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# Status of Basement Terranes in Orogens: Insights From the Cadomian Domain of the North Armorican Variscides, Western France

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**Key Points:**

- The North Armorican Cadomian domain comprises a northern part with Variscan overprint, and a southern stable and rigid part
- Variscan reworking of Cadomian terranes in the Central and Western European Variscides, occurred in portions of lithosphere which were previously stretched
- Our structural study is based on an onshore/offshore approach combining high-resolution bathymetric records and field investigations

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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**Abstract** The stable versus mobile behavior of basement terranes in orogens is discussed about the North Armorican Cadomian-floored domain (NAD) in the Armorican Variscides, Western France. Our onshore/offshore structural study demonstrates the heterogeneous nature of the NAD which comprises: (a) a southern part which remained stable during both the Paleozoic extensional and compressional (Variscan) events and (b) a northern part which was initially the locus of extensive Paleozoic sedimentary basins before recording Variscan deformation. Our work supplies a more complete structural picture of the Variscan pattern in Northern Armorica as a whole: (a) as precising the spatial distribution of Variscan strain, (b) as emphasizing its importance with a bulk shortening estimated at 30% in the North Cotentin fold-and-thrust belt, and (c) as regarding a newly identified pattern of sinistral ductile shear zones in the Morlaix area as lateral ramps that parallel the western edge of the rigid (southern) Cadomian block in a indenter kinematic setting. At a wider scale, compiling structural data set from others Cadomian terranes in the Variscan belt of Central (Bohemia) and Western (Iberia) Europe leads us to hypothetize that their stability versus reworking during the Variscan orogeny relies primarily on the mechanical/thermal state of their lithosphere at the end of the Paleozoic extensional stage.

## 1. Introduction

Most of mountain belts worldwide contain remnants of older orogenic systems commonly referred to as fragments, blocks, inliers, slivers, ribbons or terranes. These basement rocks, named as "terranes" in the present work, can behave as strong material or be variably affected by younger tectono-metamorphic events. In the latter case, and when displaying a cold and anomalously thick lithosphere, they form cratonic nuclei (e.g., Wang et al., 2014). Cadomian basement terranes (750–540 Ma) are currently disseminated in the Variscan belt (360–300 Ma) of Central and Western Europe (Figure 1). Most of them display a polyorogenic structural pattern resulting from superimposed Cadomian/Variscan deformations. One exception is the Cadomian domain in Northern Armorica (North Armorican Cadomian-floored domain [NAD] in Figure 1) which is generally thought to have escaped Carboniferous compressional events (Ballèvre et al., 2001; Bois et al., 1990a; Brun et al., 2001; D'lemos et al., 1990; Le Gall, 1990). However, the presumed stability of the NAD during the Variscan orogeny is contradicted by the tectonic and magmatic structures recorded by Paleozoic metasedimentary series and Cadomian basement rocks in the North Cotentin fold-and-thrust belt to the north (Figures 1 and 2) (Butuaye et al., 2001; Dissler & Gresselin, 1989; Dupret & Le Gall, 1984; Goguel, 1977). The NAD thus appears as a heterogeneous Cadomian-floored domain composed of reworked (Variscan overprint) and intact (strictly Cadomian) blocks. Defining the number of these blocks, as well as their spatial distribution, internal structure, and mutual relationships is a prerequisite for determining the factors and processes that might have governed their contrasted behavior during Variscan orogenic events. These issues are addressed in the present work from a multiscale and onshore/offshore study based on: (a) high-resolution (multibeam and light detection and ranging [LiDAR]) bathymetric data from the northern offshore part of the NAD, (b) field investigations at its western periphery, and (c) completed/reinterpreted available data from the Cotentin deformed belt (Figure 2a). This complementary approach enables us to define: (a) the spatial distribution of Paleozoic sedimentary basins in the pre-Variscan NAD framework, (b) the style of Variscan deformation and the amount of corresponding strain as it can be locally estimated in

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the Cotentin fold-and-thrust belt, and (c) the twofold structural zoning of the NAD during both the Paleozoic basinal stage and the subsequent Variscan orogeny. Hypotheses proposed about the mono- versus polyorogenic evolution of the NAD Cadomian-floored blocks are finally applied at a wider scale to the Neoproterozoic/Cadomian terranes present in the Variscan belt of Western and Central Europe.

## 2. Geodynamic and Geological Setting

Discrete remnants of Neoproterozoic/Cadomian terranes are disseminated in the Bohemian, Armorican, and Iberian massifs of the arc-shaped Variscides in Central and Western Europe (Figure 1). These terranes are first briefly listed below before focusing on the NAD structural pattern in Armorica. Comparing the mono- versus polyorogenic evolution of these Cadomian terranes supplies insights into the corresponding geodynamic frameworks (Section 5.3).

### 2.1. Neoproterozoic/Cadomian Terranes in the European Variscides

Neoproterozoic/Cadomian terranes in Central Europe are present in the Bohemian Variscan massif (Figure 1). They occur in two variously trending structural domains, on both sides of the Elbe fault, as parts

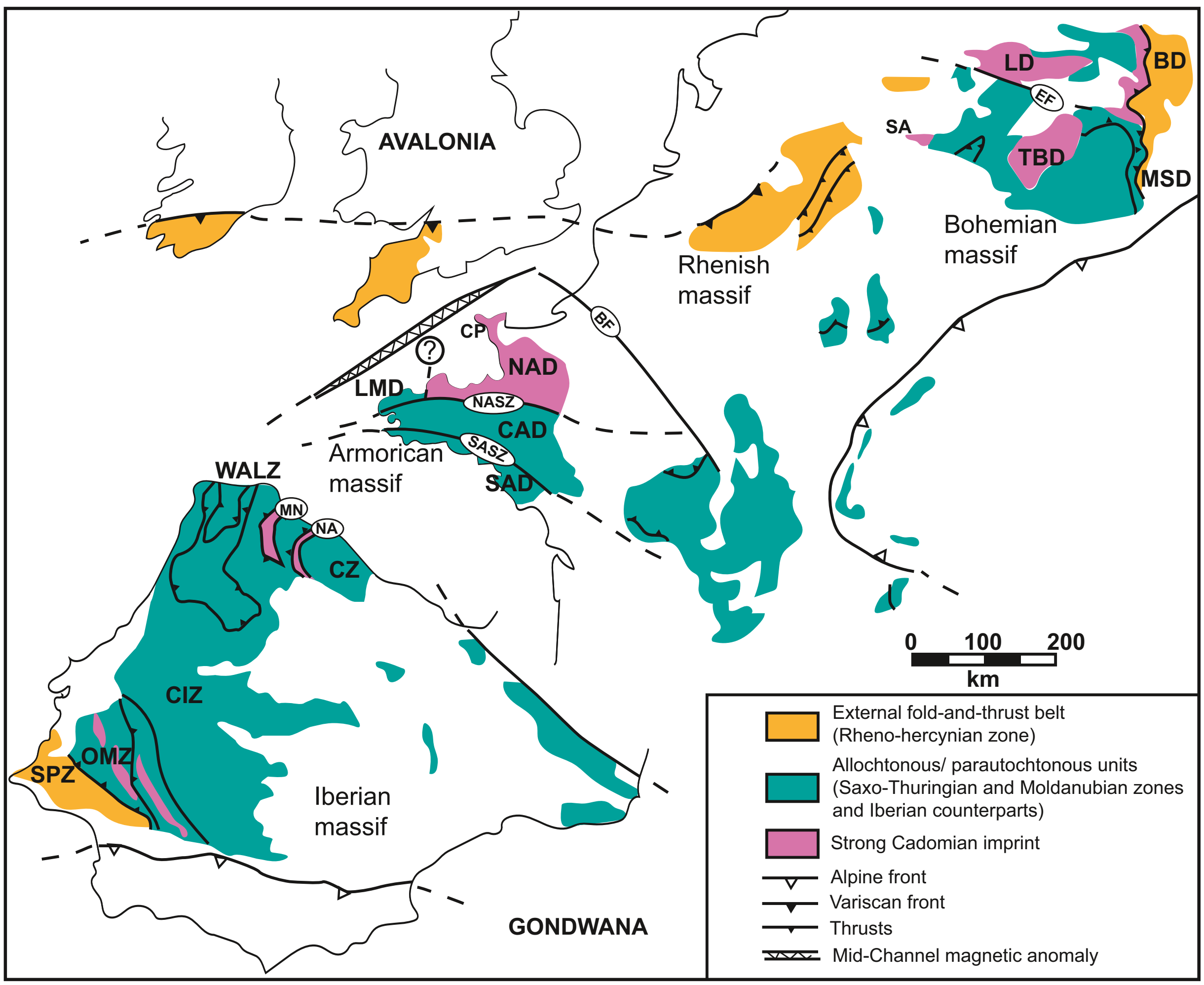
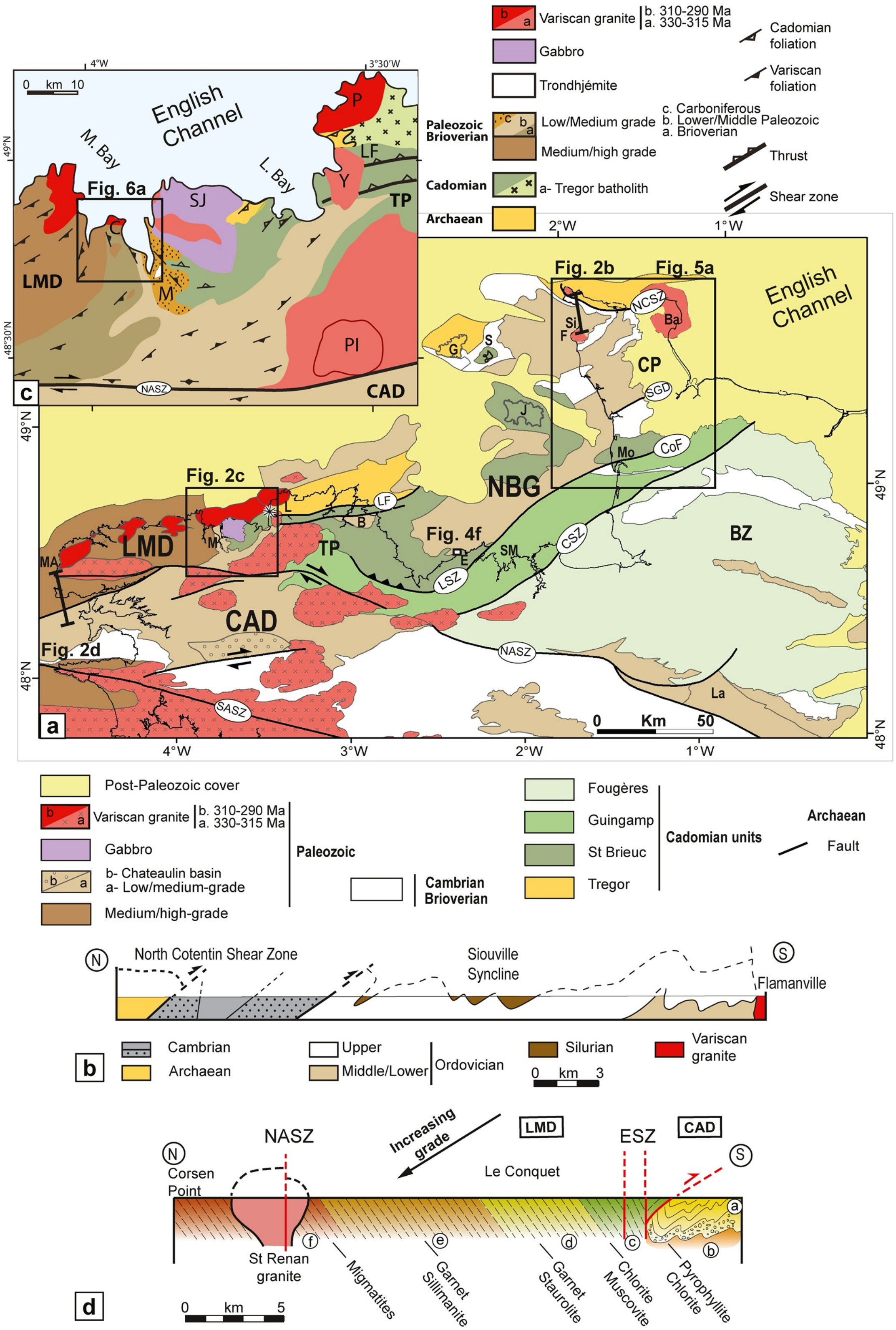



**Figure 1.** The Cadomian terranes in the Variscan belt of Central/Western Europe, modified from Martinez-Catalan (2011). BD, Brunian domain; BF, Bray fault; CAD, Center Armorican domain; CIZ, Central Iberian zone; CP, Cotentin Peninsula; CZ, Cantabrican zone; EF, Elbe fault; LMD, Leon metamorphic domain; LD, Lugian domain; MN, Mondonedo nappe; MSD, Moravo-Silesian domain; NA, Narcea antiform; NAD, North Armorican domain; NASZ, North Armorican shear zone; OMZ, Ossa Morena zone; SA, Schwartzburg antiform; SAD, South Armorican domain; SASZ, South Armorican shear zone; SPZ, South Portuguese zone; TBD, Tepla-Barrandian domain.


Variscan granite
b. 310-290 Ma
a. 330-315 Ma
Gabbro
Trondhjémite
Paleozoic Brioverian
Low/Medium grade
Medium/high grade
c. Carboniferous
b. Lower/Middle Paleozoic
a. Brioverian
Cadomian
a- Tregor batholith
Archaean
Cadomian foliation
Variscan foliation
Thrust
Shear zone
English Channel
M. Bay
L. Bay
Fig. 6a
SJ
LF
TP
LMD
CAD
NASZ
Pl
c
Fig. 2b
Fig. 5a
NCSZ
CP
SGD
CoF
NBG
Fig. 2c
Fig. 4f
LSZ
CSZ
BZ
Fig. 2d
SASZ
a
0 Km 50
Post-Paleozoic cover
Variscan granite
b. 310-290 Ma
a. 330-315 Ma
Gabbro
b- Chateaulin basin
a- Low/medium-grade
Medium/high-grade
Paleozoic
Cambrian Brioverian
Fougères
Guingamp
St Brieuc
Tregor
Cadomian units
Archaean
Fault
North Cotentin Shear Zone
Siouville Syncline
Flamanville
Cambrian
Archaean
Upper
Middle/Lower
Ordovician
Silurian
Variscan granite
0 km 3
b
NASZ
Increasing grade
LMD
ESZ
CAD
Corsen Point
Le Conquet
St Renan granite
Migmatites
Garnet Sillimanite
Garnet Staurolite
Chlorite Muscovite
Pyrophyllite Chlorite
0 km 5
d

of the Saxo-Thuringian zone of Kossmat (1927). They predominantly consist of metasedimentary (mainly turbiditic) series and associated magmatic complexes related to a subduction-induced volcanic arc. Most of these rocks recorded a polyorogenic evolution in relation with the Cadomian and Variscan collisions (e.g., Franke, 2000; Linnemann et al., 2000, for review). To the NW, pre-Paleozoic rocks at the core of the Schwarzburg anticline are involved in Cadomian thrust tectonics later reactivated as Variscan strike-slip structures (Linnemann et al., 2014). Further south, in the Tepla-Barrandian domain, well preserved Cadomian deformed terranes are locally affected by intense Variscan deformation at the margins of the domain, whereas onlapping Cambro-Ordovician series are only moderately folded in its central part (Hajna et al., 2011). NE of the Elbe fault, that is, in the Lugian domain (Sudetes massif), Neoproterozoic/Cambrian sedimentary series experienced Cadomian tectonometamorphic and plutonic events (e.g., Franke & Zelazniewicz, 2000) before recording intense Variscan deformation at the eastern margin of the domain (Schulmann & Gayer, 2000). In the adjoining Moravo-Silesian domain to the east, Cadomian metamorphic units are locally piled up into a Variscan nappe pattern (Kroner et al., 2000). The Cadomian high-grade metamorphic series in the Brunian domain are not integrated in this review since they extend beyond the Variscan front to the SE (Mazur et al., 2010). In the arc-shaped Iberian Variscides, nearly similar Neoproterozoic/Cadomian lithostratigraphic units occur in some of the Variscan zones defined by Julivert et al. (1987). Neoproterozoic metasedimentary inliers following the boundary between the Cantabrian and West Asturian Leonese zones form the cores of regional-scale antiforms (Mondonedo and Narcea structures in Figure 1) in a Variscan folded nappe pattern (Peres-Estaun et al., 1991). Further south, Neoproterozoic volcanosedimentary series are more widely distributed in the central and southern parts of the Ossa Morena zone (Figure 1). Their strong Cadomian structural imprint is partly obliterated by Variscan deformation (Ribeiro et al., 2009; Sanchez-Garcia et al., 2016).

### 2.2. The Cadomian-Floored NAD

The NAD is a $\sim 80 \times 10^3$ km$^2$ block partly bounded by crustal-scale discontinuities which are either geophysically imaged to the east beneath the Mesozoic cover of the Paris basin (Bray fault), or extensively exposed to the south along the North Armorican shear zone (Figures 1 and 2a). The latter separates Brioverian series (NAD), exclusively affected by Cadomian deformation, and Brioverian-Paleozoic terrains involved in Variscan structures further south in the Center Armorican Domain (CAD) (Chauris, 1969; Goré & Le Corre, 1987; Watts & Williams, 1979). On published maps, the location of its northern boundary is not yet definitely determined, as either following the Mid-Channel magnetic anomaly (Lefort & Segoufin, 1978) or occurring further south onshore in the North Cotentin Peninsula (Nance & Murphy, 1996). Very little is yet known about its western boundary in the Morlaix-Tregor transition zone. Our work is focused on the western onshore/offshore part of the NAD extending west of the Meso-Cenozoic cover of the Paris basin (Figure 1). Most previous structural works devoted to the NAD concerned its Cadomian history as it can be constrained from onshore geology (see below). In contrast, the sedimentary, magmatic and tectonic events recorded by the NAD in post-Cadomian times have not been so far integrated in a coherent structural framework (Figure 2a).

**Figure 2.** Main tectonic units in Northern Armorica. (a) Simplified structural map, modified from Chantraine et al. (2003). B, Brehec; Ba, Barfleur; BZ, Bocaine zone; CAD, Center Armorican domain; CoF, Coutances fault; CP, Cotentin Peninsula; CSZ, Cancale shear zone; E, Erquy; G, Guernesey island; J, Jersey island; L, Lannion; La, Laval; LF, Locquemeau fault; LMD, Leon metamorphic domain; LSZ, La Fresnaye shear zone; M, Morlaix; MA, Molene archipelago; Mo, Montmartin-sur-Mer; NASZ, North Armorican shear zone; NBG, Normano-Breton gulf; S, Sark island; SASZ, South Armorican shear zone; SGD, Saint-Germain-sur-Ay discontinuity; Si, Siouville; SM, Saint-Malo; TP, Tregor peninsula. The geological units in the LMD are not shown. Location of Figures 2b–2d and 5a is shown. (b) Structural cross-section in the North Cotentin fold-and-thrust belt, modified from Goguel (1977). Location in Figure 2a. (c) Main onshore geological units in the Leon-Tregor transition zone, compiled from the 1:50,000 geological maps Morlaix, Plestin-les-Grèves, Saint-Pol-de-Léon, and Lannion (Cabanis et al., 1981; Chantraine et al., 1985, 1999; Chauris et al., 1998). Location of Figure 6a is shown. C, Carantec; LF, Locquemeau fault; LMD, Leon metamorphic domain; M, Morlaix; NASZ, North Armorican shear zone; P, Ploumanach; Pl, Plouaret; SJ, Saint-Jean-du-Doigt; TP, Tregor Peninsula, Y, Yaudet. (d) Simplified structural section at the LMD-CAD transition zone. See text for explanations. Location in Figure 2a. ESZ, Elorn shear zone; NASZ, North Armorican shear zone. (a) Paleozoic; (b) Brioverian; (c) Brest orthogneiss; (d) Le Conquet micaschist; (e) Lesneven paragneiss; (f) Migmatite (series not shown on the map in Figure 2a).

#### 2.2.1. The Cadomian Orogenic Belt

The NAD preserves the best records of Cadomian orogenic events in NW Europe. Its exposed part in northern Brittany and Cotentin Peninsula extends as a 250 × 100 km arcuate belt that swings clockwise westwards from a general N70°E trend to a deflected map-trace over the Tregor Peninsula (Figure 2a). It comprises a stack of four major tectono-metamorphic units mainly composed of volcano-plutonic arc-type series (NW) and continental margin metasediments (SE) (Balé & Brun, 1989; Chantraine et al., 2001; Strachan et al., 1996). These units experienced low-to-medium pressure and HT metamorphic conditions during high strain shearing (Ballèvre et al., 2001; Brun & Balé, 1990) in the time-range of 620–540 Ma (Auvray et al., 1980; Vidal et al., 1981). They are from the NW to SE, the Tregor, Saint-Brieuc, Guingamp and Fougères units, and their corresponding tectonic boundaries, that is, the Locquemeau, La Fresnaye, and Cancale ductile shear zones, respectively (Figure 2a). The latter are northerly dipping crustal-scale structures (Bitri et al., 2001) which combine a prominent southwesterly directed thrust component and sinistral strike-slip movement (Brun et al., 2001). Northerly directed (antithetic) Cadomian thrusts have also been imaged offshore through the English Channel upper crust on long-recorded (SWAT) seismic reflection profiles (BIRPS & ECORS, 1986; Bois et al., 1990b; Le Gall, 1990). Some of the Cadomian structures extent to the NE in the North Cotentin Peninsula, such as the La Fresnaye and Cancale shear zones, or the Tregor-La Hague unit and its discrete inliers of ca. 2.7 Ga-old Archean rocks (Figure 2a) (Auvray et al., 1980; Vidal et al., 1981). The Cadomian structural pattern is kinematically consistent with an arc/continent accretion mechanism in a transpressive tectonic setting (Brun & Balé, 1990). The location and dip direction of the associated subduction zone are still debatable. According to the “northerly dipping” model, the suture line should occur along the La Fresnaye shear zone (Graviou, 1992; Hebert, 1995), whereas it coincides with the Mid-Channel Magnetic Anomaly in the “southerly dipping” model of Lefort (1975) and Auvray (1979).

#### 2.2.2. The Paleozoic Framework

On the geological map in Figure 2a, Paleozoic (sedimentary and magmatic) series are confined to the northern part of the NAD. The most complete sedimentary succession is exposed in the North Cotentin Peninsula as a km’s-thick pile of Cambro-Devonian rocks that disappear eastward beneath the Mesozoic cover of the Paris basin. The Paleozoic series and the Cadomian/Archean substratum are deformed into a Variscan south-verging thin-skinned fold-and-thrust belt, developed synchronously or slightly prior to the intrusion of the Flamanville (and possibly Barfleur) granites at 318 ± 1.5 Ma (U/Pb zircon; Brun et al., 1990; Martin et al., 2018) (Figures 2a and 2b). The cross-section in Figure 2b shows a decreasing structural complexity southward from southerly directed thrust sheets involving Cadomian/Archean terranes along the North Cotentin shear zone to shallower fold/thrust structures restricted to the Paleozoic sedimentary pile (Butuaye et al., 2001; Dissler & Gresselin, 1989; Dupret & Le Gall, 1984; Goguel, 1977). In parallel, the intensity of deformation shows a gradual decrease southward down to zero immediately north of the N70°-oriented Saint-Germain-sur-Ay fault. The latter is commonly regarded as an inherited Cadomian structure which was later rejuvenated as a major extensional fault bounding to the south a prominent Ordovician-Devonian sedimentary basin (Doré & Poncet, 1978; Dupret et al., 1989; Gigot et al., 1999; Le Gall, 1993). The dominantly pre-Ordovician units exposed south of the Saint-Germain-sur-Ay fault are very little affected by Variscan deformation. There, the most demonstrative evidence of Variscan overprint is the reverse reactivation of Cadomian faults (Coutances) (Doré et al., 1988; Doré & Poncet, 1978), whereas Carboniferous limestones in the discrete Montmartin-sur-Mer basin (Figure 2a) display a nearly flat-lying structure (Dupret et al., 1989).

The western offshore extent of the North Cotentin Variscan belt in the Normano-Breton Gulf (NBG) and English Channel islands areas is only partially mapped from rock sampling interpretation and geophysical records (Galdeano et al., 2001; Grandjean et al., 2001; Lefort, 1975; Oehler & Lalancette, 2019). On the geological map of Chantraine et al. (2003), discrete fault-bounded Cadomian basement inliers exposed in the Jersey-Guernesey-Serk islands are surrounded by offshore Ordovician-Devonian metasedimentary series extending as far south as the Ordovician grits in the Erquy coastal sections (Figure 2a). To the southeast, the offshore Paleozoic series are juxtaposed with Cadomian basement rocks along a NE-SW discontinuity that merges onshore to the SW with the La Fresnaye shear zone (its onshore extent to the NE along the Coutances fault is challenged below) (Figure 2a). The western extent of the offshore Paleozoic series toward the Tregor Peninsula is poorly known. To the north, they form a narrow offshore strip of Devonian sediments, as far west as the Ploumanach granitic intrusion (Figures 2a and 2c) (Chantraine et al., 2003). Onshore

Paleozoic series are locally present in the Tregor Peninsula as Ordovician volcano-sedimentary sequences restricted to the Brehec half-graben-like basin (Figure 2a) (Ballard et al., 1991; Suire et al., 1991). Their still preserved synrift depositional architecture (Egal et al., 1996; Galerne et al., 2006) argues for the relative stability of the Tregor Cadomian area during the Variscan orogeny. There, Variscan events only resulted in the reverse reactivation of the previous Tregor extensional fault bounding the Brehec half-graben to the north (Chantraine et al., 1999).

Paleozoic metasedimentary series also occur at the eastern edge of the NAD as parts of the narrow and EW-trending Bocaine Zone syncline pattern (Figure 2a). There, Brioverian molasses, spanning the Late Proterozoic-Cambrian boundary (Guerrot et al., 1992), postdate the main Cadomian events and are overlain by >1,500-km-thick Cambrian continental deposits and a relatively thin (<500 m) succession of Ordovician-Silurian shallow-marine sediments (Vernhet et al., 2002). The modest amount of Variscan shortening in this area resulted in large-wavelength synclines (Butuaye et al., 2001). Excepted the network of 320–290 Ma syntectonic granites associated to the North Armorican shear zone (Chauris, 1969; Guillet et al., 1985; Peucat et al., 1984), Paleozoic magmatism in the NAD is represented by a variety of Carboniferous intrusions involving (Figure 2a): (a) 303–318-Ma-old granites (Ploumanach, Flamanville, Barfleur) (Martin et al., 2018; Vidal, 1980), (b) a ca. 330-Ma-old submeridian doleritic dyke network (Saint-Malo and Fougeres areas, Lahaye et al., 1995; Leutwein et al., 1972; Pochon et al., 2016), and (c) a polyphase magmatic complex in the Morlaix-Tregor transition zone (299 ± 12-Ma-old Carantec granite [Chantraine et al., 1985]; Saint-Jean-du-Doigt gabbro, 347 ± 4-Ma-old [Barboni et al., 2010; Carrof et al., 2011]; trondjhemite and dolerite intrusions [Chauris, 1978]).

### 2.3. The Morlaix-Tregor Transition Zone

As defined here, the Morlaix-Tregor transition zone is subdivided into three distinct tectono-metamorphic units, ranging from greenschist to amphibolite facies (Figure 2c). They consist from the east to west of: (a) Brioverian volcano-sedimentary deformed series in the Tregor region, at the westernmost end of the NAD, (b) Paleozoic strained (Variscan) series in the Morlaix region sensu stricto, and (c) mostly undated metasedimentary series fringing the eastern edge of the Leon Variscan metamorphic domain (LMD). The transition from Brioverian to Variscan units to the east is partly obliterated by the intricate magmatic pattern evoked in Section 2.2.2.

#### 2.3.1. The Western Edge of the Tregor Cadomian Terranes

The northern part of the Tregor Peninsula is an E/W-oriented belt of pre-Paleozoic units comprising, to the north, the little deformed Tregor batholith and discrete 2.7-Ga-old Archean inliers, and to the south, a deformed volcano-plutonic complex, 615 Ma in age, bounded by the Locquemeau fault (Chantraine et al., 2001). The E-W-trending ductile fabrics (cleavage) swings counterclockwise westward in the Lannion bay, before wedging out laterally south of the nearly unstrained Saint-Jean-du-Doigt gabbroic intrusion. The Cadomian versus Variscan age of ductile deformation in the Tregor area is still controversial (Autran et al., 1979; Auvray, 1979). However, a Cadomian age is more likely (Balé & Brun, 1983) given the lack of Variscan overprint in the Brehec Ordovician half-graben (Egal et al., 1996; Galerne et al., 2006).

#### 2.3.2. The Morlaix Area Sensu Stricto

The regional structure in the Morlaix area is dominated by a submeridian belt of low/medium-grade metamorphic series decreasing in age eastward from Brioverian up to lower Carboniferous (Figure 2c). They are involved in a syncline-like structure obliterated to the east by the Saint-Jean-du-Doigt gabbro, and sharply cut to the north by the E-W-oriented Carantec granite. The youngest (Visean) series display an intricate structural pattern, with variously oriented synfold cleavages, possibly detached from the underlying and poorly dated (Ordovician-Devonian) metasedimentary series that occur with a general easterly dipping attitude further west, on the western flank of the Morlaix syncline (Cabanis, 1972). The litho-stratigraphic content of these dominantly terrigenous series differs from those developed in the CAD to the south, hence suggesting the specific context of the Morlaix basin during Paleozoic times (Cabanis et al., 1981; Chantraine et al., 1985). The anomalously N-S-trending structural grain in the Morlaix area swings clockwise southward and merges into the E-W-oriented (Variscan-type) structures in the CAD (Figure 2c). More disputable is the nature of the transition westward from the Paleozoic metasedimentary succession to dominantly micaschist series, mostly Brioverian in age (Cabanis, 1975), that in turn give way to medium/high-grade rocks in the LMD. Because of its specific geological content, comprising syntectonic granitoid complexes and the only HT metamorphic Variscan units (sillimanite/migmatite facies) north of the North Armorican shear zone, the LMD is generally considered as an exotic domain which was tectonically juxtaposed with the surrounding, and supposedly lower-grade Paleozoic series. This tectonic contact is variously interpreted as either a dextral transcurrent shear zone (Balé & Brun, 1986) or a major thrust (Ballèvre et al., 2009; Faure et al., 2008, 2010; Rolet et al., 1986). However, the thrust contact that should have supported the allochthonous-type models has never been so far documented in the field (Authemayou et al., 2019; Faure et al., 2010; Le Gall et al., 2014). Additional conflicting evidence against the allochthonous hypotheses come from the metamorphic pattern observed on the southern flank of the LMD dome, at the transition to the CAD (Figures 2a and 2d). The southerly inclined metamorphic series on the cross-section in Figure 2d recorded epizonal-mesozonal P/T conditions that increased gradually northward from the Paleozoic series (pyrophyllite-chlorite facies) toward the structurally lower part of the upper crustal pile (sillimanite/migmatite facies) without any gap or reverse position of metamorphic gradients (Jones, 1994; Paradis et al., 1983; Schulz, 2013). For clarity, the concept of two distinct juxtaposed metamorphic domains is still maintained in the present work, but in terms of infracrustal (LMD) and supracrustal (CAD-Morlaix) domains forming a quasicontinuous and coherent crustal section, exhumed on the southern limb of the regional-scale LMD dome (Authemayou et al., 2019). These two domains occur on both sides of an arbitrary map-boundary in the Brioverian series (Figure 2d). Interestingly for our purpose, the Variscan ductile fabrics in the LMD are also deflected eastward from a N70°E regional trend to a quite anomalous N-S orientation in the Morlaix area (Figure 2c). This structural anomaly, along with specific characteristics of the Paleozoic sedimentary and magmatic patterns in the Morlaix area (evoked above), have been previously attributed to a submeridian crustal-scale heterogeneity at the eastern edge of the Tregor Cadomian block, but without any detailed structural evidence and corresponding kinematic models (Chantraine et al., 1985; Chauris, 1972).

The age of the onset of Variscan deformation in Northern Armorica is still a critical issue because of missing geochronological constraints. However, correlations with the timing pattern applied to Paleozoic deformed terranes in the surrounding LMD and CAD (Darboux & Le Gall, 1988; Le Corre, 1978; Le Gall et al., 1992) suggest a single orogenic event in late Carboniferous times without a Bretonian phase at the Devonian/Carboniferous boundary (Faure et al., 2010; Rolet, 1982; van Noorden et al., 2007).

## 3. Methodology

Most of the new results obtained during the present study come from an onshore/offshore structural approach that combines field observations/measurements and high-resolution bathymetric records (Figure 3). New insights into Variscan tectonics in the North Cotentin fold-and-thrust belt are also acquired from partly revised and reinterpreted published data. Since our work is chiefly devoted to the Paleozoic (extensional) and Variscan (compressional) events recorded by the NAD, its Cadomian tectono-metamorphic history is only mentioned from the literature (Section 2.2.1). A summary of published data about the structural pattern of Proterozoic/Cadomian terranes in the Central/Western European Variscides (Section 2.1) helps to draw more global implications discussed in Section 5.4.

### 3.1. Field Structural Data

Structural field work has been focused on the Morlaix-Tregor transition zone (Figure 2a) with the aim to investigate the nature of atypical N-S-oriented Variscan ductile deformations displayed by Paleozoic series at the western periphery of the NAD (Tregor Peninsula). The most significant results have been obtained on coastal sections continuously exposed along the western and eastern sides of the Morlaix embayment (Figure 2c). Emphasis has been put on kinematic criteria prone to evaluate the validity of previous thrust models. Field observations have also been realized in the North Cotentin fold-and-thrust belt, but the most pertinent results are derived from published data that enable us to extrapolate the regional fold/thrust structure at shallow depth and then to estimate the amount of corresponding shortening.

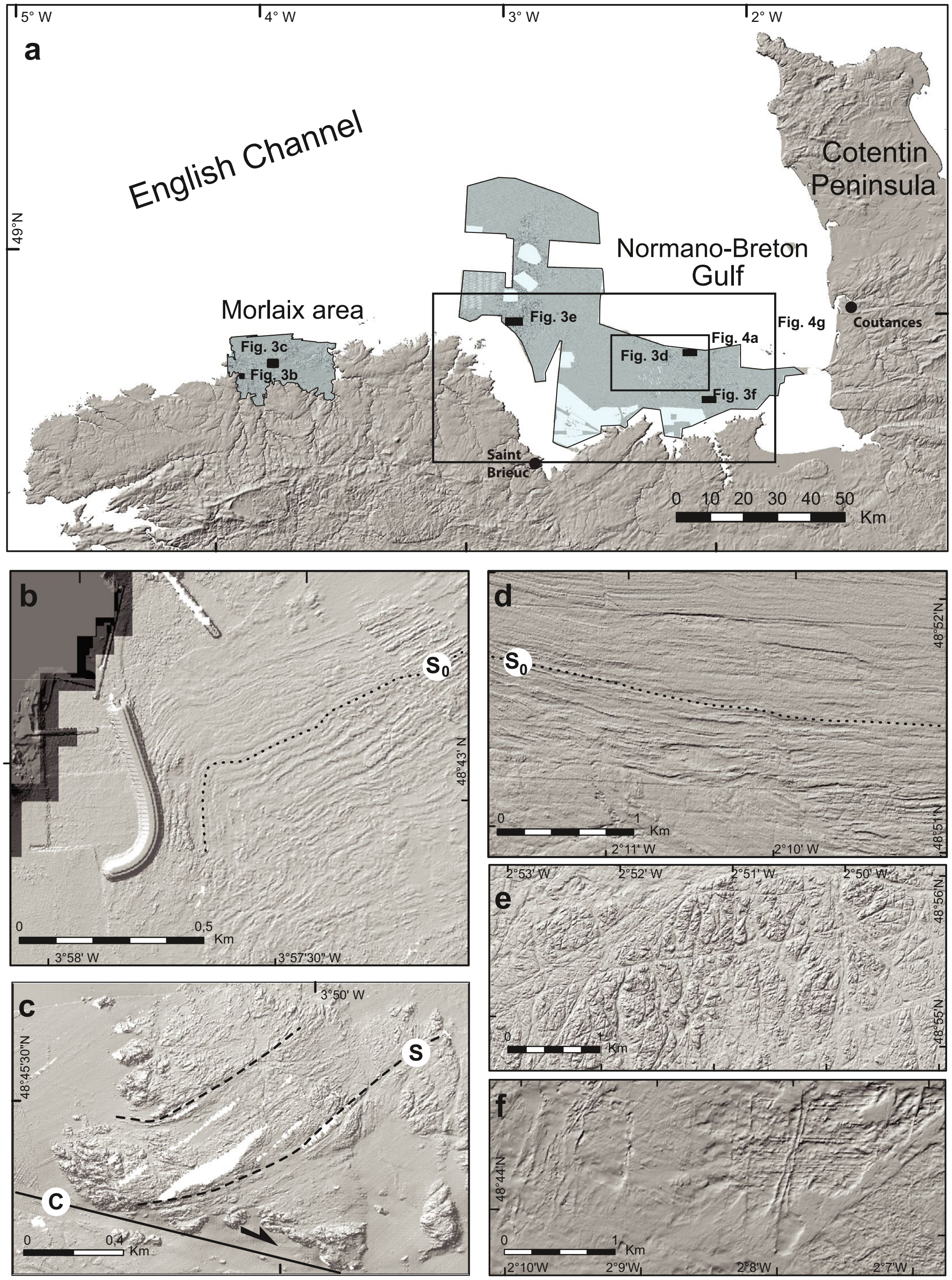



**Figure 3.** Onshore and offshore studied areas. (a) Map location of the Morlaix and Normano-Breton gulf (NBG) offshore surveys. Location of Figures 3b–3f, 4a, and 4g is shown. (b and c). Main types of structural fabrics identified in the rocky seabed of the Morlaix offshore area. Location in Figure 3a. (b) Regularly spaced and parallel lineaments interpreted as the trace of sedimentary layering in Brioverian series (drawn as a dotted line $S_0$). (c) C/S-type sigmoid fabrics indicative of a dextral ductile shear zone in the Trepied granitic intrusion (S, schistosity). (d–f). Main types of structural fabrics identified in the seafloor of the NBG offshore area. Location in Figure 3a. (d) Regularly layered and parallel lineaments interpreted as the trace of (Siluro-Devonian) sedimentary strata (drawn as a dotted line $S_0$). (e) Fracture networks in magmatic material off the Tregor Cadomian plutonic complex. (f) Submeridian topographic "ridges" correlated with lower Carboniferous doleritic dykes.

### 3.2. High-Resolution Offshore Bathymetric Data Set

#### 3.2.1. The NBG

Bathymetric data have been acquired in the NBG offshore area by Shom (Service hydrographique et océanographique de la marine) using recent multibeam echo sounders (MBES) (Simrad EM1002, EM710) onboard French navy ships Laperouse, Borda, and Macareux. The studied area includes 17 surveys performed from 2003 to 2015 (Table S1). Following conventional data processing, data precision is <5m in horizontal and <0.7 m on the vertical (both values given at 2 sigma, supposing a Gaussian distribution of uncertainties). The local chart datum, assimilated with the Lowest Astronomical Tide (LAT), has been used as the vertical reference. A compilation of all bathymetric soundings lying in the area of interest has been gridded in a digital bathymetry model (DBM), using the neighbor function of the Generic Mapping tools (Wessel et al., 2013) with a grid size of 5 m and a search radius of 15 m.

#### 3.2.2. The Morlaix Offshore Area

LiDAR data, combined with swath bathymetry records from MBES, were collected between 2005 and 2014 with high-resolution records over a ~513 km$^2$ offshore area in the Morlaix bay (Table S2). LiDAR techniques alone are commonly used in a variety of geoscience applications, however combining aerial LiDAR and echosounder records in marine context, as performed in the present work, is a much more original and complex technique (Duperret et al., 2016; Ehrhold et al., 2015; Le Gall et al., 2014; Raimbault et al., 2018). The DBM elaborated in the present study is corrected to the LAT level and at 5 m horizontal resolution (Figures 3a–3c). The LiDAR measurements are referenced to the ellipsoid RGF93 datum used by the Global Positioning System. The LiDAR vertical reference surface was first modified with Bathyelli 2.0 (Shom) to be referenced to the LAT level, and then integrated into ArcGis software to produce raster grid files at 1 and 5 m resolution. Acoustic swath-mapping surveys were also conducted in the Morlaix bay between 2005 and 2014 using different MBES in the deepest parts (from −10 m down to −80 m), as well as an interferometric sidescan sonar in shallow water (<−10 m) (Table S2). The multibeam data acquired insonified 100% of the seafloor with at least a 20% overlap of the echo-sounding corridors. Bathymetric data from raw acoustic profiles were first processed for corrections (filtering, sound speed velocity, navigation, tidal) with the Globe software (Ifremer©), in order to elaborate a DBM displaying the same vertical reference as the LiDAR data set (i.e., the LAT).

#### 3.2.3. Structural Attributes of Bathymetric Data

On the basis of diagnostic criteria previously applied to similar offshore data in the Molène archipelago (Figure 2a; Le Gall et al., 2014), the lineament pattern extracted from the DBM in the Morlaix and NBG areas has been interpreted as either (meta)sedimentary structures (layering) or ductile/brittle tectonic fabrics (schistosity, shear zones, faults) from their geometrical attributes (length, spacing, spatial distribution, sinuosity), along with onshore correlations. The key-question about the Cadomian versus Paleozoic age of the offshore tectonic fabrics has been addressed by offshore/onshore correlations.

The bathymetric survey in the NBG offshore area (Figure 3a) corresponds to a poorly mapped area extensively masked by a thin cover of Upper Cretaceous-Eocene sediments (Bouysse et al., 1975). According to the published maps of Lefort (1975) and Chantraine et al. (2003), the rocky substratum corresponds to Paleozoic series (east) and the Tregor Cadomian basement rocks (west) (Figure 2a). On the DBM in Figures 3d–3f, these two distinct varieties of bedrock material display three types of bathymetric signatures. The first type of structures corresponds to a network of parallel, closely spaced and 1–2-km-long lineaments observed in the eastern part of the survey area (Figure 3d). Their interpretation as the trace of metasedimentary strata is confirmed by their spatial coincidence with the Paleozoic series (mainly Devonian) previously mapped by Lefort (1975). The second type of structures is expressed to the west by a rough topography, further dissected by an intricate network of variously oriented fault-like structures (Figure 3e). It is confidently regarded as fractured magmatic intrusions that correlate westwards onshore with the Cadomian Tregor batholith. The third type of structures is expressed by a relatively dense network of straight and narrow ridges, averaging 2 km in length and 1 km in spacing (Figure 3f). Correlations with magnetic anomalies support their interpretation as the map-trace of the Saint-Malo dolerite dykes mentioned in Section 2.2.2. Using the same criteria allows us to discriminate two similar types of offshore basement structures in the Morlaix bay. These are: (a) parallel and closely spaced lineaments, interpreted as the trace of regularly stratified metasedimentary rocks (Figure 3b) and (b) a network of sigmoid-shaped discontinuities occurring in elongate inliers of granitic (Trepied) and gabbroic (Duons) material (12 rock sample determinations) and regarded as strike-slip ductile shear zones (Figure 3c).

## 4. Results

### 4.1. Basinal Structures of the Paleozoic Offshore Series in the NAD

The high-resolution bathymetric data acquired in the NBG offshore area provide the first comprehensive map view of Paleozoic metasedimentary series previously mapped from only scattered dredgings (Figure 4) (Lefort, 1975). The most impressive structures identified on the DBM in Figures 4a and 4b are the regularly spaced lineament pattern observed over a >200 $km^2$ area in the eastern part of the survey area. These lineaments, interpreted as a trace of metasedimentary strata in Figure 3d, partially overlap with the Ordovician/Devonian series of Lefort's map (1975). These Paleozoic sequences display interesting features regarding their depositional context. Among them, the layered package in Figures 4a and 4b is seen to thicken dramatically westwards from ca. 5–8 km toward a prominent NW-SE-oriented fault (Fa). This thickness pattern is not due to repetition by folding. Therefore, it is attributed to an initially wedge-shaped sedimentary prism developed in the hanging-wall of a syndepositional extensional fault (Fa), currently facing to the NE. The thickness of this (presumably Ordovician-Devonian) sedimentary wedge emphasizes the importance of subsidence and depositional processes, possibly in relation with NW-SE faults, in parts of the NBG offshore area. On the map in Figure 2a, these Paleozoic series are juxtaposed to the south with Cadomian basement rocks along a NE-SW discontinuity running in the offshore extent of the La Fresnaye Cadomian shear zone (Lefort, 1975). This inferred basin boundary is partly viewed on the DBM in Figures 4a and 4b as a lineament separating two distinct seafloor domains with contrasted bathymetry. Our bathymetric data set provides no information about the western limit of the NBG Paleozoic offshore series toward the Tregor Peninsula. However, the faulted and segmented trace of this limit is deduced from the sharp and NW-SE-trending eastern termination of Cadomian basement units (Tregor and Saint-Brieuc) on the magnetic map of Oehler and Lalancette (2019).

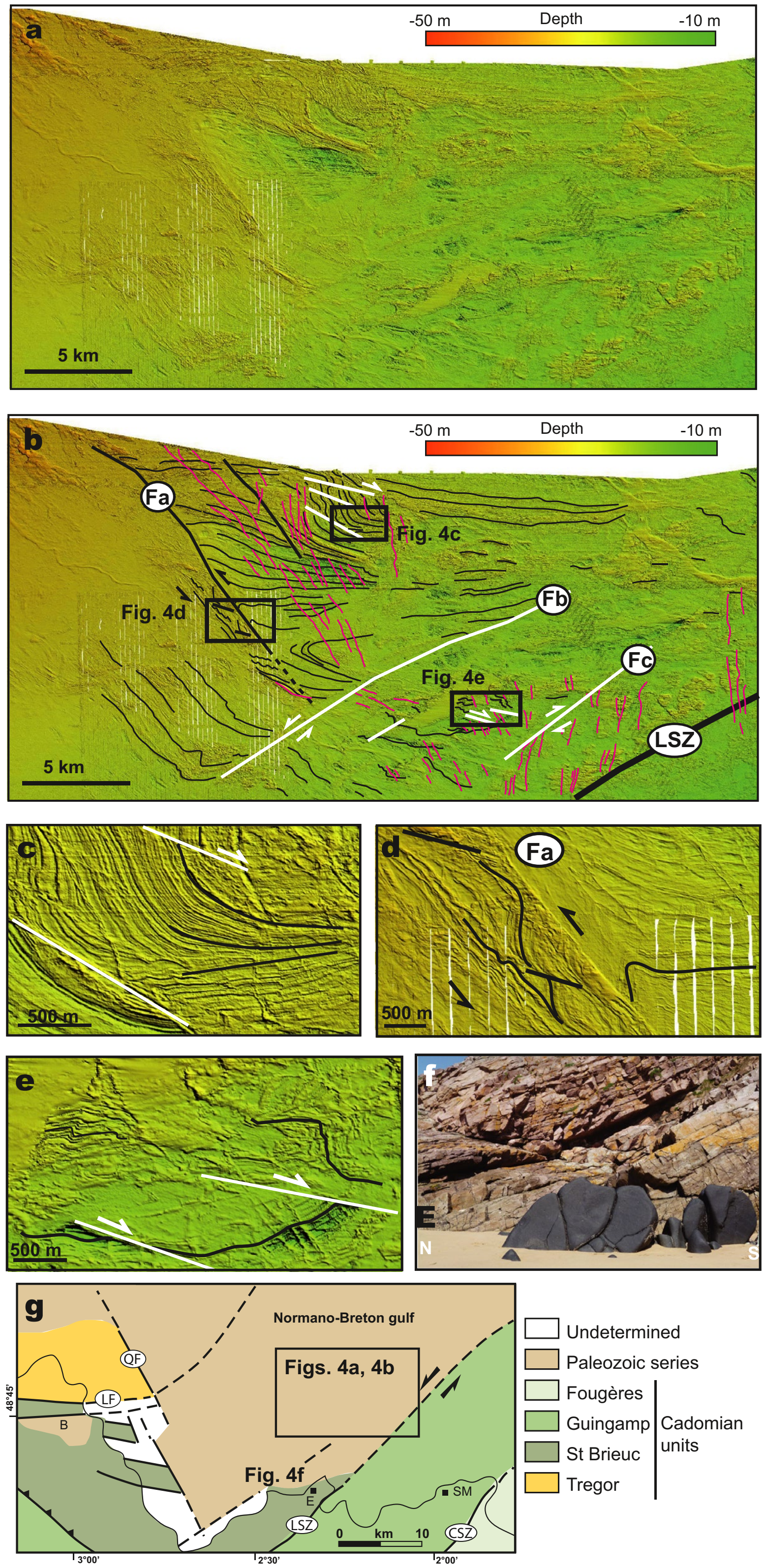
### 4.2. Variscan Tectonics in the Cadomian-Floored NAD

#### 4.2.1. Compressional Structures in the Offshore NBG Paleozoic Series

Variscan deformations in the southern part of the NBG offshore area are clearly expressed by km-scale folds imaged in well-layered Ordovician-Devonian sequences on the high-resolution DBM in Figures 4a and 4b. The intensity of Variscan shortening in this area is suggested by the development of nearly isoclinal fold structures, preferentially oriented E-W (Figures 4a and 4b). The asymmetry of second-order folds is compatible with apparent east-directed dextral shearing during folding (Figures 4c and 4e). Fold structures are dissected by a dense array of NW-SE (Fa) and NE-SW (Fb and Fc) faults that display, for most of them, a strike-slip component deduced from the curvature of drag-folds in the adjoining Paleozoic strata (Figure 4b). The sinistral rejuvenation of the syndepositional fault (Fa) (see above) is better expressed by the 2-km-wide zone of asymmetrical folds developed in its immediate (western) footwall block (Figure 4d).

#### 4.2.2. The North Cotentin Fold-And-Thrust Belt

The style of Variscan tectonics in the North Cotentin fold-and-thrust belt has been extensively described by previous authors (Section 3.2.2; Butuaye et al., 2001; Dissler & Gresselin, 1989; Dupret & Le Gall, 1984; Goguel, 1977). However, a few additional issues are here addressed on the basis of the structural cross-section elaborated in Figure 5b from revised/completed published data (Figure 2b; Goguel, 1977). In the absence of deep structural data (seismic and drilling), this cross-section is only slightly extrapolated at shallow depth, neither it represents a true balanced section. It shows many of the features of a thin-skinned foreland thrust belt with thrust ramps assumed to cut up-section in the direction of propagation (southward) from basement-rooted ramps ($\beta_a$) to shallower structures involving only Paleozoic series as far south as the Le Rozel frontal thrust. The latter separates two Paleozoic folded units possibly detached at depth along a step-like decollement level. The approximate limit of folding to the south likely marks the Variscan deformation front, close to the Saint-Germain-sur-Ay fault. From the surface/subsurface fold-and-thrust pattern


a
-50 m
Depth
-10 m
5 km
b
Fa
Fig. 4c
Fig. 4d
Fb
Fc
Fig. 4e
LSZ
c
500 m
d
e
f
N
S
g
Normano-Breton gulf
Figs. 4a, 4b
QF
LF
B
48°45'
Fig. 4f
E
SM
LSZ
CSZ
0 km 10
3°00'
2°30'
2°00'
Undetermined
Paleozoic series
Fougères
Guingamp
St Brieuc
Tregor
Cadomian units

in Figure 5b, a rough estimate of bulk shortening has been calculated by: (a) restoring the initial bed-length of specific reference stratigraphic contacts at a prefolding stage, and (b) assuming minimum displacement along each major thrust ramp from the cut-off geometry of footwall/hangingwall stratigraphic limits. These minimum estimates are based on the assumptions that the Paleozoic sedimentary template initially displayed a layer-cake architecture in each thrust-bounded units and that additional structural complexities are lacking at shallow depths. The amount of displacement along individual thrust structures is in the range 2.5–4.0 km, with a maximum value for the Cambrian-involving thrust $\beta_b$. Finally, the amount of cumulate shortening on the ca. 100-km-long deformed section is estimated to be at around 30% with a relative contribution of folding (18%) and thrusting (12%), respectively.

### 4.3. Anomalous Variscan Deformation at the Western Periphery of the NAD

The Brioverian-Paleozoic metasedimentary series (low/medium-grade) extending west of the Saint-Jean-du-Doigt gabbro are involved in a submeridian monocline-like structure (Figure 6a) never so far integrated in a regional-scale kinematic framework. This is attempted below from diagnostic structures identified on both sides of the Morlaix bay.

#### 4.3.1. The Penze Sinistral Shear Zone

West of the Morlaix bay, the low/medium-grade micaschists (probably Brioverian in age) exposed on the ~5-km-long submeridian coastal section north of the Penze river contain elongate bodies of meta-basic rocks (amphibolites) (Figure 6a) (Chantraine et al., 1985). Whatever the fine-grained, porphyric or layered facies of these rocks, they all display a prominent linear fabric corresponding to a stretching lineation ($L_1$). The latter is marked by aligned and elongated amphibole phenocrysts that plunge in the range 30–60° to the S-S/E (Figures 6b2 and 6c). In the porphyric and layered facies, the lineation lies on a weak foliation plane ($S_1$), oriented N30°-N160°E in a steep position (Figures 6b1 and 6c). In oriented thin sections (XZ), orthogonal to $S_1$ and parallel to $L_1$, elongated amphibole-muscovite-chlorite assemblages outline sigmoid-shaped $S_1$ surfaces that typically display C/S-type fabrics, indicative of sinistral shearing (Figure 6d1). In contrast, fine-grained amphibolites exclusively show a linear fabric ($L_1$), with no visible trace of foliation. When observed in lineation-normal sections, these rocks show amphibole porphyroclasts without any shape-preferred orientations, whereas lineation-parallel sections show asymmetric-shaped amphiboles and K-feldspar porphyroclasts that recorded sinistral shear-related rotations (Figure 6d2). At first approximation, the Penze elongated amphibolites relate to oblate-like strain ellipsoids and locate near the constrictional axis of the Flinn diagram, with $X >> Y > Z$ (Flinn, 1965). Their 3D-fabrics resemble those of L > S- and L-tectonites (Solar & Brown, 2001; Sullivan, 2013). The highly strained mafic rocks identified here are related to the so-called Penze submeridian sinistral ductile shear zone (PSZ), the width and southern extent of which still remain undetermined.

#### 4.3.2. The Barnenez Sinistral Shear Zone

Additional support for submeridian strike-slip tectonics in the Morlaix transition zone is found along coastal exposures east of the bay (Figures 6a and 7). There, immediately west of the Saint-Jean-du-Doigt gabbro, a narrow strip of Carboniferous schists (metapelites), oriented N-S, is intruded by: (a) a dense (undated) swarm of doleritic bodies occurring as either massive sheets (south), or a closely spaced network of <10-m-thick sills (north), parallel to the easterly dipping regional cleavage ($S_1$) and (b) a few trondhjemite dykes, <1-m-thick (Figure 7a). The entire submeridian tectono-magmatic pattern is cut at high angle to the north by the E-W-oriented Carantec granite (Figure 6a). The easterly dipping regional cleavage ($S_1$) is spa-

**Figure 4.** Structural features in offshore Paleozoic series of the NBG basin. (a) Original and (b) interpreted digital bathymetry model (DBM) showing synsedimentary and tectonic structures in Paleozoic deposits. Labeled structures are discussed in the text. Dark thick lines are shear zones. White thick lines are brittle faults. Red short lines are submeridian Carboniferous dolerite dykes. LSZ, La Fresnaye Cadomian shear zone. Focused views of the high-resolution DBM in Figure 4b showing: (c) A synsedimentary wedge thickening laterally westwards (observed in an horizontal surface); (d) Sinistral shear-related fold structures in the footwall block of the fault Fa; (e) second-order asymmetrical folds related to easterly directed dextral shearing. (f) Field view of Ordovician grits, slightly tilted (25°) to the north and intruded by a vertical and submeridian doleritic dyke (in black), lower Carboniferous in age, in the Erquy coastal area. Location in Figure 4g. (g) Sketch structural map of the western offshore boundary of the NBG Paleozoic basin. The two rectilinear (NW-SE) segments labeled "QF" are drawn from Oehler and Lalancette (2019). Same abbreviations as in Figure 2a. Location in Figure 3a.

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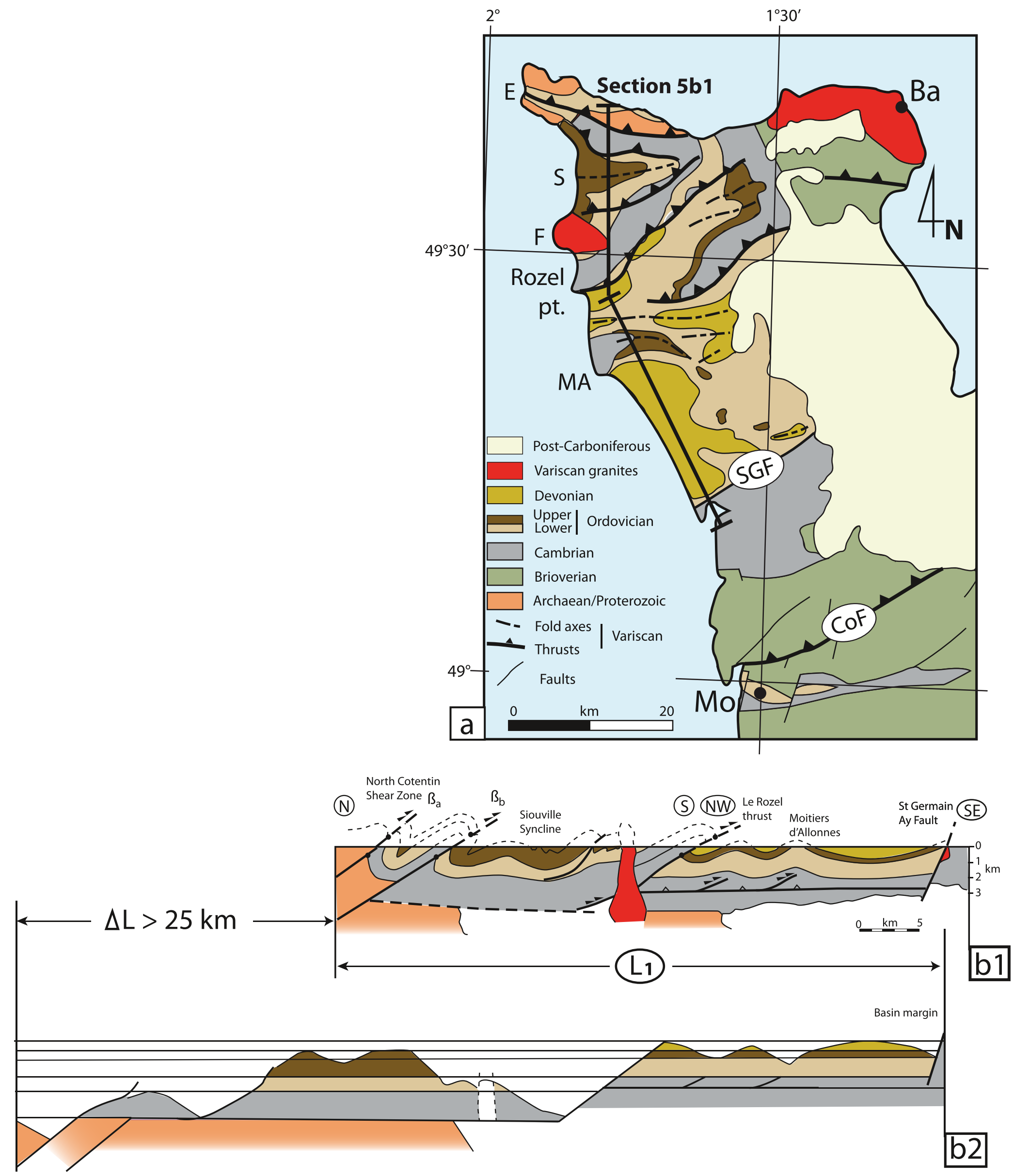


**Figure 5.** Style of Variscan deformation in the North Cotentin fold-and-thrust belt. (a) Simplified geological map, modified from Chantraine et al. (2003). The location of cross-section in Figure 5b1 is shown. Ba, Barfleur; CoF, Coutances fault; F, Flamanville; MA, Moitiers d'Allonnes; Mo, Montmartin-sur-Mer; S, Siouville syncline; SGF, Saint-Germain-sur-Ay fault. (b) Deformed (b1)/restored (b2) structural cross-sections, completed to the south and extrapolated at shallow depth from the section of Goguel (1977) in Figure 2b. Thrust ramps are labeled $\beta_{a,b}$. Bold points correspond to the cut-off points used to estimate thrust displacements. The intra-Cambrian decollement level south of the Le Rozel frontal thrust ramp is hypothetical. See text for explanations. Trace of section in Figure 5a.

tially associated with cm/dm-scale isoclinal folds involving thin volcanic layers, with axes plunging weakly (<20° in average) to the north (Figure 7b1), parallel to a stretching lineation ($L_1$) with a mean plunging attitude at 18° to 10°N (Figure 7c). The asymmetrical shape of the syn-cleavage folds indicates a component of sinistral shearing (Figure 7b1). Quite similar kinematics is revealed by: (a) S/C-type fabrics developed in dm's-wide shear zones along sill/host rock margins (Figure 7a), (b) a boudinage and stretched trondhjemite dyke (50-cm-thick), initially oblique to $S_1$, and later reoriented along sinistral shear planes parallel to $S_1$ cleavage planes (Figure 7b2), and (c) a second generation (post-$S_1$) of asymmetrical folds, with axes plunging weakly to the south (Figure 7b3). All these ductile deformations typically characterize the so-called

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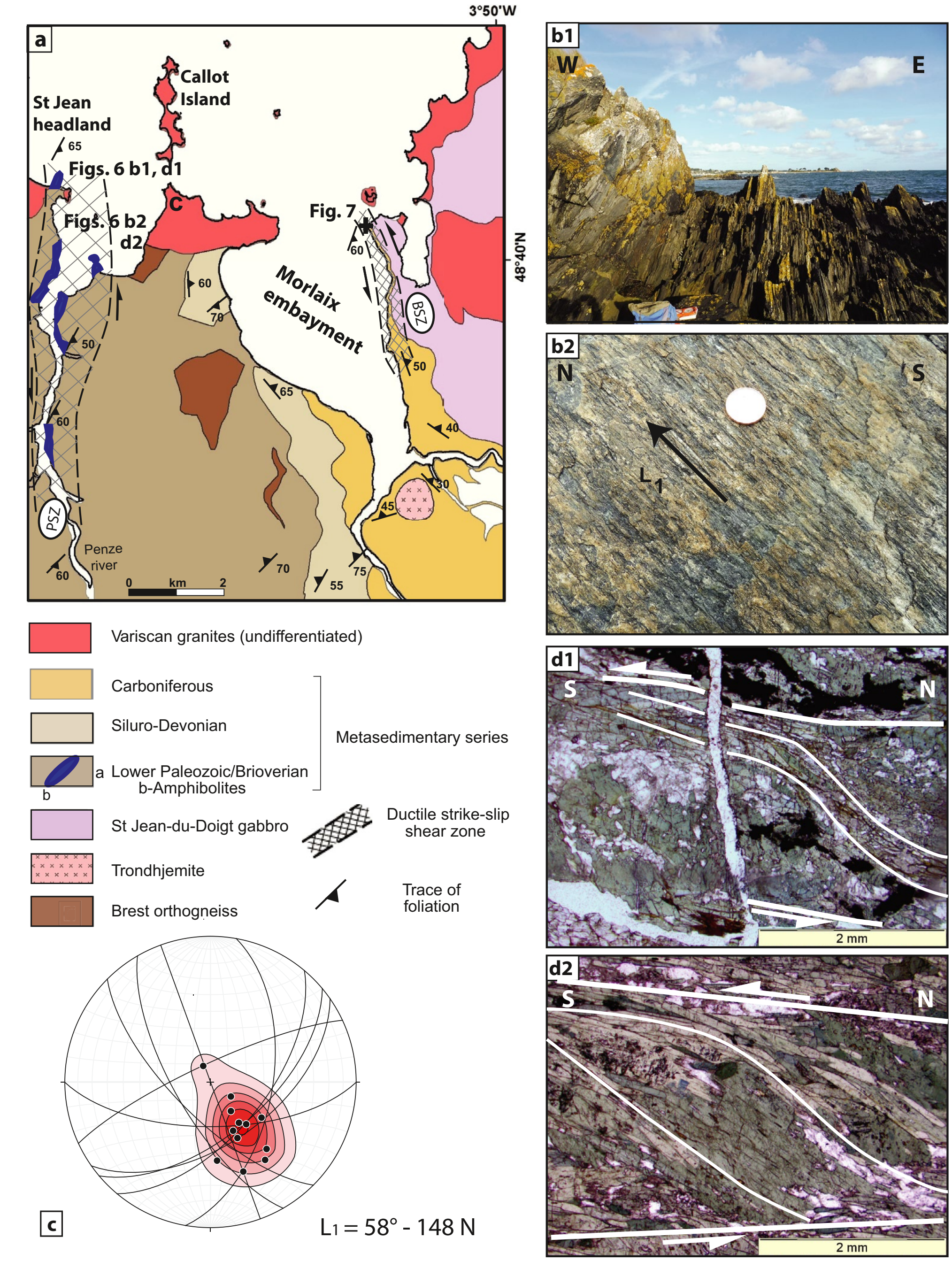


**Figure 6.** Structural evidence for the Penze high-strain sinistral ductile shear zone (PSZ) along the western side of the Morlaix bay. (a) Simplified geological map showing field measurements (foliation plane, lineation) and the location of the two sinistral shear zones identified in the present work, modified from Chantraine et al. (1985). BSZ and PSZ, Barnenez and Penze shear zones, respectively. C, Carantec. Location of Figure 7 is shown. (b1 and b2). Ductile deformation in highly strained mafic material. Location in Figure 6a. (b1) A submeridian and nearly vertical foliation in layered amphibolites (Saint-Jean Headland). (b2) Stretching lineation, plunging c. 60° to the south, marked by elongated amphiboles in L tectonite-type amphibolites. (c) Stereogram of foliation planes ($S_1$, great circles) and stretching lineation ($L_1$, black dots) in highly strained amphibolites and micaschist host-rocks. Wulff stereonet, lower hemisphere. (d1) Photomicrograph of an oriented thin section (XZ, orthogonal to $S_1$ and parallel to $L_1$) in a L/S tectonite-type (amphibolite) showing the sigmoid trace of the foliation $S_1$, in response to sinistral ductile shearing. Crossed nicols. Location in Figure 6a. (d2) Photomicrograph of an oriented thin section (southerly dipping and parallel to $L_1$) in a L tectonite-type amphibolite showing a rotated amphibole porphyroblast with asymmetrical pressure-shadows (quartz) consistent with sinistral shearing. Crossed nicols. Location in Figure 6a.

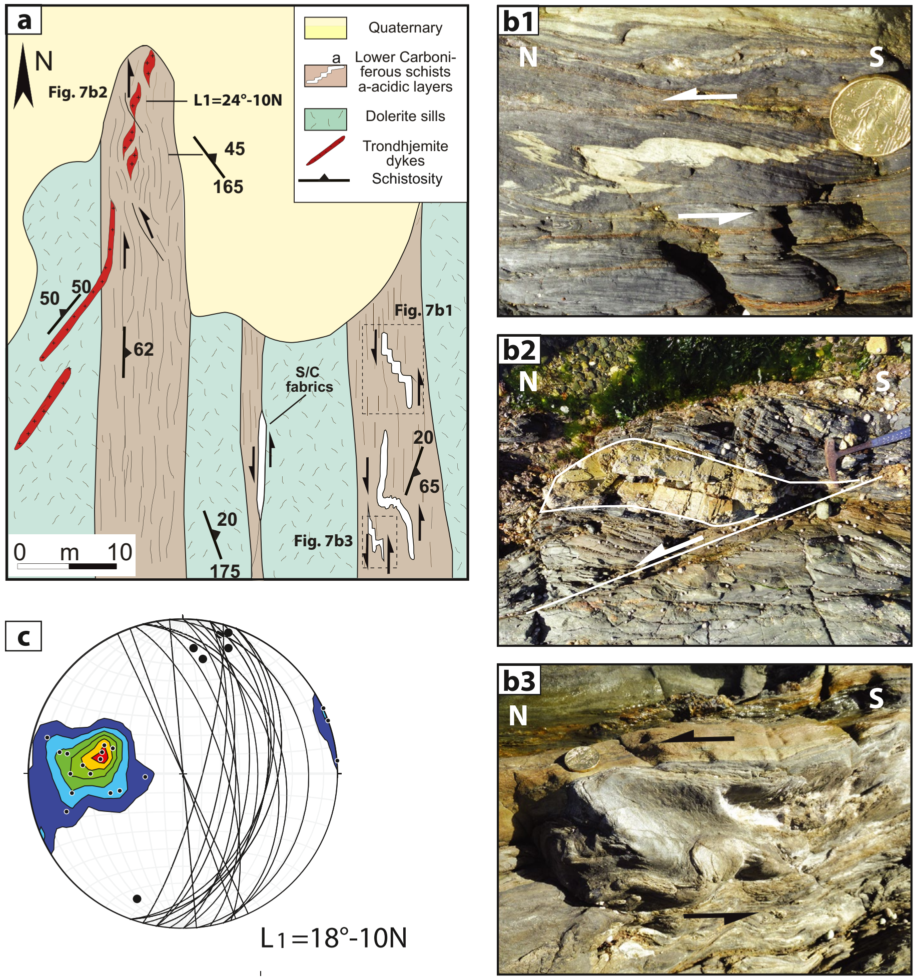


**Figure 7.** Field structural evidence for a sinistral ductile shear zone (BSZ) along the eastern coast of the Morlaix bay. Location marked by a black star in Figure 6a. (a) Structural map showing a submeridian dolerite sill network intruding Carboniferous schist host-rocks, all in turn: (i) intruded by a trondjhemite oblique dyke and (ii) affected by submeridian sinistral ductile shearing. Measurements of planar and linear structures are shown. (b1–b3). Photographs of ductile deformation observed in the field. Location in Figure 7a. (b1) Small-scale asymmetric syncleavage ($S_1$) folds in thin volcanic (felsic) layers, kinematically consistent with northerly directed sinistral shearing. Horizontal view. (b2) A asymmetrical boudinage lens of an initial trondjhemite dyke, further wrapped by sigmoid foliation surfaces $S_1$, and all disrupted by steeply dipping sinistral shear planes. Horizontal view. (b3) Second generation of asymmetrical folds, with moderately plunging axes, affecting the early foliation $S_1$, and still resulting from northerly directed sinistral shearing. (c) Wulff stereogram of ductile structures (foliation planes as great circles, stretching lineations as black dots). Lower hemisphere.

Barnenez sinistral shear zone (BSZ) which remains undetermined about its western limit (seaward), and consequently, its width-dimension.

#### 4.3.3. The Regional Shear Zone Pattern

Despite uncertainties regarding their map dimensions, the PSZ and BSZ shear zones are assumed to be representative of the Variscan kinematics experienced by the Brioverian-Paleozoic units between the Tregor (Cadomian) and LMD (Variscan) domains (Figure 6a). These ductile shear zones are parts of a more extensive regional-scale network that extends offshore in the Morlaix embayment (Figure 8). The trajectory of these ductile deformation is outlined on the DMB in Figure 8a by the trace of LiDAR/multibeam bathymetric lineaments in host-rock material (Figure 3f). The lithology of the latter has been locally determined from collected in situ rock samples (Figure 8a). North of the E-W-oriented strip of the Carantec granite, Variscan deformation is variously expressed, depending of the rock-type material. To the west, a narrow

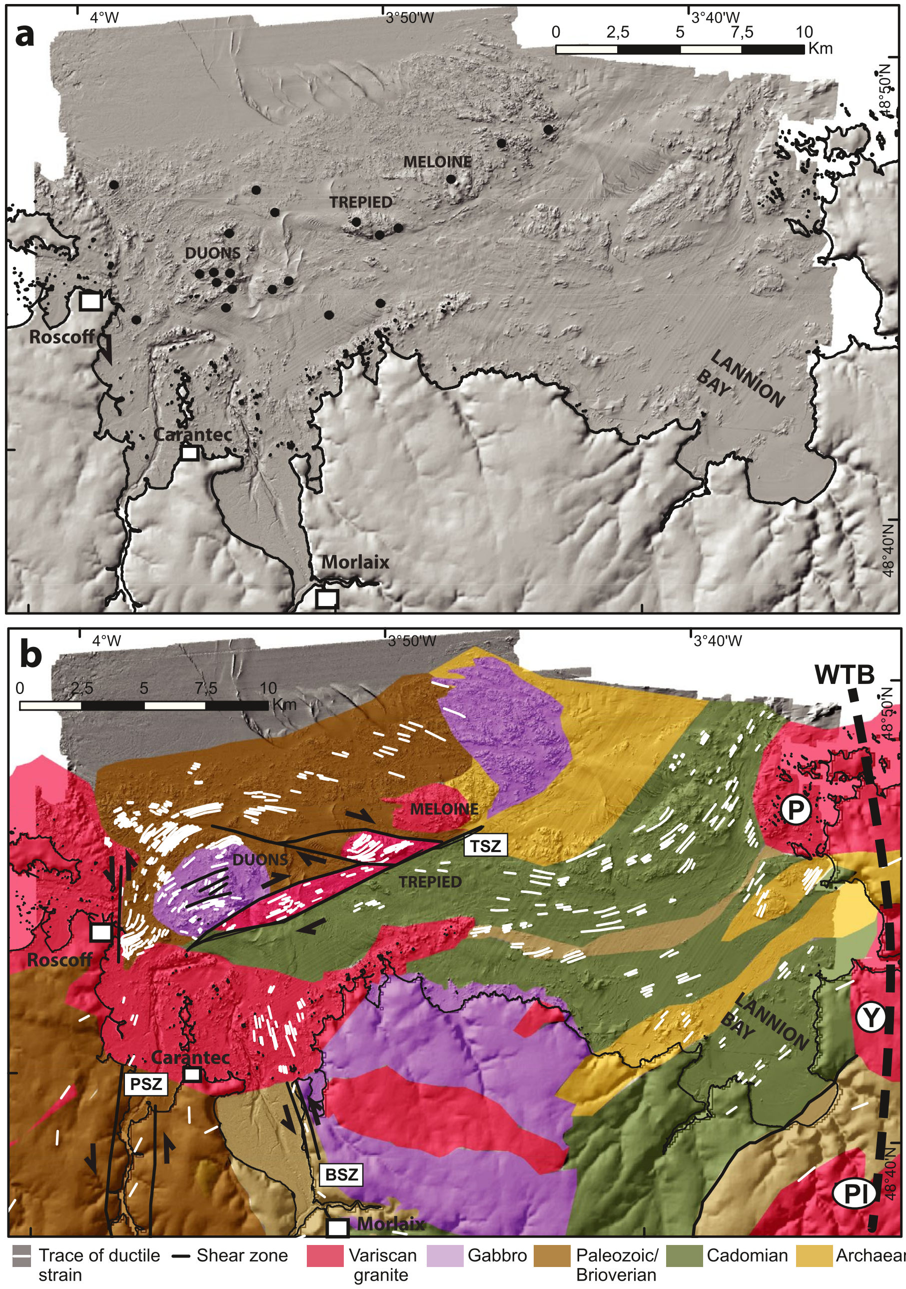


**Figure 8.** Onshore/offshore structural pattern in the Morlaix-Tregor transition zone. (a) Digital bathymetry model elaborated from light detection and ranging (LiDAR) and multibeam records in the Morlaix bay showing the main lineaments identified in the rocky substratum (see Figures 3b and 3c). Black points are rock samples collected by divers. (b) Corresponding structural map illustrating the sigmoid trace of the Variscan ductile deformation. Onshore geology simplified from the 1:50,000 geological maps Morlaix, Plestin-les-Grèves, Saint-Pol-de-Léon, and Lannion (Cabanis et al., 1981; Chantraine et al., 1985, 1999; Chauris et al., 1998). BSZ, PSZ, TSZ, Barnenez, Penze, and Trepied shear zones, respectively. P, Ploumanach; Pl, Plouaret; Y, Yaudet; WTB, West Tregor boundary.

(<1 km) and N-S-oriented band of well-stratified sediment-like structures occurs in the northern prolongation of onshore Brioverian micaschists (Figures 3b and 8b). To the north, it swings eastward into a large-scale fold limb extending as far east as the Trepied granite intrusion. The sigmoid internal fabrics observed in the granite are attributed to a ca. 2-km-wide dextral shear zone, oriented N100°E (Figures 3c and 8b). The so-called Trepied shear zone (TSZ) merges southward into a second dextral shear zone, striking N70°E, expressed by large-scale C/S-type fabrics in the southern edge of the Duons gabbro intrusion (Figure 8b).

The two oblique shear zones die out abruptly eastward against Archean bodies at the westernmost edge of the NAD. The N-S trace of the latter, referred here to as the West Tregor boundary (WTB), is outlined further SE by a granitic lineament oriented N-S and involving the Ploumanach intrusion to the north. The offshore Cadomian ductile fabrics are seen to swing counterclockwise as approaching the WTB structure.

## 5. Discussion

### 5.1. Evidence for a Long-Lived Paleozoic Basin in Northern Armorica

The discrete Ordovician-Devonian inliers in the northern part of the Armorican massif are regarded as the preserved remnants of a >80 × 80 $km^2$ sedimentary basin, referred here to as the NBG or (N)NAD basin, that encompassed the North Cotentin Peninsula and most part of the NBG offshore area (Figure 9a). The NBG basin probably connected northwestwards *via* the offshore Devonian series north of the Tregor coast into the Morlaix Paleozoic basin that, in turn, passed southward into the extensive CAD basin. The development of the NBG basin during Paleozoic times was likely controlled by an orthogonal network of master bounding faults that currently separate its (meta)sedimentary infill series from Cadomian basement rocks along its southern and western margins (Section 4.1; Figure 9a). Most part of its southern faulted boundary coincides with the offshore trace of the La Fresnaye Cadomian shear zone (LSZ). Its generally agreed NE extent onshore along the Coutances Cadomian fault, in the direct prolongation of the LSZ (Chantraine et al., 2001), is instead assumed to occur 15 km further north along the Saint-Germain-sur-Ay fault, described above as a master bounding fault during the Paleozoic basinal stage (Section 2.2.2). The La Fresnaye/Saint-Germain-sur-Ay fault is thus regarded as an inherited crustal-scale structure that nucleated along a pre-existing Cadomian shear zone to the SW and partly controlled the development of the NBG basin during most of Paleozoic times. Its extensional activity might account for the down-flexed geometry of the Erquy Ordovician coastal grits in its immediate hanging-wall to the north (Figures 4g and 9a). The NW-SE fault segments that separate the offshore Paleozoic series from the Tregor Cadomian basement (Section 4.1) might be part of a long-lived and still poorly constrained structure, that is, the Quessoye fault system (Figure 9a). Prior to our work, this transverse fault structure was only inferred from the linear morphology of the East Tregor coastline (Bessin, 2017; Bonnet et al., 2000) with a major downthrow of the NBG offshore block to the NE from the Triassic up to Eocene (Bessin, 2017; Bois et al., 1991). The inherited (Cadomian) origin of the Quessoye fault system is further suggested by its parallelism with the N140°E-oriented basement thrusts that accompany the map deflection of the Cadomian ductile shear zone pattern in the Saint-Brieuc bay (Figures 2a and 4g) (Brun et al., 2001). Its later reactivation as a syndepositional extensional fault might have started during the subsidence of the NBG Paleozoic basin, concomitantly to the La Fresnaye/Saint-Germain-sur-Ay bounding fault to the SE. The high magnitude of the subsidence recorded by the NBG basin was previously predictable at a local scale from the thickness (km's) of the Ordovician-Devonian onshore series in the North Cotentin belt (Dore & Poncet, 1978; Goguel, 1977). It is here confirmed at a wider scale from the offshore sedimentary wedge-shaped prisms imaged south of the NBG area, in relation with a NW-SE-striking synsedimentary fault.

### 5.2. Importance of Variscan Overprint in the (N)NAD

The results above (Section 4.2) supplies a number of new insights about aspects of the Variscan structural pattern in the NAD. (a) The effects of Variscan shortening in the Cadomian-floored NAD are spatially restricted to the NBG Ordovician-Devonian basin developed north of the La Fresnaye-Saint-Germain fault system (Figure 9b). (b) During basin inversion, the progressive decrease of Variscan strain southward, toward the Saint-Germain-sur-Ay fault, suggests the control of this southern basin margin on the location of the deformation front in the North Cotentin thin-skinned fold-and-thrust belt. (c) The ~30% of total shortening estimated on the 100-km-long North Cotentin deformed belt demonstrates the importance of Variscan strain in parts of the (N)NAD, in contradiction with most of previous works that systematically minimized its effects in Northern Armorica.

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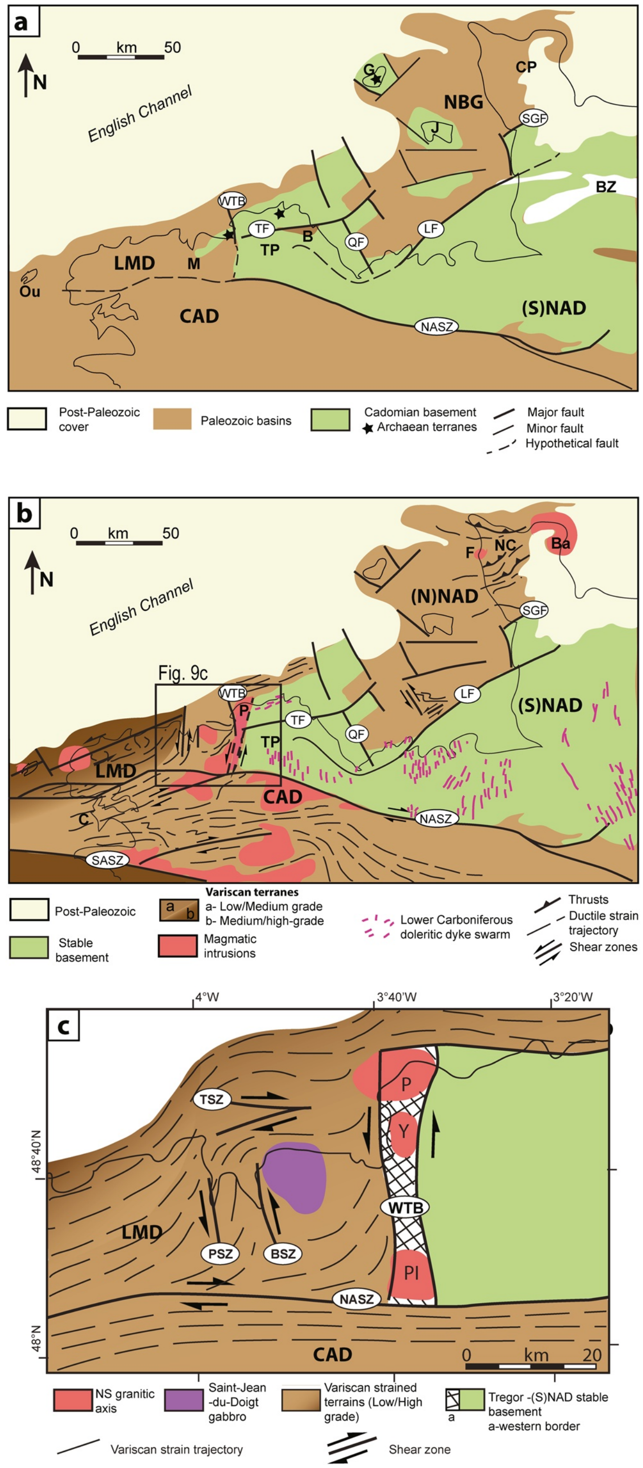


**Figure 9.** Evolution of Northern Armorica in Paleozoic times. (a) Structural arrangement of the Cadomian-floored NAD into a northern basin (NBG) and its southern basement margin (SNAD) at a pre-Carboniferous basinal stage. Present-day coastline drawn as geographical coordinates. Same abbreviations as in Figure 2a. (b) Variscan structural pattern (340–300 Ma). Location of Figure 9c is shown. Same abbreviations as in Figures 2a and 8b. (c) Indenter kinematic model showing the anomalous sigmoid trajectory of Variscan ductile strain against the western edge of the (S)NAD Cadomian block (Morlaix-Tregor transition zone). Variscan granites are not shown for clarity, excepted the NS magmatic axis along the WTB structure. Same abbreviations as in Figure 8b. Location in Figure 9b.

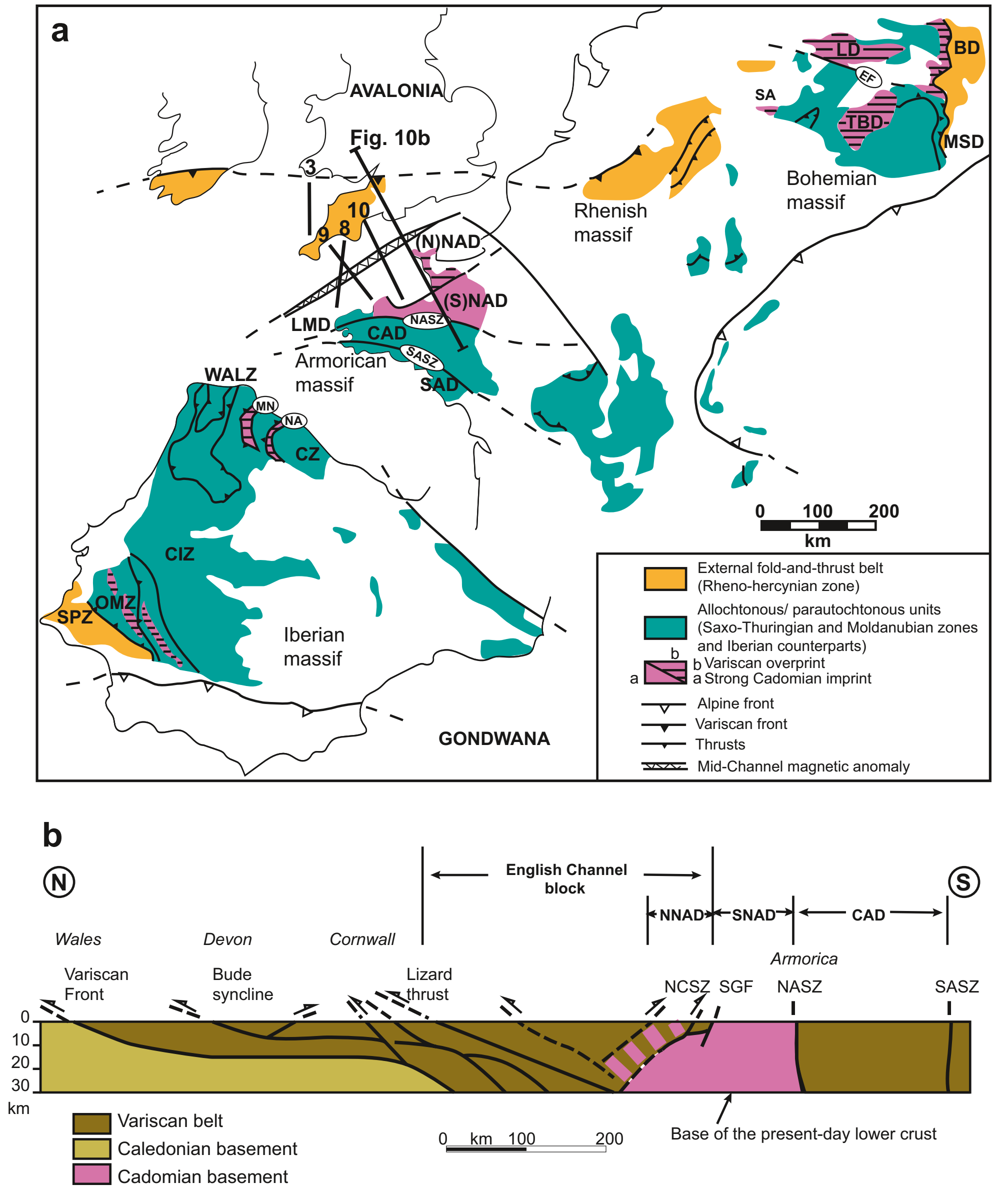


**Figure 10.** The Cadomian terranes in the Variscan belt of Western and Central Europe. (a) Map distribution showing the (S)NAD as the largest and the only basement terrane devoid of any Variscan overprint, modified from Martinez-Catalan (2011). Same abbreviations as in Figure 1. (b) Structural cross-section in the external (Rheno-Hercynian) zone of the Variscan belt showing: (i) the antithetic (southerly) verging of fold/thrust structures in the (N)NAD on the northern edge of the (S)NAD rigid block and (ii) the resulting doubly verging orogenic wedge in the English Channel block. The deep structural pattern is chiefly based on the interpretation of SWAT seismic profiles 3, 8, 9, and 10 (location shown in Figure 10a). For simplicity, granites are not shown in Cornwall and in Armorica, modified from Le Gall (1990).

### 5.3. Twofold Structural Zoning of the Cadomian-Floored NAD

On the sketch structural maps in Figures 9a and 9b, the (N)NAD and CAD are separated by a nearly E-W-oriented belt of Cadomian basement terrains forming the southern part of the NAD. The so-called (S) NAD currently extends as a fault-bounded block that widens to the east between the North Armorican shear zone (S) and the La Fresnaye/St Germain-sur-Ay fault (N) (Figures 9b and 10b). Its western edge forms a submeridian promontory (Tregor) limited by the Quessoye fault system to the east and the WTB structure to the west. If we admit that the lack of extensive Paleozoic sedimentary series over the (S)NAD is not due to erosion, this implies that the latter formed a topographically high range during the Ordovician-Devonian extensional stage. Its relative uplift during the subsidence of the surrounding (N)NAD/CAD depositional areas probably partly occurred along its composite bounding fault system (La Fresnaye/St Germain-sur-Ay, Quessoye, and WTB). During Variscan compression, part of this bounding fault network was the locus of intense strike-slip tectonics (North Armorican shear zone, BSZ, PSZ, and probably the Bray fault). In contrast, the (S)NAD behaved as a stable and rigid block as argued above (Section 2.2.2) from the undeformed structure of the Brehec (Ordovician) and Montmartin-sur-Mer (lower Carboniferous) discrete basins (Figures 2 and 9b). The rigidity of the (S)NAD block during Paleozoic times is also supported by the restricted distribution of lower Carboniferous doleritic dyke swarms in the Saint-Malo and Fougères areas (Section 2.2.2, Figure 9b), hence suggesting the brittle behavior of the (S)NAD crust during this tectono-magmatic event. The identification of the rigid NAD Cadomian block supplies satisfactory explanations to a number of anomalous Variscan structures in Northern Armorica. First, according to the indenter model in Figure 9c, the atypical N-S-trending sinistral ductile shear zone pattern (PSZ, BSZ) identified in Paleozoic terranes surrounding the western extremity of the (S)NAD stable block operated as lateral ramps that parallel the Tregor basement edge. The indenter effect expressed as far west as the LMD where the ductile pattern is similarly deflected. At that stage, the WTB structure was also rejuvenated: (a) as a sinistral fault which caused the counter-clockwise rotation of ductile fabrics in the western displaced terrains, and (b) as a pathway for multistage ascending magmas (Section 4.3.3, Figure 9c). Second, though Variscan tectonics in the (N)NAD is quite similar, in terms of tectonic style and amount of shortening, to those related to the northern Variscan frontal pattern in SW Britain/Ireland, Northern France and Germany (Cooper et al., 1984; Coward & Smallwood, 1984; Le Gall, 1992), it radically differs with the opposite (southerly) verging of regional structures in the North Cotentin fold-and-thrust (Figure 10b). The synoptic structural cross-section in Figure 10b shows the position of the (N)NAD on the southern flank of a 200-km-wide and doubly vergent orogenic wedge forming the hangingwall of the Lizard ophiolitic thrust and previously referred to as the English Channel block (Bois et al, 1990a, 1990b; Le Gall, 1990). The hinterland (antithetic) verging structures in the (N)NAD likely originated in response to the indenter effect exerted by the (S)NAD rigid block to the south. According to this scenario, the (S)NAD should have been passively translated northward, without any internal strain, along its eastern (Bray fault) and western (WTB) strike-slip bounding faults during the Variscan collision stage.

### 5.4. Reworked Versus Stable Cadomian Terranes in the European Variscides

A review of the structural framework of the Neoproterozoic/Cadomian terranes in the Variscan belt of Central and Western Europe reveals that they share some striking features: (a) They all consist of dominantly sedimentary and magmatic series formed at 750–540 Ma in a subduction-related volcanic arc setting, on the periphery of the Western Gondwana super-continent (Linnemann et al., 2014). (b) Some of them recorded collisional strain during Cadomian orogenic events, the spatial distribution of which is still a matter of debate (e.g., Linnemann et al., 2014 for details). (c) During Paleozoic times, these Neoproterozoic/Cadomian basement areas, excepted the (S)NAD, were the locus of extensive sedimentary basins developed in geodynamic settings which evolved in time and space from a back-arc to a rift (Cambrian) and then to a true oceanic (Rheic) setting (Nance et al., 2010). (d) Later on, these Paleozoic basins and their Cadomian basement, excepted the (S)NAD, underwent significant Variscan overprint during the Devono-Carboniferous collisional stage. It thus seems that direct correlations do exist between Cadomian-floored areas reworked during Variscan compressional events and those previously involved in Paleozoic basinal/extensional processes, possibly in relation with (thermal) weakening of the stretched lithosphere. Results of analog/numerical modeling have long shown than such lithosphere weakening (or strengthening) can occur as a function of the antagonist effects of competing factors, such as strain rate or thermal gradient (Kuznir & Park, 1987). At a crustal scale, it is also well-established that early extensional structures can be the preferential locus of compressional strain during basin inversion (e.g., Butler et al., 2006; Carrera & Muñoz, 2013). About the specific case of the Paleozoic lithosphere in the European Variscides, two additional key-factors, still showing antagonist effects, should be considered. First, the delay between the onset of extension and initiation of compression is critical since the progressive cooling of ascending asthenospheric material with time is known to provoke strengthening of the lithosphere (e.g., Morley, 1994). In contrast, in a collisional setting, weakening of the overriding lithosphere may occur during slab retreat or slab break-off (Boutelier & Cruden, 2017; Chen et al., 2016; Erdos et al., 2014).

## 6. Conclusions

- The generally accepted notion of the NAD as forming a coherent and stable continental block in the Variscan belt of Armorica (Western France) is revised from a multiscale and onshore/offshore structural approach including high-resolution multibeam and LiDAR records.

- During the Paleozoic basinal stage (Ordovician-Devonian) that predated the Variscan events, the NAD displays a twofold structural zoning with: (a) a northern part (NNAD) which evolved as a long-lived sedimentary basin (NBG) encompassing the North Cotentin onshore peninsula and most part of the offshore NBG. Most of its faulted boundaries with the surrounding basement terrains are inherited Cadomian structures. The high magnitude of subsidence recorded by the NBG Paleozoic basin is expressed by km's-thick sedimentary wedges clearly imaged on bathymetric records in its southern offshore part; and (b) a southern part (SNAD) which mostly escaped Paleozoic extensional/sedimentary processes.

- The early twofold partitioning of the Cadomian-floored NAD still prevailed during the Variscan orogenic events with: (a) the (S)NAD which behaved as a rigid block devoid of any significant Variscan deformation and (b) the (N)NAD which instead experienced substantial shortening, estimated to 30% from deformed/restored structural cross-sections in the North Cotentin fold-and-thrust belt.

- The identification of the (S)NAD rigid block accounts for a number of anomalous structural features in the North Armorica Variscan pattern such as: (a) N-S sinistral ductile shear zones, attributed to the indenter effect of the Tregor Cadomian promontory on surrounding Paleozoic deformed terranes, and (b) the southerly (antithetic) verging of the fold/thrust structures in the North Cotentin belt, assigned to the northerly translation of the (S)NAD block.

- At the scale of the Western/Central European Variscides, the (S)NAD is the only Cadomian-floored terrane which escaped both Paleozoic extensional/basinal processes and later Variscan compressional events. As a corollary, it is hypothetized that Variscan overprint chiefly occurred in portions of Cadomian lithosphere which were previously weakened during the Paleozoic extensional/basinal stage.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

Bathymetric data from the NBG have been acquired by Shom, as part of its mission to secure safety of navigation. Hydrographers at sea and data processing experts are thanked. Litto3D is a multi-partner program conducted by Shom. About the Morlaix offshore data set, valuable contributions of the partners are detailed on (https://www.data.gouv.fr/fr/datasets/partie-maritime-mnt-littoral-litto3d-r-finistere-2014/). Bathymetric data is available through the site https://data.shom.fr/donnees/. Many thanks are also due to other data providers (Ifremer, AFB, Roscoff Biological Station).

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