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South-West Approaches Study Phase 1 Lot 2:

A Review of Late- and Post-Variscan basins and source potential in Western Europe

Energy and Marine Geoscience Programme

Commissioned Report CR/17/031

BRITISH GEOLOGICAL SURVEY

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A Review of Late- and Post-Permian basins and source potential in Western Europe

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Keywords

Stephanian; Autunian; Late-orogenic; Post-orogenic; Variscan; basins; source rock potential

Front cover

Bibliographical reference

PHARAOH, T.C., GENT, C.M.A, MELLETT, C., GREENHALGH, E., ANDREWS, I.J. & McINROY, D.B . 2017. South-West Approaches Study Phase 1 Lot 2: A Review of Late- and Post-Variscan basins and source potential in Western Europe. *British Geological Survey Commissioned Report,* CR/17/031 130pp.

Keyworth, Nottingham British Geological Survey 2017

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Foreword and acknowledgements

This report is a published product of the 21st Century Exploration Road Map (21CXRM) SW Approaches Phase 1 project. The main objective of the project is to enhance industry knowledge and understanding of the SW Approaches area ahead of the 31st Frontier Licencing Round, currently scheduled to take place in 2018.

This BGS study for the OGA comprised a regional review of the petroleum system in late- and post-Variscan basins in western Europe.This study follows on from the case made by Smith (1993), for exploration of deep plays in the Variscan fold belt and its foreland. The study is designed to complement a major study of the regional play fairway in the SW Approaches, currently being undertaken by the University of Durham, and a review of regional gravity and magnetic potential field data, being undertaken by Getech in Leeds, under Lot 1 of this project.

The contribution of information and advice to the study from the following individuals and organisations is gratefully acknowledged:
Mark Abbott, Egdon Oil and Gas plc
Andreas Gautschi, Chief Scientific Advisor, NAGRA, Switzerland
John Hogan, Celtique Energy plc
John Knight, Centro Paleobotánico, Córdoba
Chris Pullan, CP Exploration

Translations of key publications by Jan Hennissen, Frederique Jaffeux and Pierre Josso considerably aided the integration of the French literature.

The significant contribution of Keith Henderson and Sandy Henderson to the quality of the illustrative material, is also appreciated. Emrys Phillips is thanked for an incisive internal review.

Contents

FIGURES

TABLES

Summary

A literature review of late Carboniferous-early Permian basins in NW Europe has been carried out, and a fully referenced and extensive bibliography is presented. A review of literature on the rather long and complex Variscan orogenic cycle is followed by a consideration of such aspects as the influence of basement structure, orogenic collapse, palaeotopography and palaeoclimate on the development of late Carboniferous-early Permian basins in the area of interest. This is followed by a review of such basins on a country-by-country basis: Spain, France, Germany, Switzerland, Ireland and UK. For each country, a chapter reviews the following key aspects: Variscan substrate, basin morphology, basin case-studies, stratigraphy, history of sedimentation, thermal maturity, geochemistry, source-rock potential and a concise chapter bibliography containing key references. The presence of intra-montane basins containing high-quality source rocks (Stephanian coals, Autunian lacustrine facies) is well-documented in the internide zone of the Variscides, but the publicly-available organic geochemistry database is rather limited at present. Such basins are unlikely to be present in the SW Approaches, except perhaps localised on late Variscan strike-slip faults. The northern internide (Saxothuringian) zone hosts large piedmont-type basins with half-graben geometry associated with the extensional reactivation of Variscan orogenic sutures. Such basins can contain thick Westphalian-Stephanian coal measures, and thinner Autunian sequences. As the Saxothuringian Zone extends into the SW Approaches, similar piedmont basins may be present to the south of the Cornubian Massif, although this may depend on the presence of transmontane corridors. In the northern externide (Rhenohercynian) zone, Culm (Westphalian) strata are post-mature, and Stephanian strata have been removed following inversion. Thin Autunian sequences may be present however. Basins with Stephanian and Autunian fill and source potential are unlikely to be present in the northern foreland, which was experiencing increased levels of aridity while the southern foreland in Iberia continued to enjoy a seasonal, monsoon-type climate.

1 Introduction

BACKGROUND

The 21CXRM SW Approaches Study aims to stimulate exploration of the SW Approaches to the English Channel. The objectives of the project include:

- Identification of basins containing sedimentary sequences of Stephanian (latest Carboniferous) and Autunian (early Permian) age in the Western European area of interest (AOI).
- Mapping the basins in ArcGIS 10.4.
- Establishing the tectonic history of the basins and establish their relationship in place and time to the collapsing and eroding Variscan Orogen.
- To recognise potential hydrocarbon source rocks within these basins, particularly terrestrial sources, and, where possible, gather and tabulate quantitative and qualitative geochemical data.
- To evaluate the hydrocarbon systems within these basins.
- To compare the known Stephanian (latest Carboniferous) and Autunian (early Permian) basins with the basins of the SW Approaches, to establish any structural or stratigraphic similarities.
- Report on all the above aspects to establish the source rock potential of late Carboniferous-early Permian strata in the SW Approaches.

The project results are delivered as a report with enclosures and a GIS dataset for the area of interest (AOI), which is identified in Figure 1.

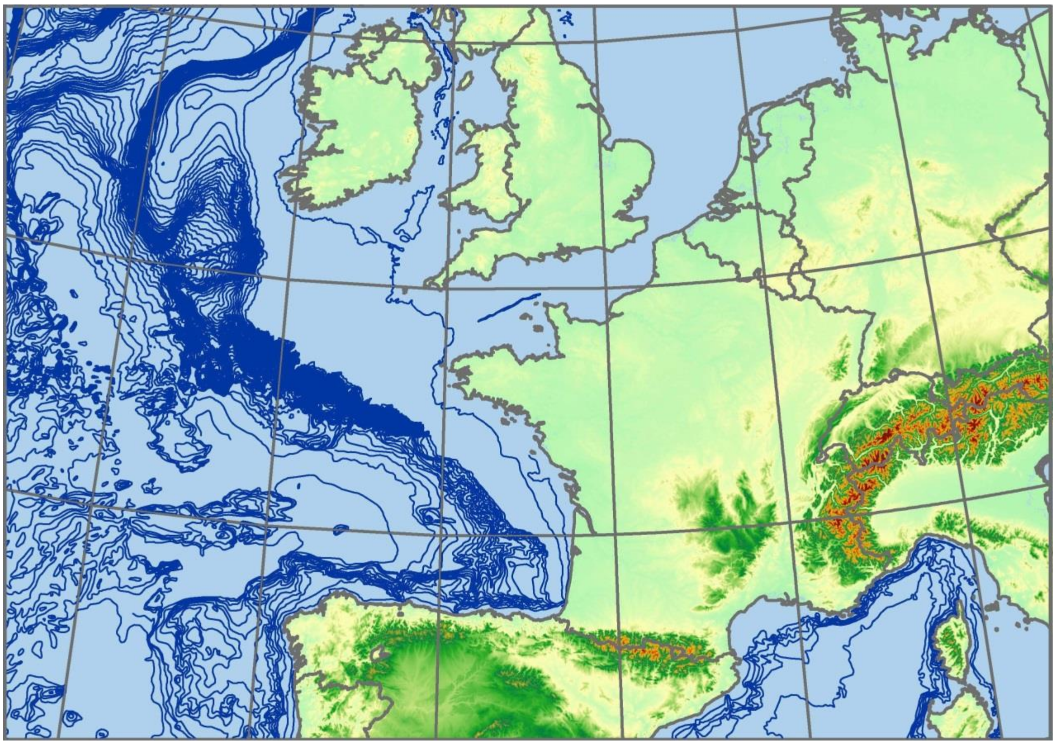

Figure 1 Extent of the project Area of Interest

METHODOLOGY

A literature search for all countries within the scope of the AOI (Figure 1) was followed by mapping of the extent of the late Carboniferous-early Permian basin outlines; Mesozoic basins in the Western Approaches and English Channel; and major Variscan and post-Variscan structures, into ArcGIS coverages. Note that the AOI is larger than that included within the Invitation to Tender, because of the importance of including northern Iberia within the study. This area lay much closer to the SW Approaches prior to opening of the Bay of Biscay by sea-floor spreading, in early Cretaceous time. A further coverage, the simplified Variscan orogenic structure, was mapped from recent publications on this topic (see Appendix). For clarity and ease of use, the above coverages are presented as 3 enclosed plates at large scale (1:3,000,000 scale). Several figures (e.g. Figure 2) reproduced at smaller scale within the text are derived from these enclosures.

The late Carboniferous-early Permian basins typically exhibit a close spatial relationship to the underlying Variscan orogenic structure, particularly in the internide massifs such as the Massif Central of France. As a consequence, understanding of the structural setting of known (and to be found) late Carboniferous-early Permian basins is incomplete without a comprehension of the orogenic substrate. Chapter 2 presents a review of the rather long and complex orogenic history of the Variscide Orogen, its sutures, major shear-zones and late- to post-orogenic extensional faulting. Further sections provide a summary of the research carried out on the orogenic topography, palaeoclimate and palaeoecology, which are critical to understanding the source rock potential of these basins.

Subsequent chapters for Spain, France, Germany, Switzerland, Ireland and the UK provide a general introduction, information on data sources, relationship to the Variscan substrate, stratigraphy, basin morphology, basin case studies, and sedimentary history; geochemistry, maturity data and modelling (where available); and a regional bibliography. Due to the large number and relatively small size of some of the basins, only the most significant (e.g. due to size or known hydrocarbon potential) and/or representative sedimentary basins, have been described from each of the countries occurring in the AOI. The relationship of the basins selected to others in the country is described in the introduction to each chapter.

The final chapter summarises the main character variation trends seen in late Carboniferous-early Permian basins across the Variscan Orogen, from south to north. These trends help prediction of the structural style, stratigraphy and source rock potential to be expected in any basins of this age preserved within the SW Approaches of the English Channel, UK Offshore.

DATA USED

The BGS has a library with a comprehensive collection of published books, reports and maps from the various national geological surveys, geological societies, coal and hydrocarbon research organisations, exploration companies etc. Some reports were also purchased from other research organisations e.g. NAGRA (National Cooperative for the Disposal of Radioactive Waste) in Switzerland. A small part of the exhaustive French literature was translated into English. This information was used to compile the text of the report. Recently published Special Publications of the Geological Society of London provided much useful and up-to-date map information used in the GIS project (see Appendix). Currently, only small amounts of geochemical data are in the public domain. This could be valuable to characterize potential source rocks. Such data can be purchased as part of confidential reports by providers such as the Institut Français du Pétrole (IFP). Several requests were sent out to potential providers of released data. At the publication of this report, no further geochemical data had been received, but it is anticipated that such data will be released in the near future, following approval from data owners and partners.

GIS PROJECT AND DATABASES

The map data were compiled into three plates, and these are enclosed in this report. The mapping is underpinned by an ArcGIS database. Further details of these databases, and the sources of mapping,, are provided in the Appendix.

2 Variscan Orogenic Setting

INTRODUCTION

The Variscan-Alleghenian Orogeny resulted from the equatorial collision of the continents Laurussia (or 'Old Red Continent') and Gondwana in the late Palaeozoic, to produce the supercontinent Pangea. In the early Permian, the orogenic belt extended from the Gulf of Mexico, through the Appalachian mountains of the USA, into western and central Europe, and apparently terminated in Romania, a (restored) distance exceeding 7000 km. The width of the orogeny is approximately 1000 km. Furthermore, metamorphic enclaves with Variscan ages have been reported within the Pontides of Turkey (Okay, 1994; Pharaoh et al., 2006) and the Alpine-Carpathian Orogenic belt, suggesting that the Variscan mountains were formerly even more extensive. Some of these Variscan enclaves were displaced from the margin of the Palaeo-Tethys and Neo-Tethys Oceans (Stampfli et al., 2001), prior to Alpine collision. The peri-Gondwanan and Gondwanan affinities of such massifs have been demonstrated by detailed U-Pb zircon dating studies (e.g. Schaltegger, 1999; Von Raumer et al., 1999). The orogen is now exposed in a number of discrete massifs in western and central Europe, extending from Spain (Iberian Massif, Pyrenees), France (Armorican Massif, Massif Central, Vosges), Germany (Schwarzwald, Harz, Erzegebirge), Austria and Czech Republic (Bohemian Massif), Slovakia and Poland (Tatra Mountains) (Figure 2). A special feature of the orogen is its complex curvilinear shape, referred to as 'oroclinal bending'. The oroclinal effect was further enhanced by 30° anti-clockwise rotation of the Iberian Peninsula with respect to the rest of western Europe, during the opening of the Bay of Biscay in the early Cretaceous.

The term 'Hercynian' (named from the Harz Mountains of Germany) is frequently used as a synonym for 'Variscan', and remains well entrenched in the French and hydrocarbon industry literature. However, this term is misleading as it describes an isolated Variscan Massif formed during the Sub-Hercynian phase of uplift in early Cretaceous time (Pharaoh et al., 2010), and is therefore atypical of the orogen as a whole. An important descriptive framework for the structure of the orogenic belt is provided by concepts such as the 'internides', to describe the high-grade metamorphic orogenic core region, usually structurally complex and allochthonous (severely displaced); 'externides', to describe the 'foothill' or 'piedmont' part of the orogen, with lower metamorphic grade and simpler style, allochthonous to parautochthonous; and the 'foreland', to describe the region beyond the orogenic front, where rocks are unmetamorphosed, little-deformed and autochthonous (untransported). Because of the trans-national and structurally complex nature of the Variscan Orogen, a very large multi-lingual literature has developed. Despite this geopolitical complication, the presence and persistence of characteristic features (e.g. patterns of sedimentation, structural style, metamorphic facies etc) led Kossmat (1927) to recognise the presence of three distinct geotectonic zones, the *Rhenohercynian*, *Saxothuringian* and *Moldanubian zones*, which can be traced across western and central Europe (Figure 2). For practical purposes, the Rhenohercynian Zone can be equated with the 'northern externides'; the Saxothuringian Zone with the 'northern internides'; and the Moldanubian Zone, with the 'central internides' (Praeg, 2004).

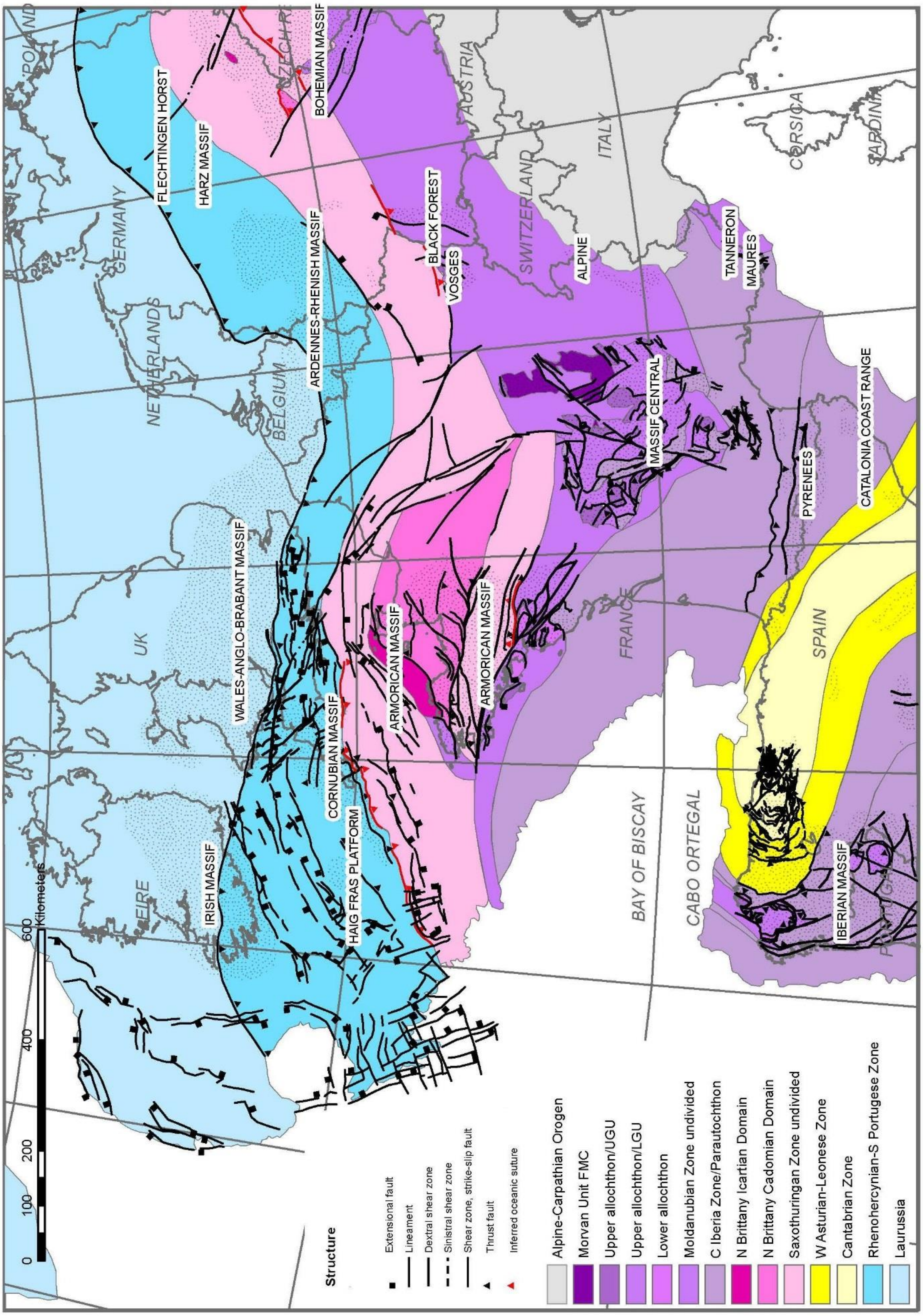

Figure 2 Simplified structure of the Variscan Orogen in Western Europe. Data sources used in this compilation are listed in the Appendix.

The cross-strike width of the orogeny, c. 1000 km, is notable, and reflects the 100 Ma long (Devonian-Carboniferous) and complex history of obduction-collision between a number of intermediate Gondwana-derived microplates and terranes (for example, Matte, 1986; 1991) Increasingly sophisticated investigations, using palaeomagnetism, seismic techniques, isotopic, petrological studies and modelling, have confirmed that the ‘zonal’ scheme is still valid, because the zonal boundaries correspond to suture zones, the former sites of Palaeozoic ocean basins separating distinct microcontinental plates. Thus Kossmat’s ‘classical’ paradigm for the Variscan Orogen is still used (Franke, 1992; 2006) and remains of value. The suture zone(s) separating terranes of Saxothuringian and Moldanubian affinity cross the outcrop of several of the massifs (Figure 2). An alternative view is that the Bohemian Massif is a supra-subduction Andean-type Orogen with thickened crust (Schulmann et al., 2009), in strong contrast to the Massif Central where such features are absent (Faure et al., 2009; Lardeaux et al., 2014).

Studies of the Variscan Orogen have long recognised its episodic nature, with phases of compression alternating with phases of sedimentation, not always coeval throughout the belt. Four discrete phases of deformation and exhumation, each lasting 20-30 Ma, and geographically restricted, record the welding of successive Gondwana-derived microplates (Figure 3) and their eventual docking (Figure 4) to the southern edge of Laurussia (Ziegler, 1982; 1990; Warr, 2012). These are the Ligerian (mid-late Devonian), Bretonian (late Devonian to early Carboniferous), Sudetian (Visean to Namurian) and Asturian (Westphalian to Stephanian) deformation phases.

There are also two views on whether two distinct orogens are superimposed, the monocyclic vs. polycyclic views of the Variscan Orogeny. In France, the Variscan Orogeny has been divided into three stages (Ledru et al., 1989; 1994): Eo-Variscan (Silurian–Devonian); Medio-Variscan (Devonian-early Carboniferous); and Neo-Variscan (mid- to late Carbonifeous). The monocyclic (or Himalayan) model contends that the Eo-Variscan cycle of subduction and accretion ended with collision in late Silurian time, followed by a long Medio-Variscan stage of intracontinental compression (e.g. Weber, 1984; Franke & Engel, 1996; Matte, 1986; Ledru et al., 1989). The bilateral symmetry of the orogeny is held to reflect inward subduction of the Rheic and Massif Central oceans, both closed by the end of the Devonian. The polycyclic model envisages two cycles of ocean opening and closure (e.g. Cogné, 1977; Pin, 1990; Ziegler, 1990; Faure et al., 1997). The Eo-Variscan Orogeny resulted in closure of the Massif Central Ocean between Gondwana and elements of Armorica, in the Ligerian Deformation Phase. This was dismembered and overprinted by a Medio-Variscan orogenic cycle which resulted in the opening and closure of the Rheic Ocean between the newly amalgamated crust, and Laurentia, during the Sudetian Deformation Phase, in early Carboniferous time. Closure was achieved by southward subduction of the Rheic Ocean from Devonian to early Carboniferous time.

Detailed isotopic and petrological studies are now improving the precision with which such deformation phases are dated, as well as demonstrating that they relate to the collision of various microplates within the orogenic collage.

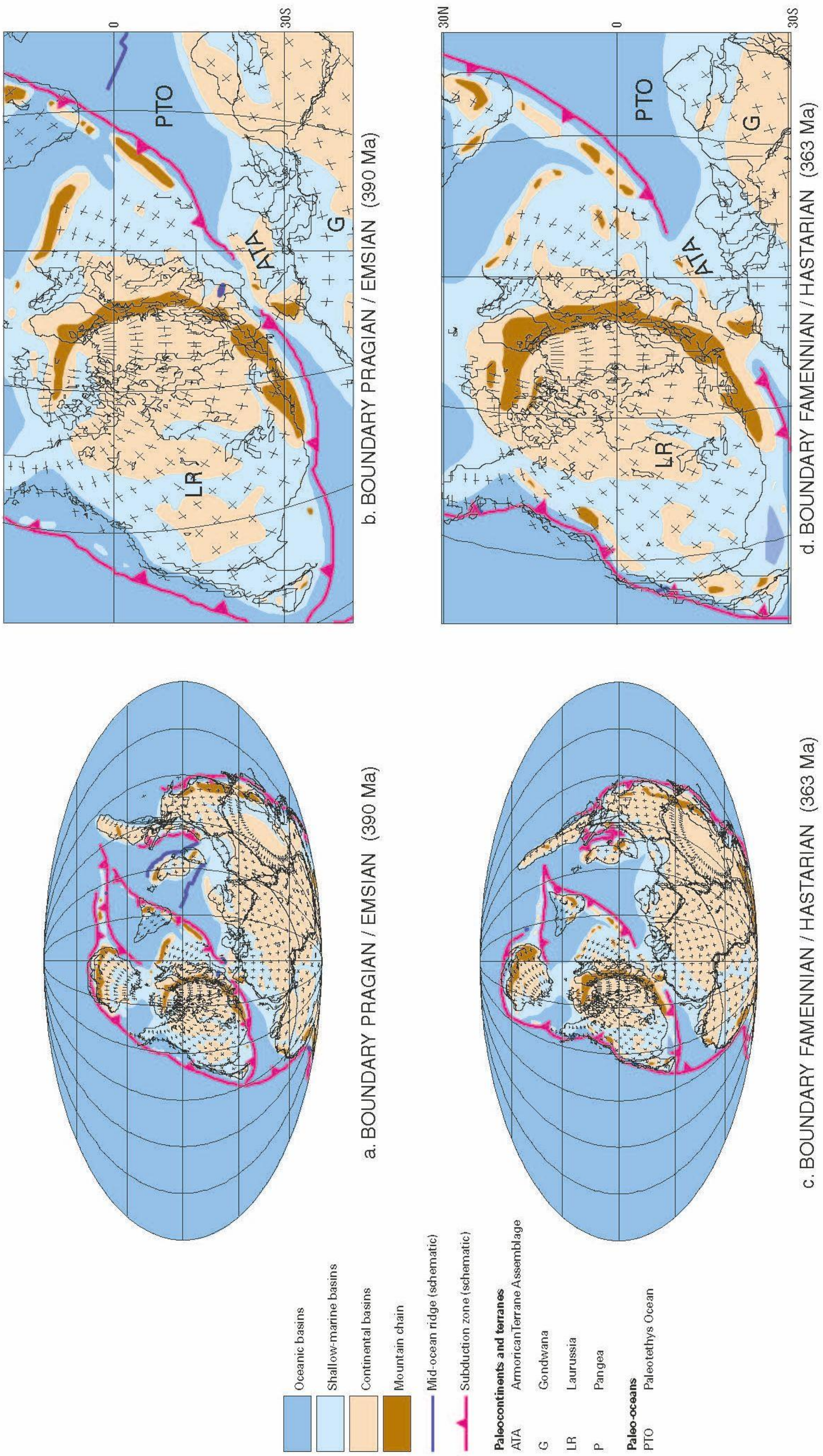

Figure 3 Palaeogeographical reconstructions for 390 Ma and 363 Ma, after C. Scotese, courtesy of Shell. Modified from Pharaoh et al. (2010).

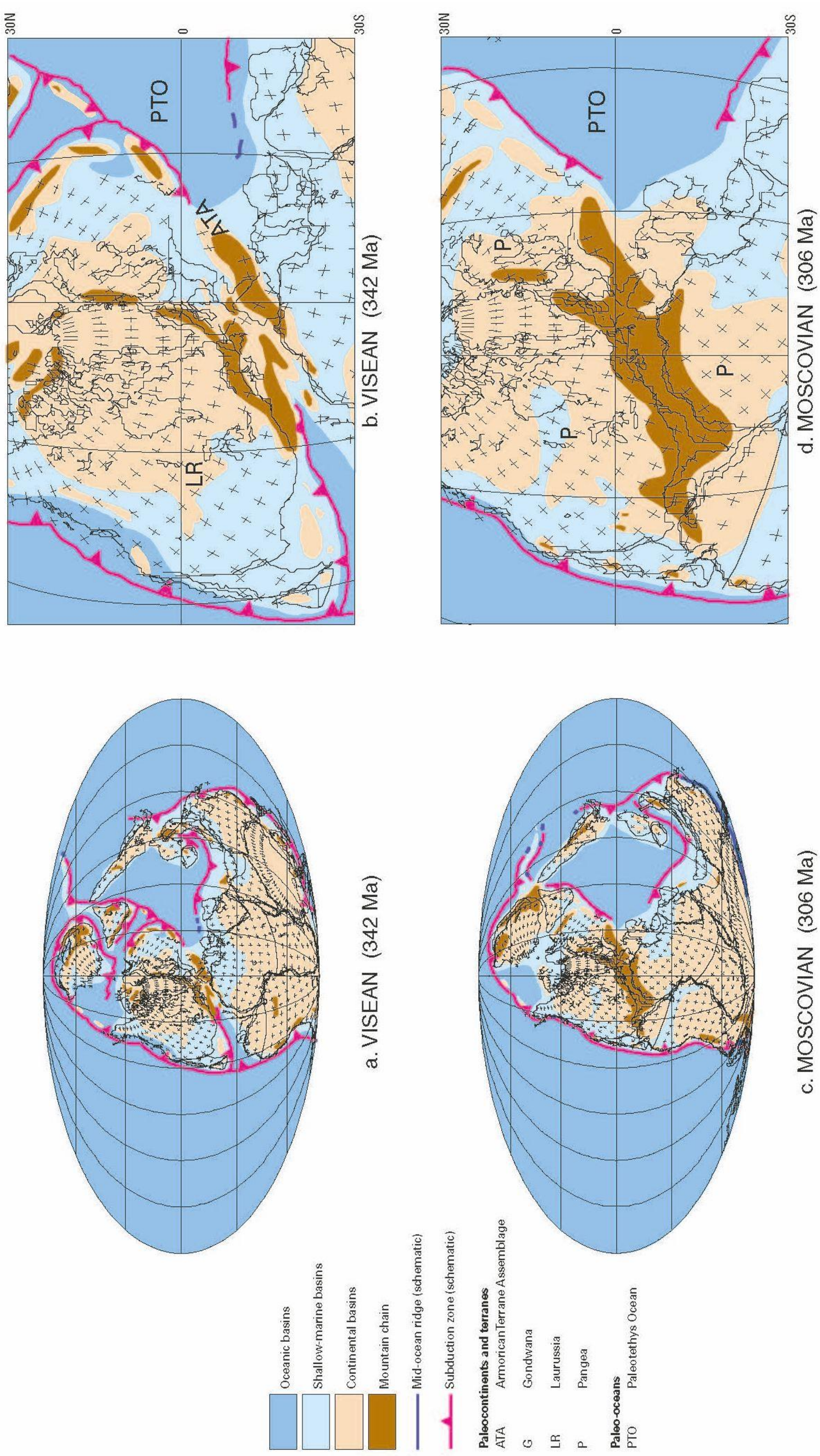

Figure 4 Palaeogeographical reconstructions for 342 Ma and 306 Ma, after C. Scotese, courtesy of Shell. Modified from Pharaoh et al. (2010).

OROGENIC STRUCTURE

Foreland Zones

The largest continents involved in the Variscan orogenic collage are Laurussia (also known as the 'Old Red Continent') and Gondwana ('the Great Southern Continent'). The final collision between these large palaeocontinents in late Carboniferous times subjected all components of the orogen to a final, Ligerian, deformation phase, welding all into a new giant supercontinent called Pangea. During this deformation phase, strata of Devonian and Carboniferous age, deposited upon (and faunally indistinguishable from) the southern margin of Laurussia (McKerrow & Cocks, 1982) were thrust over the northern foreland. The limit of thrusting and folding ('penetrative deformation') is known as the 'Variscan Front', which forms a curvilinear boundary which can be traced across the AOI (Figure 2). West of Ireland, the front is believed to trend W-E or WSW-ENE, entering the Porcupine Basin at or near its midpoint (Plates 2, 3), but this is rather speculative. North of the front, deformation is heterogeneous, and typically localised within discrete zones of basement reactivation (Corfield et al., 1996).

Rhenohercynian Zone (Northern externides)

The Rhenohercynian Zone forms a foreland-directed fold-thrust belt on the northern externide side of the orogen. In southern Britain and Ireland, a number of continental rift-basins developing sequentially northwards in Devonian time in response to extension of the continental margin of Laurussia (Shail & Leveridge, 2009). These basins began to be overthrust northwards during the Bretonian Deformation Phase, and the margin then remained in compression discontinuously until late Carboniferous time, when the Namurian to Westphalian C age strata of the Culm Basin were thrust northward over the northern foreland in the Asturian Deformation Phase. A similar sequence of events is observed in the Ardennes and Rhenish massifs (Oncken, 2000), the other major exposures of the Rhenohercynian Zone. The latter is also correlated (Martinez Catalan et al., 2014; Ballèvre et al., 2014) with the South Portugese Zone, located to south of the spectacular oroclinal bend of the Bay of Biscay region (and beyond the southern limit of the AOI).

Cantabrian Zone (Southern externides)

The Cantabrian Zone forms the symmetrical counterpart of the Rhenohercynian fold-thrust belt, on the southern side of the orogen. It also comprises a nearly complete Palaeozoic succession, weakly metamorphosed, originally deposited upon the Iberian microplate, and emplaced in a southward-vergent fold-thrust belt during the Asturian Deformation Phase (Warr, 2012). In the Montagne Noir at the southern extremity of the Massif Central, early Carboniferous flysch-type strata are deformed by large southward-verging recumbent folds and southerly directed thrusts. The basement of the Gondwana Foreland is not exposed in southern France however. The correlative of the Cantabrian Zone is inferred to extend eastward beneath the Alps in Switzerland to re-emerge in the Eastern Alps of Austria.

Rheic-Rhenohercynian Suture

The Rheic-Rhenohercynian Suture represents a fundamental divide within the Variscan Orogen, separating the externide Rhenohercynian Zone (of Laurussian affinity) from crust of the internide zones which separated from Gondwana after the Ordovician (Dallmeyer et al., 1995). The suture is a complex structure and almost certainly compound in nature (Franke, 2000; 2006). The early history of these oceans is poorly known, but the Rheic Ocean may have begun to open in early Ordovician time with the rifting of Avalonia and other terranes of the Armorican Archipelago from Gondwana (Cocks and Fortey, 1982). The suture zone is very poorly exposed reflecting the weakness of the crust within it. In Germany, the Northern Phyllite Belt at the southern border of the Rhenish Massif is interpreted as the remains of a deep water distal continental margin sequence on the northern side of the suture (Franke, 2000: 2006). The Lizard Peridotite (Clark et al., 1998) and Giessen Ophiolite (Franke, 1995) are suspect terranes (*sensu* Coney et al., 1980) formed at *c.* 397 Ma (early Devonian), either in marginal basins bordering the Rheic Ocean (Ziegler, 1982; 1990); as relics of Rheic mid-ocean ridge (Franke, 2006); or as relics of mantle peridotite from a hyper-extended continental margin (Shail & Leveridge, 2012). The ophiolites may represent relics of original marginal-basin crust associated with northward subduction at the northern margin of the ocean (Ziegler, 1990), apparently contemporaneous with Acadian deformation farther north in Avalonia. An alternative suggestion (Woodcock et al., 2007; Woodcock, 2012) involves the removal of such evidence by up to 400 km of dextral strike-slip along a putative Bristol Channel-Wight-Bray Fault Zone (Shail & Leveridge, 2009; Warr, 2012).

Obduction of the Lizard Complex, associated with overthrusting of the mid-Devonian basins by the Normannian Complex (see next section) began at about 380 Ma (Clark et al., 1998). Subsequently, in late Devonian to early Carboniferous time, a smaller Rhenohercynian Ocean basin may have opened not quite coincident with the original Rheic Suture (Franke, 2000; 2006). An alternative view is that the two oceans coexisted (Warr, 2012). The Mid-German Crystalline High (Dallmeyer et al., 1995; Franke, 2000) is a magmatic arc produced by later southward subduction of this ocean, and it is this later phase of suture development that is imaged by DEKORP deep seismic reflection profiling in Germany (Meissner & Bortfeld, 1990). Deep seismic reflection profiles in the English Channel (Bois et al., 1984; Leveridge et al., 1984) show that the suture maintains a constant southward dip of *c.* 20° into the lower crust and suggest that the Variscan Orogen is distinctly thick-skinned in aspect.

Saxothuringian Zone (Northern internides)

The Saxothuringian Zone incorporates ancient crust rifted from Gondwana in early Silurian (Ziegler, 1990) to earliest Devonian times (Paris, 1998; Martinez-Catalan et al., 2004). Palaeomagnetic data (Krs et al., 1986; Tait et al., 1995) support derivation of the Saxothuringian terranes from Gondwana at high southerly palaeolatitudes after late Ordovician time. Significant plume-related magmatism from about 500 Ma initiated rifting at the Gondwana margin (Floyd et al., 2000; Crowley et al., 2002) and generated a progression of strip-like Saxothuringian terranes referred to as the Armorican Terrane Assemblage (Tait et al., 1997) or Armorican Archipelago (Franke et al., 1999). The zone can be traced from SW Poland (Figure 2), through central Germany and northern France, possibly extending as far as the Man of War and Eddystone rocks off the Lizard Peninsula in SW England (Sandeman et al., 1997; Shail & Leveridge, 2009). The zone is thought to continue into the SW Approaches (BGS, 1996), although its distribution is highly speculative due to the absence of outcrop and sparsity of borehole provings.

The only good exposure of the zone is in the northern parts of the Bohemian and Armorican massifs. In both massifs, Neoproterozoic basement of 'Cadomian' affinity, e.g. the North Brittany Domain, largely comprising greywackes and granitoid intrusions (Linnemann et al., 1998; Hammer et al., 1998), occupy cratonic areas virtually unaffected by later Variscan deformation (Lardeaux et al., 2014). Together with the central Brittany domain, they form the Saxothuringian terrane of North Armorica. The Palaeozoic cover of the Saxothuringian terranes e.g. in Armorica and Germany, comprises Cambrian-early Ordovician shallow marine clastic strata, bimodal volcanic rocks dated at 500-480 Ma (Furnes et al., 1994; Kröner and Hegner, 1998; Floyd et al. 2000) and mid-to late Ordovician hemipelagic shales, turbidites and glacigene strata (Erdtmann, 1991). These are overlain by pelagic shales, cherts and carbonates of Silurian to mid-Devonian age. All of the above are variably metamorphosed to schists and paragneiss in the Ligerian Deformation Phase by mid-Devonian time. High-pressure metamorphic rocks (eclogite and blueschist) record subduction/obduction in the 'Eo-Variscan' orogenic cycle (Ledru, 1989). Late Devonian-Visean flysch-type sediment was fed NW from the developing orogenic belt, and unconformably overlies the deformed and metamorphosed early Palaeozoic metasedimentary successions in France and Germany.

The Mid-German Crystalline High (MGCH), lying at the northern edge of the Saxothuringian Zone in Germany, comprises Silurian to early Devonian age calc-alkaline magmatic rocks. The MGCH is associated with a prominent aeromagnetic anomaly, and is interpreted as the magmatic arc resulting from southward subduction of (Rheic) ocean crust in Silurian to early Devonian time (Franke, 1998). The Saxothuringian Zone is inferred to continue westward through the Northern Vosges towards the Armorican Massif, where the North Brittany domain lies at its core. The concealed course of the Saxothuringian Zone from the Northern Vosges beneath the Paris Basin is more speculative. In Figure 2, its distribution follows the structural interpretation of Héry (1990) and Skrzypek et al. (2014), and infers the Saxothuringian Zone is offset by a number of NW- and NNW- trending lineaments (including the Bray Fault). This can be compared with numerous alternative interpretations (e.g. Mégnien, 1980; Ziegler, 1982; 1990; Mascle, 1990; Matte, 2001; Praeg, 2004; Ballèvre et al., 2014; Faure et al., 2014). The rocks of Eddystone Reef have been correlated with the Mid-German Crystalline High (Shail & Leveridge, 2012), and form part of the Normannian Complex.

Across the continental shelf west of Armorica, the Saxothuringian Zone is attenuated by a number of major shear zones (Figure 2), namely the Central and South Armorican shear zones, and its distribution there is also a matter for speculation (e.g. the maps of Ziegler, 1982; 1990; Matte, 2001; Praeg, 2004; Ballèvre et al., 2014; Faure et al., 2014; Skrzypek et al., 2014). The Saxothuringian Zone is correlated with the Ossa Morena Zone of Iberia, in which low grade metamorphic Devonian and Carboniferous sedimentary and volcanic rocks unconformably overlie gneissose rocks which underwent Barrovian metamorphism in the Ligerian Deformation Phase (Martínez-Catalán et al., 2014).

Saxothuringian and Moldanubian Sutures

Several oceanic suture zones occur within the internides, marked by ophiolitic rocks of at least two ages (Cambrian to Silurian, and Devonian-Carboniferous). These are sometimes associated with mantle-derived eclogites of two ages (Lardeaux et al., 2014): early to mid-Devonian (Ligerian Deformation Phase); and late Devonian to early Carboniferous (Sudetian Deformation Phase). The duality of these obduction phases led Faure et al. (2009) to propose that at least two cycles of subduction/collision, possibly with opposite polarities, were involved. In general, there is still considerable debate about the location and subduction polarity associated with these sutures, particularly within the Moldanubian Zone.

The Armorican Massif is divided into two parts by an Eo-Variscan (mid-Devonian) suture corresponding to the Saxothuringian Suture in central Europe. The Saxothuringian terrane of North Armorica (described in a previous section) is separated from the Moldanubian Terrane of South Armorica by a suture at the location of the north-dipping Nort-sur-Erdre Fault (Faure et al., 2007; Ballèvre et al., 2014). Provenance studies indicate that Iberia remained attached to Gondwana until the early Devonian (Martinez-Catalan et al., 2004), and collided with Southern Armorica soon after in the mid to late Devonian Ligerian Deformation Phase (Ziegler, 1990). The latter event resulted in significant high pressure (HP) metamorphism (Franke et al., 1999; Lardeaux et al., 2014). In early Carboniferous time, widespread HP metamorphism in the Variscan internides records rapid crustal thickening following closure of the Massif Central Ocean and collision with Iberia (Ziegler, 1990) in the Sudetian Deformation Phase.

In the Massif Central, early NNW-directed Eo-Variscan subduction in late Silurian time (Ledru et al., 1989) was followed by SSE-directed subduction of the Saxothuringian Ocean in late Devonian time (Faure et al., 1997). Calc-alkaline magmatic arcs of Devonian-early Carboniferous paired to the later of these subduction zones are recognized in the Central Bohemian Plutonic Complex, southern Vosges and the Massif Central (Morvan). Both the duration of subduction and the volume of magmatic rocks decrease westward (Lardeaux et al., 2014). The Massif Central Suture (Matte et al., 1990), separating the Upper and Lower Gneiss units in the Massif Central, is marked by numerous dismembered ophiolitic bodies, metamorphosed under UHP conditions at *c.* 412 Ma (Berger et al., 2010). It marks the closure of the Galicia-Massif Central Ocean (Matte, 1990) or 'Medio-European Ocean' (Ledru et al., 1989, Faure et al., 2009), which opened in Ordovician time (Ducassou et al., 2014). The Brévennes (back-arc) Ophiolitic Unit is of Devonian age. Its relationship to the Morvan Arc (to the north) suggests a southward-dipping suture (Lardeaux et al., 2014). Further examples of ophiolite-decorated sutures occur within the South Armorican Domain e.g. Isle de Groix, Bois de Cené, Audierne (Cambro-Ordovician) and Drain (Devonian). The Middle Allochthon of the Iberian Massif also contains ophiolites of both Cambro-Ordovician (e.g. Ceán, Pombais) and Devonian (e.g. Caréon, Purrido in Cabo Ortegal) age (Ballèvre et al., 2014).

All of the sutures described above reflect closure of small ocean basins that originally separated the Gondwana-derived elements of the Armorican Archipelago (Franke, 2000). Faunal evidence (McKerrow et al., 2000) indicates that no large (i.e. >1000 km wide) oceans existed in late Palaeozoic Europe.

Moldanubian Zone (Central internides)

Highly metamorphosed gneisses, with a diversity of HP rock suites, including eclogite, granulite and garnet peridotite, of varying ages, are characteristic of the Moldanubian Zone and the upper allochthonous nappes in Iberia (Warr, 2012). The Upper Gneiss Unit ('Leptyno-Amphibolitic Complex') of the French Massif Central (Matte et al., 1990; Matte, 1998) experienced HP metamorphism at *c.* 415 Ma (Lardeaux et al., 2014), followed by Barrovian metamorphism at 385 Ma. The Braganca Complex, Cedeira and A Capelada in the Cabo Ortegal Complex (Ribeiro et al., 1990; Marcos et al., 2002) in the Upper Allochthon of NW Iberia, have been correlated with the Upper Gneiss Unit (Ballèvre et al., 2014).

A previous correlation of the Upper Gneiss Unit of the Massif Central with lithologically similar gneisses of the Gföhl Unit in the Moldanubian Zone of the Bohemian Massif (e.g. Bard et al., 1980), is now considered untenable. These two gneiss units had a very different evolution (Lardeaux et al., 2014), justifying the separation of the Moldanubian Zone into western and eastern zones.

The lowest part of the Upper Gneiss Unit in the Massif Central is interpreted as the result of subduction of a thinned ocean-continent transition (OCT) (Lardeaux et al., 2014). The Lower Gneiss Unit of the Massif Central, the Cévennes-Vendée Terrane of Matte et al. (1990), is characterized by Barrovian-type metamorphism (Lardeaux et al. 2014). The Drosendorf Unit of the Bohemian Massif is at similar metamorphic grade.

Subsequent thrusting in the Sudetian Deformation Phase (early Carboniferous) was accompanied by further high grade metamorphism. Deformation attributable to the Asturian Deformation Phase (late Carboniferous) is largely absent and Stephanian (late Carboniferous) volcanism and sedimentation continued without break into the Autunian (Permian) (Warr 2012).

Variscan Oroclinal development

Few mountain chains are perfectly straight because of the rarity of orthogonal closure of the continental landmasses driving their formation. Oroclinal curvature of the resulting mountain belt can result from any (or a combination) of the following circumstances:

- Oblique (strike-slip) collision of ribbon terranes
- Indenter tectonics, resulting from irregular continental margins, promontories or entrained microplates
- Intra-crustal delamination
- Varying orientation of the stress-field during orogeny

The Variscan Orogen contains some of the tightest bends in any mountain belt, ancient or modern, approaching 180° in the Ibero-Armorican Arc (Warr, 2012). In more recent orogenic analogues, e.g. Japan and NW America, equally strong oroclinal bending results from the oblique accretion ('terrane- wreck') of ribbon-like microcontinents (Johnston, 2001; Van der Voo, 2004). Certainly, the apparent lateral continuity of the Saxothuringian and Moldanubian Zones between the Bohemian and Iberian massifs, over a strike length of >3000 km and terrane width of 200-350 km (Figure 2), suggests a ribbon-like aspect ratio for many of the Variscan terranes. A 90° rotation caused by bending of the Moravo-Silesian Zone around the Bohemian Massif was interpreted by Winchester et al. (2002, 2006) to be a consequence of indenter tectonics around a promontory on the East European Craton margin of Laurussia. The Ibero-

Armorican Arc may have originated as a consequence of impingement of promontories on the Canadian margin of Laurussia. Deep seismic reflection data indicate delamination of the middle crust from the lower crust in Iberia (Simancas et al., 2006) and Germany (Franke et al., 1999), as well as elsewhere in the Variscides. Such a detachment would have facilitated rotation of the more viscous orogenic middle and upper crust with respect to a hot, ductile and thickened lower crust. Finally, as described above, although S-N orogenic compression ended in the western and central European Variscides at the end of the Carboniferous, the lithosphere of Pangea remained in stress as a result of continuing E-W compression within the Ural (Sonenshain, 1984; Coward, 1995; Brown et al., 2002; 2006), and Alleghenian segments (Hatcher, 2010; Hibbard et al., 2010) until Permian time.

VARISCAN OROGENIC TOPOGRAPHY

The topic of orogenic topography is of considerable interest for the questions addressed by this report. An early attempt to establish Variscan palaeorelief was published by Becq-Giraudon & Van Den Driessche (1994). Studying periglacial strata of Stephanian to Autunian age in the Massif Central, they envisaged the rapid development (from 320 to 295 Ma) of an orogenic plateau up to 5000 m high (comparable to the Tibetan Plateau), followed by rapid denudation to 1000 m by 275 Ma, and eradication of the plateau by 240 Ma, at the end of the Autunian (Ducassou et al., 2014).

From the preceding account of Variscan orogenic evolution, it is clear that the formation of the mountain belt was a rather long (?100 Ma), and possibly polycyclic (Faure et al., 2009; Lardeaux et al., 2014) process. This was not a ‘simple’ progressive impingement of one continent (e.g. India) with another (e.g. Asia), quickly producing an orogenic plateau with a predictable watershed. The Himalayas have risen 1 to 2.5 km in the last 10 Ma, accompanied by extension orthogonal to compression, westward into the Turkish-Mediterranean region, and eastwards, into SE Asia (England, 1993; England & Molnar, 1997). The evolution of the Variscide Orogen appears to have been far more complex. As a result, it is likely that the location of the divide moved over time. In addition, in modern orogens, the variation in crustal thickness can be assumed to be a proxy for variation in topographic height, assuming Airy Isostasy (Dewey, 1988). Theoretical studies suggest that thickening of the positively buoyant crust during collision generates radial extensional forces, so that orogenic belts widen, rather than rise above 3 km height, or 65 km crustal thickness, assuming typical crust and mantle viscosities (Dewey, 1988). It is likely that the Variscan Orogen exhibited considerable crustal thickness (and topographic) variation as a result of episodes of continental obduction, as well as the exhumation of lower crust and mantle rocks, following HP metamorphism in the Bohemian Massif and Massif Central (as described earlier). However, following post-orogenic reordering (Meissner, 1989; Ziegler, 1990) the crustal thickness of the Variscides today is observed (Meissner & Bortfeld, 1990) to be a relatively uniform 30 km (or c. 10.5 s Two-Way Travel Time on seismic sections). As a consequence, estimating the palaeorelief of the mountain belt is difficult.

There are, nevertheless, some clues to the magnitude of Variscan palaeorelief:

1. Stratigraphic thickness of late- and post- orogenic sequences of Stephanian-Autunian age onlapping palaeorelief (Wagner & Castro, 2011),
2. Studies of detrital mineral provenance to track the history of uplift and erosion, e.g. comparison of zircon and white mica (Ducasseau et al., 2014) and
3. Estimates of uplift rates provided by apatite fission track (AFTA) and other isotopic data.

Two case studies are presented below to illustrate this approach:

1. Intra-montane basins within the Cantabrian Zone of northern Iberia.
2. Provenance study of detrital minerals in the Palaeozoic cover of the Proterozoic Mauges Unit, in the south of the Armorican Massif

In the intra-montane coalfield basins of the Cantabrian Zone, strata of Barruelian and Saberian age have been correlated between the individual basins using the lacustrine intervals which contain *Leaia* bands (Wagner & Castro, 2011). These strata onlap onto a rugged topographic relief approaching 5000 m in magnitude (Figure 5).

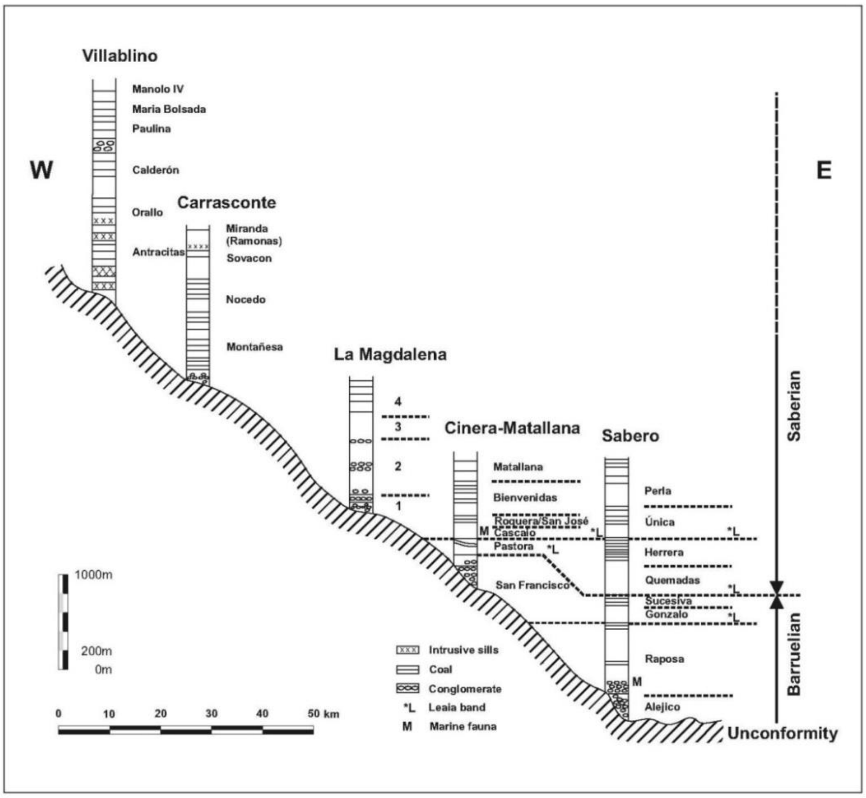

Figure 5 Stratigraphical columns for Stephanian sequences at the southern margin of the Cantabrian Zone. After Wagner & Castro (2011). Correlations are based on major lacustrine intervals with *Leaia* bands.

The sedimentary cover of the Mauges Metamorphic Unit forms part of the Upper Allochthon in the south of the Armorican Massif (Ballèvre et al., 2009) and comprises weakly metamorphosed sedimentary rocks of early Ordovician to early Late Carboniferous age (Ancenis Basin). Two chronometers (U-Pb on zircon, and $^{39}Ar/^{40}Ar$ on white mica) have been used as complementary tools on minerals with very different obduracy and blocking temperature to determine the age of rocks undergoing erosion during Palaeozoic time (Ducassou et al., 2014). The results have been used to document the emergence of orogenic relief as early as the early Devonian (Ducassou et al., 2009), following an early phase of obduction and eclogite formation. A second major tectonic event accompanied by widespread migmatisation in the late Devonian, coincided with a break in sedimentation, possibly as a result of a period of uplift and erosion. A third deformation phase is associated with the development of blueschist-eclogite metamorphsim following a second phase of obduction during the late Devonian to early Carboniferous. Erosion of a Champtoceaux Gneiss-type metamorphic source soon followed (Ducassou et al., 2009). The study clearly demonstrates that the creation of Variscan topography was episodic, and over a long period of time, in contrast to the relatively simple pattern deduced from earlier studies e.g. Becq-Giraudon & Van Den Driessche (1994).

It is clear that application of the above techniques, while in their infancy in the Variscides, show considerable potential for unravelling the late- to post-orogenic erosional history, particularly if combined with other chronometers, e.g. Sm-Nd which could be used to date detrital garnets. A large number of AFTA data are probably also available in the published literature, but have not yet been integrated into a synthesis of this topic. The complexity of the Variscan Orogeny makes it likely that only the latest, low temperature history of Variscan uplift can be recovered from such data, and even then, assumes no complication from later tectonic events, e.g. the Alpine Orogeny and Cenozoic volcanic activity.

It is concluded from the review of the Variscan Orogen presented above, that by the end of the Carboniferous, it is likely that the SW Approaches lay on the northern side of the Variscan divide (or divides), which most likely lay within the hot buoyant internide zones of the orogen. The southern side of the divide would have (at least initially) received moist tropical air from the equatorial belt just to the south. The northern side, lying in a topographically-induced rain-shadow, would have suffered increasing aridity and desertification as Pangea drifted into the northern ('New Red') desert regime (McCann et al., 2008). In addition, the Variscan Orogen (as will be described below) is likely to have been partitioned into a number of intra-montane basins, much like the 'Basin and Range' of the Western Cordillera (Wernicke, 1981, and the Altai and Tienshan basins of Mongolia and China (Cunningham, 2007).

LATE- AND POST-OROGENIC COLLAPSE

The significance of the inter-relationship between late orogenic collapse and Stephanian-Autunian deposition was presented by Ziegler (1982; 1990) and coworkers (Ziegler et al., 2004). This model requires delamination and thinning of the lithosphere and thermal re-equilibration following lithospheric orogenic root and slab break-off, illustrated in Figure 6.

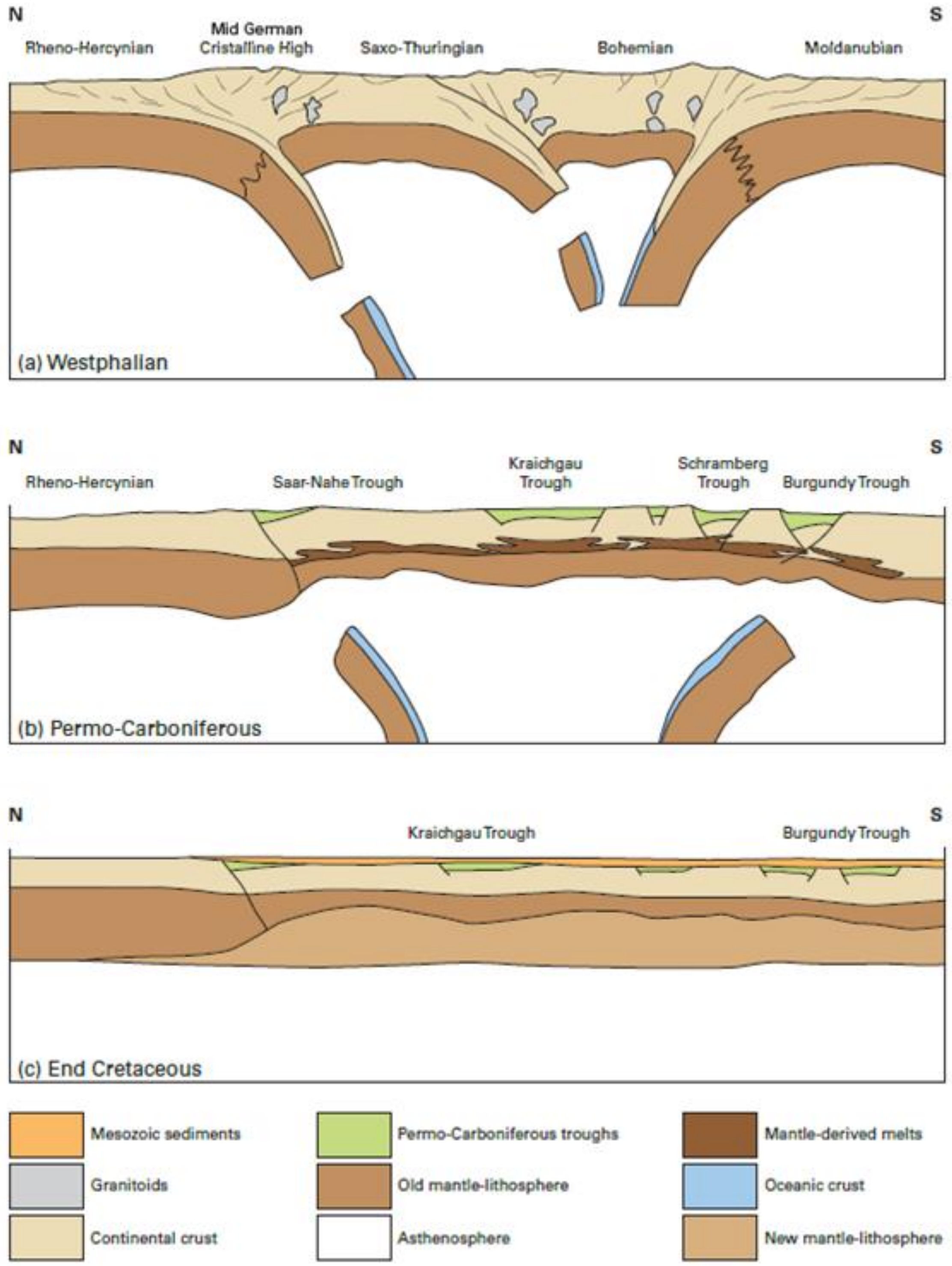

Figure 6 Schematic model for post-orogenic collapse and lithospheric delamination, after Ziegler et al. (2004).

Important consequences of the return to a thinner, relatively uniform crustal thickness include exhumation of lower- to mid-crustal rocks and the formation of intramontane basins and magmatism (Burg et al., 1994; Rey et al., 1997). Detachment of the lithospheric keel and relict subduction slabs results in high heat flow due to asthenospheric upwelling, while uplift and extension of the crustal welt may be compensated by radial compression of the orogenic peripheries (e.g. Dewey, 1988). The results of 1D modelling (England, 1993) suggest that isostatic adjustment following the loss of up to half the mantle lithosphere results in a rapid rise of the land surface by 1-3 km, followed by a progressive reduction in elevation due primarily to extension, rather than erosion. 2D modelling confirms the 1D modelling results, and suggests that up to 6 km of rapid topographic uplift may be possible (Marotta et al., 1999). Replacement of the detached bodies by warm asthenosphere causes a rise in heat flow and magmatism (England, 1993).

Praeg (2004) recognized three principal stages in the collapse of the Variscides:

1. Collapse of the internides in late Visean to mid Westphalian time (*c.* 335-310 Ma).
2. Reorientation and expansion of collapse of the externides during mid Westphalian to late Stephanian times (*c.* 310-299 Ma).
3. Collapse of the foreland in late Stephanian to Autunian times (*c.* 300-290 Ma).

Praeg (2004) argued that these stages reflect three successive detachments of negatively buoyant lithospheric material, in particular the collisionally thickened orogenic root; and two slabs of Rheic Ocean lithosphere (Figure 6) previously subducted to south (beneath the orogen), and to north, beneath the foreland. The recognition of a diachronous pattern of extension, starting in late Westphalian-Stephanian times in the Internides, and extending northward towards the foreland during the Permian, was first proposed by Lorenz & Nicholls (1976; 1984). Subsequently, studies of the Stephanian-Autunian basins in the Massif Central inferred that they formed as transpressional pull-apart basins (e.g. Arthaud & Matte, 1977; Ziegler, 1982, 1990; van Wees et al., 2000). However, this was contested by Faure (1995), who recognized that the majority of these basins had the form of 'simple' extensional half-grabens, the apparent diversity of structural trends reflected diversity of basin orientation.

From the late Visean (*c*. 330 Ma), the Variscan Orogeny entered a stage of crustal thinning and high heat flow (Malavielle, 1993; Burg. et al., 1994; Faure, 1995; Rey et al. 1997). High heat flow during this late orogenic period is associated with the intrusion (and extrusion) of voluminous magmatic suites throughout the mountain belt (Lagarde et al., 1992) during the period 340-270 Ma. Late-orogenic extension involved two main tectonic phases (Burg et al., 1994; Faure, 1995; Praeg, 2004) which occurred during late Visean-Westphalian (mid-Carboniferous, NW-SE) and late Westphalian-Autunian (late Carboniferous-early Permian, NE-SW) times. The extension direction varied along the mountain belt in each deformation phase, and in some places varied by up to 90° between the tectonic phases (Burg et al., 1994). The timing of the two deformation phases is based on radiometric dating of synkinematic igneous rocks and minerals within the shear-zones (Faure, 1995). Extension began in the central parts of the internides, mainly involving ductile extension and the rapid exhumation of lower and middle crust along normal shear-zones. Then it expanded outwards, in part coeval with thrusting and nappe propagation across the externides (e.g. Burg et al., 1994; Faure, 1995; Rey et al., 1997). In the second phase, final emplacement of the high-grade metamorphic domes (e.g. Velay, Montagne Noir) occurred along low-angle ductile shear zones in the internides, in the style of Basin and Range-type 'core complexes' (Wernicke, 1981; Echtler & Malavielle, 1990; Maluski et al., 1991). Formation of the extensional Stephanian-Autunian basins which are bounded by high-angle faults (Burg et al., 1994) then followed throughout the internides, and later (early Permian) in the externides.

For example, the Saint-Étienne Basin (Stephanian) is developed along the hangingwall of the Pilat extensional shear zone (Lardeaux et al., 2014). This originated as a ductile extensional detachment fault at *c.* 320 Ma, associated with emplacement of the Velay Dome and the post-orogenic collapse of the eastern Massif Central (Malavielle et al., 1990; Burg et al., 1991; Ledru et al., 2001). There is a similar relationship between the emplacement of the Montagne Noir Dome, and the formation of the Stephanian-Autunian in age Graissessac-Lodève Basin (Faure & Becq-Giraudon, 1993; Faure, 1995).

The Nort-sur-Erdre Fault, located along the Saxothuringian Suture which divides the North and South Armorican Terranes, was also an important boundary at this stage. To the south, rapid exhumation of lower and middle crust preceded deposition of the unmetamorphosed early Carboniferous strata in the Ancenis Basin adjacent to the fault. Strata of Stephanian B age rest unconformably on Westphalian C-D, Namurian and Givetian sedimentary sequences, in the Chantonnay-Vouvant basin complex (the 'Sillon Houiller Vendéen'), lying within a strand of the South Armorican Shear Zone (SASZ). To the north, sedimentary basins also developed adjacent to the North Armorican Shear Zone (NASZ) in the Chateaulin (Dinantian) and Laval (Dinantian plus Namurian) areas. These relationships clearly demonstrate the pre-Givetian, Eo-Variscan age of the accretion events in Armorica, and the important control early formed ductile shear zones continued to exert on the development of spatially-related post-collisional sedimentary basins. Thus the geometry of the steep brittle faults controlling the late basins were very heavily influenced by the orientation of the earlier, low-angle ductile detachments. The timing of extension in each basin was heavily dependent on its location within the orogen.

CHRONOSTRATIGRAPHY OF THE CARBONIFEROUS-PERMIAN TRANSITION

A detailed biostratigraphic framework is available for the late Carboniferous continental basins of the Variscides and the foreland. Fossil flora have contributed to a high-resolution biostratigraphic framework with substage resolution of 2-5 Ma. Due to the northward drift of Pangea, coal formation ended in the Westphalian in the northern foreland, but continued through the Stephanian in the internides and southern foreland. Thus in the northern foreland, the Stephanian-Permian boundary lies in barren strata (Besly, 1998), and is poorly constrained. In the internides, fossil flora have been strongly influenced by palaeoenvironmental factors (Broutin et al., 1986; Becq-Giraudon, 1993). The Stephanian-'Autunian' boundary is diachronous, at around 270 Ma, and should not be used as a chronostratigraphic term (Menning et al., 2002). In France and Germany, the remainder of the Lower Permian is referred to as the 'Saxonian'; and the Upper Permian is referred to as the 'Thuringian'. Both of these informal units have poorly defined boundaries and cannot be correlated with the condont faunas used to define the international timescale in central Asia.

SYSTEM	SUB-SYSTEM	SERIES	"GLOBAL" STAGES	SUBSTAGES (Western Europe)	REGIONAL STAGES	MIDCONTINENT USA	APPALACHIANS
CARBONIFEROUS	PENNSYLVANIAN	UPPER	GZHELIAN	Autunian	STEPHANIAN	Virgilian	Dunkard Monongahela Conemaugh
				Stephanian C			
				Stephanian B		Missourian	
				Sabenan			
			KASIMOVIAN	Barruelian			
				Cantabrian			
		MIDDLE	MOSCOVIAN	Asturian	WESTPHALIAN	Desmoinesian	basal Conemaugh Allegheny
				Bolsovian		Atokan	Kanawha
				Duckmantian			
				Langsettian		Morrowan	
		LOWER	BASHKIRIAN	Yeadonian	NAMURIAN		New River
				Marsdenian			Pocahontas
				Kinderscoutian			
				Alportian			
				Chokierian			
	MISS.	UPPER	SERPUKHOVIAN	Amsbergian		Chesterian	
				Pendleian			

Table 1 Chronostratigraphical terminology for Western Europe, used in this study compared with Global and American terminology. After Heckel & Clayton (2006) and Wagner & Winkler Prins (2016).

The substages (A-C) of the Stephanian were originally defined in the St Étienne Basin. More recently, these substages have been modified as a result of detailed studies in Iberia (e.g. Wagner & Winkler Prins, 1985; Knight & Wagner, 2014) such that the last stage of the Westphalian (D = Asturian), is followed by Cantabrian and Barruelian substages (formerly Stephanian A), of *c.* 2 Ma and 3 Ma duration respectively (Wagner & Winkler Prins, 1985; Doubinger et al., 1995; Menning et al., 2000). A third, Saberian substage has been proposed above the Barruelian (Knight & Wagner, 2014), based on the succession in the Sabero Coalfield which overlies Barruelian strata, resting on the Asturian Unconformity. It is equivalent to the early part of Stephanian B.

Volcanic ashes were erupted frequently during this time period, the surface expression of the emplacement of voluminous granites into the internides of the Variscides late in the orogeny. Many of these have been altered to 'tonstein', but if they contain zircon, can yield high precision (*c.* ± 1 Ma) ages by the U-Pb dating method. The most advanced technique is so-called Thermal Ionisation Mass Spectrometry (TIMS). This method has yielded a rather precise age of 302.3 Ma for the base of the proposed Saberian substage (J. Knight, *pers, comm.* 2017). The accepted age for the Carboniferous-Permian boundary is 298.8

Ma (Davydov et al., 2012). Thus the proposed Saberian sub-stage, and the remainder of Stephanian B-C substages, are some 3.5 Ma in duration. The widespread abundance of volcanic ashes in late Carboniferous-early Permian basins throughout western and central Europe leads to hope of a high-precision, radiometrically-constrained timescale for this period in the near future.

LATE- TO POST-OROGENIC BASINS

Variscan central internides

The development of Stephanian-Autunian half-graben has been recognized throughout the Variscan internides (e.g. Henk, 1993; Burg et al., 1994; Faure, 1995), accompanying the extension and thinning of the previously thickened crust. The Massif Central contains over 60 coal-bearing basins of Stephanian age (Vetter, 1971; 1986). They are typically small (1-200 km^2) and parallel to the trend of basement lineaments. Many contain evidence of one or more phases of syn-depositional compression, observed in outcrop (e.g. Blès et al., 1989) and in seismic reflection sections (Ziegler, 1990). This deformation was widely attributed to pull-apart in a regional wrench-fault regime (e.g. Arthaud & Matte, 1975; 1977; Gélard et al., 1986; Bonijoly & Castaing, 1987; Blès et al., 1989). Reorientation of the principal stress field, from N-S compression in late Westphalian time, to E-W compression during mid-Stephanian times, was inferred from these studies (Gélard et al., 1986; Ziegler, 1982; 1990).

Subsequently, Faure (1995) demonstrated that a single fixed (NE-SW) extensional stress field, which included a component of orthogonal (NW-SE) compression and transtension, is able to account for all the structural features of the different Massif Central basins, depending on their orientation. Apparent thrusts in the two largest basins were reinterpreted as gravity-driven sheets (Faure, 1995). The Stephanian coal basins ('Houillers') are invariably overlain/concealed by larger early Permian sedimentary basins (Vetter, 1986; Plates 2, 3, this report). The boundary between the two sedimentary sequences is generally non-erosive, but locally discordant (Becq-Giraudon & Ven den Driessche, 1993). Episodic syn-depositional thickening of the sedimentary sequences adjacent to the basin-controlling faults is reported (e.g. Courel et al., 1986; Becq-Giraudon & Ven den Driessche, 1993).

In the south of the Massif Central, up to 5 km of Stephanian strata are present, including Stephanian A; in the northern Massif Central, the Stephanian thins to less than 2 km and the basal beds are Stephanian B (Vetter, 1986; Mascle, 1990; Praeg, 2004).

Variscan northern internides

The structural relationship of the Carboniferous basins to earlier ductile shear-zones in the Armorican Massif was described above, and the pull-apart model has been widely applied (Mascle, 1990). This is based upon the association with shear zones, rhomboid basin shape, the evidence for syn-depositional fault movement, and rapid subsidence (Rolet, 1984). However the Dinantian basins (e.g. Laval, section on late- and post-orogenic collapse) are larger and highly deformed, and normal extension cannot be precluded; the later basins comprise repeatedly deformed packages of Namurian, upper Westphalian and Stephanian coal-bearing strata, are smaller and more plausibly explained by the 'pull-apart' model (Praeg, 2004).

Autunian strata are thin (Arpheuilles borehole, Carentan basin), or absent, in the Paris Basin (Vetter, 1986; Chateauneuf, 1984, Mascle, 1990; Praeg, 2004).

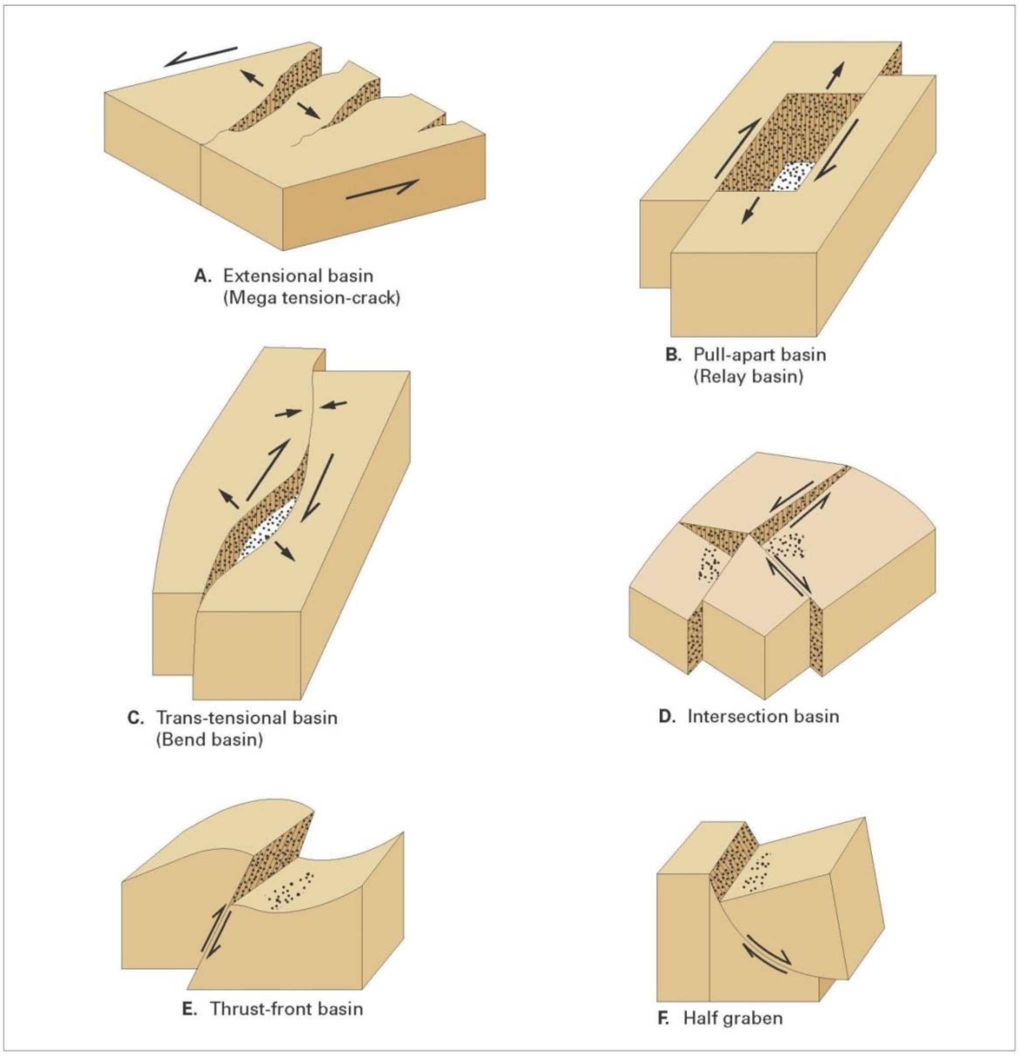

Figure 7 Genetic models for intra-montane basins (after Gélard et al., 1986).

Variscan externides

In the externides, extension and subsidence started later than in the internides. Autunian strata were encountered in the 86/18-1 well in the Western Approaches Trough. Subsidence in the Crediton Trough also began at this time, although the early Permian sequence there is dominated by volcanic rocks of the Exeter Group (Edwards et al., 1997). A similar, volcanic-dominated sequence was penetrated by two other wells (73/12-1A, 74/1-1A) in the Melville Basin.

Rocks of probable Stephanian age are known from six wells in the north and west of the Porcupine Basin (Robeson et al., 1988; Croker & Shannon, 1987; Naylor & Shannon, 2011). For example, definitive Stephanian ages have been established from the sedimentary rocks encountered by the Irish offshore boreholes 34/15-1, 26/28-1 and 26/28-2 (Naylor & Shannon, 2011). Deminex also report the presence of supposed Autunian strata in borehole

34/15-1 (Tate & Dobson, 1989), but unequivocal Permian strata have not been reported from the Porcupine Basin (Naylor & Shannon, 2011), nor indeed, west of Ireland (Tate & Dobson, 1989; Roberts et al., 1999; Praeg, 2004).

The South Wales Coalfield, Bristol and Somerset Coalfield and the concealed coalfields of Oxfordshire and Kent occur close to the Variscan Front (Plate 3) and contain strata as young as Westphalian D (Asturian) in age (Davies et al., 2013; Waters et al., 2013). Farther north, boreholes in the St George's Channel Basin (103/2-1) and Kish Bank Basin (33/22-1) of the Irish Sea, 150 km north of the Variscan Front, also penetrate strata of this age (Naylor & Shannon, 2011). However, in all the sedimentary basins to north of the Variscan Front, no strata of Stephanian or Autunian age have been proven, and the earliest strata of Collyhurst (Rotliegend) facies are believed to be of somewhat younger (but indeterminate) age (Jackson et al., 1997). The only exception appears to be the Stafford Basin, where the Salop Formation has been attributed a Stephanian A (Cantabrian) age (Waters et al., 1994; Besly & Cleal., 1997). Around the margins of the southern North Sea in the Netherlands and Germany (Plate 3), up to 600 m of Stephanian strata may be present (Kombrink et al., 2010). The extensional structures associated with this later phase of Permian subsidence, e.g. the East Malvern Boundary Fault (Barclay et al., 1997) have a N-S orientation, and postdate orogenic collapse.

PALAEOGEOGRAPHY AND PALAEOCLIMATE

The palaeoclimate of the AOI in late Carboniferous and early Permian times has been reconstructed using the following lines of evidence:

- Palaeomagnetic data, constraining the palaeolatitude (but not palaeolongitude) of Pangea, enabling palaeogeographic reconstruction;
- Sedimentological indicators of desiccation/inundation, climatic cyclicity etc;
- Minerology of contemporary soil profiles and sediments; and
- Palaeontological and palaeobotanical clues to ecological niches, although this may require comparison with more recent biota, which may be inappropriate or difficult given the passage of 300 Ma.

Palaeomagnetic-based reconstructions

Most reconstructions agree that in late Carboniferous times, the Variscan-Alleghenian Orogen formed a central welt in Pangaea (Figure 4d). Figure 4d for Moscovian time (306 Ma) and Figure 8d for Sakmarian time (290 Ma), bracket the time interval considered here. During this period of 16 Ma, the SW Approaches moved from the Equator to about 10°N; Northern Spain from about 4°S to 6°N. Using the Earth's present climatic regime in a uniformitarian way, the AOI moved from a moist equable, equatorial climatic regime in the late Carboniferous, to more arid northern desert conditions with greater seasonality, in the early Permian. The palaeographic reconstructions (Figure 4d, 8d) also show a large Palaeotethys Ocean (PTO) opening east of Turkey. The AOI lay too far west of this ocean to benefit from any climatic amelioration, due to the prevailing westerly winds at the intertropical convergence (Gebhardt & Hiete, 2013). Contemporaneous widespread glaciation in the southern hemisphere manifested itself by repeated changes between semi-arid and

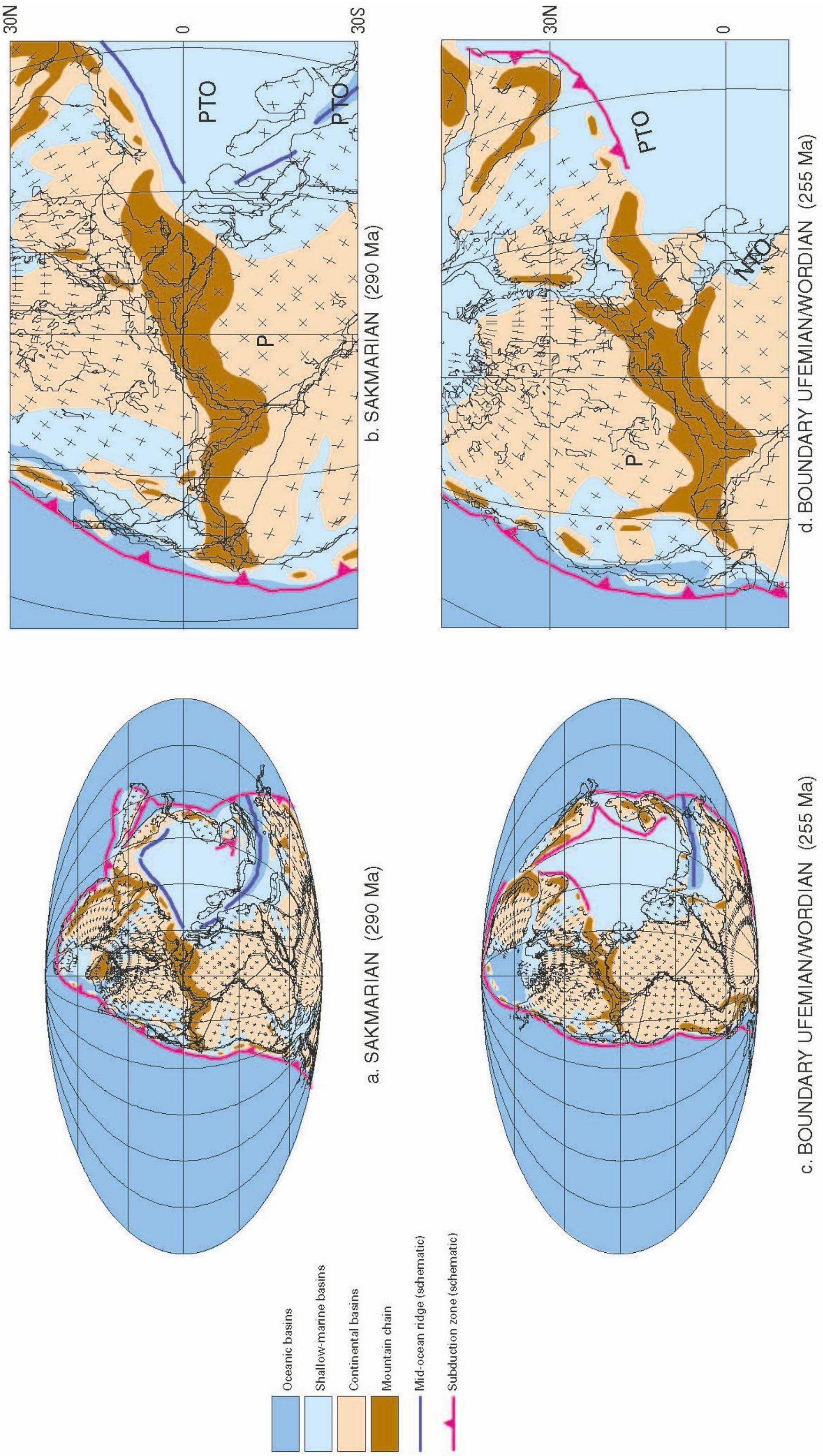

Figure 8 Palaeogeographical reconstructions for 290 Ma and 255 Ma, after C. Scotese, courtesy of Shell. Modified after Pharaoh et al. (2010).

humid climate in the northern hemisphere (e.g. Falcoln-Lang, 2003; Roscher & Schneider, 2006), enhancing the trend caused by northward continental drift. The local morphology of the

Saale Basin resulted in a Stephanian climate characterized by a seasonal wet-dry (monsoon) climate with relatively high precipitation (Gebhardt et al., 2000).

Sedimentological/mineralogical indicators

Primary (syn-depositional) reddening of strata occurs as a result of diagenesis under oxidizing conditions. Presently, this occurs in the equatorial, intertropical and desert climatic belts. In southern Britain, the first indications of primary reddening are in strata of late Duckmatian to Bolsovian (Westphalian B/C) age (Waters et al., 2013). Initially, strata of grey and red colour are interlayered. Shales, being less permeable to oxidizing shallow groundwaters, may preserve their grey colour better than sandstones. Strata of Asturian-Cantabrian age, referred to the Warwickshire Group, are predominantly redbeds (Davies et al., 2013), although the coal-poor Halesowen Formation (Asturian) is largely grey. The youngest preserved strata are those of the Salop Formation, comprising red and red-brown interbedded mudstone and sandstone, with thin beds of *Spirorbis* limestone indicating fresh water conditions. These strata were deposited in well-drained, proximal to distal alluvial plain settings, containing evidence of localized shallow lake formation.

In the Massif Central, these conditions arrived rather later, about 16 Ma later than in central Britain. The earliest redbeds in the Decazeville Basin underlie coal-bearing strata of Stephanian B age (Châteauneuf & Farjanel, 1989). Red ferralitic to bauxitic paleosols containing haematite, boehmite and kaolinite are interpreted to have formed in a damp, tropical climate, probably under a dense vegetation cover (Bellenguez & Revel, 1986). However, redbed facies are quite rare in the Stephanian of France (Châteauneuf & Farjanel, 1989). The alternating grey-red facies described above is also typical of Autunian strata in the basins of Aumance, Saint-Affrique and Lodève. Saxonian-aged strata are typically entirely red facies in France, and reddening was ubiquitous on the north shore of the Palaeo-Tethys Ocean (including the Iberian Block, Corsica, Sardinia and Puglia, during Thuringian time. In these strata, the most abundant clay mineral is illite rather than kaolinite, which formed in a predominantly dry climate (Creuzot, 1983). Uranium deposits e.g. in the Lodève (Mathis et al., 1990), Bourbon-l'Archambault (Mathis & Brulhet, 1990), Autun, Blanzy, Saint-Affrique and elsewhere (Héry, 1990) are often associated with bituminous shales. The uranium is sourced by contemporary acid volcanism and precipitated syndepositionally/diagenetically (along with sulphide mineralization) in the more reducing environment associated with the shales.

Seasonal cyclicity

The occurrence of evaporite minerals is significant because they are sensitive indicators of lake water chemistry (Allen & Allen, 2006). Hydrologically closed lakes commonly form in regions dominated by internal drainage (e.g. the Chad Basin) and are associated with the formation of chemical and biochemical sediments, as well as evaporites. Hydrologically open or through-flowing lakes, typical of continental rifts such as East Africa and Baikal, are dominated by terrigenous clastic input and where river input is negligible, alkaline earth carbonates (Allen & Allen, 2006).

Other important factors (in addition to climate) are the slope of the nearshore zone, bathymetry, stratification of the water column, and size and shape of the lake. Many

Holocene/Quaternary lakes show levels\salinities with a frequency of cycling reflecting Milankovitch forcing of the climate. Evaporites are absent from the French Permian, but continental carbonates and palaeosols are frequent (Châteauneuf & Farjanel, 1989). For example, in the Aumance Basin, red mudstones contain carbonate crusts, stromatolitic encrustations, desiccation cracks, rain-pit impressions and palaeosols (Ngos, 1987; Broutin & Gisbert, 1985). Distinctive seasonal dolomitic crusts in Saint-Affrique and Lodève are referred to as ‘ruffs’, and are formed by pronounced wet/dry seasonality (Châteauneuf & Farjanel, 1989). Calcisols and vertisols were ubiquitous under such conditions.

Lake development is not only restricted to Autunian time. For example, Lojka et al. (2010) demonstrated the existence of a large (>5000 km^2) freshwater lake in the Central Bohemian Massif in Stephanian B time. They identified two hydrological states: a high lake level associated with a thermally stratified water body, organic matter production and reducing conditions on the lake bed; and low lake level, associated with a more oxygenated and less-stratified water body. These seasonal variations produced a regular couplet lamination comprising alternations of organic (algal, microbial remains)-rich clays, with detrital silt laminae, accompanied by authigenic siderite and humified or burnt terrestrial plant debris. The couplet laminations typically vary between 1 and 5 mm thick, so that the 22 m section analysed record thousands, perhaps tens of thousands, of years of lacustrine sedimentation. Couplet formation was attributed to seasonal changes in rainfall/sediment input, as in modern tropical lakes, but spectral analysis also revealed other decadal- to centennial-scale changes in rate of silt supply (Lojka et al., 2010).

Another long-lasting lake within the Saar-Naahe Basin, Autunian-age ‘Lake Odernheim’, was studied by Müller et al. (2006), who investigated the carbon and oxygen isotopic composition of the laminated bituminous shales. The sedimentary organic matter comprised a mixture of detrital vascular plant material and lake-derived phytosynthetic algal matter, together with a contribution from bacterial biomass, modified by bacterial sulphate reduction in anaerobic conditions on the lake bed. The observed geochemical changes are attributed to temporal variation in the lake’s water balance, including times of stronger evaporation, as well as times of significant freshwater input.

The Saale Basin of eastern Germany demonstrates similar changes to the French basins: increasing reddening of strata through the Stephanian, while rivers changed from semi-permanent meandering systems to periodic braided river systems. Gebhardt & Hiete (2013) showed that Time-Series Analysis could be applied to fining- and coarsening-upward cyclicity in an 800 m thick section of Stephanian age. They conclude that some of these cycles are climatically driven, with Milankovitch periodicities in the 400 ka and 100 ka range.

Palaeontological and palaeobotanical evidence

The late Carboniferous-early Permian is a period of floral upheaval. Most of the Carboniferous *Pteridophytes* rapidly became extinct in Stephanian C/early Autunian times. Most of the *Lepidophytes* and *Calamites*, adapted to marshy environments, were replaced by *Pteridospermales* and *Coniferales*. The pollen of the latter is adapted for preservation in arid environments. The large fronds of the *Pteridophytes* were replaced with needle-like leaves adapted for decreased fluid intake (Châteauneuf & Farjanel, 1989).

GEOTHERMAL REGIMES

The late Carboniferous-early Permian basins developed during Variscan late- and post-orogenic collapse, associated with core-complex unroofing, uplift and granite emplacement, with an enhanced geothermal gradient due to asthenospheric upwelling (Ziegler et al., 2004). Considerable volumes of magma were erupted, and bimodal (basalt-rhyolite) volcanic sequences are found in most basins, even if only in the form of volcanic ashes. A considerable amount of data on coal rank and vitrinite reflectance has been gathered in the different countries, and will be discussed in the subsequent text.

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3 Spain

INTRODUCTION

The Stephanian strata of the Cantabrian Mountains unconformably overlie Precambrian to Carboniferous age basement within the Variscan Externides and Foreland (Figure 9). They postdate the Asturian Deformation Phase and the regional Asturian Unconformity (Figure 10). In general the basins are rather small intra-montane basins (graben or half-graben) with high subsidence rates, nucleated on large strike-slip or normal faults. Some basin-bounding faults developed by the extensional reactivation of Variscan compressional faults, but also bear evidence of Alpine reactivation. The origin of formation of these basins is controversial. Some researchers (e.g. Bahamonde & Nuno, 1991; Colmonero et al., 2002) suggest the basins are piggy-back basins, or due to thrust-loading (e.g. Heredia, 1991). Other authors (e.g. Heward, 1978; Heward & Reading, 1980) suggest a pull-apart origin as a result of strike-slip movement on the regional faults in the south of the Cantabrian Mountains. Another theory is that the basins formed in an extensional regime, possibly related to late-Variscan gravitational collapse, as is clearly the case in the West Asturian-Leonese Zone (e.g Colmenero et al., 2002). Probably all these types are represented. Some of the coal basins did experience syntectonic deformation. The ages of the successions were established by detailed studies of the flora (e.g. Wagner, 1971; Knight, 1971).

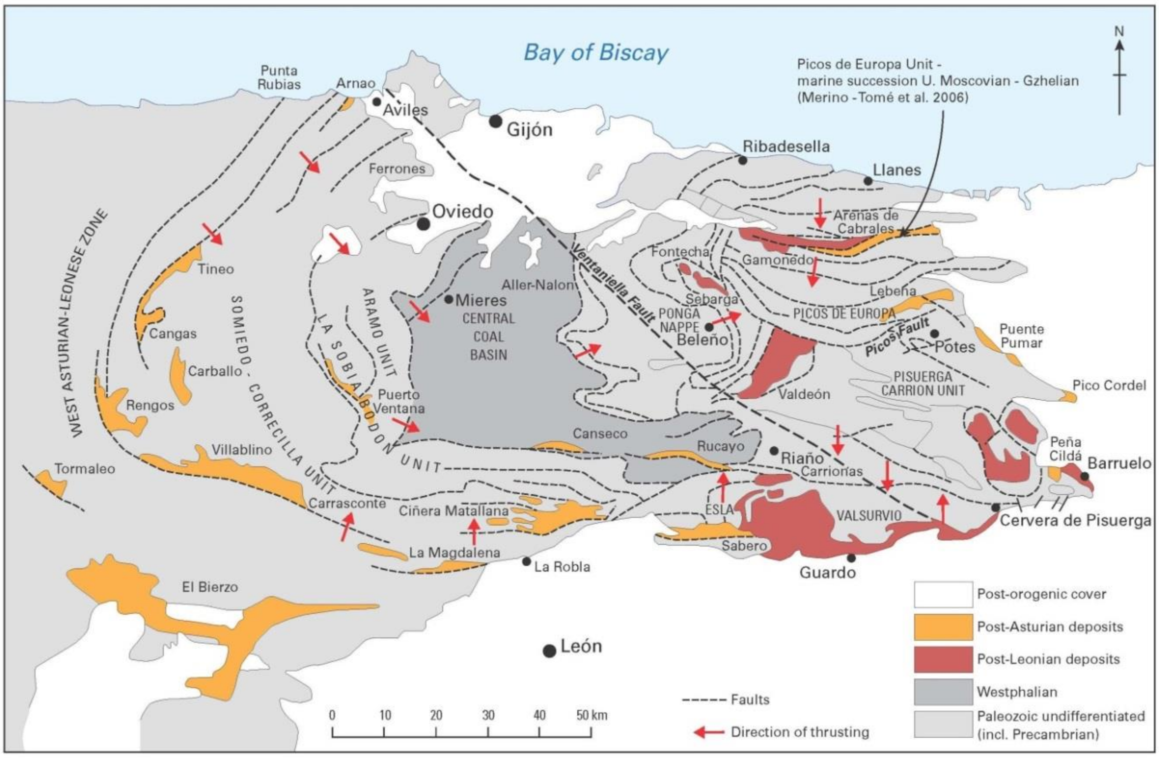

Figure 9 Stephanian outcrops of the Cantabrian Mountains, NW Spain (after Wagner & Castro, 2011; Knight & Wagner, 2014).

DATA SOURCES

Much useful information is included in regional syntheses, such as 'The Geology of Spain' in English (Gibbons & Moreno, 2002) and 'Geología de España' (Vera, 2004) in Spanish. Coal analytical data are summarized in reports by the Instituto Nacional del Carbon (INCAR-CSIC) based in Oviedo, Spain.

VARISCAN BASEMENT STRUCTURE AND HISTORY

The coal basins of the Cantabrian Mountains lie within the Cantabrian (Southern) Foreland and West Asturian-Leonese (externide) Zones of the Iberian Massif, where they occur within the spectacular orocline of the Ibero-Armorican Arc (Figure 2). The Cantabrian Zone comprises Devonian and Carboniferous rocks deformed by imbricate nappes and thrusts directed eastwards towards the foreland in the core of the arc. Metamorphic grade is very low in the east (diagenetic grade), rising to epizonal in the west and locally near igneous intrusions and fault zones. The West Asturian-Leonese Zone is separated from the Cantabrian Zone by the Narcea Antiform. Emplacement of these nappe complexes occurred piggy-back style during Carboniferous times. The oroclinal structure of the region was explained by Pérez-Estaun et al. (1988) in terms of a progressive change in the nappe emplacement direction (see Chapter 2, section on Oroclinal structure). Late in Carboniferous times the orogen began to collapse, but the relationship of the Stephanian-Autunian basins to their substrate clearly shows that they were being formed during the last stages of oroclinal bending and nappe emplacement. A later phase of extension is associated with the NW-SE trending rift in the Bay of Biscay coinciding with the opening of the Atlantic (e.g. Espina et al., 2004), in Triassic to Cretaceous times, during which Iberia rotated 30° anti-clockwise relative to France. Reactivation of many pre-existing faults occurred during the Alpine Orogeny in the Cenozoic.

BASIN MORPHOLOGY

The origin of the Cantabrian basins have long been the subject of debate. Wagner & Varker (1972) and Wagner & Winkler Prins (1985) suggested that all the Stephanian coalfields within the Cantabrian Zone were part of a single extensional basin controlled by normal faults. An alternative hypothesis suggests that the basins are remnants of E-W-trending pull-aparts generated by strike-slip motion on the major faults such as the Leon and Sabero-Gordon faults (Heward & Reading, 1980). More recently, the Redondo, Barruelo and other coalfields have been interpreted as foreland basins overridden by thrusting (Bahamonde & Nuno, 1991; Colmonero et al., 2002). The age of the sequences varies from basin to basin. Abundant sills and dykes are present.

STRATIGRAPHY

Namurian-Asturian (Westphalian D) coal-bearing successions attain thicknesses of several thousands of metres within the Asturian Central Coal Basin (Figure 9). Cantabrian-Barruelian (Stephanian A in age) strata unconformably overlie older coal measures above the Leonian Unconformity (Figure 10). Stephanian B-C and Autunian strata rest unconformably on the Asturian Unconformity in basins throughout the area e.g. Sabero, Cinera-Matallana, Canseco-Salamon, Ventana in the Cantabrian Zone; La Magdalena, Villablino, Rengos, Carballo, Cangas and Tineo on the Narcea Antiform; and El Bierzo in the West Asturian-Leonese Zone (Figure 9).

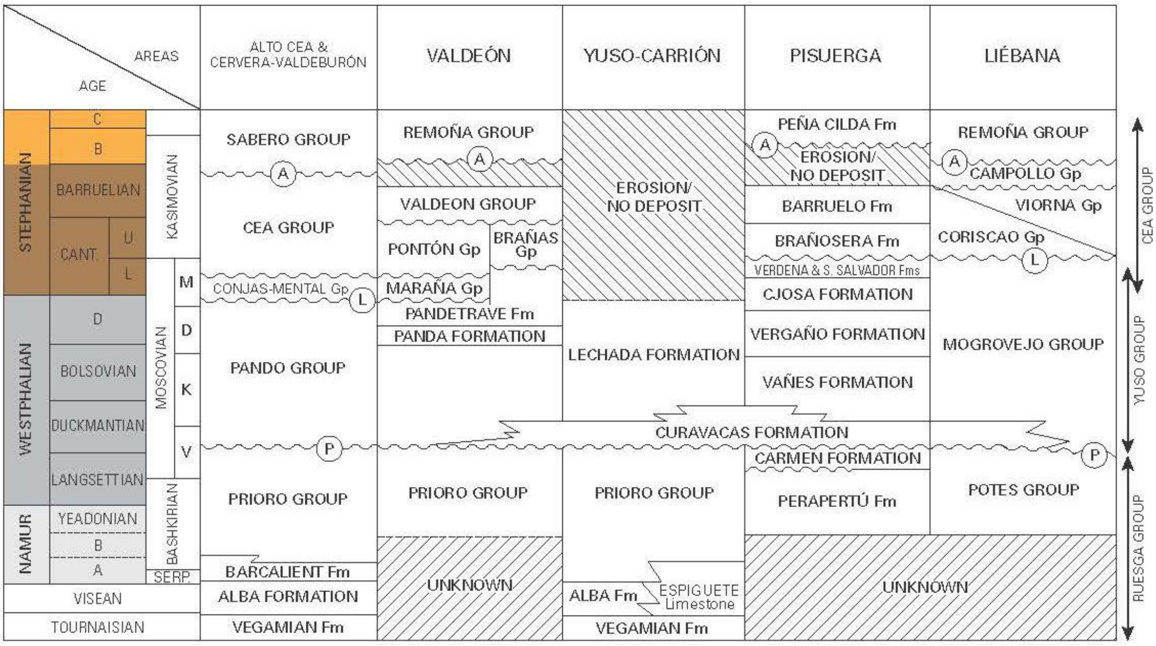

Figure 10 Chronostratigraphic and lithostratigraphic correlation of Carboniferous strata in the Cantabrian region. After Colmenero et al. (2002). Key to unconformities: P, Palentian Unconformity; L, Leonian Unconformity; A, Asturian Unconformity.

These late Carboniferous to early Permian sequences crop out in the cores of a series of synclinal basins lying more or less parallel to the structure of the orogenic substrate. Typically the strata are strongly folded and faulted, with one flank of the fold structure well-preserved, and the other severely faulted by Variscan late orogenic/gravitational collapse, and/or later Alpine reactivation.

SEDIMENTARY HISTORY

The basin-fill in each coalfield typically forms a large-scale (1500 to 3000 m thick) fining-upward sequence (Heward, 1978; Colmenero et al., 1996) that can be divided into a three part large-scale, fining-upward succession. The initial sedimentation comprised coarse clastics and conglomerates infilling palaeo-relief: proximal breccias, conglomerates and pebble beds. The second stage represents a less energetic system of conglomerates interbedded with sandstones, mudstones and rarer coal seams. The final stage mainly comprises alternating sandstones, siltstones and mudstones (mainly lacustrine in origin). Abundant sills and dykes occur cross cutting or intercalated in the sequence.

The sedimentary depositional model is an alluvial fan system grading into a lacustrine environment (Figure 11). Small proximal alluvial-fans infilling valley topography coalesced before a lower energy distal fluival-alluvial fan/lacustrine environment was established with sediments transported large distances by sheet-flood/fluvial channel systems (Heward, 1978).

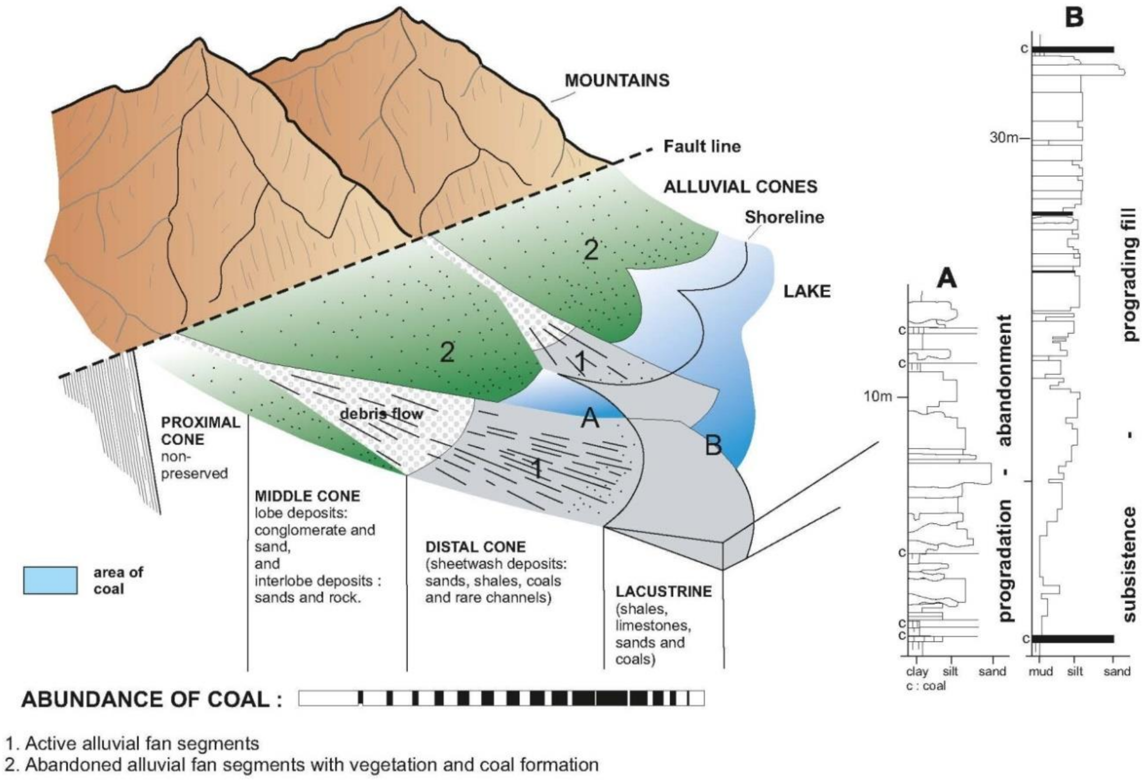

Figure 11 Reconstructed sedimentary environment for Stephanian basins of Cantabria, after Heward, (1978).

BASIN CASE STUDIES

Sabero Coalfield

Up to 2500m of Barruelian-Stephanian B strata (Knight, 1971; Knight & Winkler Prins, 1985) unconformably overlie older Palaeozoic strata of the Esla Nappe. Towards the eastern end of the basin, the Barruelian-Stephanian B sequence unconformably overlies Cantabrian (Stephanian A) age strata (Colmenero et al., 2008). The basin structure is a tight W-E trending syncline, 17km long by 3km wide, orientated parallel to the Sabero-Gordon Fault and faulted on its southern limb (Figure 12). Figure 13 shows a SW-NE orientated cross-section, and clearly shows the internal unconformities within the Stephanian sequence resulting from the continued propagation of the Esla Nappe. A total of 30 coal seams have been identified within the sedimentary sequence, mostly in its middle and upper part (Figure 14). The medium coal rank (Bituminous C, B, A, with Vitrinite Reflectance (VR) 0.92-1.50%) is not influenced by igneous intrusions or P-T metamorphism (Colmenero et al., 2008).

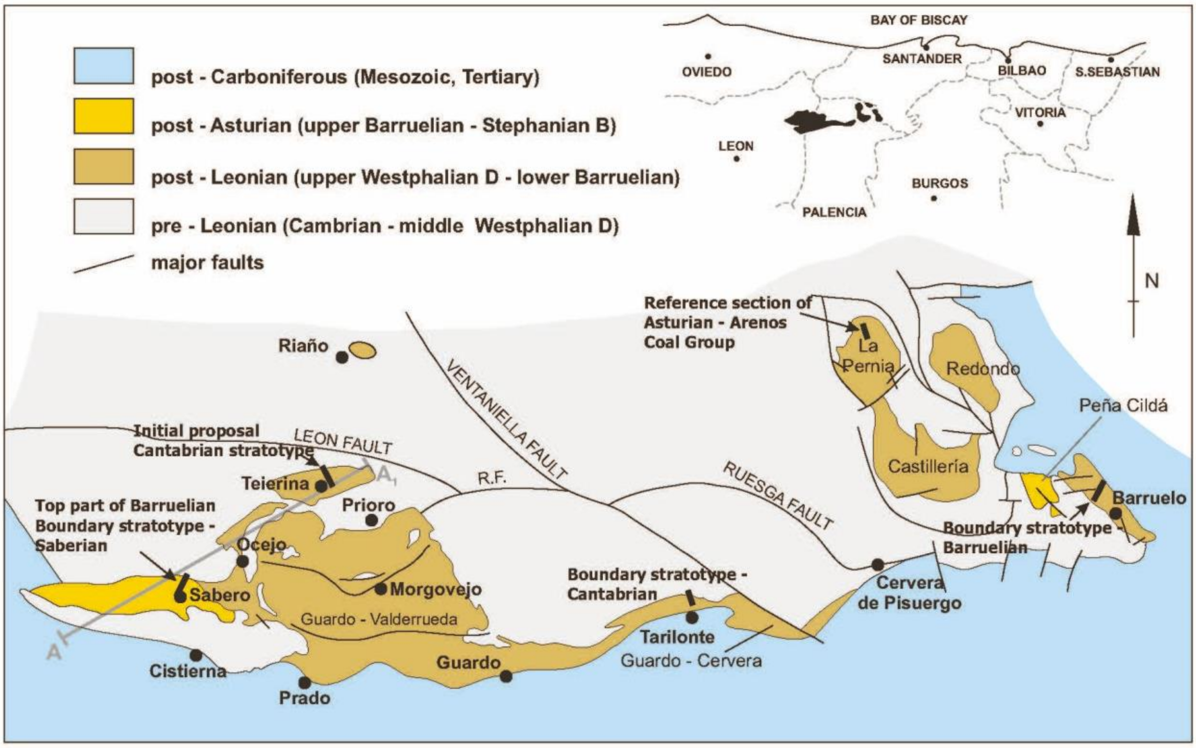

Figure 12 Location map for the Sabero Coalfield and its environs. After Knight & Wagner (2014).

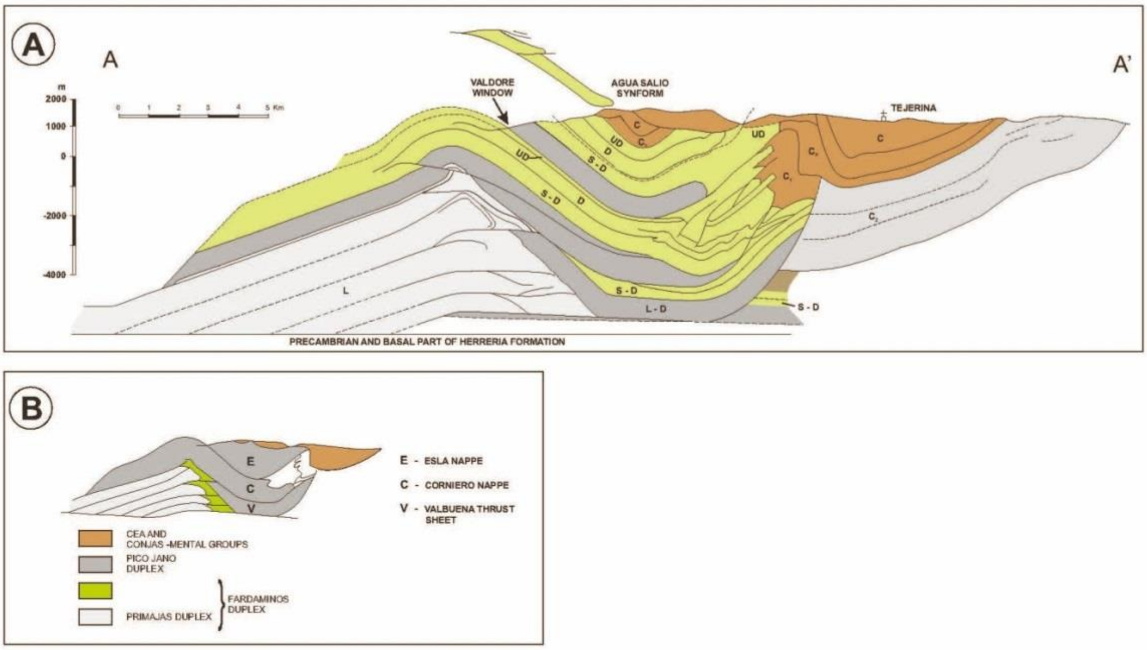

Figure 13 Geological cross-section through the Esla Nappe in the vinity of the Sabero Coalfield. After Pérez Estaun & Bastida (1990). A. Key: L, Cambrian; L-O, Cambro-Ordovician; S-D, Siluro-Devonian; C1, Lower Carboniferous and Namurian; C2, Upper Carboniferous (Pando Group); C3, Upper Carboniferous (Conjas-Mental Group); C4, Upper Carboniferous (Cea Group). B. Key: Structural units distinguished in section A.

Ciñera Matallana

The Ciñera Matallana coalfield (Figure 9) contains up to 1500 m of Stephanian B strata (Wagner, 1971) located within the core of a W-E syncline 15 km long and 5 km wide, and unconformably overlying folded Palaeozoic rocks of the Cantabrian Zone. The structure is truncated by faults belonging to the Savero-Gordon lineament (Alonso, 1989). A total of 30 seams have been identified within the sedimentary sequence, the thickest being up to 20 m thick. The coals are of medium to high coal rank.(Bituminous C, B, A. Anthracite, C, B, A) with VR 0.76-4.03% (Colmenero et al. 2008).

El Bierzo Coalfield

This is the largest and westernmost coalfield in the Cantabrian Mountains. Strata of Stephanian B-C age up to 3500 m thick unconformably overstep Precambrian rocks of the Narcea Antiform, and Cambro-Ordovician siliciclastics. The latter are folded into large open folds and cross-cut by thrusts, within the West Asturian-Leonese Zone (Figure 9). The coalfield is subdivided into three sectors by a series of W-E trending open folds, cut by faults propagating from basement features (Pérez-Estaun, 1978; Fernandez-Garcia et al., 1984). Approximately 70 coal seams have been mined in the different sectors. Maturity data suggest a medium/high coal rank (Bituminous A, Anthracite, C, B, A) with VR 1.87-5.25% (Colmenero et al. 2008). Southward increasing coal rank (to anthracite) possibly results from increasing proximity to the Boal-Los Ancares structural belt, which contains numerous small gabbro and I-type granodiorite intrusions along its axis.

GEOCHEMISTRY

Although much geochemical data exists for the Westphalian coals of the Central Asturian Basin (e.g. Piedad-Sanchez et al., 2004), data for the Stephanian-Autunian sequences appears to be more limited and difficult to access.

THERMAL HISTORY

The west of the region was metamorphosed during regional Variscan deformation as well as in response to the emplacement of high-level sub-volcanic intrusions. Metamorphism towards the east of the region is in general low grade (diagenetic zone) and is mainly a result of hot fluid circulation using major faults as conduits, as shown by the change in coal rank across the region (Colmenero & Prado, 1993; Garcia-Lopez et al., 1999).

SOURCE ROCK POTENTIAL

Stephanian sequences in Northern Iberia are thick and coal-rich, although the basins are invariably small in area. There is a large database on coal chemistry and rank, the latter ranging from medium (bituminous C) to high (anthracite A). VR ranges from 0.6 to 6%. In general, the coals are vitrinite-rich (70-80 volume %) and inertinite contents are low (<10 volume%) (Colmenero et al., 2008). The rank increases from east (Cantabrian Zone) to west (Narcea Antiform and West Asturian-Leonese Zone). High thermal fluxes are locally associated with magmatic and hydrothermal activity (Colmenero & Prado, 1993). Data on the

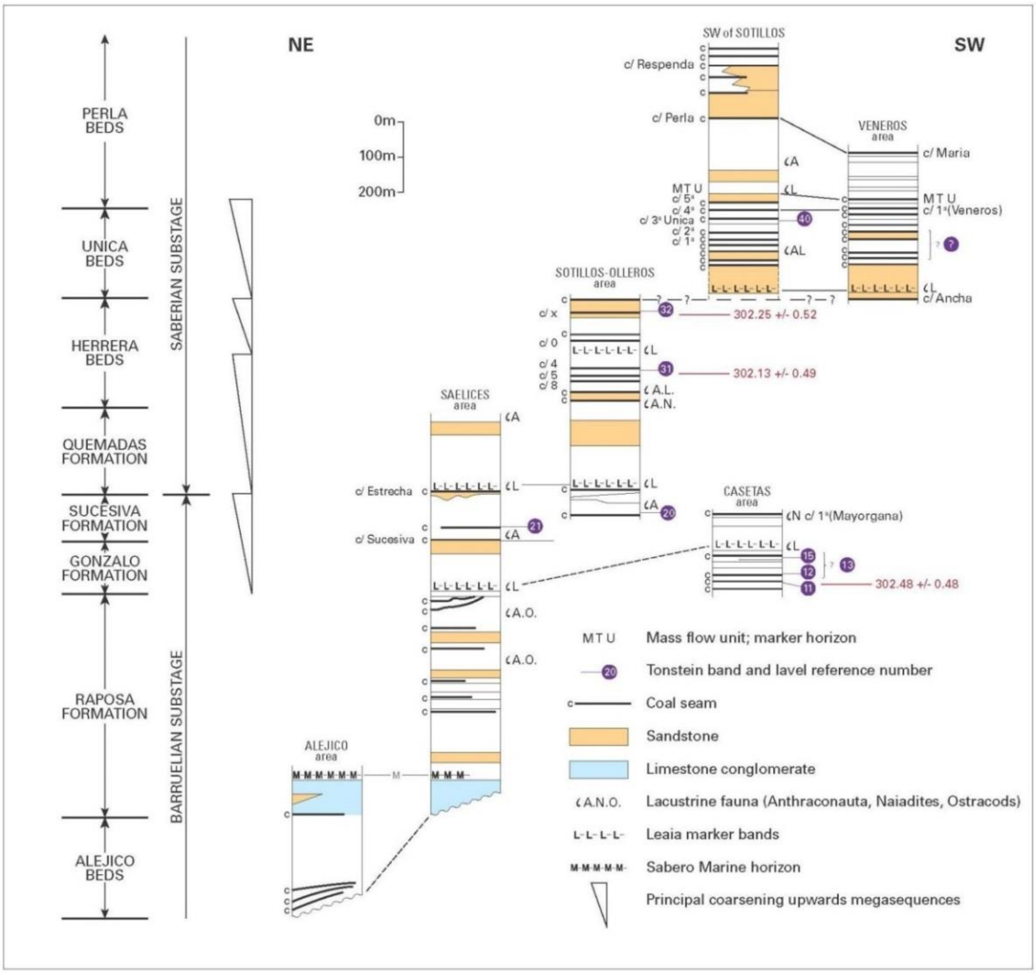

Figure 14 Generalised stratigraphic columns for the Sabero Coalfield (Leon, NW Spain). After Knight, Burger & Bieg (2000).

Autunian sequences is much more limited, and the lacustrine source is much poorly characterised than farther north in Europe.

MIGRATION PATHWAYS AND RESERVOIRS

Most of the Carboniferous-Permian basins shown in Figure 9 crop-out, so discussion of potential reservoir rocks is of doubtful value. A few of the basins in the north of the Cantabrian Zone are concealed beneath Mesozoic strata, and here potential reservoir rocks include Jurassic carbonate sequences and thick early Cretaceous siliciclastic sequences deposited in the Basque Trough, marginal to the developing Bay of Biscay Rift.

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4 France

INTRODUCTION

According to Vetter (1986), there are two types of Stephanian-Autunian basin in France. Firstly, large piedmont basins in the Variscan foothills (e.g. Saar-Lorraine, Alps, thrusted part of the Cévennes), that are dominated by fluvial braidplains and semi-persistent freshwater lakes. Secondly, small intra-montane basins, approximately one hundred in number, characterised by rapid subsidence leading to the accumulation of locally very thick (>20 m) coal seams. Coal measures sedimentation was still very active in the foothill basins during the Westphalian stage, and in the intra-montane basins of the Massif Central during the Stephanian stage. During the Autunian, coal-seams are mostly thin and scarce, but bituminous shales can be found.

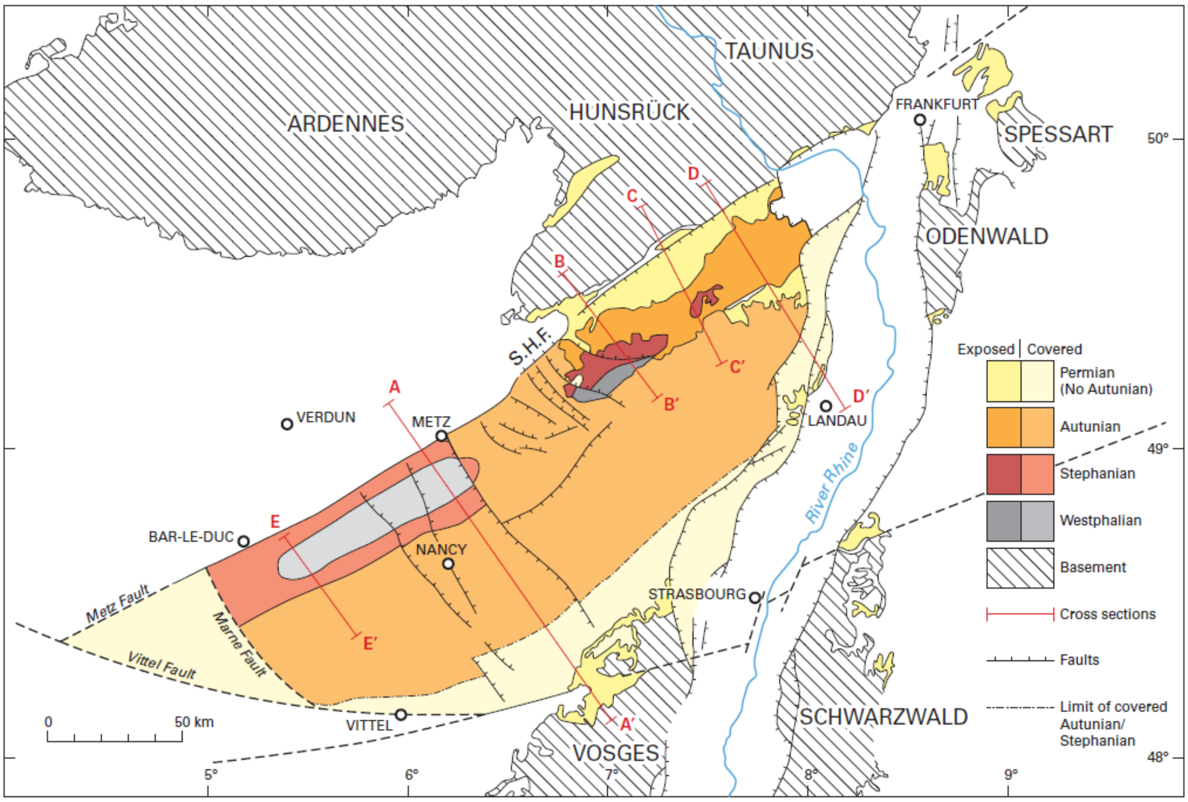

Figure 15 Map of the whole Saar-Lorraine-Nahe Basin, including the subsurface and exposed Permo-Carboniferous. SHF=South Hunsrück Fault. Cross sections B-D are found in the Chapter 5 (Figure 27) Modified from Châteauneuf & Farjanel (1989) and Korsch & Schäfer (1995).

The best example of the large piedmont-type basin, is the Saar-Lorraine (in French, Sarre-Lorraine) Basin stretching 180 km from the River Meuse in France to the River Lauter in the German Palatinate (Figure 15). The wide basin is delimited by faults to north (Metz, South Hunsrück) and south (Vittel) (Figure 15), and its coals have been mined on both sides of the French-German border. Coal sedimentation was well developed during the Westphalian, as well as periodically during the Stephanian. In Lorraine, the basin is completely concealed by a Triassic cover sequence, but its limits are well known from exploration boreholes. The total thickness of Westphalian (A, B, C and D) strata is 3400 m. Stephanian strata here are barren redbed facies unlike the coal-rich Stephanian basins elsewhere. The former more closely resemble the Saxonian of the Massif Central basins (Vetter, 1986). Other examples of piedmont-type basins can be seen within the Alpine Zone, stretching 100 km between Guillestre and the Petit Saint-Bernard pass (Briançonnais, Maurienne, Tarentaise) before continuing into the Swiss Valais. Here sedimentation continued from Namurian into the Stephanian A, although Wesphalian B strata are absent. The highest strata are of Stephanian B age and devoid of coal. The basins were later caught up in the Alpine movements, leading to the locally intense deformation of the sedimentary sequences (Fabre et al., 1960; Mercier & Baudoin, 1985).

A large number of the Stephanian intra-montane basins (approximately 60) are embedded within, and unconformable upon, the metamorphic core of the Massif Central (Figure 16, 17). A further four basins contain preserved Autunian strata, which overlie Stephanian strata and partially obscure them. This gave rise to the philosophical concept of 'The Autunian Flood' (Courel, 1984; Vetter, 1984). The reality is probably more prosaic: development of rapidly subsiding rift basins (Stephanian) followed by thermal subsidence in Autunian time, leading to a 'steers-head' type sectional geometry. The area of these basins varies considerably, approximately 200 km² for the basin of Saint-Étienne, 25 km² for Carnaux and a few thousand square metres for isolated remnants. 4000-5000 m of strata are locally preserved in these rapidly subsiding basins. The eastern part of the massif is dominated by SW-NE trending basins, namely the Autun, Blanzy-Bert-Le Creusot, Sainte-Foy l'Argentière and Saint-Étienne basins. The SSW-NNE trending Sillon Houiller 'coal trench' can be traced across the Massif Central for more than 250 km between Noyant and Decazeville. The trench comprises a succession of narrow, long and heavily tectonised basins, such as the Saint-Éloy, Messeix and Champagnac basins. The western part of the massif is affected by NW-SE-trending faults, which control the trend of the small basins of Ahun, Bosmoreau and Argentat. Other basins, particularly in the south of the massif, are orientated W-E. Examples include the Sincey-Les-Rouvray Basin, the Rodez Basin, and Lodève-Graissessac Basin. A further 25 such basins are found in the external zone of the Alps; and a progressively smaller number in the Armorican Massif (Carentan/Littry), the Vosges (Ronchamp), Provence (Maures, Estérel), the western Pyrenees and Corsica.

Concealed coal basins (proved by exploration boreholes) extend from the periphery of the Massif Central, and are referred to as 'houiller' in the French literature. Such basins include: the Jura Houiller; the Bas-Dauphiné Basin; the Cévennes Basin; and several possible sub-basins underlying the Mesozoic Paris Basin (Plate 3), as proven by the Indre, Arpheuilles, Ligueil and Ciran boreholes (Mégnien, 1980; Debrand-Passard et al., 1984). Limnic sediments are recognized as early as the Namurian e.g. in the Gironville 101 borehole (Vetter, 1984).

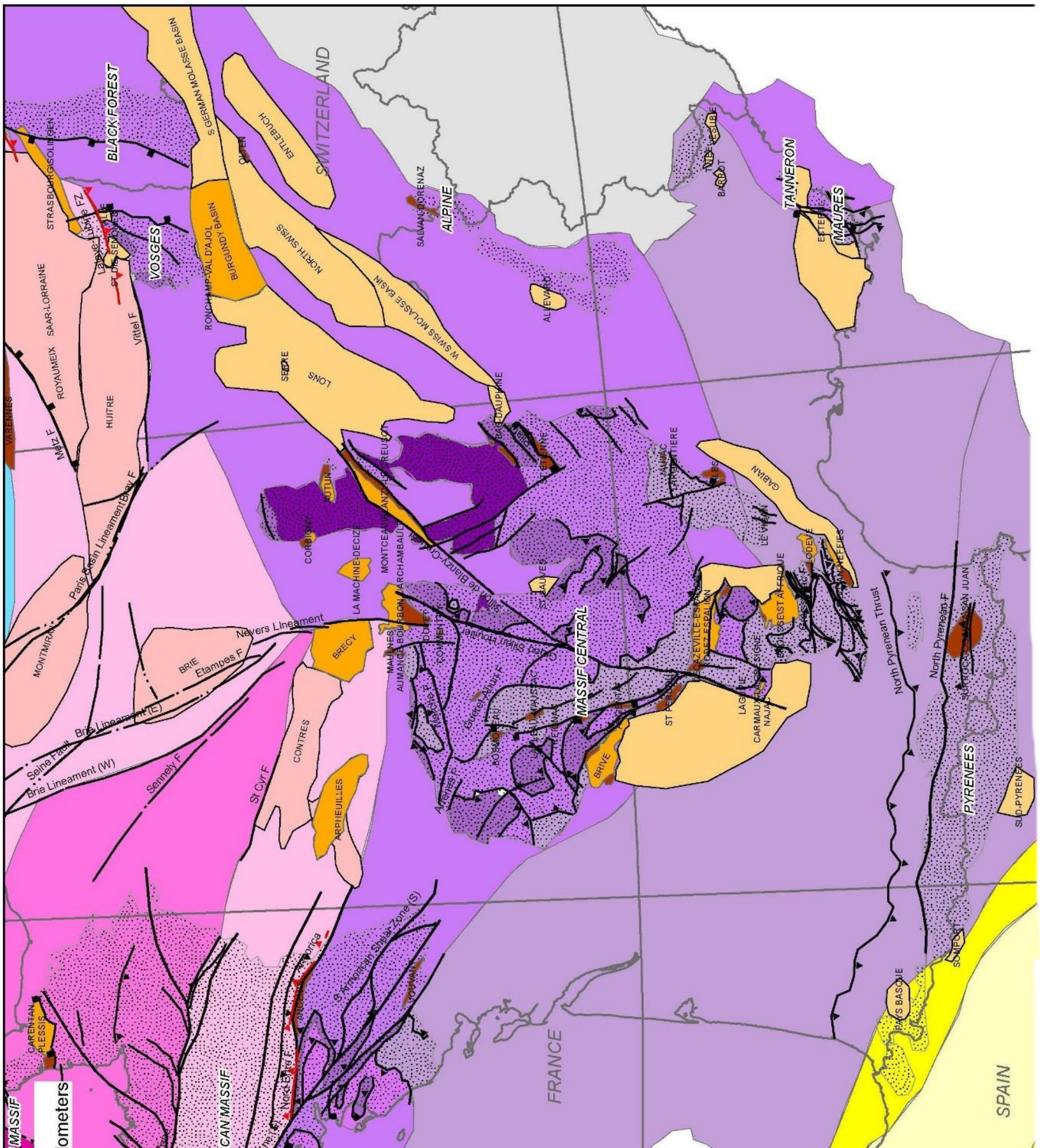

Figure 16 Late Carboniferous and Permian basins and their Variscan basement in the Massif Central and Armorican Massif. Mapping data sources listen in Appendix. For key to Variscan orogenic elements see Figure 2.

The four basins surrounding the Massif Central (Figure 17) are:

- The Paris Basin to the north
- The Bressan Plain to the east (Bas-Dauphiné, Lons Basin, Bresse Louhannaise). Between the Massif Central and the Jura
- The Southeast Basin
- The north east Aquitane Basin (Quercy Basin and Causses region) to the south west

The Paris Basin

There are several Permo-Carboniferous basins on the northern border of the Massif Central (Decize la Machine, Aumance, Commentry, Doyet, Deneuille). These basins contain Autunian bituminous shales underlain by Stephanian coal measures, both of which have been prospected as solid fuel (Châteauneuf & Becq-Giraudon, 1990). The Autunian shales are thought to extend beneath the SW margin of the Paris Basin (Mascle, 1990).

Success rates drilling the SW Paris Basin Permo-Carboniferous sequences have been low (Mascle, 1990). However, recent reprocessing of legacy seismic data targeting deeper Palaeozoic horizons has enabled a greater understanding of the deeper basins (Beccaletto et al., 2011). Beccaletto et al. (2015) reprocessed 36 regional seismic lines (1480 line km) over the SW Paris Basin, and tied an interpretation to 22 deep wells across the region. The authors were able to constrain the presence of three Mesozoic-covered Stephano-Permian basins, the Arpheuilles, Contres and Brécy basins, containing up to 3000 m of Stephano-Permian succession.

The Bressan Plain

The Permo-Carboniferous basins of the Bressan Plain are similar in character to the Blanzy-le-Creusot and St. Étienne basins outcropping on the Massif Central, and Ronchamp outcropping on the southern Vosges Massif. In fact, the basins extend under the Mesozoic cover of the Bressan Plain. The structural lineation of the Permo-Carboniferous troughs follow a WSW-ENE trend of concealed en-echelon basins which can be traced from the Massif Central to the Jura, and under the Swiss and German Molasse Basins (Mascle, 1990). Exploration in the 1980s and 1990s yielded a few small discoveries of oil at Chaleyriat and gas at Vaux-en-Bugey (Blanc et al., 1991). However, exploration in the complex tectonic region is difficult, especially as the Palaeozoic is buried beneath regional décollement horizons (Blanc et al., 1991). The Autunian succession is absent in many wells, but thick bituminous shales have been proven at Ronchamp and St Étienne (Matter, 1987) and in Switzerland.

The Southeast Basin

The Southeast Basin represents a thick sedimentary basin mainly filled with up to 10 km of Mesozoic and Cenozoic strata. The presence of Permo-Carboniferous basins are known on the Massif Central at Alès and Lodève-Graissessac. It is also encountered in wells flanking the massif, especially the Alès and Gabian Basins, which have outcrop extension on the

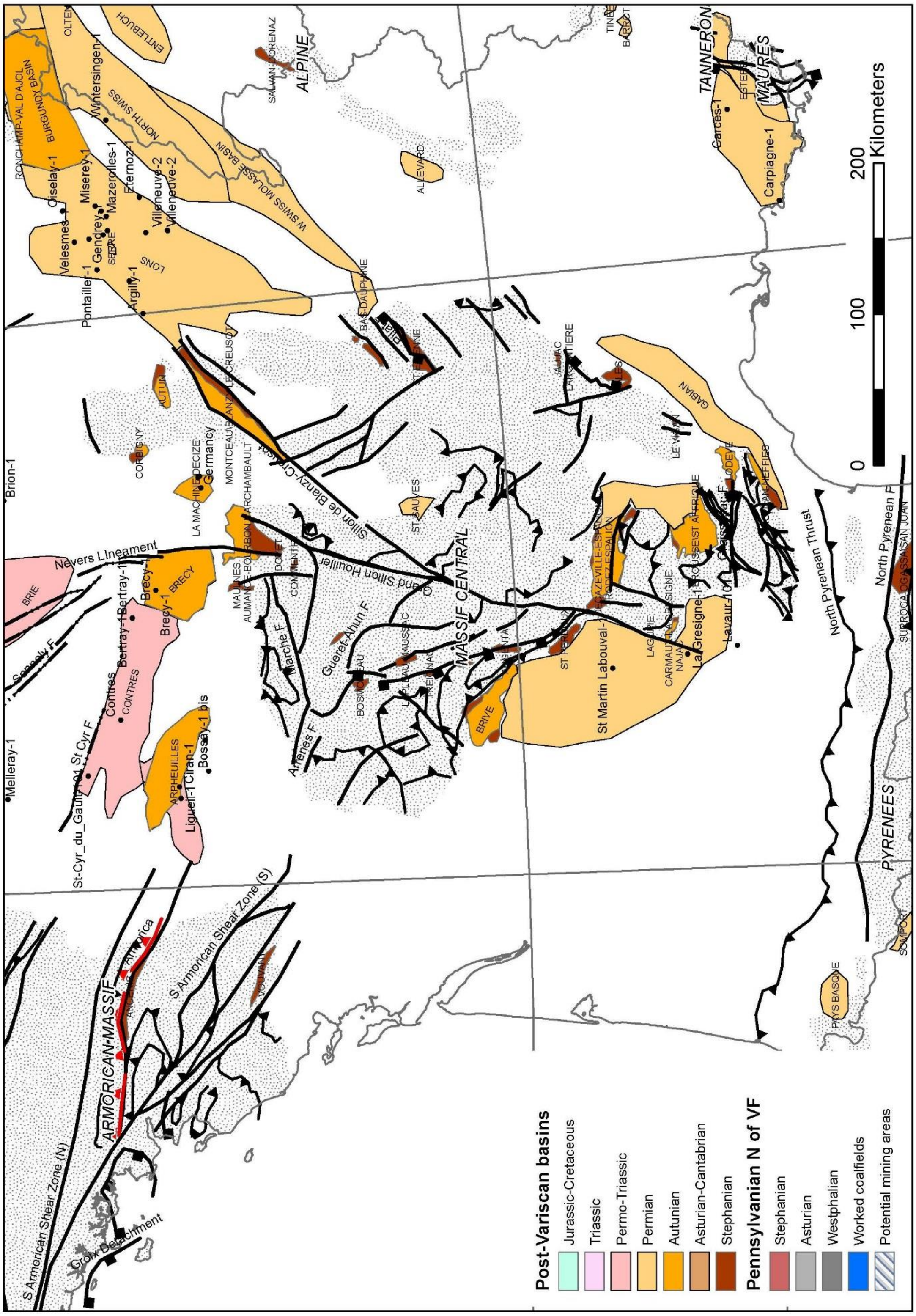

Figure 17 Late Carboniferous and Permian basins and their relationship to Variscan massifs, in the Massif Central and Armorican Massif. Location of boreholes is also shown. For key to structures see Figure 2. Massif Central. The Gabian field is found in Triassic reservoir and produced 200,000 barrels of oil generated from early Permian (Autunian) lacustrine shales (Mascle et al., 1996).

Massif Central. The Gabian field is found in Triassic reservoir and produced 200,000 barrels of oil generated from early Permian (Autunian) lacustrine shales (Mascle et al., 1996).
The presence of a petroleum system is demonstrated by oil staining within Triassic sediments, and the small Gabian oil field. However away from the immediate flanks of the Massif Central, the existence of potential source rocks is poorly understood and has not yielded any encouraging discoveries (Mascle, 1990). Most tectonic activity and uplift in the area occurred during the Cenozoic, after the maximum burial and generation of Palaeozoic source rocks, reducing the chance of accumulation survival to present day (Mascle et al., 1996).

The Aquitane Basin:

To the west of the Massif Central is the Aquitane Basin, one of France's most important hydrocarbon provinces. It is known to be underlain by Permo-Carboniferous strata, however the latter are difficult to predict and often metamorphosed.

The northeastern extension of the Aquitane Basin incorporates the Quercy Basin, which runs N-S parallel to the western margin of the Massif Central. The Quercy Basin outcrops on the Massif Central at Brive (to the north), and at the smaller outcrops of Grésigne, Najac, Cérou and Carmaux. Wells and seismic reflection data have recognised a Permo-Carboniferous sequence within the Quercy Basin, however the potential of the system is based on the outcrop, especially the larger Brive Basin (Mascle, 1990).

Stephanian Strata

The Stephanian strata are lithologically similar to the limnic Westphalian (Châteauneuf & Farjanel, 1989). There is an abundance of coarse clastic sediments, sideritic limestones associated with coals and some bituminous shale on the roof of thick coal layers. Active volcanism resulted in lava flows, tuffs and other pyroclastic material (Decazeville, Gros Blanc de Brassac, Ahun, Saint-Étienne basins). Altered volcanic ashes (tonsteins) are commonly present. Coal seams show a great variety of thickness and regularity. There are basins where the seams are insignificant (Saint-Perdoux, Argentat), and others with amalgamated seams locally reaching 100 m thick (Decazeville, Saint-Eloy). In most basins (Lorraine, Saint-Étienne, Cèvennes), the layers can be irregular and thin over wide areas.

Autunian Strata

Autunian strata are typically fluvial clastic sequences with lacustrine sequences dominated by bituminous shale (Châteauneuf & Farjanel, 1989). The basins of Bert-Moncombroux and Aumance are the only ones with several layers of exploitable coal. Thin coal seams are present in Autun and Montceau-les-Mines. The other Autunian basins: Saar-Palatinate, Graissesac-Lodève, Saint-Affrique, Rodez, and Brive, do not have coal seams, sometimes only thin coaly streaks. In the Armorican Massif, coal occurs in the Littry Basin, but is not present in the Armorican and Vendean 'coal trenches'. The relationship of the Autunian to Stephanian strata varies. It is clearly discordant on Stephanian B strata in Autun, Aumance, Noyant, and Rodez. A final W-E phase of compression, the Bourbonnaise Deformation Phase, was invoked by Grolier (1971) to explain this discordance. Discordance of Stephanian C upon Stephanian B strata in the Decazeville Basin suggests that the deformation phase may be more precisely constrained to the Stephanian B/C boundary. In the east of the massif, Stephanian C strata are present and Autunian strata overlie them in apparent concordance e.g. in the Blanzy-le-Creuzot and Saint-Étienne basins (Châteauneuf & Farjanel, 1989).

DATA SOURCES

B.R.G.M. synthesis memoirs and map atlases cover the Paris Basin (Mégnien, 1980), Lorraine Basin (Donsimoni, 1981), SE France (Debrand-Passard et al., 1984), and French Permian basins (Châteauneuf & Farjanel, 1989). B.R.G.M. also host a digital data information service called InfoTerre, which provides access to borehole location and other information. Smaller volumes describe the results of specific exploration/assessment programmes in the limnic (lacustrine) coalfields of the Massif Central (Memoir 149, 1986) and for uranium deposits nationwide (Chronique de la recherché minière, 1990). Useful information is contained in the reports of the Elf-Aquitaine Exploration-Production Research Centre, at Pau, Aquitaine. Institut Français du Pétrole (IFP) have assessed the hydrocarbon potential of the same regional areas covered by the B.R.G.M. memoirs. These confidential reports are available for purchase at prices ranging from €2500 (for reports in French on the Alsace, Lorraine, N Jura, S Jura, and SE basins) to €4500 (for reports in English on the Paris Basin, Aquitaine Basin). These reports have not been purchased for this project because of their high cost.

VARISCAN BASEMENT STRUCTURE AND HISTORY

The Variscan basement of France has been studied in great detail, as described in Chapter 2, to which the reader is referred.

BASIN MORPHOLOGY

As described above, there is a fundamental contrast between the large piedmont-type basins (e.g. Lorraine) and the intra-montane basins (e.g. Massif Central). The former type comprise large assymetric graben with many thousand metres of fill, aligned along SW-NE trending sutures and thrust zones in the piedmont, and overlying a Saxothuringian substrate. The Lorraine Basin is controlled by a steep fault along its northern margin (Metz Fault). The Carentan Basin is rather smaller in area, and controlled by a steep fault on its southern margin.

The intra-montane basins are smaller and more variable in orientation, strongly controlled by brittle extensional reactivation of Variscan ductile structures, e.g. associated with core-complex uplift and orogenic collapse (Faure, 1995, 1997; Praeg, 2004). Although a diversity of structural types (Figure 7) were identified by studies in the 1980's, and a rotating compressional stress field invoked (e.g. Ziegler, 1990), in the 1990's it was recognized that virtually all are half-graben resulting from the extension of orogenically-thickened crust (Faure, 1995).

BASIN CASE STUDIES

Lorraine-Saar-Nahe Basin

The most substantial piedmont-type basin in France is the cross-border Lorraine-Saar-Nahe Basin. The 300 x 100 km basin crosses from Germany into France (Figures 15, 24), with a 100 x 40 km surface exposure in Germany (see Chapter 5). Although continuous, the basin is called the Lorraine Basin (France), and the Saar-Nahe Basin (Germany).

The French extension of the basin was well studied in the 20th century as it was an important coal mining district (Donsimoni, 1981). Subsequently, it has been reassessed focussing on Westphalian palaeoclimates and palaeoenvironments (Fleck et al., 2001; Izart et al., 2005), and recently for coal-bed methane potential (Izart et al., 2016).

The asymmetric half-graben is bounded to the north by the steep south-dipping South Hunsrück and Metz Faults. These have been interpreted either as a steep dextral strike-slip fault system (Korsch & Schäfer, 1991), or as deep crustal listric faults (Henk, 1993). Basin initiation occurred in the Namurian and continued until the Middle Permian, preserving up to 8000 m of continental clastic succession (Figure 18) (Schäfer, 2011). Extensive work dating the volcanic and palynological history of the basin has constrained the depositional and structural history (Schäfer, 2011, and references therein).

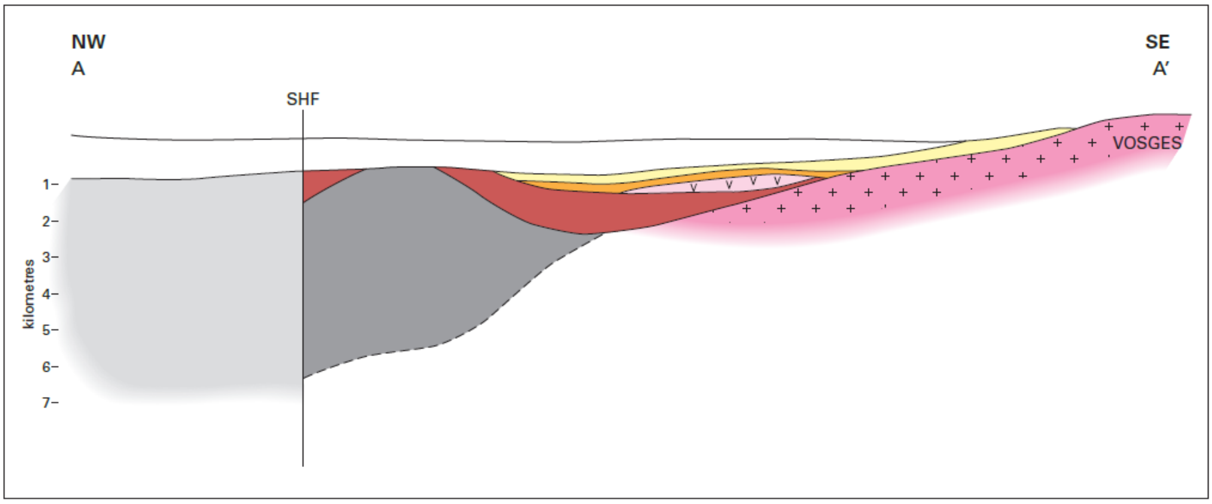

Figure 18 Cross section A through the buried Permo-Carboniferous of the Lorraine-Saar-Nahe. Line location and key shown on Figure 15. Modified from Korsch & Schäfer (1995).

In France, in contrast to Germany, the Autunian is thought to be devoid of any lacustrine shales, with continental sedimentation continuing in red-bed type facies (Izart et al. 2016). However, the French Westphalian and early Stephanian coals have been extensively studied and sampled. The deep borehole at Gironville 101 records some of the earliest basin fill encountering 4.5 km of Westphalian A-C (Figure 19) (Donsimoni, 1981). Samples have yielded a vitrinite reflectance succession commonly used for thermal modelling (Izart et al. 2016).

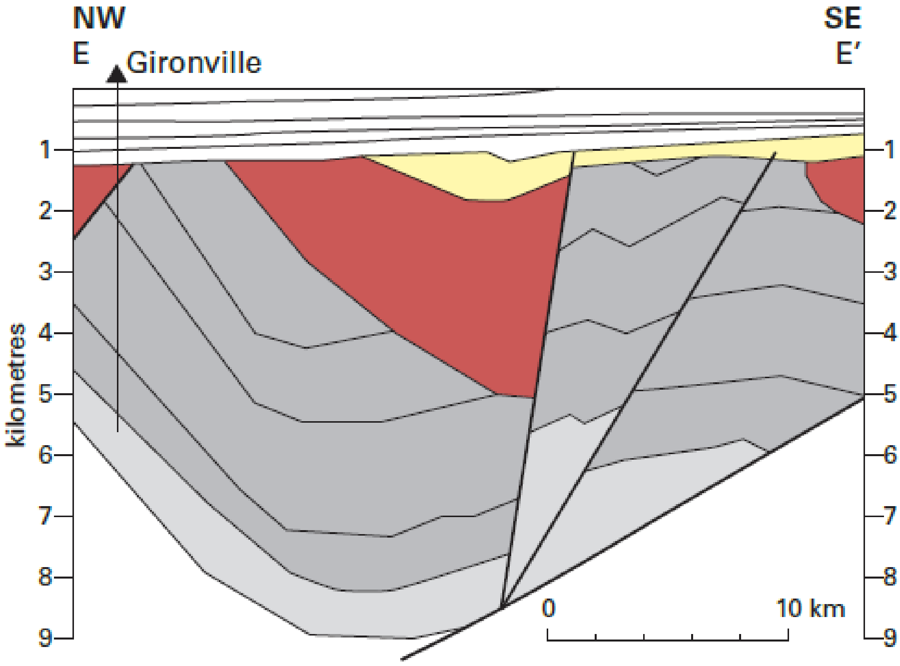

Figure 19 Cross section W-E through the buried Permo-Carboniferous of the Lorraine-Saar-Nahe Basin including the deep well Gironville 101. Cross section line location and key shown on Figure 15. Modified from Izart et al. (2016).

The Mesozoic succession is mostly complete in the Lorraine region. A hiatus follows the Upper Rotliegend with up to 1200 m of erosion until deposition of the Lower Triassic Bunter Sandstone, Muschelkalk limestone and Keuper evaporates (Donsimoni, 1981; Izart et al., 2016). Deposition of Triassic, Jurassic and Cretaceous sediments occurred, especially towards the west, on the margins of the thermally subsiding Paris-Basin (Donsimoni, 1981; Izart et al., 2016). Maximum burial was reached in the Cretaceous and was terminated by regional uplift related to rifting of the North Atlantic (Ziegler, 1990; Izart et al., 2016).

Given the lack of Autunian shales, the coals in the Lorraine region of the Lorraine-Saar-Nahe Basin are the major potential source rock (Figure 20) (Chungkham, 2009). The Westphalian B/C was assessed from the Saucy 1 borehole in Lorraine by Fleck et al. (2001). They used Rock-Eval on the more organic-rich horizons, including coals. The coals reached 76 wt% TOC, with S_1 up to 13 mg HC/g rock and S_2 up to 249 mg HC/g rock. Claystones are split into coaly claystone and claystones. The latter has TOC up to 4 wt% with S_1 0.4 mg HC/g rock and S_2 3.4 mg HC/g rock. The Stephanian coals are similar, however less frequent, than the Westphalian coals (Chungkham, 2009). Farther west, Autunian coals encountered by the borehole at Lhuitre (Figure 17) are mature (Tmax > 460) and show petroleum potential (S_1+S_2) of 17-107 mg HC/g rock (Mascle, 1990). In general only the lower Westphalian A, B and, in part, C are in the gas-window (Table 2). The younger sediments are in the oil-window with the Autunian, where present, marginally mature to immature (Izart et al., 2016).

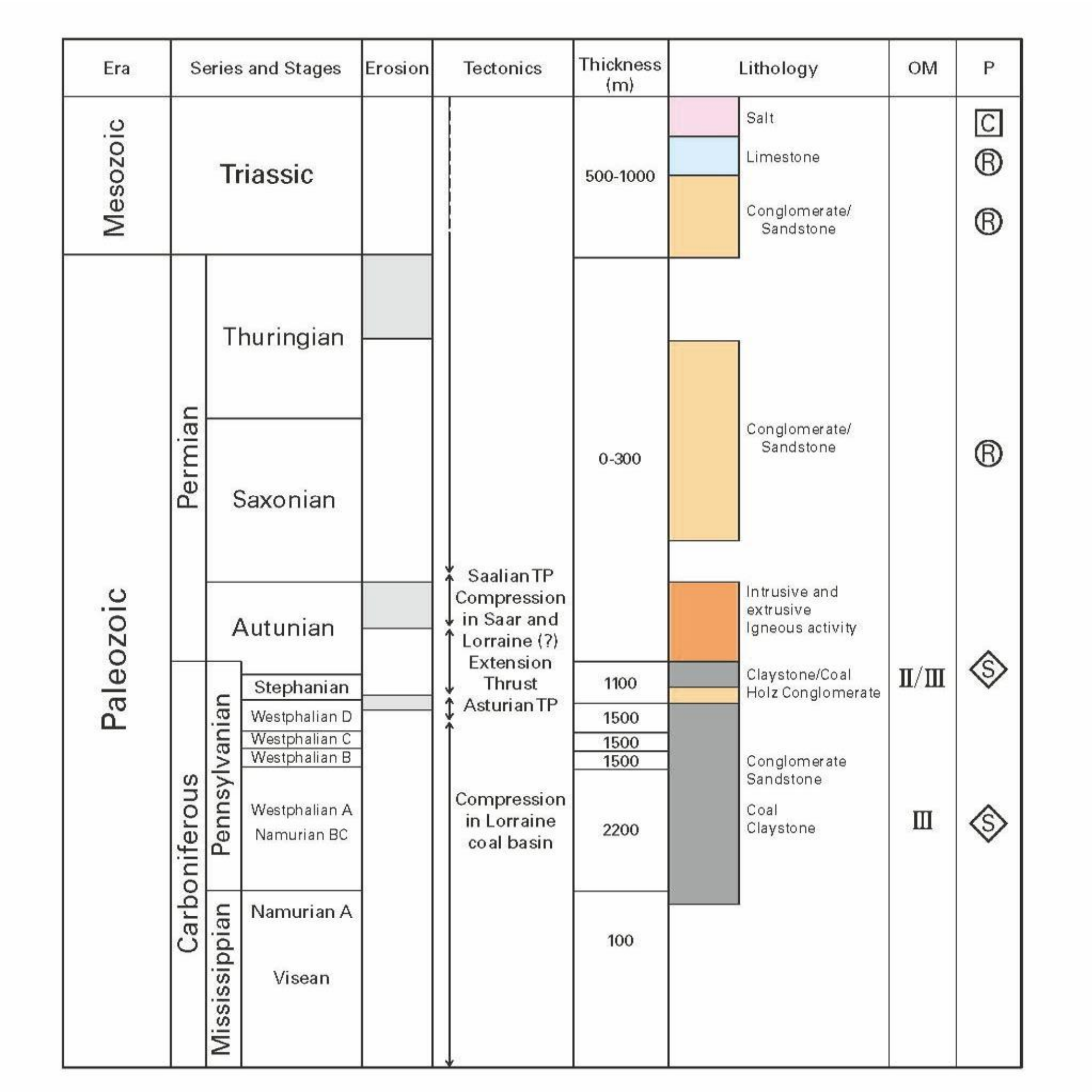

Figure 20 Lithostratigraphy and Palaeozoic petroleum system summary of the Lorraine-Saar-Nahe Basin. OM = Organic matter type. P = Petroleum system. C = Cap rock. R = Reservoir. S = Source rock. Modified from Izart et al. (2016).

Table 2 The geochemical and thermal input parameters for basin modelling (Izart et al., 2016). VR = Vitrinite Reflectance. TOC= Total Organic Carbon. HI = Hydrogen Index

Unit	VR%	TOC %	HI mgHC/g rock	Heat Flow mWm^{-2}
Stephanian		4	100	60
Westphalian D		1	150	50
Westphalian C	0.7-0.8	4	150	50
Westphalian B	1-1.18	1	150	50
Westphalian A & Namurian	1.9-2.4	1	150	50

The Permo-Carboniferous is a proven source rock interval in the western part of the Lorraine Basin where it has sourced small oil and gas accumulations, notably at Trois-Fontaines and Forcelles (Espitalié et al., 1987). The Trois-Fontaines field is a small gas field in Triassic aged sandstone whereas the Forcelles field is an oilfield in Triassic Keuper dolomites, both are trapped in small horsts capped with claystones (Izart et al., 2016).

As of 2008, only 170 of 1040 wells in the Paris Basin had reached Palaeozoic strata (Chungkham, 2009). Most of the fifty wells which penetrated a thick succession of Permo-Carboniferous are located to the east, in the Lorraine Basin (Chungkham, 2009). Although few wells have reached sufficient depths, there have been Palaeozoic-sourced shows within the overlying Triassic succession (Chungkham, 2009). The shows have a mixture of sources: the Permo-Carboniferous coals of the Lorraine Basin; bituminous shales just north of the Massif Central, and small hidden Permo-Carboniferous basins beneath Mesozoic cover (Mascle, 1990; Beccaletto et al.; 2011; Beccaletto et al., 2015).

The Lorraine Basin area is an underexplored region, both conventionally and unconventionally, but has a large potential (Chungkham, 2009). Within the Elixer Lorraine permit (5360 km^2), it was estimated to contain 2.6×10^{10} -1.8×10^{13} m^3 of unconventional oil and gas, and 6.2×10^{10} m^3 conventional Carboniferous gas in Triassic reservoirs (Izart et al., 2016). Further resource assessment for coal-bed methane have also given favourable properties for the coal seams of the Lorraine and Saar-Nahe regions (Izart et al., 2016).

Blanzy-Le Creuzot

The Blanzy-Le Creuzot Basin is filled with Stephanian and Autunian strata and lies in the NE of the Massif Central (Figures 16, 17). It is developed within a SW-NE trending splay of the Sillon Houiller Fault System, and occurs between Variscan granite-gneisses of the Morvan Massif in the north, and Charolais, in the south. This fault splays off the Sillon Houiller 150 km to the SW, where the smaller basins of Bert and Saint Sauves d'Auvergne lie, and extends a further 150 km NE towards the Vosges. The major bounding syn-depositional fault of the basin, with a downthrow exceeding 1000 m, lies on the NW margin (Figure 21) (Châteauneuf & Farjanel, 1989). The worked Stephanian coals, lie in a ribbon on the SE border (Blanzy), and within small patches in the NW (Le Creuzot). Autunian strata conformably overlie Stephanian strata at Blanzy, although the boundary is imprecisely defined. The former comprise grey, green and black alternating shales and sandstones, with thin coals. Intervals of bituminous shales are comparable in thickness and lithology to those of the Autun Basin (Figure 21). The Autunian strata are well dated by the *Walchia* and *Callipteris* floras (Châteauneuf & Farjanel, 1989). The bituminous shales contain fish scales and nodules of dolomitic limestone. A number of boreholes prove >1000 m thickness of Autunian strata. The overlying Saxonian strata comprise red or variegated sandstones and conglomerates, containing occasional silicified wood, stromatolites and tetrapod tracks.

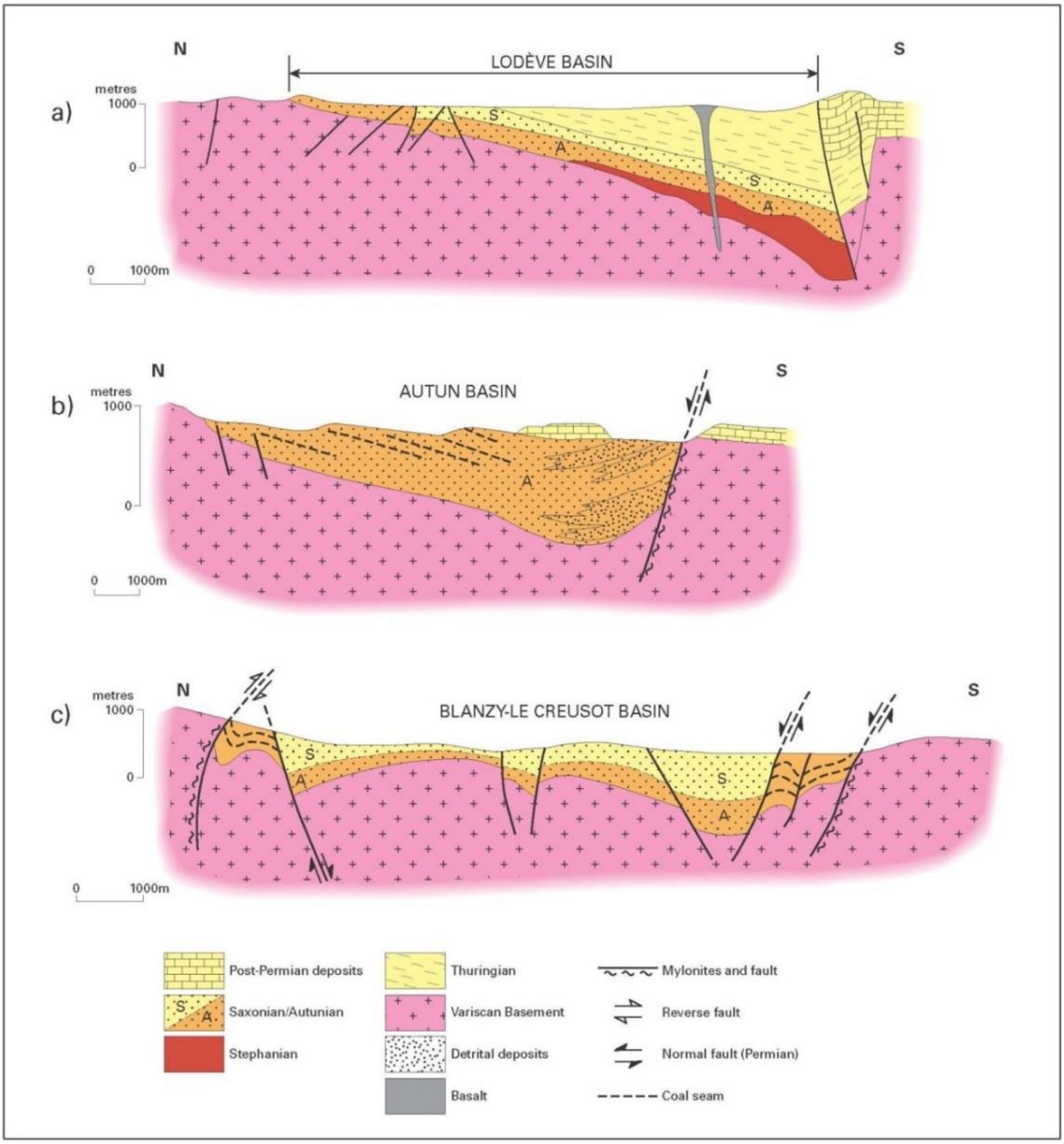

Figure 21 Schematic cross-sections for three intra-montane basins in the Massif Central. (After Cassinis et al., 1995; Blès et al., 1989; and McCann et al., 2008).

Carentan

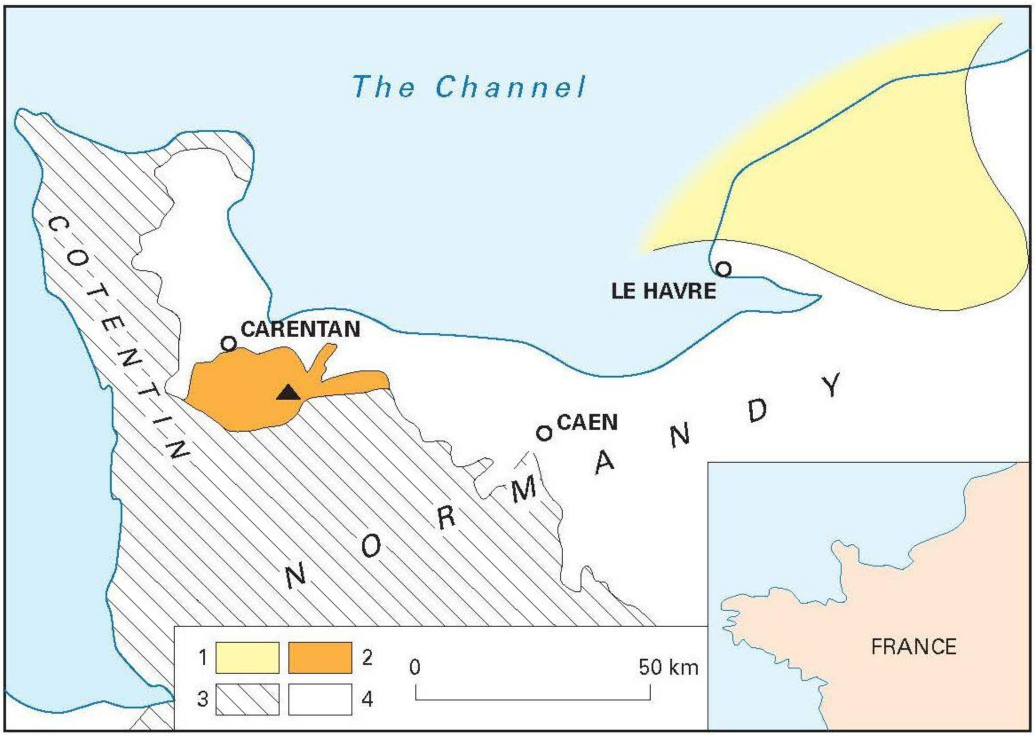

Figure 22 Location map of the Permian in Normandy. Black triangle is the location of the St. Fromond borehole. 1 Concealed Permian in the Villequier Trough. 2. Outcrop Carentan Basin. 3. Variscan and Cadomian basement. 4. Mesozoic cover. Modified from Doré (1994).

Introduction

The Carentan Basin is a small 40 km by 20 km basin near the town of Carentan, Normandy, North France (Figure 22). The basin is located in a trough formed on the NE edge of the Armorican Massif. The Westphalian and Stephanian coals of this basin were worked until the end of the 20th Century. It is the closest onshore Permo-Carboniferous basin to the SW Approaches and may provide the best analogy to basins found around the margins of the Armorican Massif.

Data Sources

The Carentan Basin is summarised in the BRGM Permian basin synthesis memoir (Châteauneuf & Farjanel, 1989). There are coal exploration boreholes, which were used by Châteauneuf & Farjanel (1989) in their report.

Basin Morphology

The Carentan Basin is a half-graben with an E-W trending boundary fault along the southern margin. The throw on the fault is at least 1000 m as proven by the St. Fromond borehole (Figure 22) which is drilled close the boundary fault. The thickest successions are in the east, thinning to the west (Châteauneuf & Farjanel, 1989). Volcanic rocks appear to be located more proximally along the graben boundary faults. Farther to the west, the Villequier Trough contains a Permian succession which extends under the Paris Basin and into The Channel (Doré, 1994).

Regional Stratigraphy

Due to the low topographic relief, there are few surface outcrops which significantly hinders outcrop sampling and interpretation. The stratigraphy of the Carentan Basin is mainly known from coal mining boreholes and workings across the basin. The late Carboniferous is represented by a folded Westphalian B-C coal series which rests unconformably on the metamorphosed Variscan basement (Cambrian to Devonian). The Westphalian is not widespread and the coal has only been worked in the west of the basin at Plessis-Lastelle (Châteauneuf & Farjanel, 1989). The Stephanian coal measures overlie the Westphalian strata and are variably folded. The angular discordance between the Westphalian and Stephanian is minor. Stephanian coal seams were first worked in the 1740's at Littry, *c.* 30 km east of Carentan (Coquel et al., 1969). The coal measures include occasional volcanic sequences with lava flows and ash layers (Châteauneuf & Farjanel, 1989). Autunian strata generally rest conformably on the Upper Stephanian coal measures. Exceptions can be found at the Plessis-Lastelle coal workings where Upper Autunian strata rest unconformably on the Westphalian C-D coal measures (Châteauneuf & Farjanel, 1989).

The Stephanian-Autunian is subdivided into six lithostratigraphic units (Châteauneuf & Farjanel, 1989). This is based on the St Fromond borehole (Figure 22) which penetrated 831 m of a typical Permian succession and is summarised in Figure 23. In general, the Stephanian-Autunian succession consists of a coal basin transitioning to an arid red-bed depositional environment via an Autunian lacustrine dominated sequence (Châteauneuf & Farjanel, 1989). Biostratigraphy of the Autunian series IV-VI is hindered by a lack of fossils, it has been suggested to be Upper Autunian in age, but an early Saxonian age cannot be discounted (Doré, 1994)

Overlying the Autunian are the Triassic (Keuper) iridescent marls. However, a paucity of biomarkers makes the placing of the Stephanian-Autunian and Autunian-Keuper boundaries difficult (Doré, 1994). The well studied Lorraine-Saar-Nahe and Paris Basins to the south-west are analogous to the Carentan (Mascle, 1990).

Stratigraphy

A detailed decription of the Stephanian-Autunian succession in the Carentan Basin is presented because of the great relevance of the basin to the SW Approaches. Châteauneuf & Farjanel (1989) postulated that the Carentan basin and the Permian deposits of SW England might be satellite basins in a larger Permian basin located along the modern day axis of The Channel.

The Stephanian-Autunian sequence has been subdivided into six lithostratigraphic units (Figure 23) (Châteauneuf & Farjanel, 1989).

Series I

The Stephanian coal measures are represented by a typical coal depositional system. Coals and mudstones are overlain by conglomerate and sand-dominated fluvial sequences (Châteauneuf

& Farjanel, 1989). Occasionally, the coarse-clastic fluvial sequences are amalgamated in a stacked- channel succession. The fluvial sequence is interpreted as the deposits of a high energy anastomosing river system, with a mud-rich, swampy flood-plain (Châteauneuf & Farjanel, 1989).

Series II, Lower Red Siltstone

This series consists of a basal conglomerate overlain by a succession of siltstones, sandstones and mudstones. Colour changes from red to brown with occasional grey-green beds indicate changes from oxic to anoxic deposition within small seasonal lakes (Châteauneuf & Farjanel, 1989). Rain-drop impressions, mudcracks, and carbonated horizons suggest a transition towards a semi-arid continental regime from the more humid Stephanian times (Doré, 1994).

Series III, Saint-Martin-de-Blagny-Limestone

This series is characterised by the recurrence of grey lacustrine limestones with bituminous laminae and red siltstones. Again mudstones range in colour from green-grey to dark purple, and brown-red depending on oxidation state when deposited (Châteauneuf & Farjanel, 1989). The magnesian limestones (11-45% $MgCO_3$) vary from light grey compact limestones to grey-black laminated limestones with alternating thin carbonate layers and dark laminae. The shallow lake bed algal mat laminae contain shale, organic matter and fine pyrite granules and are occasionally disturbed by bioturbation or uncommon salt pseudomorphs (Châteauneuf & Farjanel, 1989; Doré, 1994). Phases of localised volcanic activity, notably, tuffs and basalts, are commonly interbedded with sediments (Châteauneuf & Farjanel, 1989).

The only fossils recorded in the Autunian succession are all non-marine and include bivalves (*Anthracomya carbonaria*), phyllopods (*Estheria tenella*), and non-marine fish (teeth of *Diplodus*, and caudal spines of *Acanthodes*) (Châteauneuf & Farjanel, 1989). Correlation with the Lower Rotliegendes of the Saarle and Saar-Nahe, as well as the Middle to Upper Autunian of the Massif Central, is advocated (Châteauneuf & Farjanel, 1989).

Series IV, Middle Red Siltstone:

In the Middle Red Siltstone, carbonates are absent and there is a return to mainly red siltstone deposition. The lithology is almost identical to the lower siltstone unit: thinly bedded red siltstones, fine sandstone lenses, and mudstones containing desiccation cracks and rain-drop impressions (Châteauneuf & Farjanel, 1989).

Series V, Cartigny-l'Epinay Conglomerate and Sandstone:

The barren series contains coarse locally derived continental deposits (Châteauneuf & Farjanel, 1989). Several conglomerate, breccia, and coarse sandstone coarsening-upward sequences represent a proximal succession of an alluvial fan (Doré, 1994).

Series VI, Saint-Jean-de-Daye (Upper Red Mudstone):

This is a thick (>300 m) succession of monotonous red to burgundy coloured mudstones, with occasional coarser silt and sandstone intervals. In general the sequence is poorly known and only found in the west of the region. It contains rain drop imprints, ash beds and tonsteins suggesting a lack of current reworking (Châteauneuf & Farjanel, 1989).

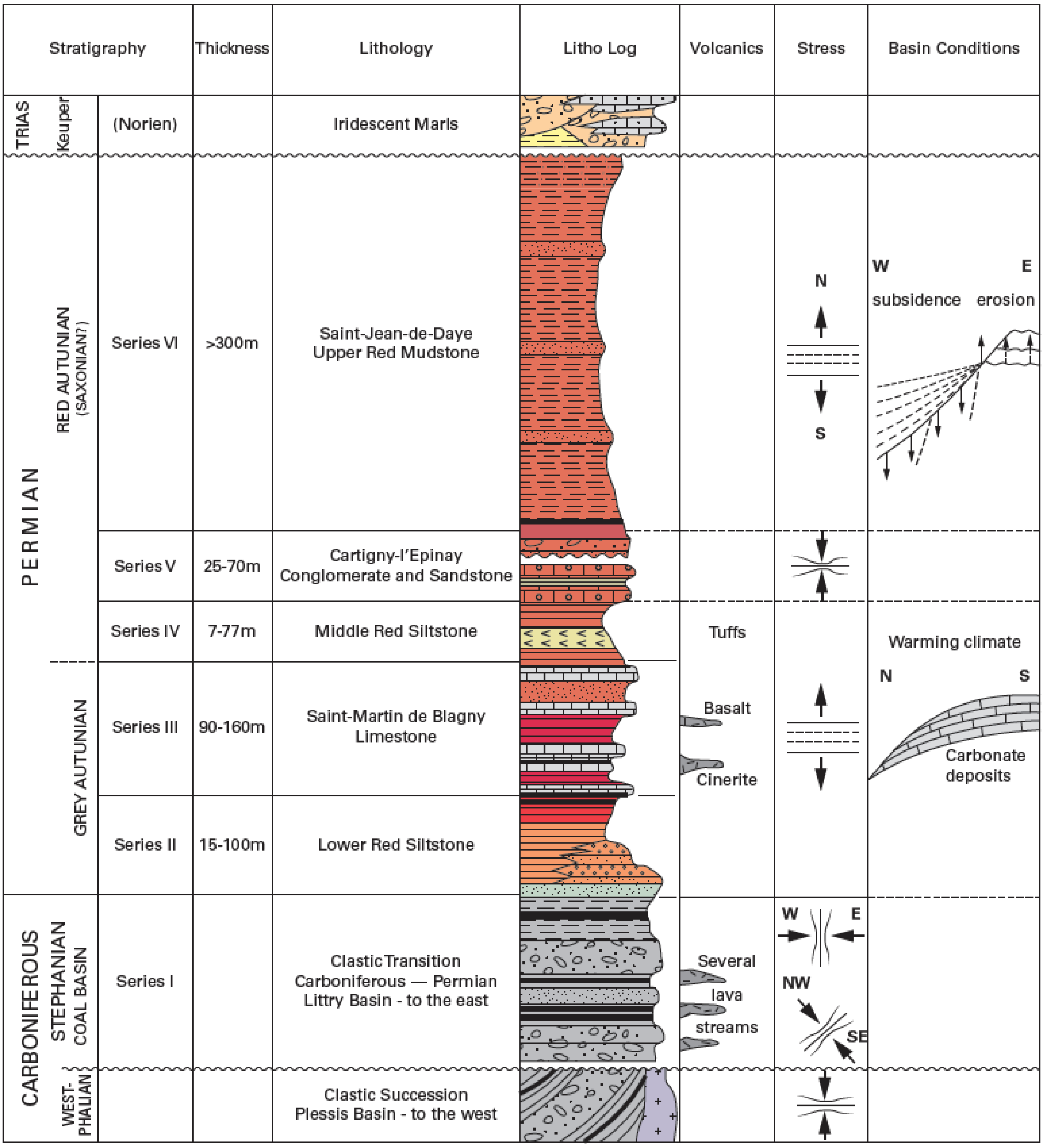

Figure 23 Lithostratigraphic summary of the Carentan Basin based on the St. Fromond borehole. Modified from Châteauneuf & Farjanel (1989).

Geochemistry and Thermal Modelling

Geochemical studies of the coals and lacustrine sequence in the Carentan basin have not been undertaken. The sedimentary succession is often compared to the Permo-Carboniferous sequences found in the Lorraine-Saar-Nahe basin and basins of the Massif Central (Aumance, Autun, Decize etc). More extensive geochemistry has been done on these known source rocks (Châteauneuf and Becq-Giraudon, 1990). Lack of geochemical data mean that there is no maturity profile to calibrate basin thermal modelling. The basin's location between the well-studied Wessex and Paris Basin could give an indication on the basin history.

Source Rock Potential

In terms of a hydrocarbon system, the Stephanian and Autunian strata in the Carentan Basin contain potential source rocks in late Carboniferous coals and a minor source in the Autunian bituminous shales. Questions remain over the yield potential from the carbonaceous source rocks, and if, or when, the Permo-Carboniferous has generated hydrocarbons.

SEDIMENTARY HISTORY

A reconstruction of sedimentary environmemts during the deposition of Stephanian strata in the Aumance Basin is shown in Figure 24. Torrent cones at the faulted margin of the basin graded laterally into large braidplain systems. Coals were deposited in quiet water conditions within lakes developed in marginal marshes. Rapid subsidence led to the development of very thick seams in the Lower Stephanian (Vetter, 1986). In the Upper Stephanian, coals are thinner and rarer. Aumance is one of the few basins in which the Autunian sequence has exploitable coals. In general, bituminous lacustrine laminites are more typical of Autunian deposition.

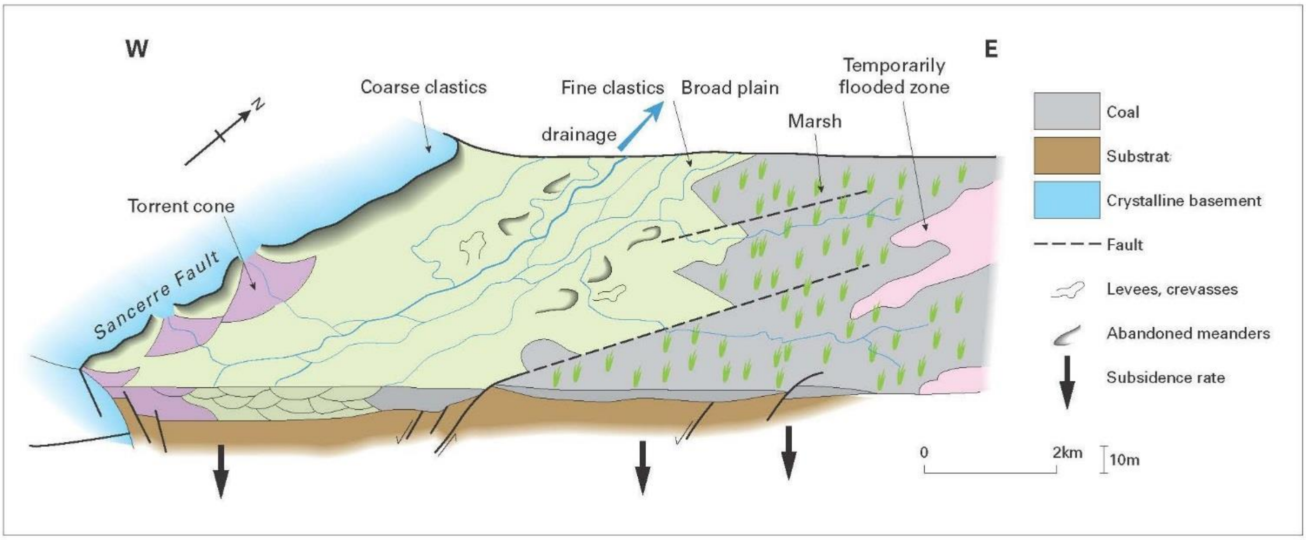

Figure 24 Depositional evironments in Stephanian strata of the Aumance Basin, after Vetter, (1986).

GEOCHEMISTRY

The geochemistry of the French Permo-Carboniferous has been undertaken by IFP and is available for purchase in a series of non-exclusive reports. Other than this work, geochemical assessment of coals and bituminous shales was completed in the late 1980s and published, albeit with limited tabulated data (Espitalié et al., 1987; Châteauneuf & Becq-Giraudon, 1990; Mascle, 1990). Several studies have looked into the maturity of coals in the various small basins of the Massif Central. The maturity is known to be variable from basin to basin, probably as a result of local hydrothermal and volcanic events during the Upper Palaeozoic (Courel et al., 1994; Copard et al., 2000; Copard et al., 2002; Wang & Zhuang, 2006, Berlendis et al., 2014)

Paris Basin

At outcrop the coals are high quality with a petroleum potential (S_1+S_2) of 152 mg HC/ g rock (Mascle, 1990). Bitunminous shales had been extracted as fuel from outcrop sporadically since the 1850s. In total it is estimated that from one single mine at Meglin (north Massif Central), 3 Mt of fuel was extracted, yielding on average 50 L HC/ ton of rock (Châteauneuf & Becq-Giraudon, 1990). The bituminous shales have high TOCs of 7-20 wt% (n=7), with an average petroleum potential of 71 mg HC/g rock (Mascle, 1990). The thickness of coal seams varies from a few meters to tens of meters (Vetter, 1971). The organic matter type is a mixture between terrestrial lignite, spores and pollens, and lacustrine algae (Châteauneuf & Becq-Giraudon, 1990). The maturation of the succession is variable, with some samples in the oil window, and others overmature. The variability in maturity is attributed to localised hydrothermal and volcanic events common across the Massif Central (Mascle, 1990; Copard et al., 2000). It has been estimated that across the Massif Central (at outcrop or near surface) there are 581 Mt of shales with a yield of 50 mg HC/ g rock representing 35 Mt of hydrocarbon (Châteauneuf & Becq-Giraudon, 1990).

The Bressan Plain

The Stephanian coals of several sub-basins have been explored, exploited and well characterised in the Bas-Dauphiné, Lons-le-Saunier and Ronchamp basins. At Lons-le-Saunier coals range from 30-80 wt% TOC (n=50), with a hydrogen index (HI) 100-300, and petroleum potential (S_1+S_2) of 40-180 mg HC/g rock. It is thought that these coals have sourced small volumes of oil in Briod (5km east of Lons-le-Saunier). The Vellempoulières Gas field to the east of Jura has produced over 100 million m^3 of gas (as of 1990), with a source again attributed to more mature Stephanian coals.

The Autunian succession is less well constrained given its absence in many wells. However, as proven at Ronchamp, St. Étienne and in Switzerland, thick bituminous shales can be found (Matter, 1987). Samples from Ronchamp and Bas-Dauphiné range from 5-10 wt% TOC, a HI of 100-700 consisting of a mixed organic matter type, I and III. One sample from the Bas-Dauphiné contained TOC of 32 wt% with a petroleum potential of 218 mg HG/ g rock.

The Southeast Basin

Outcrop geochemistry of 13 Stephanian coals samples from Alès gives a TOC range of 25-81 wt% (average 63 %) with a S_2 2.6-117 mg HC/ g rock (average 62 mg HC/ g rock) and HI 5-219 (Mascle et al., 1996). The Permian outcrop (n=3) gives 1-4 wt% TOC with S_2 0.2-1.0 mg HC/ g rock, however it is known in the Gabian Oil Field TOC reach up to 5 wt% (Mascle et al., 1996).

The Aquitane Basin

The Stephanian coal seams aggregate to tens of meters thick in the Brive Basin, however they are not of high quality. From three samples, TOC ranged from 37-47 wt%. However, the south-western crop of the Quercy Basin at Carmaux contains a 600 m Stephanian succession with 23 coal seams, giving an amalgamated coal thickness of tens of meters (Mascle, 1990).

The Autunian succession at Brive contains both coals and bituminous shales. The coals are reported to be of high potential, likewise the thinner bituminous shales. The shales contained up to 2.5 wt% TOC with a petroleum potential of 40 mg HC/ g rock in the early oil window (Tmax = 440ºC) (Mascle, 1990). These are similar to samples collected from the deep well Lavaur 101 (Figure 17), which had 1-11 wt% TOC and petroleum potentials of 37mg HC/ g rock (Blanc et al., 1991).

Within the centre of the Massif Central there are several basins which can be used as analogies to the Quercy Basin. The coal basins of Decazeville, Figeac, Rodez and St Affrique all contain Permo-Carboniferous sedimentary fill, and are controlled by large regional faults. The fill of these basins gives an insight into the potential of the buried Quercy Basin. Many basins contain only thin coal seams accumulating to several tens of meters of coal. The Decazeville basin contains a 1800 m thick Stephano-Autunian sequence, with a total of 110 m of coal (including one seam reaching up to 60 m) (Vetter, 1968). Numerous levels of bituminous shales are also present, with TOC averaging 2 wt% and reaching 7 wt% (Mascle, 1990).

The quality and maturation of the potential source rocks is variable. Maturation is strongly affected by the local burial history, and importantly local hydrothermal and volcanic activity (Courel et al., 1994; Copard et al., 2000; Copard et al., 2002). The quality of the bituminous shales as a source is strongly controlled by the organic matter type, mainly type III but occasionally type I (Mascle, 1990). The petroleum potential of the Autunian schists ranges from 5-36 mg HC/ g rock across the basins (Mascle, 1990).

OFFSHORE WELLS

Information on the wells drilled in the SW Channel Basin, off Brittany, was supplied by OGA. Kulzern-1 (dry) terminated in granitic basement after penetrating 750 m of Upper Permian overlying about 800 m of Autunian strata (Mascle, 1990). Garlizzen-1 terminated in 'Stephano-Westphalian'. Thus these two wells, plus 86/18-1 in the UK sector, demonstrate the presence of Autunian strata, at least on the southern edge of the SW Approaches, where the Variscan basement is of inferred Saxothuringian affinity. Brezell-1 (shows) terminated in Permian, and Rea Gwenn-1 (dry) and Polkerris-1 (dry) terminated in Triassic strata. The wells Lizern-1 (shows), Glazenn-1 (dry), Kerluz-1 (dry) and Krogen-1 (shows) terminated in Upper Jurassic or Early Cretaceous strata. Without further information on the stratigraphic level at which the hydrocarbon indications occurred, it is not possible to comment on the validity of an early Permian source in this region.

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5 Germany

INTRODUCTION

There are several Permo-Carboniferous basins in Germany including the Saale Basin, the Southern German Molasse Basin and the Thuringian Forest Basin (Plates 2, 3). The most substantial basin is the cross-border Lorraine-Saar-Nahe Basin. This Permo-Carboniferous basin is one of the largest and best exposed in western Europe. The 300 x 100 km basin crosses from Germany into France (Figures 15, 25), with a well-studied surface exposure around 100 x 40 km in Germany (Figure 26). Although they form a continuous international basin, the basin is often split into the Lorraine Basin (France), and the Saar-Nahe Basin (Germany). This is a legacy of two nationally important coal mining districts (Izart et al., 2016). The asymmetric half-graben is bounded to the north by the south-dipping South Hunsrück Fault, to the west by the Marne Fault, and to the east by the Rhine Graben. Basin initiation occurred in the Namurian and continued until the Middle Permian, preserving an 8000 m thick continental clastic succession (Schäfer, 2011). Extensive work dating the volcanic and palynological history of the basin has constrained the depositional and structural history (Schäfer, 2011; and references therein.). The Thuringian Forest and Saale basins lie to ENE along the Variscan strike.

DATA SOURCES

The Lorraine-Saar-Nahe Basin has been extensively studied both sides of the border. The legacy data from the mine workings and boreholes has been essential for many basin modelling, stratigraphic and tectonic studies (Donsimoni, 1981; Korsch & Schäfer, 1995; Hertle & Littke, 2000; Schäfer, 2011; Izart et al., 2016; and references therein).

VARISCAN BASEMENT STRUCTURE AND HISTORY

The South Hunsrück Fault, the syndepositional basin-controlling fault on the NW margin of the Nahe Basin, also defines the southern edge of the Rhenish Massif (Plate 2). The Northern Phyllite Zone, exposed on the southern slope of the massif and the Harz Massif, represents the deformed slope of the Rhenohercynian continental margin (Oncken, 2000; Franke, 2006; McCann, 2008). Just to the north, an exotic nappe of ophiolitic rocks (Giessen-Harz Nappe) has been translated northward away from the Rhenohercynian Suture, in a very similar structural position to the Lizard Complex (see Chapter 2). South of the suture (Plate 1), and forming the floor of the basin, the crust of the upper plate is formed by the Mid-German Crystalline Rise (MGCR), interpreted as an arc-magmatic complex of Ordovician-Silurian age, generated by subduction of the Rheic Ocean (Franke, 2000; 2006). This unit is inferred to lie on the northern margin of the Saxothuringian Zone (Franke, 1995; 2006).

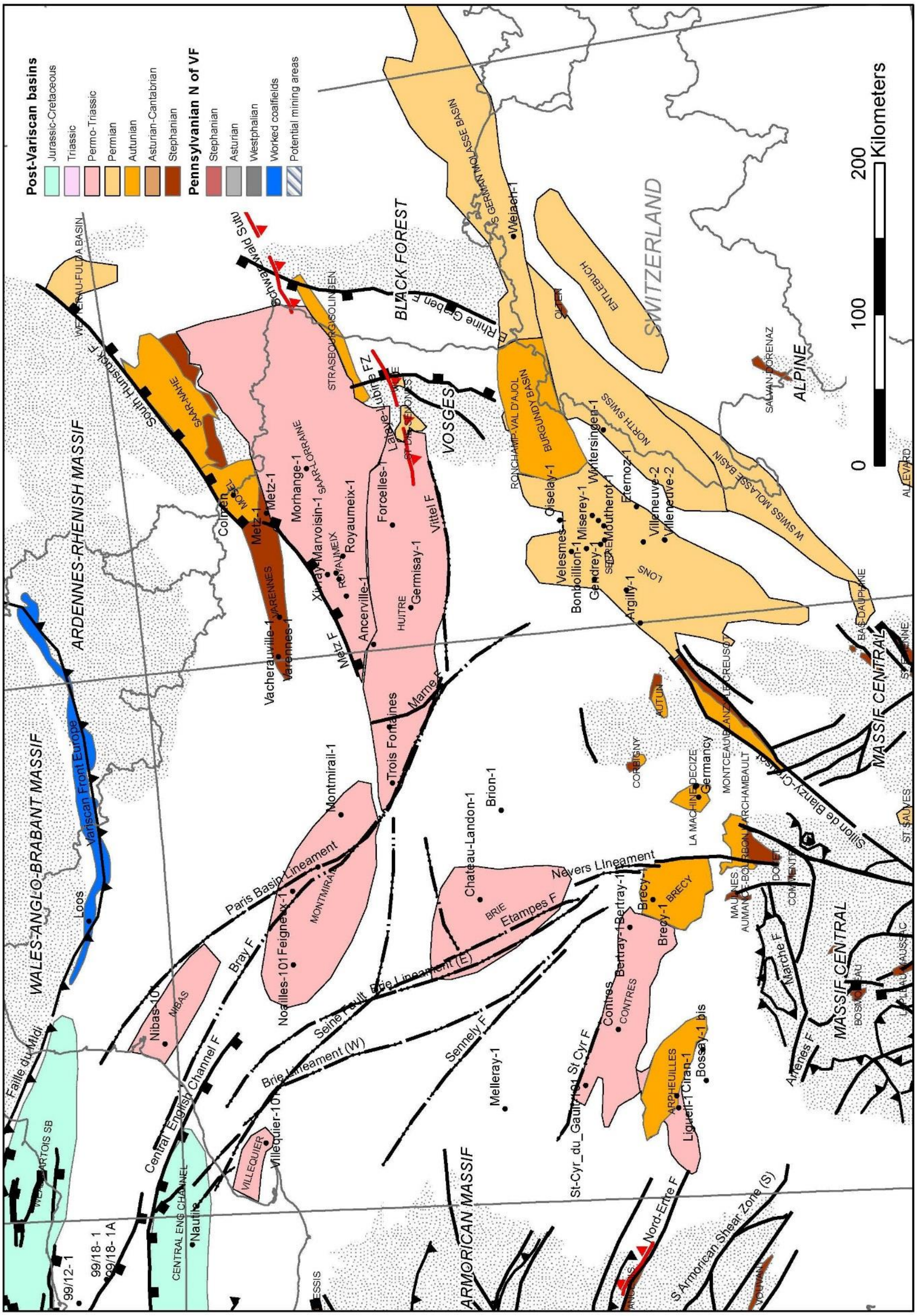

Figure 25 Late Carboniferous-early Permian sub-basins of the Paris Basin, Saar-Nahe and the northern Massif Central. Key to structures shown on Fig. 2.

BASIN MORPHOLOGY

The Lorraine-Saar-Nahe Basin is a large half-graben, bounded to the north by the South Hunsrück Fault (SHF) (Figures 26, 27). The nature of the SHF is debated, Henk (1993) proposed a southward-dipping fault soling at a mid-crustal detachment (c. 16 km depth), whereas Korsch & Schäfer (1995) suggested a steep fault, part of a dextral strike-slip regime, on the basis of seismic interpretation. The basin is limited to the west at the Marne Fault (Izart et al., 2016) and to the east by the Rhine Graben (Korsch & Schäfer, 1995). Throughout the basins history a shift in the depocentre along the SHF has been attributed to various tectonic events (Korsch & Schäfer, 1995; Schäfer and Korsch, 1998; Schäfer, 2011; Averbuch & Piromallo, 2012).

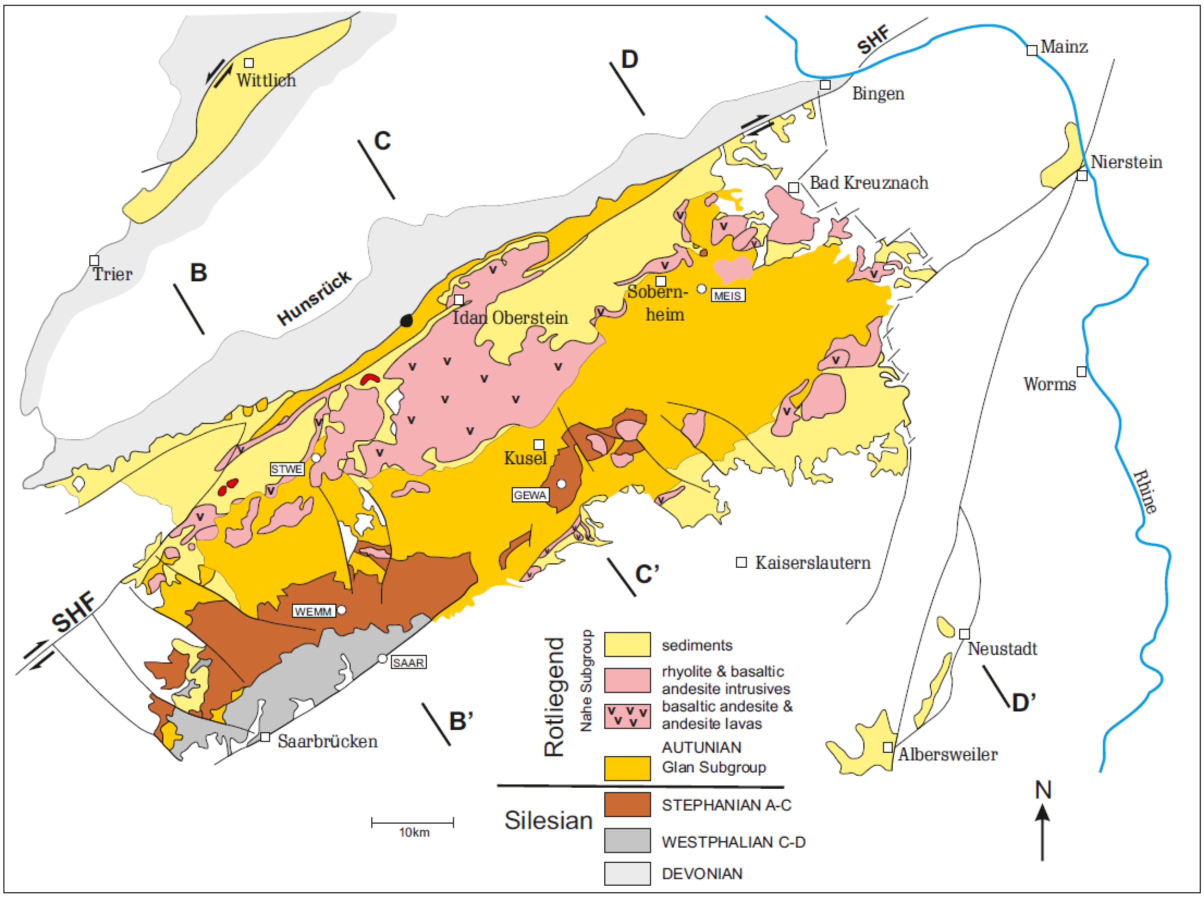

Figure 26: Map of the surface exposure of the Lorraine-Saar-Nahe Basin. Well locations used in cross-sections highlighted. Locations of cross sections B, C, D are shown. SHF= South Hunsrück Fault. Modified from Schäfer (2011).

The evolution of the basin is very complex and related to the suture zone between the Rhenohercynian and Saxothuringian zones (McCann et al., 2006). Phases of inversion caused several transpressional events. One of the most significant was a deformation phase between Westphalian D and Stephanian A which led to the erosion of up to 1500 m of sediment (Figure 27) along the large axial Saarbrücken Anticline (Korsch & Schäfer, 1995; Stollhofen, 1998). Post orogenic lithospheric stretching in late Autunian to Saxonian times resulted in a regional period of volcanism followed by continental redbed deposition. Movement along the SHF continued in the late Permian as transpression caused uplift and backthrusting, with minor lateral displacement. Since Mesozoic times the SHF has been relatively inactive, apart from up to 8 km of displacement on the Rhine Graben bounding faults (Korsch & Schäfer, 1995). The fault appears to be still active to the present day.

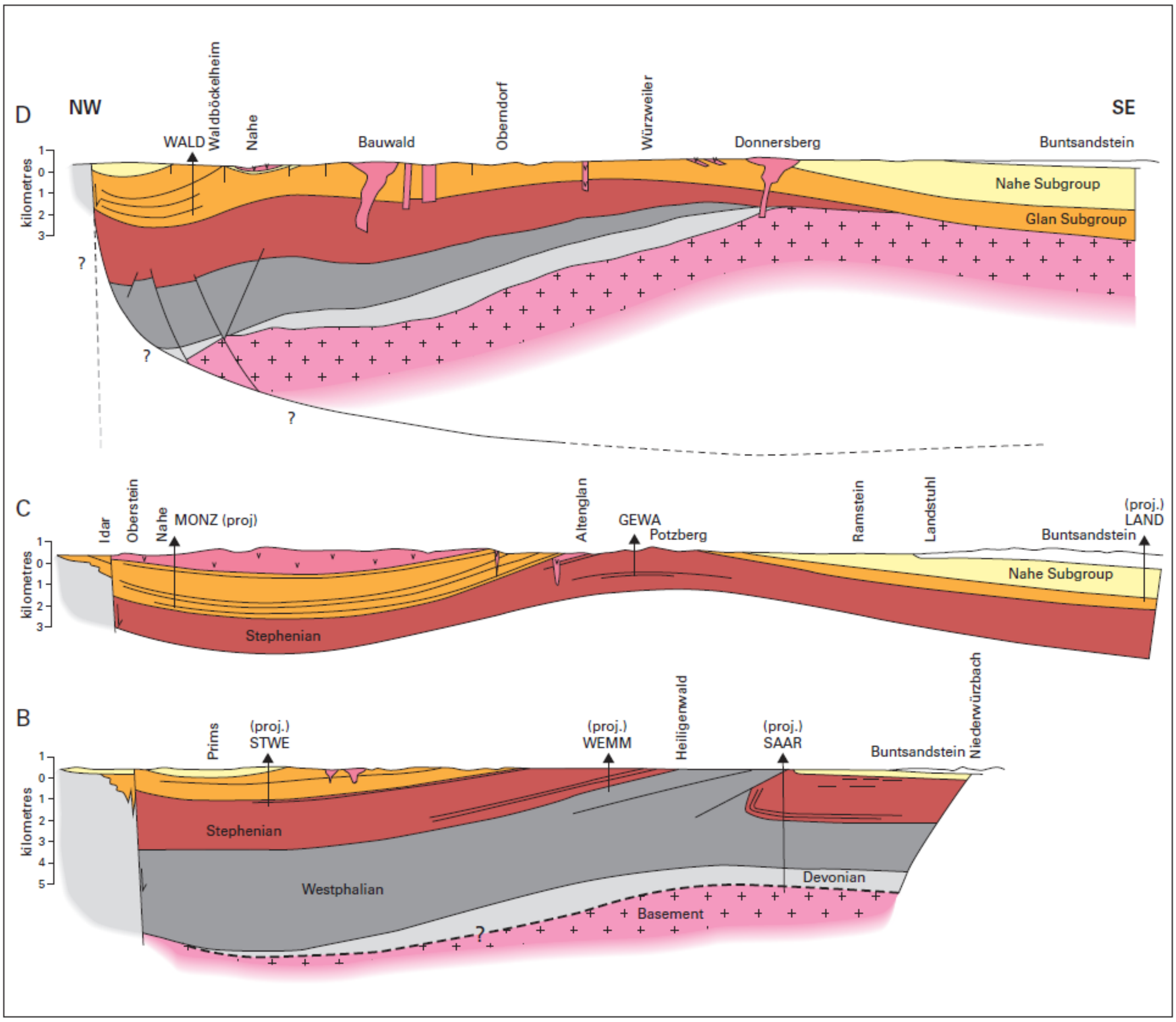

Figure 27 Cross sections B, C, D through the exposed Lorraine-Saar-Nahe Basin. Section C shows the possible deeper structure of the basin. Cross-section locations shown on Figure 26 (Modified from Henk, 1993 and Schäfer, 2011).

STRATIGRAPHY

The Lorraine-Saar-Nahe Basin contains over 8000 m of continental clastic and volcanic fill ranging from the late Visean to Permian (Upper Rotliegend) (Figure 20) (Schäfer and Korsch, 1998). It has been studied intensively in the surface exposure of the Saar-Nahe Basin, based on numerous boreholes, outcrop and seismic lines (Korsch & Schäfer (1995) and references therein). Basin subsidence was initiated after a period of non-deposition in the latest Namurian (early Westphalian), with the deposition of the thin (*c.* 100 m) Spiesen Conglomerate. Conformably overlying the conglomerate is up to 5 km of Westphalian coal measures of the Saarbrücken Subgroup, which is Westphalian A-D in age (Donsimoni, 1981; Korsch & Schäfer, 1995).

A regional unconformity separates the Stephanian from the Westphalian, with a 2-3 Ma hiatus (Korsch & Schäfer, 1995). In the east, Stephanian deposition overstep onto Middle Devonian strata represents up to 1.5 km of erosion (Korsch & Schäfer, 1991). Stephanian deposition restarted with the Ottweiller Subgroup and the Holz Conglomerate (Stephanian A). The Stephanian succession totals up to 2.6 km of fluvial, alluvial, lacustrine and deltaic deposits, including some minor coal seams (Schäfer, 2011).

Autunian strata of the Glan Subgroup follow the Stephanian without break, and comprise a lacustrine-dominated succession up to 1.45 km thick (Schäfer, 1989; Stapf, 1997; Müller et al., 2006). The boundary between the Autunian and Stephanian is considered to be the base of the Dirmingen Conglomerate (the lowest member of the Lower Rotliegend).

Extensive volcanic activity marks the end of the Autunian Glan Subgroup and the beginning of the Saxonian Nahe Subgroup. The basal unit of the Donnersberg Formation of the Nahe Subgroup is primarily felsic and tholeiitic basaltic intrusives and extrusives (Lippolt & Hess, 1989). The volcanics are interbedded with the redbed deposits in the Saxonian, a total thickness of up to 1.65 km. Rare lakes formed in the semi-arid depositional environment, creating isolated organic-rich pockets, with thin coals (Stollhofen & Stanistreet, 1994). Given the redbed deposition, lack of fossils, distinctive ash horizons resulting from the frequent regional volcanic events form excellent basin-wide chronostratigraphic markers in the Westphalian to the Saxonian (Lippolt & Hess, 1989; Königer et al., 2002).

The Permo-Carboniferous was then overlain by a Mesozoic succession similar, but thinner, to the cover in the Lorraine region (Izart et al., 2016)

SEDIMENTARY HISTORY

The formations can be summarised into a particular depositional environment as summarised in Donsimoni (1981), Schäfer & Korsch (1998) and (Schäfer, 2005).

The Saarbrücken Subgroup (Namurian and Westphalian)

The coal measures of the Carboniferous in general show a cyclic repetition of several facies (Table 3)(Fleck et al., 2001).

Provenance studies of the clastic sediments in the Westphalian C and D suggest a Rhenohercynian origin with palaeoflow from the north (Schäfer, 2011). Isopach mapping shows a north-eastward shift in the depocentre from the Westphalian A to Westphalian D (Schäfer, 1989; Korsch & Schäfer, 1995). Overall, the intramontane fill was most likely deposited in a deltaic setting with lacustrine deltas. Fluctuating water tables on delta platforms with swamps, meandering and braided river systems, supported rich forests of conifers (Schäfer, 2011).

Table 3 A summary of the facies identified in Westphalian coals in the French sector of the Lorraine-Saar-Nahe Basin. After Fleck et al. (2001)

Facies	Lithology	Depositional Environment

1	Conglomerates and sandstones	Major alluvial fan braided river channel system
2	Channelised sandstones. Trough cross-bedded.	Meandering river channel with proximal crevasse splay channels
3	Massive laminated siltstones and thin clay lenses.	Silt-rich levee deposits
4	Thin interbedded sandstones, siltstones and claystones. Laminated and ripple cross-laminated	Overbank deposits
5	Bioturbated siltstones and claystones, rooted with siderite concreations.	Hydromorphic palaeosol. (Bog/swamp soils)
6	Coal	Swamps
7	Massive or laminated carbonaceous claystones, laminated and ripple cross-laminated.	Flood plain deposits, small lakes and levee deposits
8	Coarsening Upward sequences. Claystones to sandstones. Lenticular, wavy and flaser bedded.	Minor deltaic systems and distal crevasse splays

The Ottweiller Subgroup (Stephanian)

The basal Holz Conglomerate denotes a change in provenance direction, with sediment derived from the south rather than the north (Schäfer & Korsch, 1998). The conglomerate is matrix-supported, with rounded to well-rounded, quartz and quartzite, pebbles and boulders. Coarse sands sourced from the Vosges granitods form the matrix, with large clasts thought to be reworked Westhpalian deposits (Schäfer & Korsch, 1998; Schäfer, 2011). The conglomerate fines upwards into a meandering river system with lake basins. In Stephanian B time, a change in source to the SW (under the present Paris Basin), gave rise to a series of channelized sandstones, floodplain deposits and rarer coals of a SW-NE flowing braided river system. Sediments are feldspar-rich, with conglomerates containing granitoids, quartz, quartzites and uncommon black chert (Schäfer & Korsch, 1998; Schäfer, 2011).

The Glan Subgroup (Autunian)

Depositional settings transitioned from a fluvatile-deltaic system in the Stephanian to the lacustrine-dominated Autunian. The Autunian comprises a sequence of alternating sandstones, siltstones, mudstones, black shales and carbonates (Stapf, 1997; Schäfer & Korsch, 1998). A large number of lakes existed throughout the Autunian, they were in general short-lived, and possibly interconnected (Schäfer et al., 1990; Stapf, 1997). Aside from the lacustrine shales, other fluvial deposits have been preserved. Lake delta, oxbow lakes, flood plains and minor crevasse splays have all been documented as part of the fluvio-lacustrine system (Schäfer & Sneh, 1983). Laminated bituminous ‘paper shales’ formed in the deeper section of the lake, whereas the shoreline contains more bioturbated mudstones, desiccated mudstones, carbonates and stromatolites (Schäfer & Stapf, 1978). The laminated paper shales contain fragments of quartz, feldspar, and carbonates, with illite as the main clay constituent (Schäfer et al., 1990). The darker laminations are rich in organic matter, probably from algae and plant remains, preserving rare fish skeletons (Schäfer et al., 1990). The lakes developed in a savanna-type environment with occasional large inputs of fresh water in the wet season, probably from flash floods (Müller et al., 2006). Periods of dry-season quiescence resulted in strong evaporation, precipitation of carbonates and occasional algae blooms (Müller et al., 2006). The shales were deposited in an intermittently stagnant anoxic lake, with largely siliciclastic sedimentation, and are not therefore true 'black shales' (Schäfer et al., 1990).

GEOCHEMISTRY

Although the region has been exploited for coal and explored for oil and gas. There has not been an extensive geochemical study across all stratigraphic horizons, however small studies have been compiled. Geochemistry in the Lorraine Basin has focused on the Westphalian coals (see earlier section)

Detailed geochemistry has been undertaken on specific lake intervals in the Autunian Glan Subgroup. Over one lake cycle the TOC was seen to vary from between 0.5 and 1.0% in the pre- and post- lake, whereas the black shales reach up to 2.9% (Müller et al., 2006). Further studies on another core have given a range of TOC values from 0.15-3.9 wt% with an average of 1.57 wt% (Schäfer et al., 1990). Kerogen type also shifts on lake deposition from type III in pre-and post-lake, and type II for the black shales (Müller et al., 2006). However, oxidative processes and maturity are thought to reduce the dominant algal and bacterial material from type I to type II kerogen (Müller et al., 2006). The Autunian age 'Lake Odernheim' deposits studied had a low to moderate maturity 0.5-0.8 % VR and yielded S_2 0.1-14.5 mg HC/g rock (Müller et al., 2006).

The enhanced geothermal gradient during the late Carboniferous to early Permian in the Saar-Nahe Basin could have been as high as 50^{o}C/km, and this is thought to have increased diagenesis and reduced the organic material richness (Teichmüller et al., 1983; Schäfer et al., 1990).

THERMAL MODELLING

There has been no unified thermal modelling across both the Lorraine and Saar-Nahe Basins, however both regions individually have been studied. The two basins share a similar tectonic history during the Palaeozoic, with a different Mesozoic history, resulting in a greater depositional thickness in the east (Saar-Nahe) than in the west (Lorraine) (Izart et al., 2016). Both regions have many boreholes and mine workings with data to which thermal models can be calibrated. The Saar-Nahe area in particular has been modelled extensively since the 1980s (Teichmüller et al., 1983; Henk, 1993; Hertle and Littke, 2000; Littke et al., 2000).

For the Saar-Nahe Basin coalification was syn-kinematic, with maxiumum burial during the Permo-Carboniferous with a maturity gradient of between 0.2-1.75% Ro/km. Heat flow varied from 50-75 mW/m^2 during the deposition, however, there would have been local affects from volcanic activity (Littke et al. 2000). In total between 1800 and 3000 m of Permo-Carboniferous strata were removed (Hertle & Littke, 2000; Littke et al., 2000). Maturity modelling in general suggests that, the Westphalian is in the dry gas-window or overmature, whereas the Stephanian is gas-window to oil-window and the Autunian in the oil-window to immature (Littke et al., 2000).

SOURCE ROCK POTENTIAL

The Lorraine-Saar-Nahe does contain a working petroleum system as proven in the Lorraine Basin (see previous section). The source for the oil and gas is thought to be entirely from the Westphalian and Stephanian coals (Mascle, 1990). Carboniferous-sourced oil and migration on the eastward side of the Rhine Graben is known from bitumen coating within the Lower Rotliegend sandstones (Aretz et al., 2015), however no accumulations have been found.

Given the rapid burial and increased palaeogeothermal gradient, generation of hydrocarbons would have occurred during the late Palaeozoic. Such a long trap period reduces the chance of large accumulations surviving. As proven in France however, small accumulations can persevere (Mascle, 1990).

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6 Switzerland

INTRODUCTION

The late Palaeozoic of Switzerland is a poorly understood system comprising a few isolated outcrops within deformed crystalline massifs. Nonetheless, drilling and seismic campaigns have identified continental Permo-Carboniferous troughs in narrow en-echelon transtensional grabens, concealed by Mesozoic strata in the northern part of the country (Diebold, 1989; Gorin et al., 1993). These troughs interlink with a system of narrow grabens spreading from the Jura of eastern France, through northern Switzerland and into southern Germany 9Figure 28, 29)(Kettel & Herzog, 1988).

The North Swiss Basin is the name given to a series of these elongate grabens. Weiach-1, a deep borehole drilled by NAGRA in 1983 (Diebold, 1989) was drilled at the depocentre. The thick Stephanian coal measures and Autunian shales encountered opened a new potential Palaeozoic petroleum system across north Switzerland (Vollmayr & Wendt, 1987). Since the 1980’s no commercial discoveries have been found in Switzerland, however other Permo-Carboniferous basins, such as Entlebuch have been discovered (McCann, 2008)

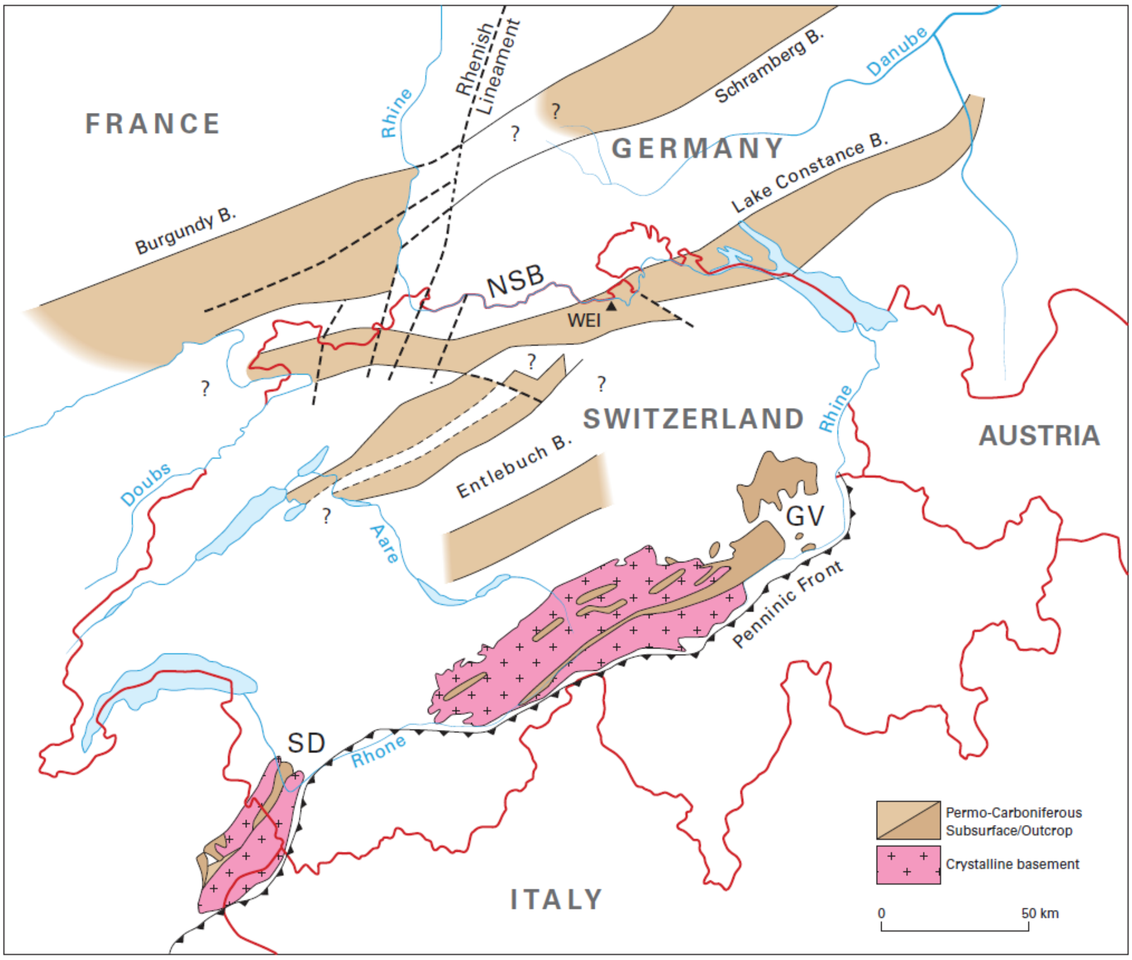

Figure 28 Outcrop and subsurface Permo-Carboniferous basins in Switzerland. (WEI, Weiach 1 well; GV, Glarner Verrucano Basin; SD, Salval-Dorénez Basin). Modified from McCann et al. (2006).

DATA SOURCES

Aside from publically available scientific papers, other information was sourced from *The Geology of Central Europe* (McCann, 2008) and references therein, and the Nagra technical report (NTB 88-08) for deep borehole Weiach 1.

VARISCAN BASEMENT STRUCTURE AND HISTORY

In Switzerland, the late Carboniferous-early Permian basins reviewed are mostly concealed beneath a thick sedimentary cover of Triassic to Cretaceous age (Figures 30, 31). The Variscan basement is equally obscured by younger strata. This is not the case in the Alpine internides where uplift and erosion has removed the Triassic and younger cover, and produced excellent outcrop of rather deformed late Carboniferous-early Permian strata (see McCann et al., 2008).

BASIN MORPHOLOGY

The Permo-Carboniferous strata of the North Swiss Basin and Entlebuch Basin were deposited in intra-montane grabens. The grabens formed as a series of en-echelon pull-apart basins in response to late-Variscan wrench tectonics (Figure 32) (Diebold, 1988; McCann, 2006). The pull-apart basins are narrow, 10-12 km wide, but filled with >1500 m of continental clastic deposits (Matter, 1987; Blüm, 1989).

In the south of Switzerland there are several outcrops of Permo-Carboniferous within the Aiguilles-Rouges, Arpile, and Aar crystalline massifs. Many of these exposures are small, strongly deformed inliers with poor marker horizons, making dating difficult. Two of the larger basins; the Salvan-Dorénaz Basin in the SW and the Glarner Verrucano Basin in the SE, are narrow NE-SW trending synclinal fills containing up to 1700 m of Permo-Carboniferous intra-montane deposits (Figure 28)(Capuzzo & Wetzel, 2004; McCann, 2008). Both basins show fills with a similar stratigraphy to the North Swiss Basin (McCann, 2008)

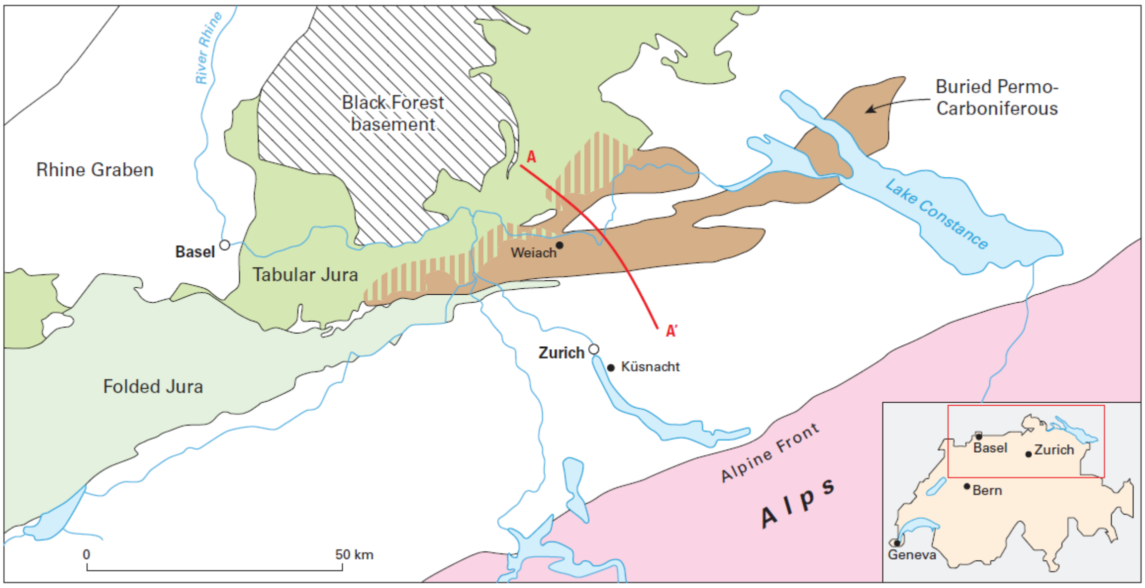

Figure 29 Main tectonic terrains of northern Switzerland. The well Weiach-1 is shown (black dot). The well-known covered Permo-Carboniferous Basin is shown. Modified from Mazurek et al. (2006).

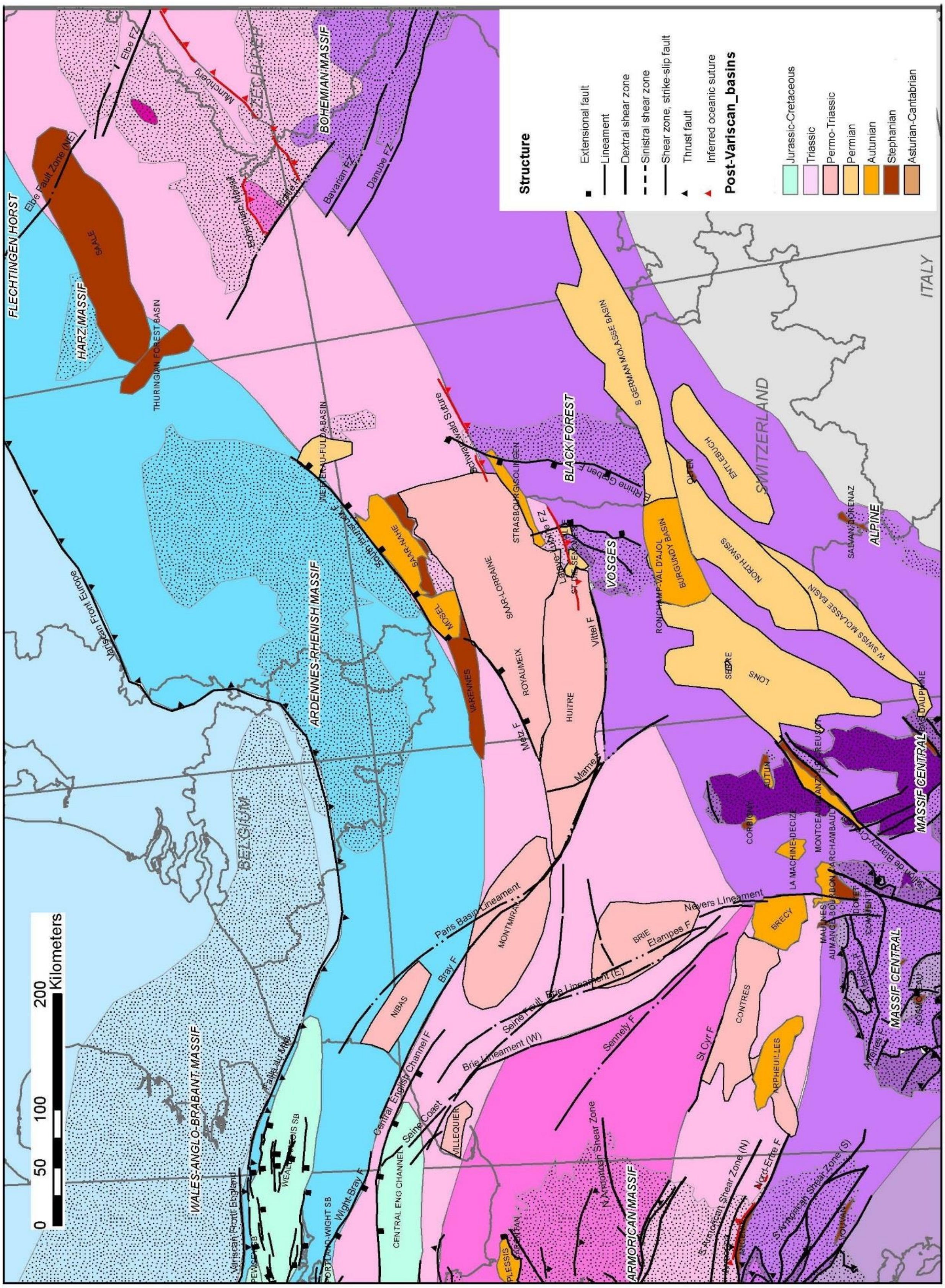

Figure 30 Relationship of Late Carboniferous - early Permian basins to the Variscan substrate in NE France and Switzerland. Mapping data sources are given in the Appendix. Key to Variscan orogenic geology shown in Figure 2.

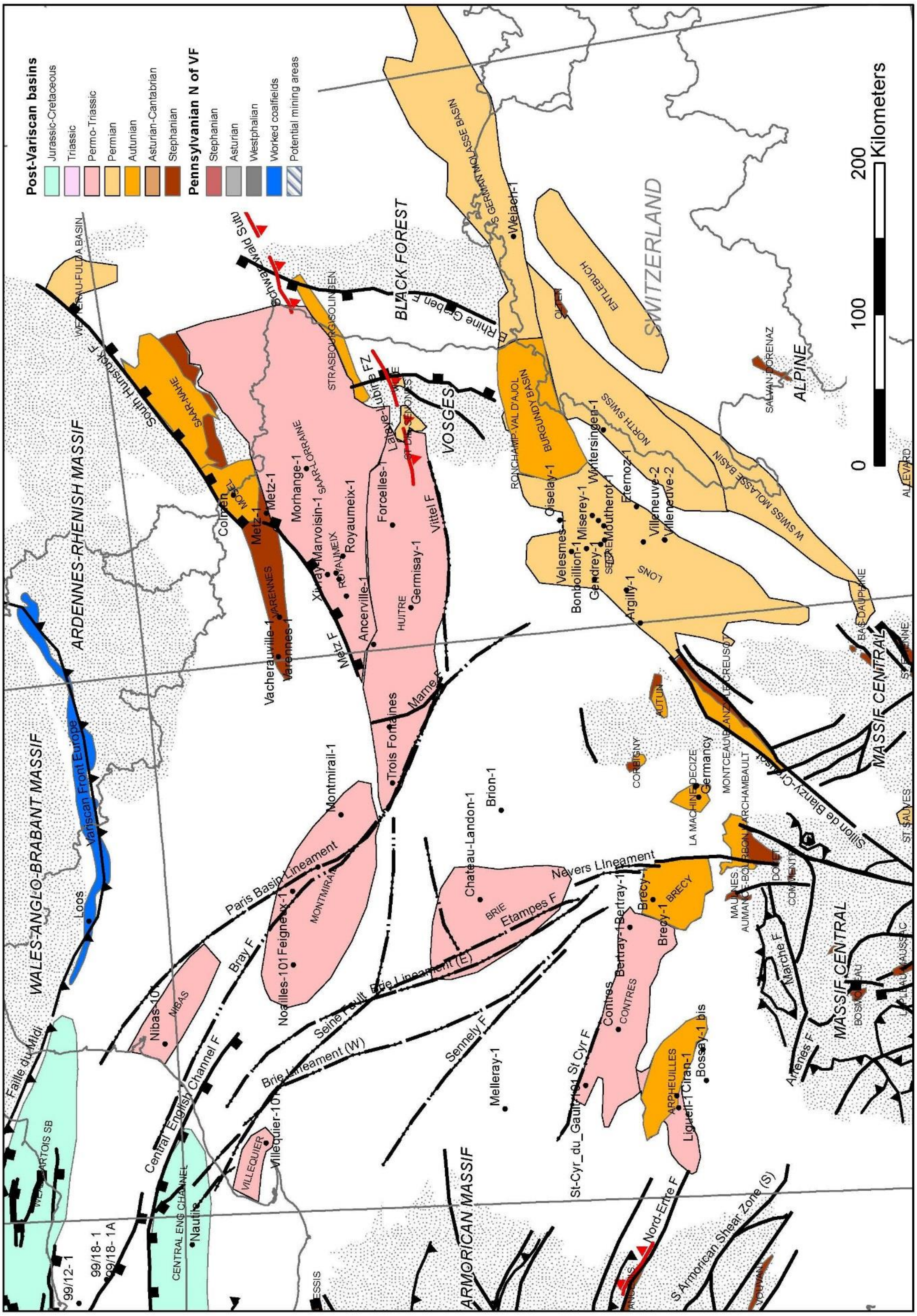

Figure 31 Relationship of Late Carboniferous - early Permian basins to the Variscan massifs in NE France and Switzerland. Borehole locations are shown. Key to structures is given on Figure 2. Mapping data sources are given in the Appendix.

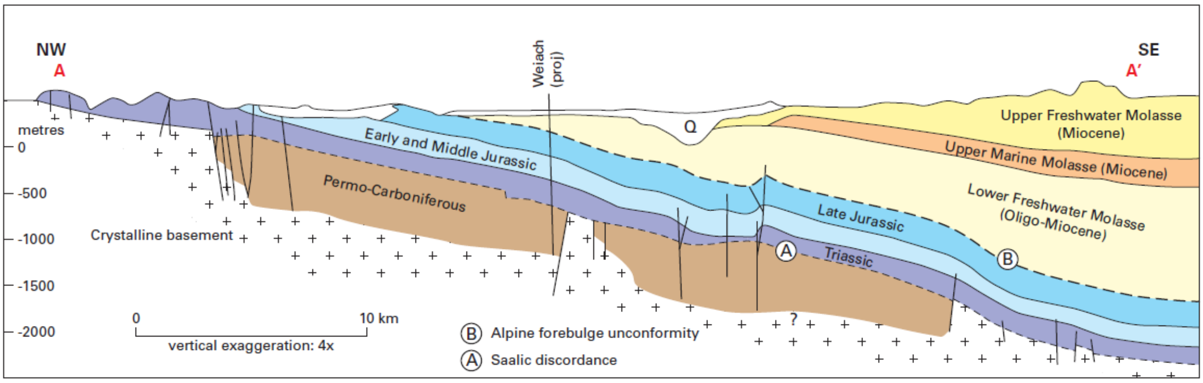

Figure 32 Typical cross-section passing close to the Weiach-1 well. The exact geometry of the underlying Permo-Carboniferous Basins is poorly understood. Line A-A' on Figure 29. Q = Quaternary. Modified from Mazurek et al. (2006).

STRATIGRAPHY

Only one well has penetrated the Permo-Carboniferous in the North Swiss Basin (Figures 32, 33). Palynology by Hochuli (1985) on the borehole Weiach-1 has confirmed 572 m of Stephanian (including 201 m of coal measures) and 457 m of Autunian clastic deposits which were subdivided into 11 lithofacies (Matter, 1987; Nagra, 1993). The Autunian-Saxonian conformably overlies the Stephanian and consists of four lithological units: a 136 m thick Lacustrine Unit; a 194 m thick Lower Alluvial Fan unit; a 67 m Playa Lake unit, and the Upper Alluvial Fan unit (not encountered by the Weiach-1 borehole) (Matter, 1987; Blüm, 1989; Nagra, 1993)

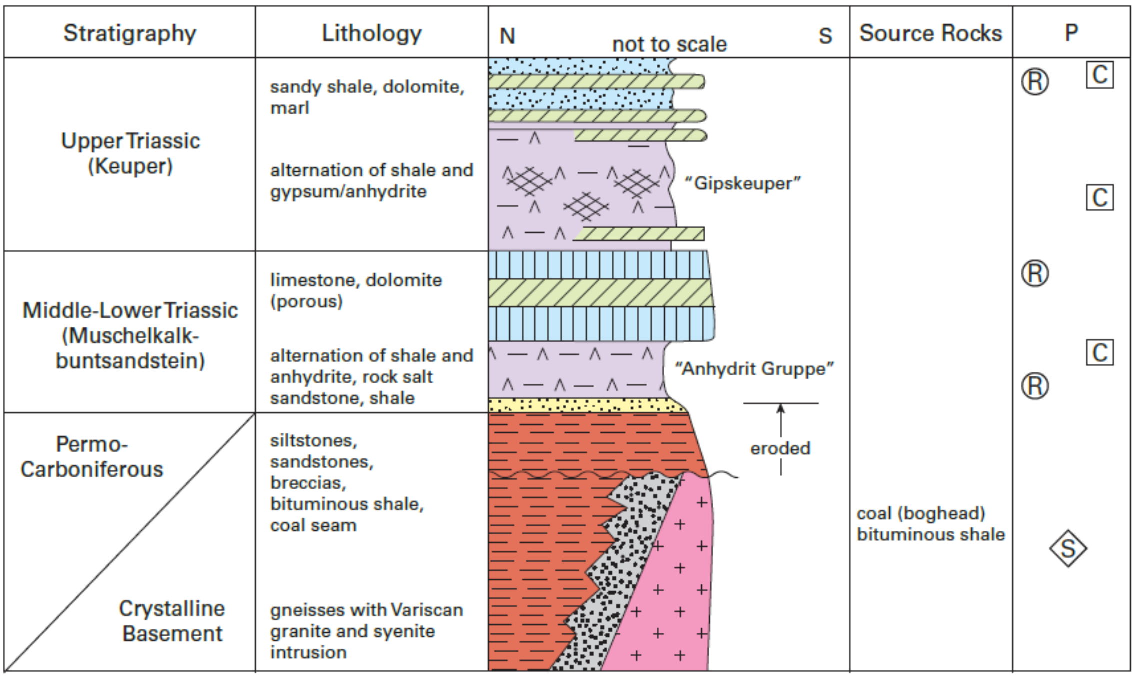

Figure 33 Schematic stratigraphic and lithologic column for the Palaeozoic petroleum system of the North Swiss Basin. P = Petroleum System. C = Cap rock. R = Reservoir. S = Source rock. Modified from Schegg et al. (1999)

The Permo-Carboniferous is unconformably overlain by a thin (9 m) Lower Triassic Buntersandstein (Bunter Sandstone) and thicker (163 m) Middle Triassic (Muschekalk). The Muschelkalk sequence comprises an anhydrite group followed by a sequence of limestones and dolomites. The Upper Triassic (Keuper) evaporitic gypsum and anhydrite sequence acts as the main alpine décollement horizon (Figure 33) (Sommaruga, 2011). The Permo-Carboniferous is relatively undeformed compared to the overlying Mesozoic and Cenozoic sediments. The Triassic décollement in Switzerland has preserved the underlying strata from severe deformation in the Alpine Orogeny (Sommaruga, 2011).

At the French-Swiss border near Geneva, seismic reflection surveys have highlighted the presence of continuous high-amplitude reflectors beneath at depth Mesozoic cover. The identified Permo-Carboniferous troughs sit along a SW-NE lineament passing from southern Germany to the Massif Central (Gorin et al. 1993). The high-amplitude of the seismic reflectors beneath the Triassic cover is thought to represent a Carboniferous coal-bearing sequence (Gorin et al., 1993). The seismic reflectors are however poorly imaged (Sommaruga, 2011).

SEDIMENTARY HISTORY

The interpretation of the sedimentology of the Permo-Carboniferous sequence is based on studies of the Weiach-1 deep borehole (Matter, 1987; Diebold, 1989; Nagra, 1993)

The Coal Series

The Stephanian Coal Series consists of six coal deposition cycles totalling 32 m of coal, with a maximum 4 m thick seam (Matter, 1987). These are mud-or sand-dominated sequences. The mud-dominated sequences contain bituminous and laminated shales as well as a yellow siderite-rich claystone. The sand-dominated sequences contain either amalgamated trough-cross bedded sandstones, or isolated sand lenses within the silt and mudstone succession. The Coal Series has been interpreted as flood plain and fluvial deposits of an anastomosing river system (Matter, 1987). This represents a series of interconnected rivers, often with low flow rates, surrounded by peat bogs and marshes (Diebold, 1989).

The Lacustrine Series

The Autunian Lacustrine Series consists of several cycles of lake sedimentation passing into tributary deltas. Basal black laminated weakly limy mudstones grade into grey muddy sandstone and stromatolitic shallow-water sands. Finally, the succession coarsens to the fining-upward sequences of a tributary delta (Matter, 1987). Frequent fish scales, ostracods and *Lioestheria* (shrimp) indicate oxygen-rich waters, however the infrequent bioturbation suggests an occasional anoxic lake bottom. The lacustrine series represents a replacement of the isolated swamps, large river systems and swamps of the fluvatile Coal Series by widespread shallow lakes (Diebold, 1989).

The Lower Alluvial Fan Series

Coarsening-upward sequences of a prograding alluvial fan overlie the lacustrine series. Two sequences have been recorded, both several tens of metres thick, coarsening from silts and sands to conglomerates and breccias at the top (Matter, 1987). A change in climate from semihumid to semi-arid is suggested by a colour change from grey to red, an increase in calcrete, and less bioturbation (Diebold, 1989).

The Playa Series

This series is represented by a series of thin red sandstones, silts and clays. Dessication cracks and adhesion ripples suggest an arid environment (Matter, 1987). Dating of the Playa Series is difficult due to the lack of fossiliferous material, nonetheless, it is thought to represent the red-bed sequence of the Upper Rotliegend (Diebold, 1989)

GEOCHEMISTRY

The Permo-Carboniferous sequence in Weiach-1 borehole was studied by the NAGRA project in the 1980s. However, the project did not run organic geochemical analyses. Vitrinite reflectance values were collected throughout the sequence to establish the maturity of the coals and as an aid to understanding basin evolution.

The vitrinite reflectance values determined increase from 0.45 %Ro in the Jurassic to 1.28 %Ro nearing the base Carboniferous (Nagra, 2002). The boundary between the lacustrine unit and the lower alluvial fan separates two maturity gradients. These are thought to represent two palaeogeothermal gradients separated by the Saalian Unconformity (Schegg et al., 1999; Mazurek et al., 2006). The Autunian here is type II and similar to the lacustrine paper shales found in the Lorraine-Saar-Nahe Basin, however here the algal oil shales make up to 30% of the Autunian section (Kettel & Herzog, 1988). The Stephanian Coal Series is mostly type III kerogens with a minor proportion of type II. Further eastward into the German Molasse basin, kerogen of the Permo-Carboniferous becomes progressively dominated by type III kerogens (Kettel & Herzog, 1988).

THERMAL MODELLING

The extensive vitrinite reflectance sampling in Weiach-1 borehole has given rise to numerous basin modelling studies for the oil and gas, and geothermal industry (Kempter, 1987; Schegg & Leu, 1998; Schegg et al., 1999; Mazurek et al., 2006; Chelle-Michou et al., 2017).

To explain the high vitrinite reflectance values, up to 1200 m of erosion in the Permian has been suggested (Kempter, 1987). The raised vitrinite reflectance values can also be attributed to a raised palaeoheatflow and/or more minor burial (Schegg & Leu, 1998). A more comprehensive regional study by Mazurek (2006) suggested that the Permo-Carboniferous trough initially had geothermal gradients of 100-160^{o}C/km with Permian erosion of 200-600 m of strata. The high heat flow was attributed to active orogenic processes and the shallow emplacement of granitic intrusions within the crystalline basement.

Schegg et al. (1999) modelled the hydrocarbon generation, migration and accumulation for the whole North Swiss Basin succession. The authors only accounted for the Stephanian coals in the Permo-Carboniferous system. They used hydrogen-rich North Sea coals as an analogy with an average TOC of 80%, and Hydrogen Index (HI) 228 mg HC/mg TOC. Depending on whether the Carboniferous coals were proximal or distal their hydrocarbons were generated in the Miocene or Jurassic respectively. Up to 30 mg/g oil and 20 mg/g of gas were modelled to have been generated from the coals hydrogen rich coals

SOURCE ROCK POTENTIAL

The depositional and structural setting resembles that of some Permo-Carboniferous basins of the Massif Central (Diebold, 1989; Châteauneuf & Farjanel, 1989) which have sourced both solid combustibles (Châteauneuf & Becq-Giraudon, 1990) and extractable subsurface hydrocarbons (Mascle, 1990). Surface asphalt deposits of the Val de Travers are not sourced from the low maturity Jura source rocks (Todorov et al., 1993), and they are thought to have migrated up-dip from source rocks in the molasse basin. However, the exact source age for this accumulation is not known (Schegg et al., 1999).

The Stephanian-Autunian of the North Swiss Basin is not yet a proven source in Switzerland, however, along the extension of this en-echelon basin trend into France and Germany, there is evidence of a working petroleum system. Several small Mesozoic oil and gas discoveries eastward in the German Molasse Basin, are thought to have been charged by Permo-Carboniferous sourced hydrocarbons (Kettel & Herzog, 1988; Kettel, 1989). In France, the same lineament is inferred to crop out at Ronchamp, Autun, St. Étienne and Blanzy-Le Creusot (Mascle, 1990), where the Permo-Carboniferous is a source interval (see Chapter 4) South of the North Swiss Basin the gas discovery in the late Jurassic Malm at Entlebuch is thought to be sourced from the underlying Permo-Carboniferous coals (Vollmayr & Wendt, 1987). The Carboniferous is dated as Westphalian, however the presence of an Autunian or Stephanian source is not discounted (Vollmayr & Wendt, 1987).

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7 Ireland

INTRODUCTION

The late- to post-Variscan basins of Ireland include the Fastnet, North Celtic Sea and the Porcupine Basins (Figure. 34). Part of the Shelf Edge and Cockburn basins also lie within Irish waters at the western end of the Western Approaches Trough. The Porcupine Basin proper comprises three sub-basins; the Main Porcupine Basin, Porcupine-Seabight Basin and a smaller Northern Porcupine Basin. The basins contain up to 13 km of Upper Palaeozoic to Cenozoic strata. The Fastnet Basin and North Celtic Sea Basin have a NE-SW elongate morphology and contain up to 6 km of Mesozoic strata and an uncertain amount of late Palaeozoic strata.

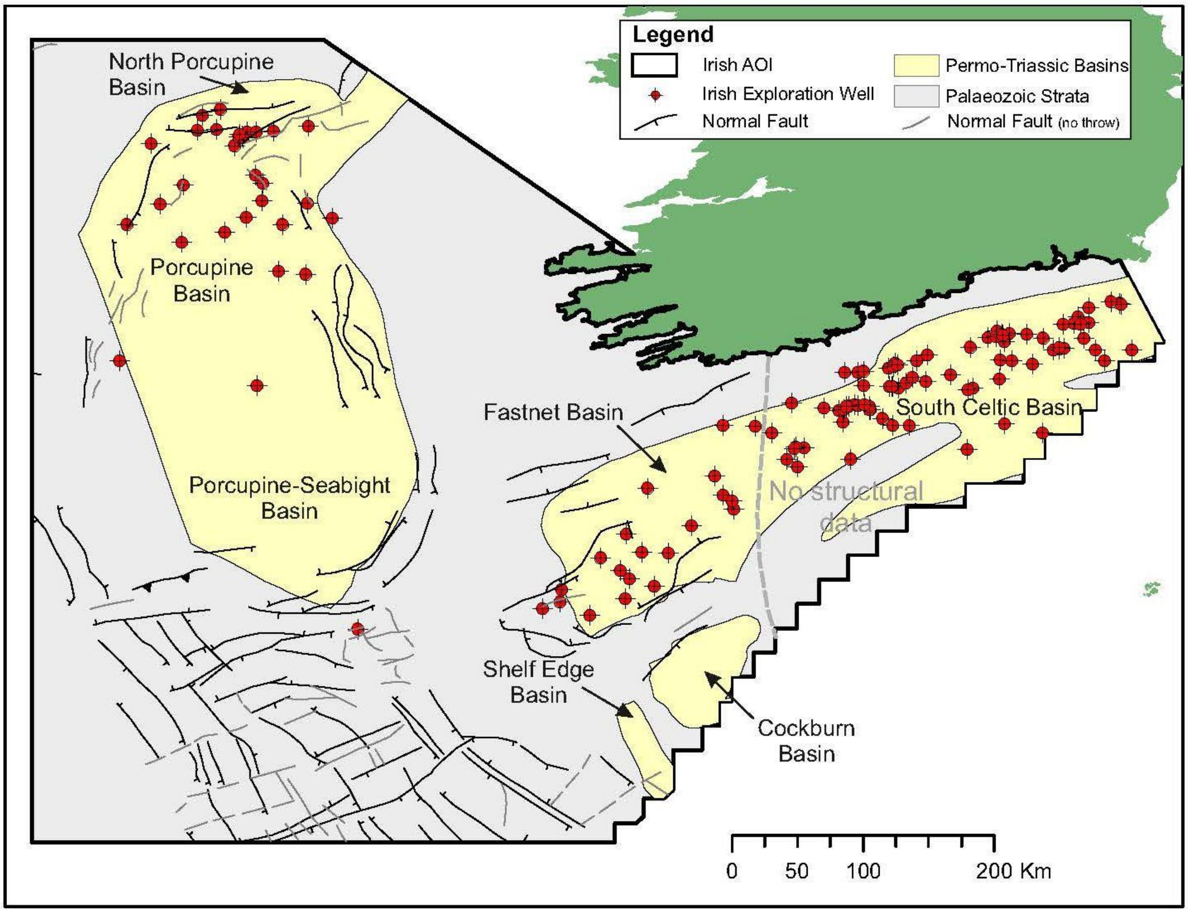

Figure 34 Map showing the location of Porcupine, Fastnet, Shelf Edge, Cockburn and South Celtic Sea basins within the Irish part of the AOI. The major structures developed within Palaeozoic and Permo-Triassic strata are also shown. After Dorschel et al. (2010)

DATA SOURCES

Irish offshore basins have been the subject of intermittent exploration since the first well was drilled in 1970. In the Irish part of the AOI a total of 168 wells have been drilled (Figure 34). Well data was not available for consultation in this report and information about stratigraphy, geochemistry and thermal modelling was collated from published literature and confidential reports (see country bibliography section).

VARISCAN BASEMENT STRUCTURE AND HISTORY

Rhenohercynian Zone

In Irish waters, the mapping of the Variscan basement follows BGS (1996). The width of the inferred Rhenohercynian Zone apparently increases to over 350 km, with the major inferred Variscan thrusts trending SW-NE, rather oblique to the inferred Variscan Front (Figure 2), as noted by Praeg (2004).

STRATIGRAPHY

Rocks of probable Stephanian age are known from six wells in the north and west of the Porcupine Basin (Robeson et al., 1988; Croker & Shannon, 1987; Naylor & Shannon, 2011), and a definite Stephanian age established in 34/15-1, 26/28-1 and 26/28-2 (Naylor & Shannon, 2011). Deminex also report the presence of supposed Autunian strata in 34/15-1 (Tate & Dobson, 1989), but unequivocal Permian strata have not been reported from the Porcupine Basin (Naylor & Shannon, 2011), nor indeed, west of Ireland (Tate & Dobson, 1989; Roberts et al., 1999; Praeg, 2004).

A generalised stratigraphy of the Porcupine Basin is shown in Figure 35 and Figure 36.

GEOCHEMISTRY

In the Porcupine Basin, source rocks have been identified regionally in the Middle Jurassic, Upper Jurassic and Lower Cretaceous, although the Cenozoic, Lower Jurassic and Carboniferous may have localised source potential (Croker & Shannon, 1987; Croker & Shannon, 1995). The source rocks identified in the Celtic Sea Basins are of Lower Jurassic, Middle Jurassic, Upper Jurassic and, locally, Uppermost Jurassic/Lowermost Cretaceous age (Caston, 1995; Howell & Griffiths, 1995; Murphy et al., 1995; Shannon & Naylor, 1998). The only identified source rock in the Fastnet Basin is the Lower Lias (Robinson et al., 1981; Shannon & Naylor, 1998; Mikkelsen, 2013).

Numerous oil and gas fields, discoveries and shows prove the presence of an active hydrocarbon system in the Porcupine, Celtic Sea and Fastnet basins. Oil-source rock correlations suggest these hydrocarbons are generated from Mesozoic source rocks (Caston, 1995; Craven, 1995; Howell & Griffiths, 1995; Shannon & Naylor, 1998; Butterworth et al., 1999; Scotchman, 2001). Largely undeformed Palaeozoic sediments have also been drilled in the Porcupine Basin, where the Upper Carboniferous Westphalian coal beds have source rock potential for gas and condensate (Croker & Shannon, 1987; Shannon & Naylor, 1998). Croker & Shannon (1987) also suggested that sapropel-rich shales within the Carboniferous sequence may have moderate potential for oil at the basin margins, with potential for gas towards the basin centre. However, the presence of a Palaeozoic source rock in the North Celtic Sea and Fastnet basins remains largely speculative.

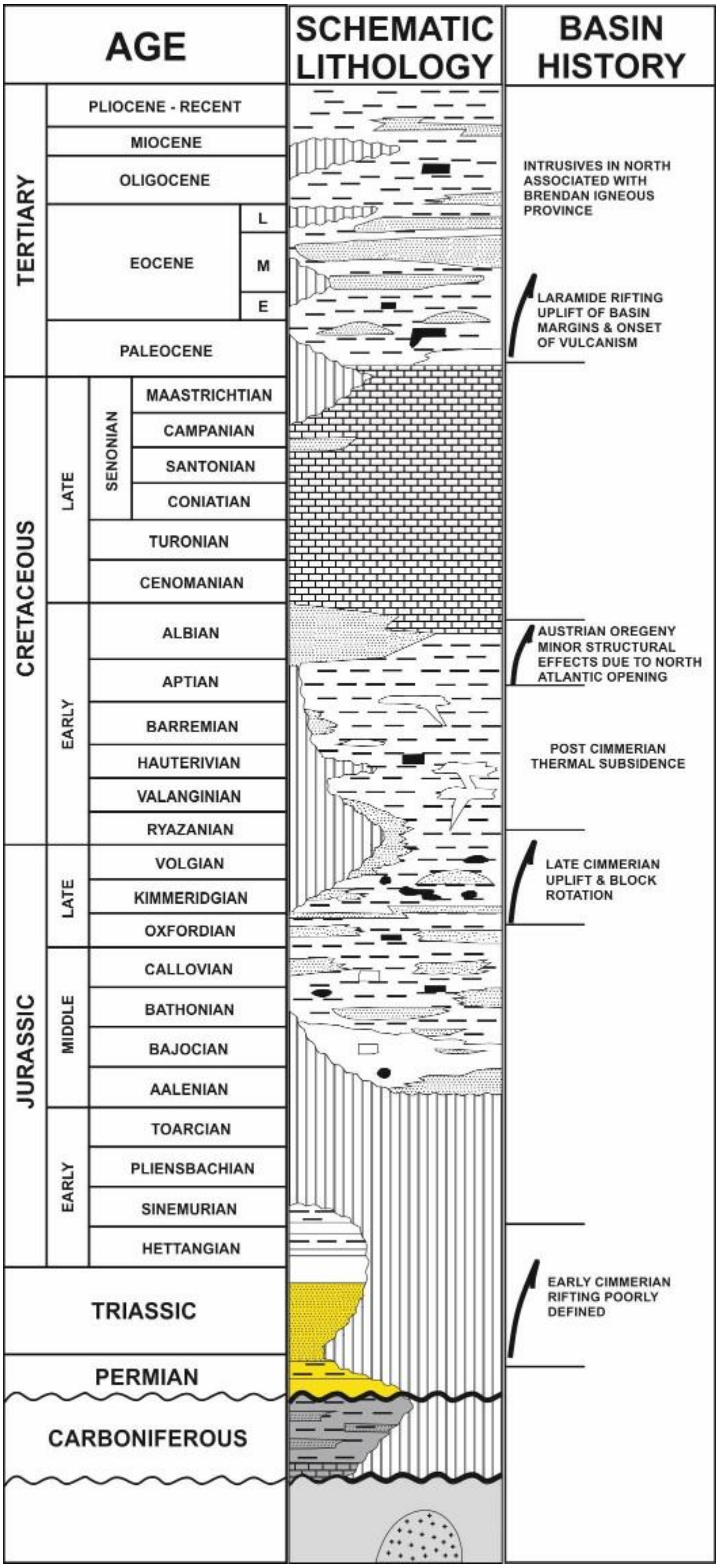

Figure 35 Generalised stratigraphy and tectonic history of the Porcupine Basin. Modified from Tate & Dobson (1989).

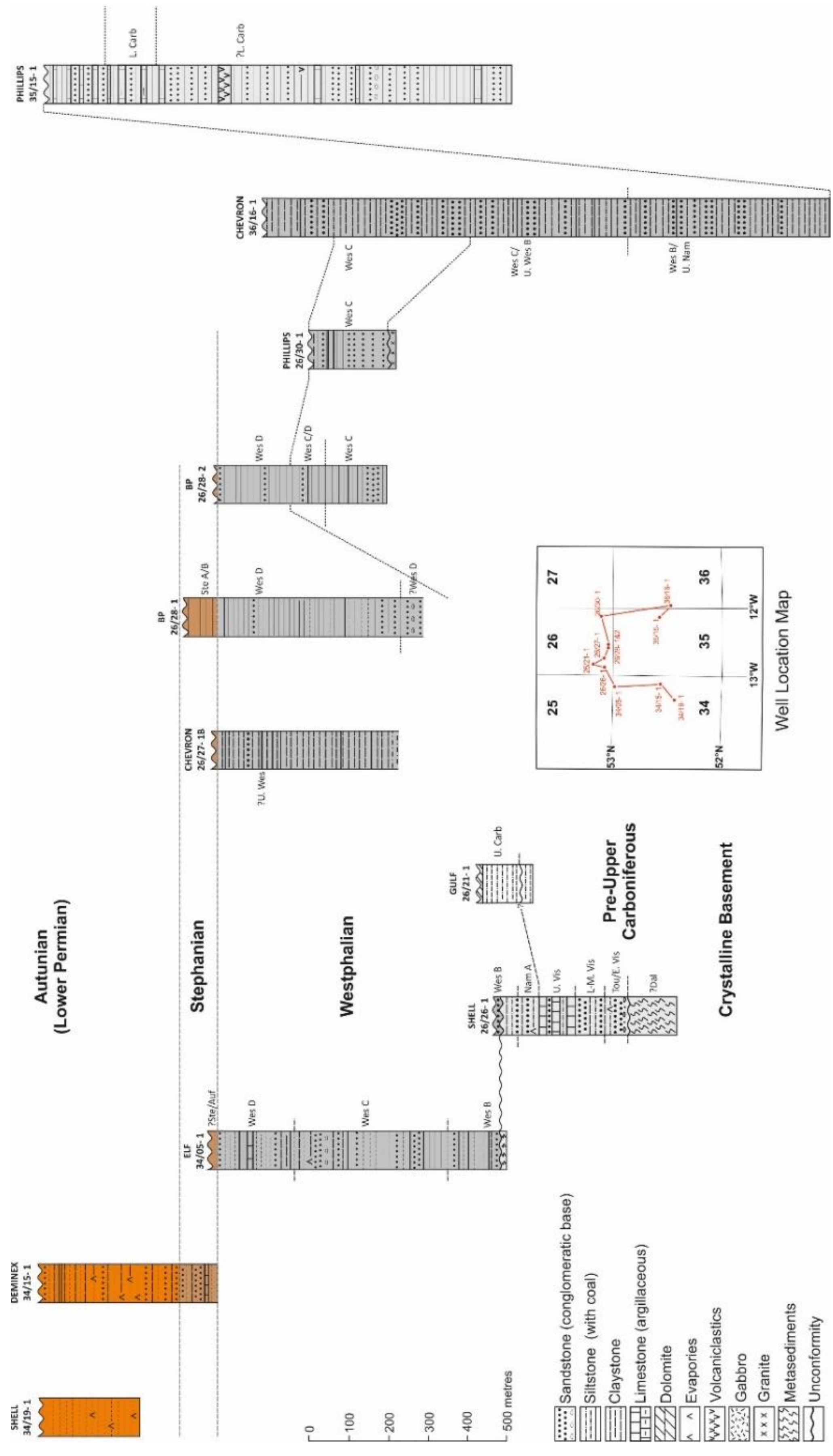

Figure 36 Well transect from the Porcupine Basin. Modified from Tate & Dobson (1989)

THERMAL MODELLING

Due to limited well penetrations and basin modelling studies, there are few estimates of (palaeo-) maturity of potential Palaeozoic source rocks within the Irish AOI, but extrapolation from known or modelled maturities of Mesozoic source rocks may provide some insight. Prior to deposition of the Mesozoic and younger sediments, regional maturity gradients indicate a significant episode of elevated crustal heat flow in western and southwestern Ireland during Variscan times (Keeley, 1996). Additionally, Corcoran & Clayton (2001) have proposed a phase of regional exhumation during the late Carboniferous – late Permian. Both of these events would need to be incorporated in any basin model to predict the maturation history of potential Palaeozoic source rocks.

Present-day maturities of Jurassic source rocks in the Porcupine Basin have been modelled and range from mature to over-mature (Ro = 0.7% - >4.7%), with the onset of hydrocarbon generation in the Cretaceous (Naeth et al., 2005). Generation from a deeper Palaeozoic source would have therefore occurred before this, and is likely the have been exhausted prior to the present-day. High maturities would have been attained in the southern Porcupine Basin by the early Cretaceous, due to elevated heat flows associated with the development of the Mid Atlantic Ridge (Naeth et al., 2005).

In the North Celtic Sea Basin, the Top Lias is modelled to be in the late oil window – wet gas window at the present-day, with maturity decreasing towards the basin margins (Howell & Griffiths, 1995). The main phase of hydrocarbon generation and expulsion in this region is predicted to have occurred in the late Cretaceous to early Cenozoic (Caston, 1995; Craven, 1995; Howell & Griffiths, 1995), prior to an estimated regional exhumation of *c*. 1 km across the Celtic Sea during the Cenozoic (Menpes & Hillis, 1995; Murdoch et al., 1995).

SOURCE ROCK POTENTIAL

There is limited positive evidence in the public domain to support the presence of a mature Palaeozoic source rock within the Irish offshore basins of the study area; conversely, there is insufficient data to confidently assert the complete absence of a Palaeozoic source. Regional extrapolation would suggest that, if any, a Carboniferous gas-prone source would be most likely, but would certainly be over-mature in the basin centres present-day. The Corrib gas field in the Slyne Basin is sourced from Westphalian coals (Stout, 2013), and this play, although still to be proven, may extend into other Permo-Triassic basins offshore Ireland (Corcoran & Clayton, 2001). A major risk for plays invoking a Palaeozoic source is the maturation history, which would likely have significant lateral variation given the complex tectonic history of the area. Corcoran & Clayton (2001) suggested that where Carboniferous source rocks are present, they will only be a significant source of hydrocarbons in basins that have experienced relatively low heat flow during the late Carboniferous – early Permian, but sufficient Mesozoic burial to reach the hydrocarbon generation threshold.

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8 UK

INTRODUCTION

In the UK, the late- and post-Variscan basins are located offshore in the SW Approaches of the English Channel and Bristol Channel (Figures 37, 38). The Western Approaches Trough is the principle structure and it is a WSW-ENE trending basin that lies at the western end of the English Channel, bounded to the north by the Cornubian Platform and to the south by the Amorican Massif (Figure 39). The basin is split geopolitically in two along the median line between the UK and France. In the UK sector, the basin can be subdivided into a number of sub-basins, principally the Melville Basin, St Mary's Basin and Plymouth Bay Basin. The Shelf Edge Basin is a NW-SE trending basin that lies at the south-western tip of the Western Approaches Trough. This basin extends northwards into Irish territorial waters. North of the Western Approaches Trough lie the South Celtic Sea and Haig Fras basins as well as part of the Cockburn Basin which predominantly lies in Irish waters (see Chapter 7).

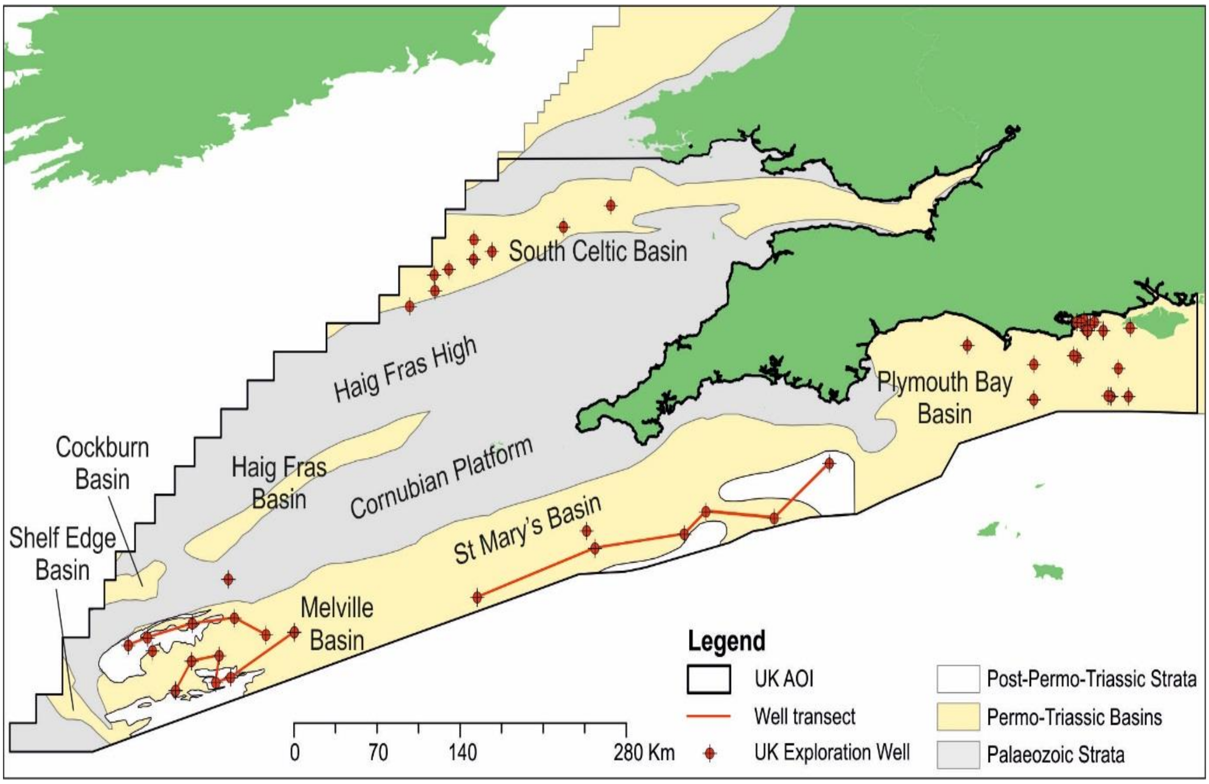

Figure 37 Location map showing basins with potential Stephanian-Autunian strata. Standard colours: Pre-Westphalian, very light grey; Westphalian, medium grey; Stephanian, brown; Autunian, orange; Permo-Trias, yellow; Jurassic and younger, white.

DATA SOURCES

A total of 54 exploration wells have been drilled within the Area of Interest (UK AOI) (Figure 37). No wells have been drilled in the Cockburn Basin, Shelf Edge Basin or Haig Fras Basin. The majority of wells were drilled during the late 1970's and have been summarised in British Geological Survey (BGS) Offshore Regional Reports for the English Channel (Hamblin et al., 1992), western English Channel and its western approaches (Evans et al., 1990) and Cardigan Bay and the Bristol Channel (Tappin et al., 1994). More recently, wells from the Melville Basin were reappraised for the United Kingdom Promote 2015 (DECC 2014). The review presented here is underpinned by published literature, released well data and BGS confidential reports.

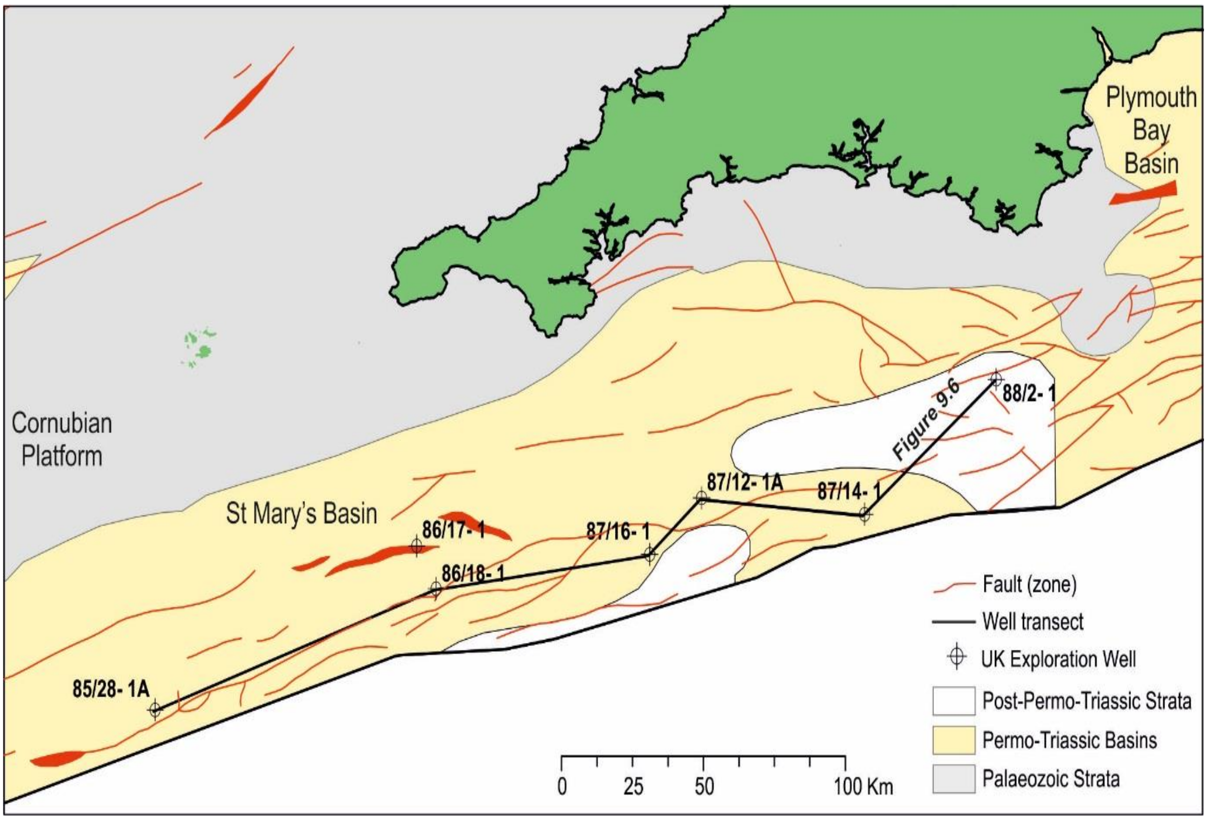

Figure 38 Location of St Mary's Basin: Stephanian-Autunian named basins, basin-controlling faults, cross-section location, key wells, Variscan structure

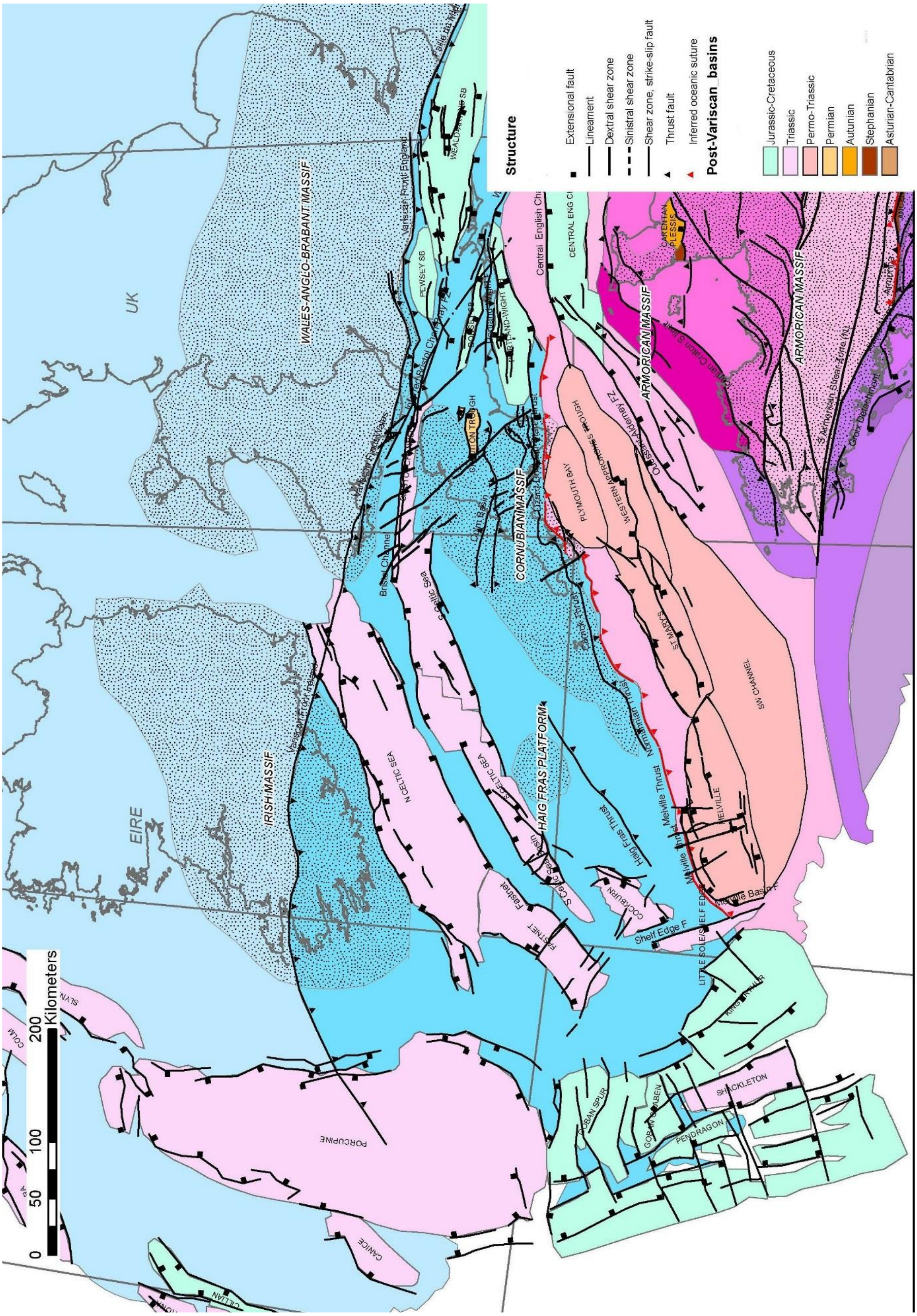

Figure 39 Relationship of Permian and Mesozoic basins to the Variscan substrate in the Western Approaches. Key to Variscan orogenic structure on Figure 2. Mapping sources identified in the Appendix.

VARISCAN BASEMENT STRUCTURE AND HISTORY

Foreland

The South Wales Coalfield, Bristol and Somerset Coalfield and the concealed coalfields of Oxfordshire and Kent lie close to the Variscan Front (Plate 3), containing strata as young as Westphalian D (Asturian) age (Waters et al., 2013). Slightly farther north, boreholes in the St George's Channel Basin (103/2-1) and Kish Bank Basin (33/22-1) of the Irish Sea, about 150 km north of the Variscan Front, also penetrate strata of this age (Naylor & Shannon, 2011). However, in all these basins north of the Variscan Front, no strata of Stephanian and Autunian age have definitely been proven, and the earliest strata of Collyhurst (Rotliegend) facies are somewhat younger (Jackson et al., 1997). The only exception appears to be the Stafford Basin, where the Salop Formation is attributed a Stephanian A (Cantabrian) age (Waters et al., 1994; Besly & Cleal., 1997); and on the margin of the southern North Sea in the Netherlands and Germany (Kombrink et al., 2010) as depicted on Plate 3, where up to 600 m of Stephanian may be present. The extensional structures associated with this later phase of Permian subsidence, e.g. the East Malvern Boundary Fault (Barclay et al., 1997) have a N-S orientation, and post-date orogenic collapse.

Rhenohercynian Zone

In SW England, the Rhenohercynian passive margin underwent a phase of rift-related extension in early Devonian time, with exhumation of mantle peridotites (Lizard Complex) by mid-Devonian time (Shail & Leveridge, 2009). Variscan convergence commenced in the late Eifelian, at the same time as rifting farther north. Collision in early Carboniferous time resulted in closure of the Rhenohercynian Basin, uplift of deep marine sedimentary rocks from the distal continental margin, inversion of a series of late Devonian successor basins and impingement of a Saxothuringian upper plate, correlative with the MGCR (Shail & Leveridge, 2009). Convergence ceased in the late Carboniferous and was replaced by an extensional regime which reactivated earlier fault zones. Exhumation of the orogenic lower plate is considered to have been coeval with emplacement of early Permian granites and rifting of the upper plate, which initiated sedimentary basin formation in the SW Approaches Trough (Shail & Leveridge, 2009). If indeed true, these basins likely contain at least some early Permian strata.

A series of NW-SE trending strike-slip faults with dextral offset (Figures 2, 39) developed at about this time, and may have facilitated granite emplacement by the pull-apart mechanism. The Sticklepath-Lustleigh Fault Zone is perhaps the best known example but there are many others mapped (BGS, 1996). Although the presence of a WNW trending, recurved fault extending from the Isle of Wight-Bray Fault towards the Bristol Channel, with perhaps hundreds of kms of dextral displacement has been widely postulated in geodynamic models (e.g. Holder & Leveridge, 1986; Woodcock et al., 2007; Woodcock & Strachan, 2012), such a structure would (if it exists) appear to have no influence on the geometry of various (seismically well-constrained) W-E trending Mesozoic basins of the Wessex Basin (Whittaker, 1985). This putative structure is therefore indicated as a 'lineament' in the mapping presented (Figure 40, Plates 1 and 2).

Saxothuringian Zone

The extent of the Saxothuringian Zone in the SW Approaches is not known with any degree of certainty, because of the paucity of well control and/or exposure. The mapping presented here (Plate 1, Figures 2, 39) infers the extension of the zone WSW from Man of War and Eddystone Rocks, parallel to the Normannian and Melville thrusts (BGS, 1996; Praeg, 2004), but the hard evidence for this hypothesis is, in fact, rather flimsy. It depends on the assumption that (as in the Lorraine-Saar-Nahe Basin), the major basins are developing in the hangingwall of the major orogenic suture zone.

Offshore Wells

Thirteen wells have reached Variscan Basement in Quadrants 73, 83, 86, 93, 97, 98 and 103 (Evans, 1990; Hamblin, et al. 1992). These contain a mixture of lithologies including those described as slate, phyllite, pelite and quartzite. Well 87/12-1A is unique in that it contains Middle Devonian carbonates, with rugose corals, algae, stromatoporoids, ostracods, gastropods etc. Further studies of these basement provings, using isotopic and petrological techniques, may be appropriate to establish their age and affinity

STRATIGRAPHY

The stratigraphy of the Western Approaches Trough is summarised in Figure 40. Late Carboniferous-early Permian strata are encountered in 4 wells: 73/12-1A, 74/1-1A, 86/18-1 and 87/12-1A. Figure 41 shows the location of wells in the Melville Basin. Figure 42 is a section which schematically illustrates the structure and stratigraphy of the Melville and adjacent Shelf Edge Basin. Figures 43 and 44 are well transects illustrating the stratigraphy of the Melville Basin (north and south)

The stratigraphy of the Cockburn Basin and Shelf Edge Basin have been interpreted from seismic data as no wells have been drilled in these basins. The Shelf Edge Basin is characterised by a number of pre-Upper Cretaceous half grabens. Permo-Triassic strata are anticipated in the Cockburn Basin (Figure 45).

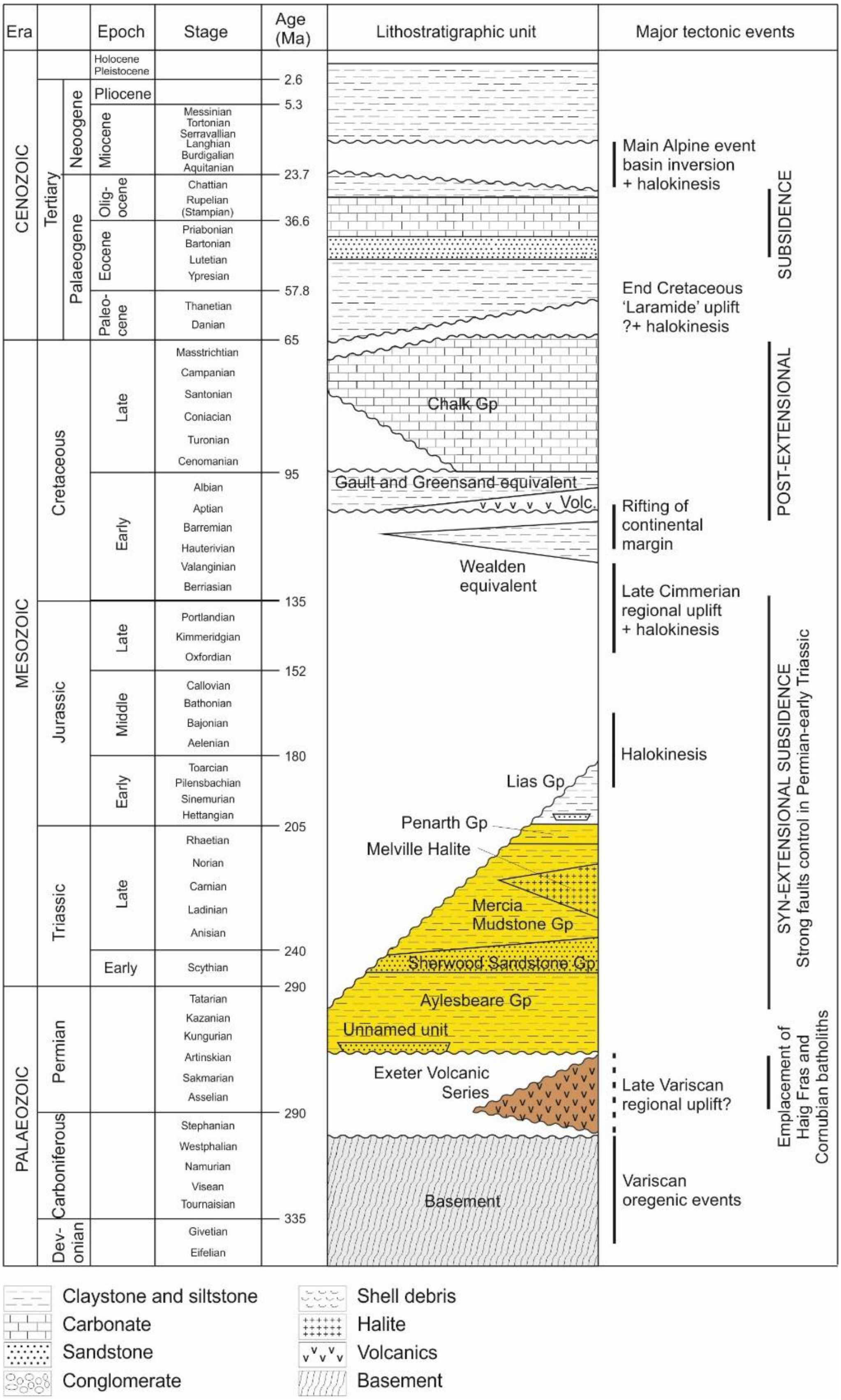

Figure 40 Simplified stratigraphy, lithofacies and tectonic history of the Western Approaches Trough. Modified after Smith (1996).

Well stratigraphy

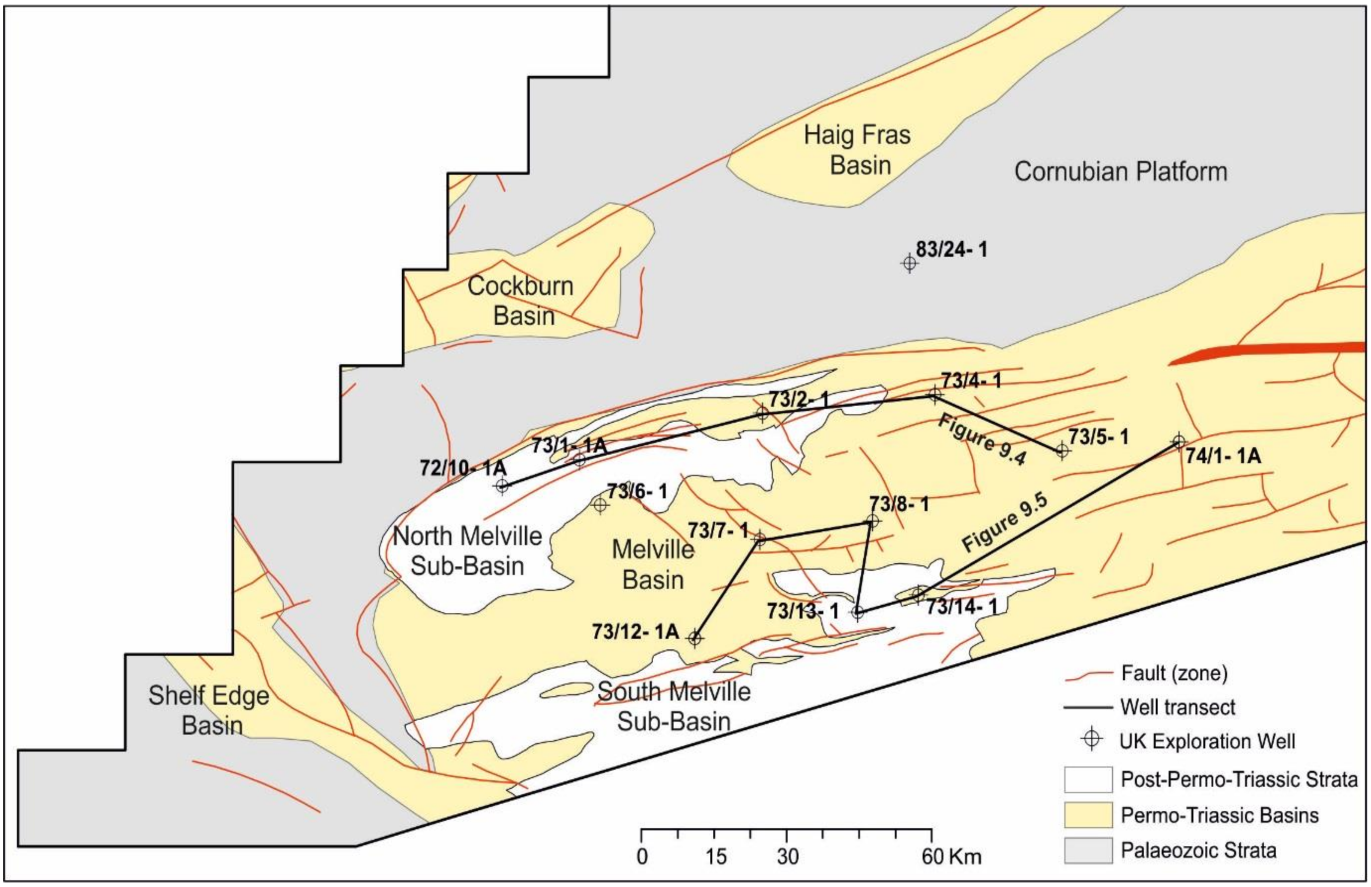

Figure 41 Location of Melville Basin: Stephanian-Autunian named basins, basin controlling faults, cross-section location, Variscan structure.

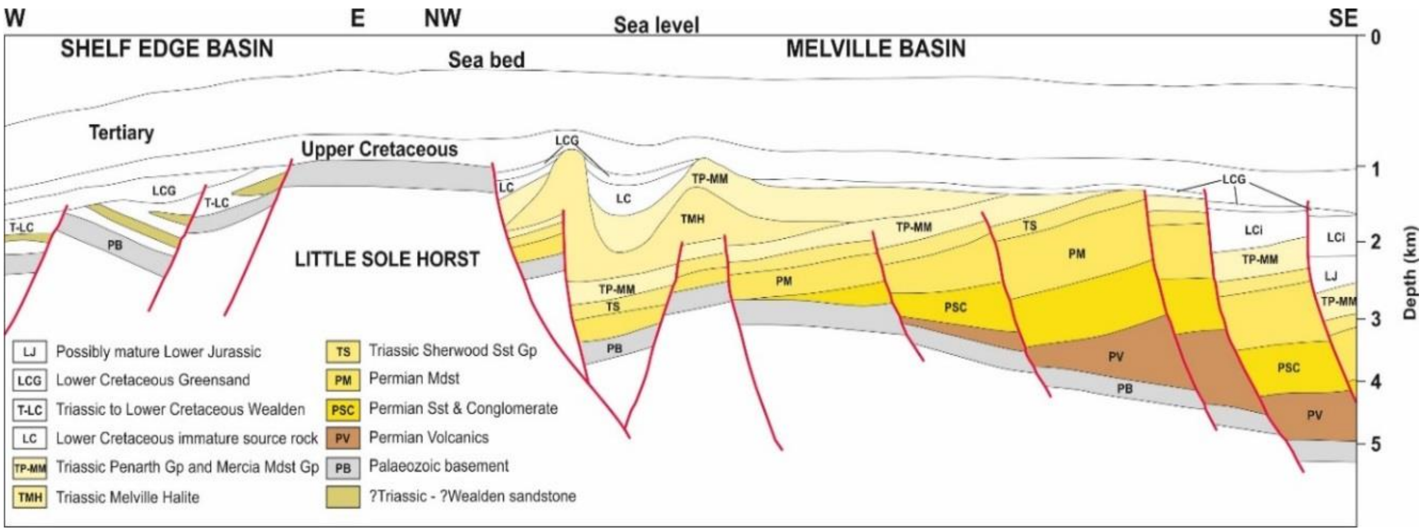

Figure 42 Schematic summary of the stratigraphy of the Melville Basin and Shelf Edge Basin in the Western Approaches Trough. Modified after Smith (1996).

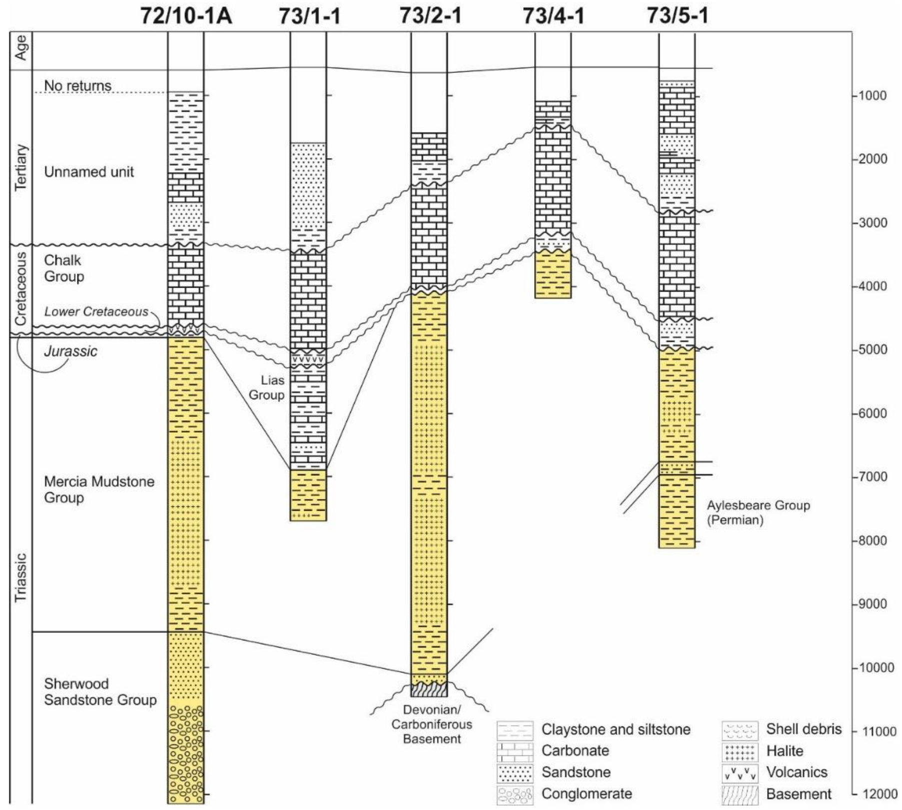

Figure 43 Well profile, Melville Basin north. Key colours as in Figure 40.

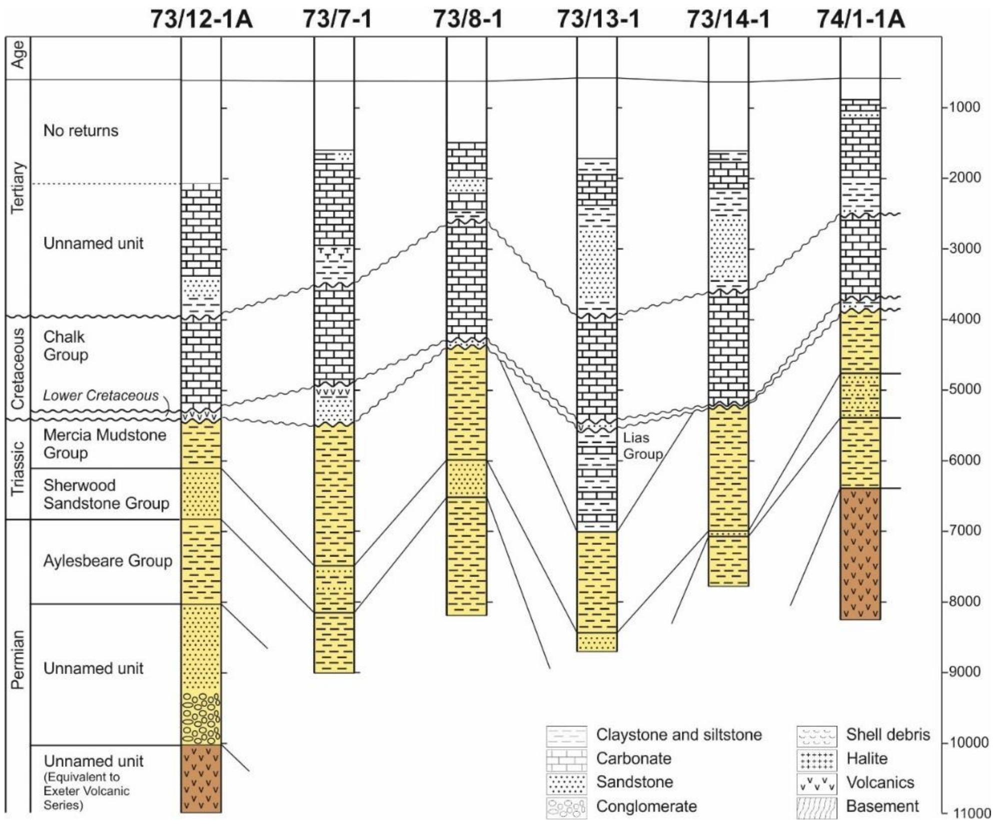

Figure 44 Well profile, Melville Basin south. Colours as in Figure 40.

SEDIMENTOLOGY

Permian

Aylesbeare Mudstone Group

Defined on the south Devon coast, the Aylesbeare Group is composed mainly of red-brown silty mudstone and clayey siltstone. It has traditionally been regarded as late Permian in age, a date that has recently been supported by magnetostratigraphic studies (Hounslow et al., 2016). However, some publications assign it an early Triassic age (Henson, 1970; BGS Lexicon).

In Quadrants 73-74 and 97-98, many wells penetrate the Aylesbeare Group with mudstone/claystone lithologies dominating and only minor sandstones (e.g. 73/5-1, 73/7-1, 73/8-1, 73/14-11, Figures 43 and 44). Well 98/11-2 has the thickest succession with 1463 m (4,800 ft) resting on Variscan basement. It is also reported to contain traces of anhydrite. In other wells, it is absent.

Exeter Group

The Exeter Group comprises sandstones, breccias and locally some mudstones, in a predominantly volcanic sequence (Edwards et al., 1997). The Whipton Formation contains late Permian palynomorphs (Warrington & Scrivener, 1990).

Conglomerates and breccias

Outcrops in coastal Devon include breccias and sandstones deposited in alluvial-fans and aeolian deposits derived from the area of present-day Dartmoor (Hamblin et al., 1992).

Permo-Triassic conglomerates and breccias are found below Aylesbeare Group mudstones in several offshore wells. These have not been dated, but a Permian age is likely on the basis of their stratigraphic relationships. In well 73/12-1A, 581 m (1,905 ft) of sandstones and breccio-conglomerates lie between Aylesbeare Group mudstones and Permian volcanics. In well 72/10-1A, conglomerates at the base of the drilled succession are assigned to the Triassic Sherwood Sandstone Group (Evans, 1990), but they could equally be of Permian age.

Farther east, wells 98/16-2, 98/18-1 and 98/22-2 contain breccias and conglomerates. In the latter two wells, these rest on Variscan basement. The ‘Basal Conglomerate’ at TD in well 98/16-2 only drilled 73 ft. Well 98/18-1 drilled 161 m (529 ft) of ‘un-named breccia, conglomerate and claystone’. Well 98/22-2 drilled 221 m (72 ft) of ‘Permo-Triassic breccia’ with a further 66 m (216 ft) of overlying sandstone and conglomerate assigned to the ‘Sherwood Sandstone Group’.

Exeter Volcanics:

In the Exeter and Crediton Trough area of Devon, a variety of basaltic and lamprophyric lavas and intrusions have been dated at 291–282 Ma (early Permian) (Scrivener, 2006). These are up to 240 m thick in Devon. These volcanic and igneous units are coeval with widespread volcanic activity throughout Europe during the latest Carboniferous to early Permian (Timmerman, 2004).

Both seismic and aeromagnetic data suggest extensive development of lavas in the Melville Basin (Evans, 1990). Permian volcanics have been penetrated in wells 73/12-1A and 74/01-1A. These are undated, but Evans (1990) suggests that they are contemporaneous with the Exeter volcanic rocks onshore. Deep seismic reflectors in the Plymouth Bay Basin are also interpreted as volcanic horizons (Pinet et al., 1987).

Undifferentiated Permo-Triassic sediments*:*

In wells 87/12-1A and 86/18-1, a presumed Permo-Triassic unit of interbedded claystones, siltstones and sandstones has been assigned 'late Carboniferous to Permian' and 'Autunian' ages respectively. On this basis, the strata are considered older than the Aylesbeare Group; whether they are coeval with the breccias and conglomerates that underlie that group is not known.

In well 86/18-1, a rich miospore assemblage suggests an early Late or late Early Permian age at the top of the unit, an Early Permian age at 6140-6150 ft (measured depth sub-sea) and a tentative Carboniferous age at the base (released RRI biostratigraphy report, but the Carboniferous designation was doubted by B Owens pers. comm. 1982).

In well 87/12-1A, a diverse miospore assemblage of Early Permian age has been identified (released BP biostratigraphy report).

GEOCHEMISTRY

In the SW Approaches, Lower Jurassic mudstones are thought to be the only viable source rock (DECC, 2014). Evidence for this include oil shows in the 73/14-1 well which have been correlated to a Lower Lias source (Dungworth et al., 1986). The Palaeozoic section encountered by well 73/2-1 in the Melville Basin is comprised of schist and therefore has no source potential (Petra-Chem, 1983).

The Upper Devonian to Carboniferous section of well 86/18-1 in St Mary's Basin, although moderately tectonised, contained dark grey to black, carbonaceous shales at the top of the interval (BNOC Development Ltd). No RockEval data from this section were available for this study, but the Lower Permian sandstones were water-bearing and only traces of methane in the background gas readings were reported, suggesting this interval has no source potential. This is supported by RockEval analysis of the Palaeozoic section of well 83/24-1 which demonstrated that interval had no source potential for oil or gas (Cooles et al., 1981).

No shows and only trace background gas were recorded in the metamorphosed Palaeozoic section in wells 98/23-1 (Bulman, 1983) and 93/2-2 (Holm, 1987). In Quad 98 of the Channel Basin, multiple oil-source rock correlations have typed the migrant hydrocarbons to a Lower Lias source (PaleoChem Ltd, 1983c; Collins, 1991a; Collins, 1991b; Warburton, 1995), with some possible contribution from an Upper Jurassic source (GeoChem Laboratories, 1979; GeoChem Laboratories, 1984). The ?Devonian/Carboniferous section of well 99/18-1B is thought to have been deposited in oxidative conditions, so the sequence is not considered to have had any source potential, even prior to metamorphism (PaleoChem Ltd, 1984).

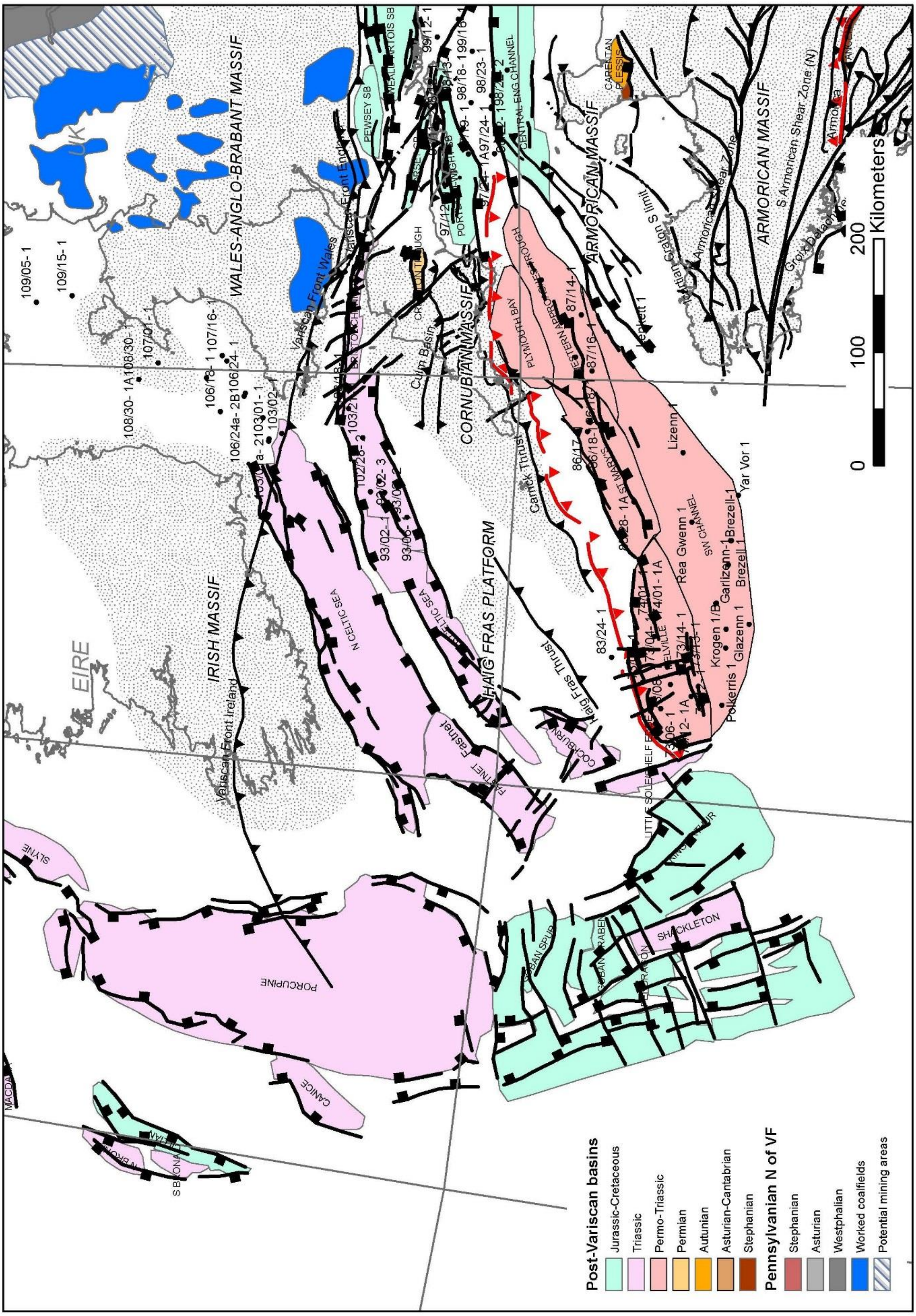

Figure 45 Relationship of Permian and Mesozoic basins to the Variscan substrate in the Western Approaches. For key to structures see Figure 2.

THERMAL MODELLING

The SW Approaches experienced two phases of Cenozoic inversion, with estimates ranging from 1300 ft (DECC, 2014) to approximately 3300 ft (Menpes & Hillis, 1995) of sediments eroded by these events. In the Melville Basin, the Triassic section is estimated to be in the main oil window at a depth of approximately 8400 ft in the 73/13-1 well (PaleoChem Ltd, 1983a) and is in the wet gas window at depths in the range of 8737-9288' in the 72/10-1 well (Cooper & Collins, 1979).

Much greater amounts of missing section have been proposed for the St Mary's Basin, although this might be a localised effect. PaleoChem Ltd (1983b) estimated approximately 6600 ft of erosion at the 86/17-1 well location; consequently sediments in the well that have reached (palaeo-) maturity for oil generation are found at present-day depths of only 2900 ft. Vitrinite reflectance of 4.52% for the Devonian-Carboniferous slate in well 83/24-1 was reported by Cooles et al. (1981) indicating the section is over-mature.

Erosion in the Channel Basin has been estimated at 3000-4000 ft from maturity gradients (Collins, 1991a; Collins, 1991b), with the top of the oil window reported at a present-day burial depth of 2200 ft in well 98/23-1 (PaleoChem Ltd, 1983c).

SOURCE ROCK POTENTIAL

Wells which have penetrated the Palaeozoic section in the SW Approaches, South Celtic Sea and English Channel area have encountered low-grade metamorphic rocks, which have no source potential. It has been suggested that this metamorphosed Palaeozoic section extends across much of the area (Evans et al., 1981; Houchen, 1991), thus limiting the likelihood of Palaeozoic-sourced plays in the region. Oil-source rock correlations have favoured a Lower Lias source for the hydrocarbon shows; no data available for this report supported a Palaeozoic source for migrant hydrocarbons in the basins within the UK AOI.

RESERVOIR POTENTIAL

The most likely reservoir for hydrocarbons generated from late Carboniferous-Permian source rocks in the AOI (UK) is the Triassic Sherwood Sandstone Group (Figure 40), as at Wytch Farm and in the Eastern Irish Sea fields. For this the regional seal would be the Mercia Mudstone Group, particularly where it contains halite (e.g. the Melville Halite). Middle Jurassic and Cretaceous sands are another reservoir possibility, where they are preserved, with a Jurassic or Cretaceous mudstone seal.

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9 Conclusions

- Late- to post- orogenic basins of Stephanian (latest Carboniferous) to Autunian (early Permian) age are developed throughout the Variscan Orogen.
- These basins are mostly half-graben resulting from the brittle extension of thickened Variscan crust, principally by extensional reactivation of Variscan ductile structures.
- The Palaeozoic play in general is underexplored in Europe.

In the central internides (e.g. the Moldanubian Zone of the Massif Central):

- Numerous Autunian basins are developed upon Stephanian basins, and having a larger area of exposure ('steershead profile') largely conceal them. They in turn are concealed by even more extensive later Permian strata (Saxonian-Thuringian).
- The most southerly basins have all Stephanian Zones (A-C) present and show no/slight discordance with the relatively thick Autunian strata.
- Basins are of variable but mostly small size (<1 to 200 km^2), variable shape and orientation.
- They are small intramontane basins deposited in areas of rugged relief, perhaps >3km.
- Rapid subsidence led to deep basin fills (up to 5 km) and thick coal-rich sequences.
- Basins are localized on earlier zones of ductile deformation related to late orogenic collapse, either shear zones formed during core complex/dome formation, or major transcurrent zones (e.g. the Sillon-Houiller).
- Potential source rocks include well-documented Stephanian coals and Autunian bituminous shales of lacustrine facies.

In the northern internides (e.g. the Saxothuringian Zone of the Armorican Massif, Paris Basin, Lorraine, and probably, the South-West Approaches):

- Stephanian basins are much less numerous, elongate and usually associated with major shear zones (e.g. the South Armorican Shear Zone) or orogenic sutures (e.g. the Rhenohercynian Suture).
- Basal sequences start later (Stephanian B-C) and Autunian strata are thin or absent.
- Stephanian-Autunian basins may be associated with earlier basins of late Visean to Namurian (and locally Westphalian) age, which postdate early (EoVariscan) collision, obduction and high-pressure metamorphism; the same ductile zones are reactivated in latest Carboniferous time.
- Basins may be small (e.g. Carentan) or large, as in Lorraine-Saar-Nahe, perhaps reflecting the scale of structural heterogeneity in the Variscan substrate, and hence the structures in the cover.
- Sedimentology suggests large regional braidplains/playa lakes within large foothill basins.
- Potential source rocks are Stephanian coal measures, although these are increasingly reddened to the north; and thin Autunian intervals of bituminous shale (e.g. Carentan).

In the northern externides (e.g. the Rhenohercynian Zone of southern Britain and Ireland, south of the Variscan Front):

- Basins rest unconformably on metamorphosed Carboniferous ('Culm facies') strata of flyschoid aspect.
- Strata of proven Stephanian age are absent; Autunian strata may be present associated with volcanic rocks (e.g. Exeter Group).
- Extensional basins with W-E trend develop in the hangingwalls of reactivated Variscan thrusts (e.g. Crediton Trough, Bristol Channel Basin).
- Source rocks might include Culm where at anomalously low maturity, away from granite intrusions (Cornubian Batholith) and zones of high heat flow (e.g. South Wales Coalfield).

In the northern foreland (e.g. central Britain and Ireland, north of the Variscan Front):

- The youngest Carboniferous strata preserved are of Westphalian D (locally perhaps Stephanian A) age, strongly affected by reddening, akin to the Westoe Formation of the southern North Sea.
- The size of such late Carboniferous basins is variable, but they are discontinuously developed as a W-E trending series of foreland basins, immediately north of the orogenic front.
- Autunian, Saxonian and Thuringian (Cisuralian) strata are absent.
- Source rocks might include bituminous coals of the Pennine Coal Measures Group away from zones of high heat flow (e.g. South Wales Coalfield).

In the southern externides and foreland (e.g. Cantabrian Zone of Iberian Massif):

- A full Stephanian (A-C) sequence locally rests upon Westphalian D (Asturian) strata.
- Basins tend to be rather small, controlled by (and caught up in) strong developing orogenic topography (3-5 km?).
- Thick Autunian sequences imply rapid local subsidence.
- A large variety of structural types is recognized: valley fills, wrench and thrust-tip basins.
- Source rocks may include Stephanian coals and thick Autunian bituminous lacustrine shales.

Source rock potential:

- Currently, the publically available geochemical datasets do not allow adequate characterization of the Autunian source potential.
- Sedimentological descriptions and other published data suggest that bituminous laminites of lacustrine origin and Type I/II kerogen potential, indicative of long-lasting,

well-drained lake basins, are found in Autunian sequences at least as far north as Carentan, in the Cotentin Penisula or Armorica.

- Large geochemical datasets are available in France but have to be purchased from IFP.
- Detailed studies suggest that some of these lakes persisted over time periods exceeding 20 ka.
- The contacts established by the project team during this brief project lead to the expectation that geochemical data will be released in the near future, in Switzerland.
- Sampling and analysis of key lacustrine sequences, e.g. in Spain and France, would rectify the present data scarcity.
- Palaeozoic sources are implicated for fields in the Lorraine-Saar-Nahe Basin; marginal to the Massif Central (Gabin); solid fuels within the Massif Central; the Entlebuch discovery; central Iberia (Puertollano); oil seeps in the Jura; and oil and gas fields in southern Germany
- Therefore sources do exist, and have generated.

Consequences for the prospectivity of late Carboniferous-early Permian strata in the South-West Approaches:

- Basins of this age developing on Saxothuringian crust, adjacent to major orogenic sutures, may have source potential.
- The distribution of such crust in the SW Approaches region is not well known, and present mapping is model-driven.
- Such basins will probably be small and localized to the immediate vicinity of orogenic suture zones, which might make them easier targets to identify on seismic data.
- The presence of one or several basins containing Autunian strata has been proven by three wells in the French and UK sectors, but no released geochemical data are available.
- The presence of large piedmont-type basins (e.g. of Saar-Nahe proportions) would probably require the development of long-lasting trans-montane corridors within the foothills (e.g. like Lake Geneva today).
- The potential source rocks would have been deeply buried beneath thick basin fills of later Permian and Triassic (and Jurassic-Cretaceous, now eroded), age.
- The presence of both Stephanian coal source/Autunian lacustrine sources (as at Carentan) is possible, at least on the southern edge of the Western Approaches Trough, founded on Saxothuringian crust.

10 Recommendations for further work

- Tabulation and analysis of geochemical data released as a result of this study.
- Sampling and geochemical analysis of key, well-documented Stephanian-Autunian sections, in northern Spain and elsewhere, to enhance the above dataset.
- Sampling and geochemical analysis of key Stephanian-Autunian sections in boreholes in France, Germany and Switzerland, to enhance the above datasets.
- Structural field studies in northern Spain and the Massif Central to understand the relationship of the basins to Variscan substrate during late- and post-orogenic collapse.
- Calibration of the structural and stratigraphic data gathered by this study to structural syntheses derived from study of the seismic reflection, gravity and magnetic potential field datasets.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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Appendix

ENCLOSURES

Plate 1 Variscan Orogen & Structure. Simplified Variscan orogenic structure. Note that large areas of granite are not depicted. The distribution of the Saxothuringian and Rhenohercynian zones beneath the Paris Basin, English Channel and SW Approaches is highly speculative. The projection used is UTM30N ED50.

Plate 2 Variscan Orogen & Structure & post-Variscan basins. Simplified Variscan orogenic structure with late Carboniferous-early Permian and (locally) Permian-Mesozoic basins superimposed. The projection used is UTM30N ED50.

Plate 3 Structure & Pennsylvanian strata north of the Variscan Front & post-Variscan basins. Late Carboniferous-early Permian and (locally) Permian-Mesozoic basins, with available borehole locations and named structures. Note that the location of the boreholes is not known with precision in many cases. For this reason, no shapefile coverage is provided of boreholes. The projection used is UTM30N ED50.

GIS AND MAPPING DATABASE

The ArcGIS project and all its coverages are in the projection UTM30N_ED1950. The following coverages are provided:

1.1.1 SWAP_Variscan_polygons_3

Simplified Variscan orogenic domains, derived from the following map sources:
Ziegler et al., (1990); Franke (1995) ; Pharaoh et al. (2006); Lardeaux et al. (2014); Ballèvre et al. (2014); Skrzypek et al. (2014) ; Schneider et al. (2014) ; Martinez Catalan et al. (2014) ; Faure et al. (2014) ; and many references therein. Note that polygons are completed to the 2000 m isobath to permit palinspastic reconstruction of the Bay of Biscay.

1.1.2 Variscan_Permian_Structure

Simplified Variscan structure (sutures, thrusts, shear zones, late-orogenic extensional faults) and post-Variscan structure (normal faults). Mapping sources as for SWAP_Variscan_polygons_3; Vetter (1986); Héry (1990); Mascle (1990).

1.1.3 Variscan_massifs_All_stipple

Outline of the Variscan massifs.

1.1.4 SPBAtlas_Fig6_4

Westphalian, Asturian and Stephanian subcrop in the southern North Sea. Mapping (Kombrink et al., 2010) from the Southern Permian Basin Atlas (Doornenbal & Stevenson, 2010).

1.1.5 SPBAtlas_Fig6_17

Coalfield information north of the Variscan Front. Mapping (Kombrink et al., 2010) from the Southern Permian Basin Atlas (Doornenbal & Stevenson, 2010).

1.1.6 Post-Variscan_basins

Polygon outlines for the late Carboniferous-early Permian basins which are the subject of this report, as well as mapped Permian-Cretaceous basins which might contain strata of late Carboniferous-early Permian age. Only such basins located south of the Variscan Front are mapped. Mapping sources as for SWAP_Variscan_polygons_3; Vetter (1986); Héry (1990); Mascle (1990).