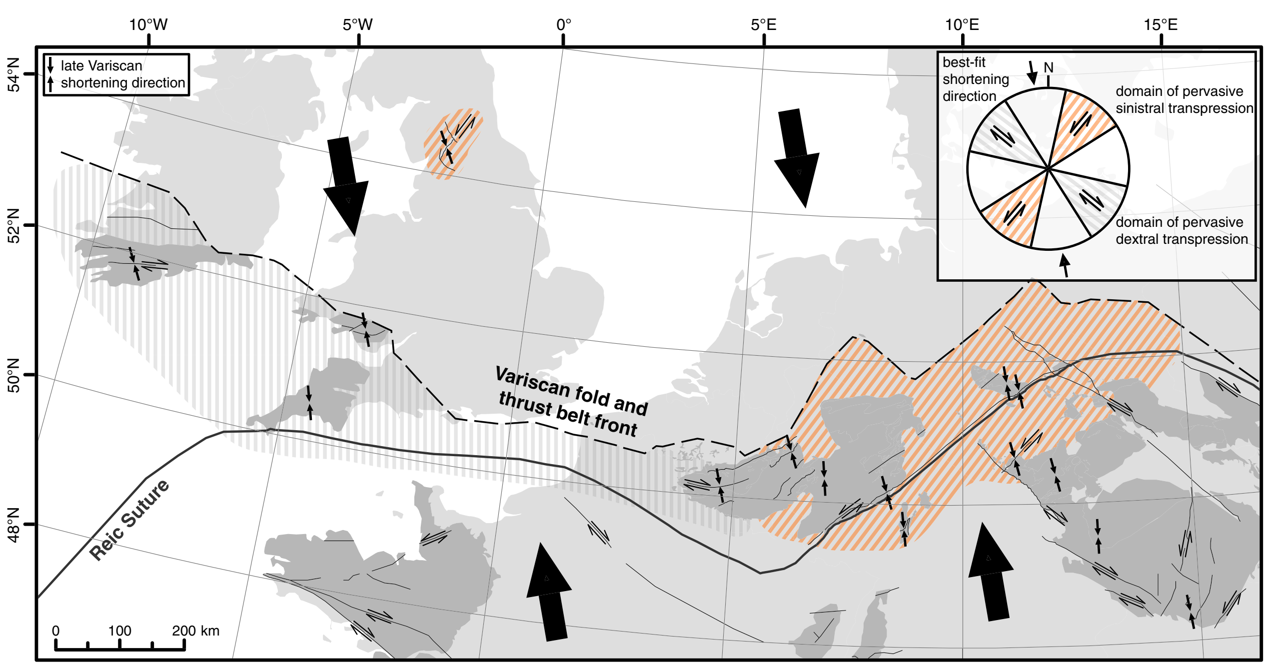
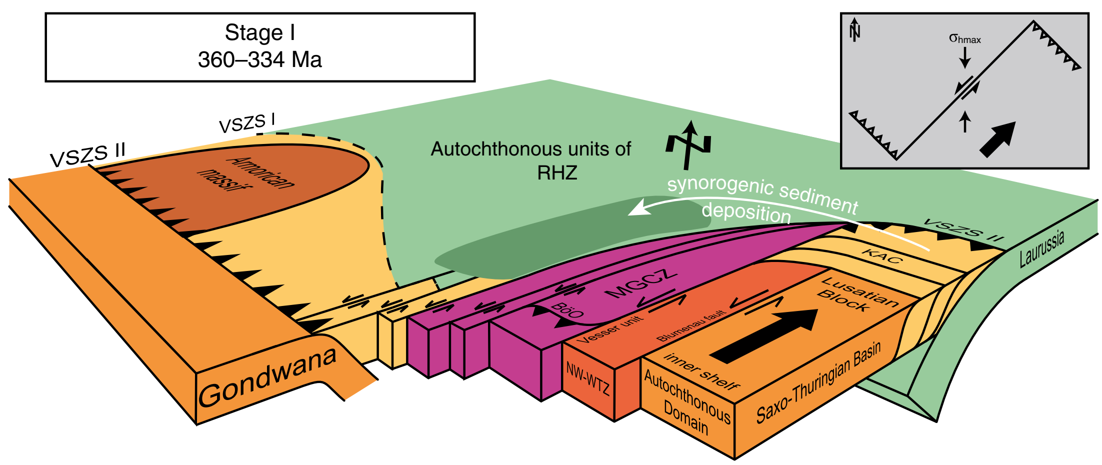


Fig. 8. The late Variscan (334–300 Ma) inferred shortening direction along the Rheic Suture Zone of selected faults and structures (references in text). Note that NNW–SSE directed shortening predominates along the entire suture zone. Depending on the trend of the Rheic suture, the shortening produces a dextral transpressive domain along NW–SE trending segments of the suture and a sinistral domain along NE–SW trending segments.

Thus, the classical interpretation of the Schwarzburg Unit as being an anticline needs revision. We argue, that rather a deformation stage prior to 334 Ma has to be considered (stage 1) and interpret the boundary between the Kernzone Complex and Frohnberg Formation, i.e. the Blumenau Thrust, as an initial strike-slip fault that juxtaposed the already metamorphosed NW part of the Schwarzburg Unit with the non-metamorphic SE part prior to 334 Ma. Due to the subsequent rotation of the shortening direction towards NNW (Kroner et al., 2016-in review), the fault was reactivated and thrusted the NW part onto the SE part of the Schwarzburg Unit (stage 2). In the rocks of the NW part we observe a gradual structural and metamorphic transition from the Kernzone Complex to the Altenfeld Subformation and propose that both units were contiguous prior to the final folding and thrusting. However, the Kernzone Complex accommodated most of the deformation, i.e. the formation of s2 and the folding of s1. The s2-parallel incorporation of Cambrian to Ordovician granitoids as tectonic slices predates the deformation and hence, excludes a Cadomian origin for the s2 foliation (Linnemann et al., 1999; Linnemann et al., 2000; Heuse et al., 2001; Kemnitz et al., 2002).

There are ample evidences for a deformation event prior to the late Variscan folding and thrusting in the Allochthonous Domain and the SE Wrench-and-Thrust Zone of the Saxo-Thuringian Zone (Kroner et al., 2007). This early Variscan deformation is associated with NE directed shortening and occurred in the Late Devonian to Early Carboniferous (Wiefel, 1976; Lange et al., 1999; Gehmlich et al., 2000; Willner et al., 2000; Hahn et al., 2010). At the same time (360–335 Ma) deformation in the Mid-German Crystalline Zone is characterized by NE striking sinistral strike-slip (Wunderlich, 1989; Krohe, 1991, 1992; Will, 2001a; Scherer et al., 2002; Zeh and Wunderlich, 2003; Franzke et al., 2007). Palaeostress analysis revealing c. N–S compression in the Mid-German Crystalline Zone (Flöttmann and Oncken, 1992; Will, 2001b) is compatible with a NE striking sinistral transform boundary (Kroner and Romer, 2013) because the maximum horizontal compression is at an angle of c. 45° to the active strike-slip fault zone



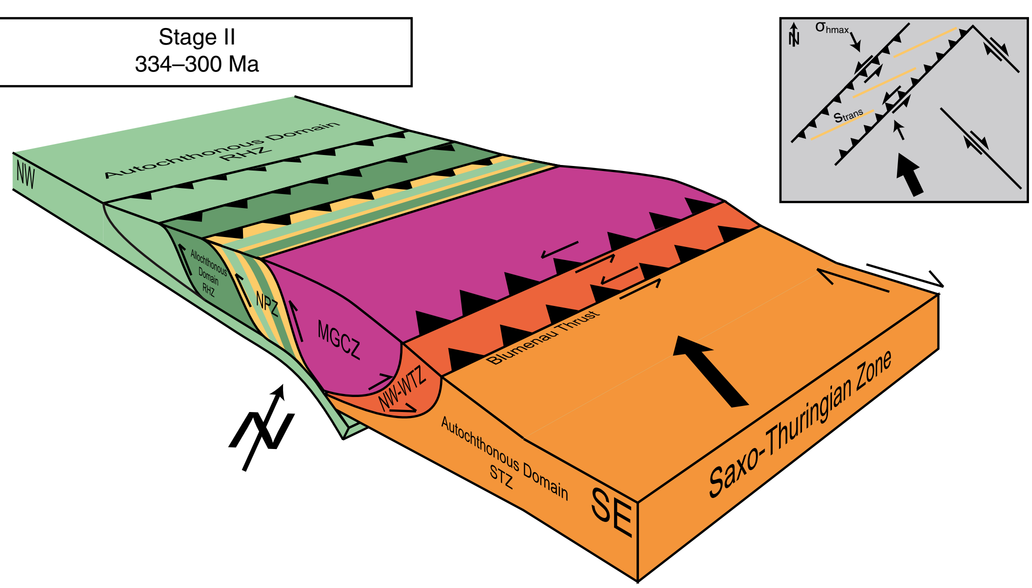


Fig. 9. Sketches explaining the two deformation stages (not to scale). Stage I: Explanation of the NE trending Saxo-Thuringian–Rheno-Hercynian boundary as a transform plate boundary connecting intracontinental subduction zones south of the Armorican Massif and in the Sudetes (360–334 Ma). White arrow indicates potential source areas for the Gondwana-derived sedimentary rocks in the allochthonous Rheno-Hercynian mélanges (cf. Gansslosser, 1999; Huckriede et al., 2004; Eckelmann et al., 2014). Stage II: The late Variscan formation of the orogenic wedge obliterates the initial transform plate boundary (334–300 Ma). NNW–SSE convergence causes sinistral transpression by reactivation of NE trending pre-existing faults. The orogenic wedge is confined by NW-trending dextral faults (e.g. Elbe Shear Zone in the E, Franconian Line in the W). Inset sketches display the principal orientation of faults in relation to the maximum horizontal compressive stress axis (σ_{hmax}) and plate convergence vector. Yellow lines indicate the strike of the transecting cleavage (s_{trans}) which is orthogonal to the maximum horizontal stress axis. Note that NE striking thrusts show a sinistral component. NW striking dextral shear zones (e.g. Elbe Shear Zone, Franconian Line, Pfahl Shear Zone) are compatible with NNW–SSE directed shortening. Abbreviations: BöO — Böllstein Odenwald; KAC — Kaczawa Accretionary Complex; MGCZ — Mid-German Crystalline Zone; NPZ — Northern Phyllite Zone; NW-WTZ — Northwest Wrench-and-Thrust Zone of Saxo-Thuringia (STZ); RHZ — Rheno-Hercynian Zone; s_{trans} — transecting cleavage; VSZS I — Variscan Subduction Zone System I; VSZS II — Variscan Subduction Zone System II (cf. Kroner and Romer, 2013).

(Wdowinski, 1998). Hence, the initial juxtaposition of the shelf areas of Laurussia and Gondwana is the result of strike-slip tectonics parallel to the intervening suture (Fig. 9).

5. Conclusions

Our structural data set demonstrates that the late Variscan strain increment, i.e. the fold–cleavage relationship, is compatible with a doubly-vergent but oblique Rheno-Hercynian–Saxo-Thuringian orogenic wedge. The statistical analysis reveals an orientation maximum of the youngest cleavage that deviates from the strike of the fold-and-thrust belt by c. 22°, i.e. the shortening direction is NNW–SSE. The presence of clockwise transection of the folds by the cleavage (up to −16°) indicates pervasive sinistral transpression. We distinguish three types of fold–cleavage relationships: NE trending folds (I) with or (II) without a transecting cleavage, and (III) non-transected, ENE trending folds. The occurrence of different fold–cleavage types is explained by strain partitioning due to NNW convergence obliquely to pre-existent NE trending mechanical anisotropies. In terms of plate tectonics we propose that the classical boundary of the Rheno-Hercynian and the Saxo-Thuringian zone represents an initial transform plate boundary (>334 Ma) that was finally affected by sinistral transpression. Although the parallel strike of the geological units pretends a simple fold-and-thrust belt architecture, detailed structural investigations reveal that the belt resulted from a polyphase history with oblique convergence.

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