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Notes

An integrated study of Permo-Triassic basins along the North Atlantic passive margin: implication for future exploration

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Abstract: Permo-Triassic rift basins offer important hydrocarbon targets along the Atlantic margins. Their fill is dominated by continental red beds, comprising braided fluvial, alluvial fan, aeolian, floodplain and lacustrine facies. These relatively lightly explored basins span both the Atlantic and Tethyan domains and developed above a complex basement with inherited structural fabrics. Sparse data in offshore regions constrain understanding of depositional geometries and sedimentary architecture, further impeded by their deep burial beneath younger strata, combined with the effects of later deformation during continental breakup. This paper provides results from a multidisciplinary analysis of basins along the Atlantic margin. Regional seismic and well data, combined with geochemical provenance analysis from the European North Atlantic margins, are integrated with detailed outcrop studies in Morocco and Nova Scotia. The research provides new insights into regional basin tectonostratigraphic evolution, sediment fill, and reservoir distribution, architecture and quality at a range of scales. Regional seismic profiles, supported by key well data, indicate the presence of post-orogenic collapse basins, focused narrow rifts and low-magnitude multiple extensional depocentres. Significantly, Permo-Triassic basin geometries are different and more varied than the overlying Jurassic and younger basins. Provenance analysis using Pb isotopic composition of detrital K-feldspar yields new and robust controls on the sediment dispersal patterns of Triassic sandstones in the NE Atlantic margin. The evolving sedimentary architecture is characterized by detailed sedimentological studies of key outcrops of age equivalent Permian–Triassic rifts in Morocco and Nova Scotia. The interplay of tectonics and climate is observed to influence sedimentation, which has significant implications for reservoir distribution in analogue basins. New digital outcrop techniques are providing improved reservoir models, and identification of key marker horizons and sequence boundaries offers a potential subsurface correlation tool. Future work will address source and seal distribution within the potentially petroliferous basins.

Keywords: Permian Triassic Atlantic Borderland basins, Morocco, Atlas, Fundy, continental red beds, provenance, rifting

Integrated regional study

The Late Mesozoic and Cenozoic development of basins along the Atlantic margin (Fig. 1) has been documented in a number of regional syntheses (e.g. Blystad *et al.* 1995; Doré *et al.* 1999; Naylor *et al.* 1999; Stoker *et al.* 2005). Seismic and well data from the Northern Atlantic margin show the extensive presence of Permo-Triassic strata, preserved in a suite of elongate, largely fault-bounded basins (Fig. 2). Their depositional extent and regional architecture are generally poorly constrained. This is due to overprinting of later rifting and continental breakup, together with deformation in the thick overlying Jurassic to Cenozoic strata and the effects of early Cenozoic igneous activity in the North Atlantic Igneous Province. However, the frequently sandy nature of the lower part of the Permo-Triassic succession makes it a potentially important reservoir target in petroleum exploration.

Previous studies have focused either on individual basins or plays. This study extends from Norway to Morocco (Fig. 1) and offers a broad perspective that examines the influence of regional as well as local and small-scale controls, investigating the complete spectrum of scales from regional crustal, through outcrop and to the pore scale. The aims of this paper are to (a) present initial results from an interdisciplinary basin analysis of Atlantic Margin Permo-Triassic successions and (b) illustrate how regional basin analysis, using a range of techniques and at scales through orders of magnitude from the basin to the pore throat, can provide an improved understanding of basin development and reservoir architecture, with implications for petroleum prospectivity.

Geological framework

The North Atlantic passive continental margin has a complex history, influenced by the inherited basement framework (Fig. 2). The Caledonian Orogeny, in latest Silurian to earliest Devonian times, resulted in the accretion of terranes with different crustal composition and structural fabrics (Coward 1995). Following the Variscan Orogeny in latest Carboniferous times, further structural fabrics were added to the basement of the newly formed Pangaean Supercontinent. In the region west of mid-Norway through to western Ireland, comprising the Caledonian domain, the major structures strike NE–SW to north–south. Further south in the

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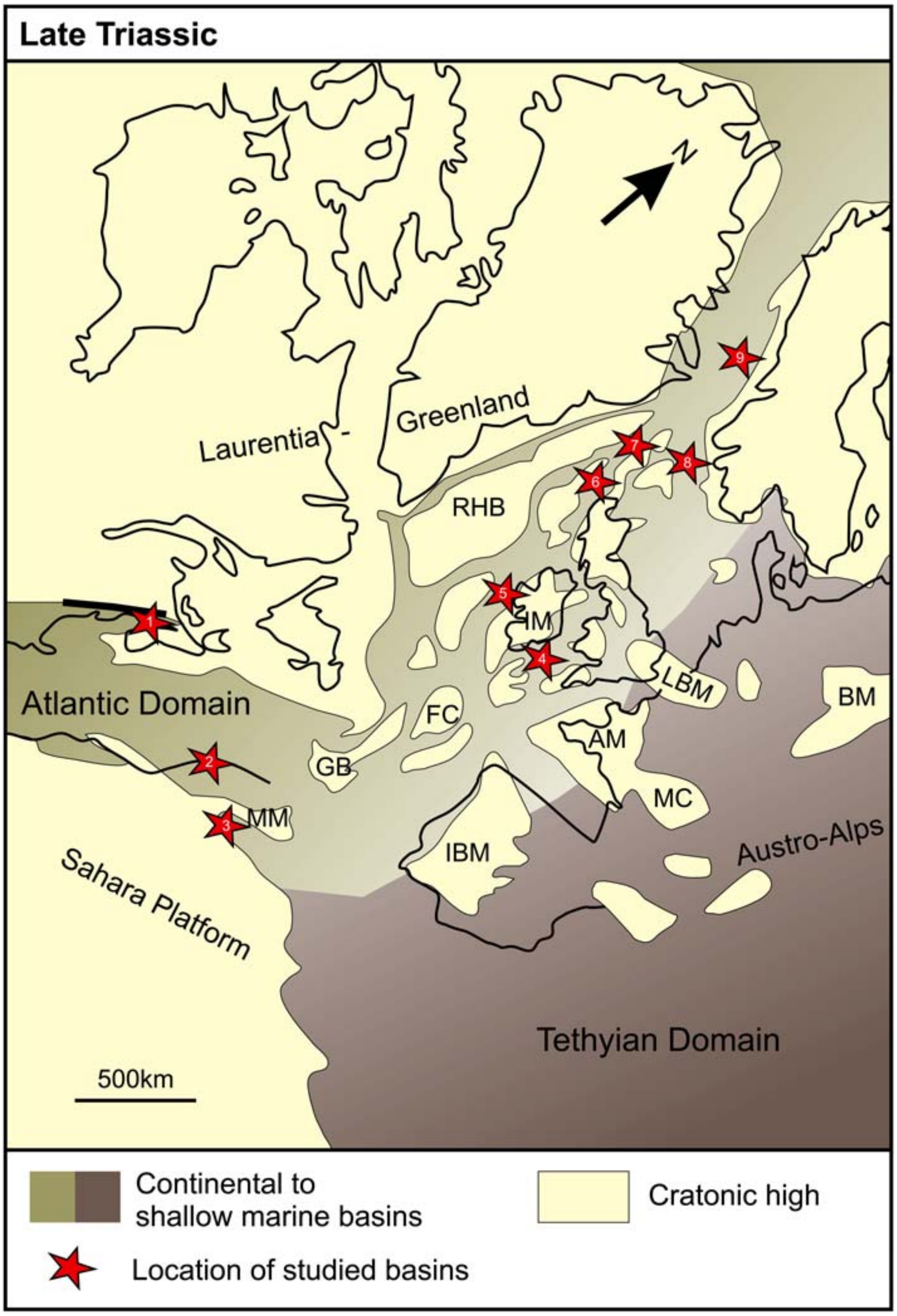

Fig. 1. Location map showing the main Permian–Triassic basins on the northern and central Atlantic borderland. Basins reviewed in this paper are denoted with numbered stars. 1, Fundy Basin; 2, Argana Basin; 3, Central High Atlas Basin; 4, Celtic Sea basins; 5, Slyne and Rockall basins; 6, Solan Bank High; 7, Magnus–East Shetland basins; 8, Horda Platform; 9, Froan Basin. MM, Moroccan Massif; IBM, Iberian Massif; FC, Flemish Cap; AM, Armorican Massif; LBM, London Brabant Massif; GB, Grand Banks; BM, Belgian Massif; MS, Massif Central; IM, Irish Massif; RHB, Rockall High Bank.

Variscan region the orientation of the structures was predominantly east–west. The inherited Caledonian and Variscan fabric provided the structural template that controlled the location, orientation and development of the Permo-Triassic basins (Naylor & Shannon 2009; Štolfová & Shannon 2009). The accreted terranes that constitute the Pangaean Supercontinent have a range of compositions and these exerted a major control on the composition of the Permo-Triassic sediments, and determined their reservoir quality. The basins examined in this study extend from the North Atlantic offshore mid-Norway, west of the major Caledonian Iapetus suture and fold belt, across the Variscan orogenic fold belt and core complex to the Moroccan basins of the central Atlantic. They also include outcrop studies from the conjugate margin basins of offshore Canada (Nova Scotia).

Structural style and evolution: regional seismic analysis

The shapes of the preserved remnant Permo-Triassic basins of the Atlantic margin show a clear association with the underlying structural fabrics (Doré *et al.* 1999). West of Norway, the UK and western Ireland basins developed in a broadly NE–SW to north–south belt, parallel to the Caledonian domain. Further south, basin orientation is dominated by an east–west trend parallel to the Variscan structures, with a similar trend documented in the region of the Innuitian fold belt north of Greenland.

The basins west of mid-Norway, exemplified by the Froan Basin on the Trøndelag Platform (Fig. 3) contain several kilometres of Permo-Triassic strata and the basins are often controlled by eastward-dipping master growth faults. The overall basin trend

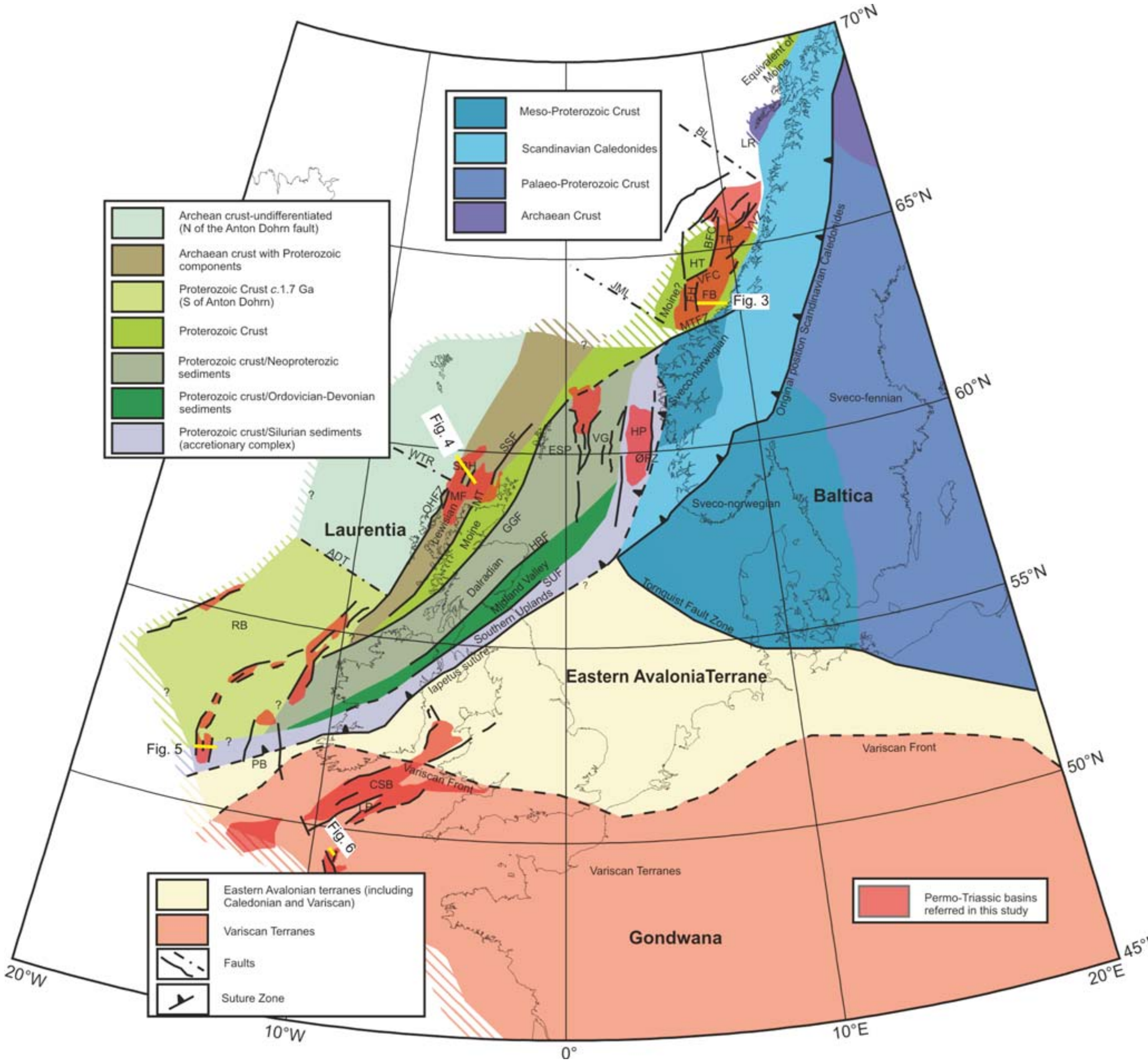

Fig. 2. Simplified structural and terrane map of the Northwest European Atlantic margin. Superimposed on this is the location of the various Permo-Triassic basins involved in the present study. The location of Figures 3–6 is also shown. Abbreviations: ADT, Anton Dohrn Transfer; BFC, Bremstein Fault Complex; BL, Bivrost Lineament; CSB, Celtic Sea basins; ESP, East Shetland Platform; FB, Froan Basin; FH, Frøya High; GGF, Great Glen Fault; HBF, Highland Boundary Fault; HP, Horda Platform; HT, Halten Terrace; JML, Jan Mayen Lineament; LP, Labadie Bank–Pembrokeshire Ridge; LR, Lofoten Ridge; MF, Minch Fault; MTFZ, Møre, Trøndelag Fault Zone; MT, Moine Thrust; ØFZ, Øygarden Fault Zone; OHFZ, Outer Hebrides Fault Zone; PB, Porcupine Basin; RB, Rockall Basin; SBH, Solan Bank High; SSF, Shetland Spine Fault; SUF, Southern Upland Fault; TP, Trøndelag Platform; VFC, Vingleia Fault Complex; VG, Viking Graben; WTR, Wyville–Thompson Ridge; YVZ, Ylvingen Fault Zone. Dashed areas represent uncertain terrane occurrence or boundary. From Štolfová & Shannon (2009).

appears to be influenced by a Caledonian structural fabric (e.g. the Ylvingen Fault Zone). However, no evidence is seen of direct reactivation of individual major Caledonian thrust structures. The basins are therefore interpreted as the product of narrow 'classical' rifting (McKenzie 1978; Buck *et al.* 1999).

The Permo-Triassic basins immediately west of the UK show similar pronounced half-graben geometries. The North Minch Basin is interpreted as having developed by strain localization in a narrow rift system, with a slight northwestward migration of strain through time resulting in the progressive movement of active fault systems (Štolfová & Shannon 2009). In the Magnus Basin, where the Permo-Triassic is preserved in a series of rotated fault blocks, initial palaeotopographic infill was followed by late Triassic and younger growth faulting, which also has the characteristic geometry of a narrow rift system (Štolfová & Shannon 2009).

In a number of areas a series of small, Permo-Triassic half-graben basins are controlled directly by growth faults developed along pre-existing Caledonian structures. The West Orkney Basin is probably associated with reactivation along the Caledonian and Precambrian Moine Thrust and Outer Hebrides Fault Zone complex. The Slyne and Erris basins west of Ireland (Naylor *et al.* 1999) and the Magnus Basin NE of Shetlands lie close to the projected offshore extensions of the Great Glen Fault complex, a major strike-slip Caledonian fault system that was reactivated initially in Devonian times and later in Permo-Triassic times.

The Solan Bank High, an elongate fault-bounded basement block running along a Caledonian structural fabric, acted as a barrier to

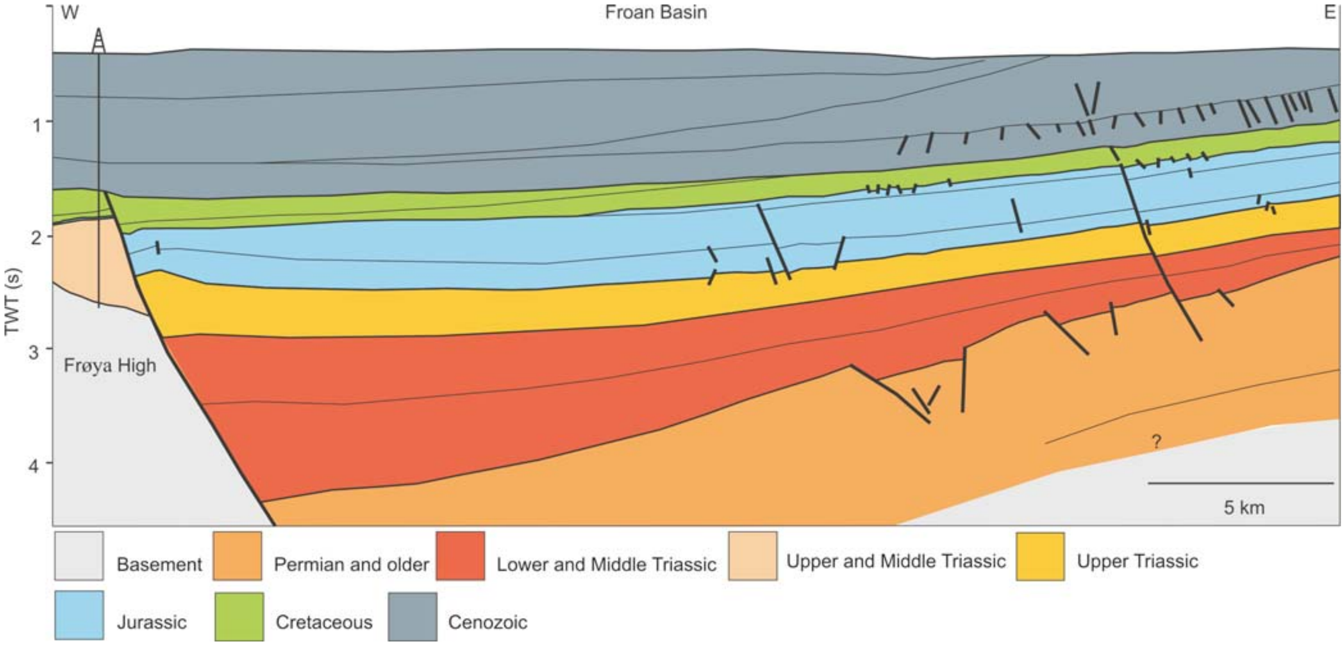

Fig. 3. Geoseismic profile across the Froan Basin showing typical half-graben geometry characteristic of a narrow 'classical' rift. The thick Permo-Triassic succession is subdivided into three seismic packages indicating different structural styles and demonstrating clear growth faulting, especially in the central, second package.

westward progression of the narrow rift system that fringed the west coast of Scotland. To the east, the basins are typical narrow rifts while the large basin to the west has a different style, with thick uniform sediments showing no evidence of major growth faulting, albeit modified and eroded by later tectonism (Fig. 4).

This pattern of uniformly thick sediments, with subtle fault-controlled thickness variations, is seen in much of the Irish Atlantic margin region. This is interpreted to represent wide rift basin development resulting from strain delocalization and lateral migration of the locus of extension (Buck *et al.* 1999; Buiter *et al.* 2008). Wide rift zones, often composed of multiple low-magnitude rifts, are predicted to develop in regions of higher than normal heat flow with relatively thick crust (Buck 1991; Hopper & Buck 1996). The margins of the Irish Rockall Basin exhibit uniformly thick interpreted Permo-Triassic successions, with subtly different internal stratigraphy between adjacent basins, inset by younger faults as a string of north–south trending 'perched' basins (Fig. 5). The overall interpretation is wide basin extension producing a broad region of Permo-Triassic deposition.

The Triassic successions over much of the Celtic Sea region, south of Ireland, are characterized by uniform sediment thickness across wide areas. Subtle internal wedging of individual seismic packages occurs, with fault polarity changes, but the overall succession is not markedly asymmetric. A wide rift basin system above the Variscan basement domain is suggested. Inferred Permian strata lie unconformably beneath the Triassic succession in small, isolated half-grabens with common syn-sedimentary wedging (Fig. 6). These probably developed in response to post-orogenic collapse of thickened, hot Variscan crust. Similar features are observed in the outcrop study of the marginal Moroccan basins.

The overall Permo-Triassic succession in the European North Atlantic margin region thickens northwards from the Celtic Sea region offshore Ireland to the mid-Norwegian basins. In most basins distinct seismic sequences can be identified, reflecting different phases of early post-Pangaean rift development. While these can be mapped through individual basins, correlation between the various basins is only tentative at this stage due largely to limited well control. Nonetheless, regional patterns can be recognized. Permian strata are only locally developed in the south but have a significant thickness in the northern basins. In the south (e.g. Celtic Sea region) interpreted Permian strata occur within small, fault-controlled half-graben basins that are hinged by extensionally reactivated Variscan structures. These are interpreted as early Variscan collapse intermontane basins. Further

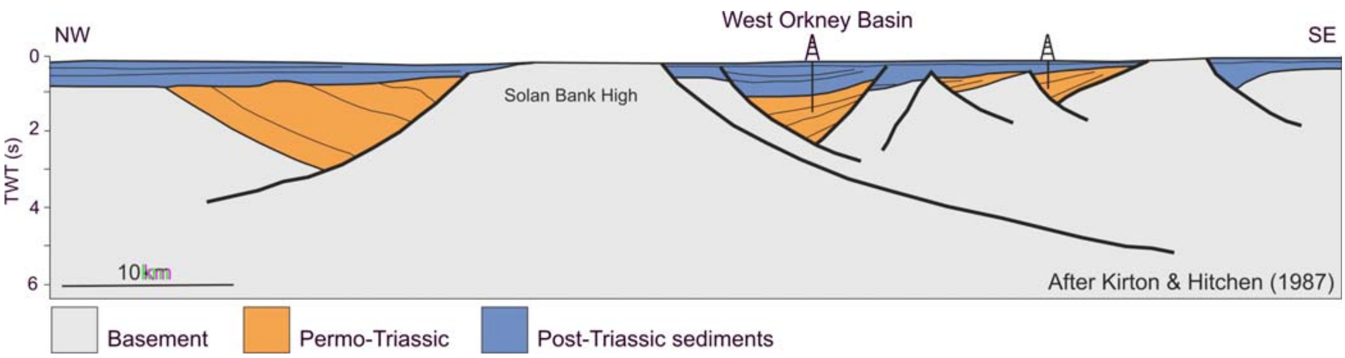

Fig. 4. Geoseismic profile across the Solan Bank High. The basement high compartmentalized the rifting style, with a series of narrow rift half-grabens developed to the SE while the remnants of an eroded and tilted wide-rift system occurs to the NW. This lacks evidence of major growth faulting and probably had a more extensive thick, uniform depositional geometry.

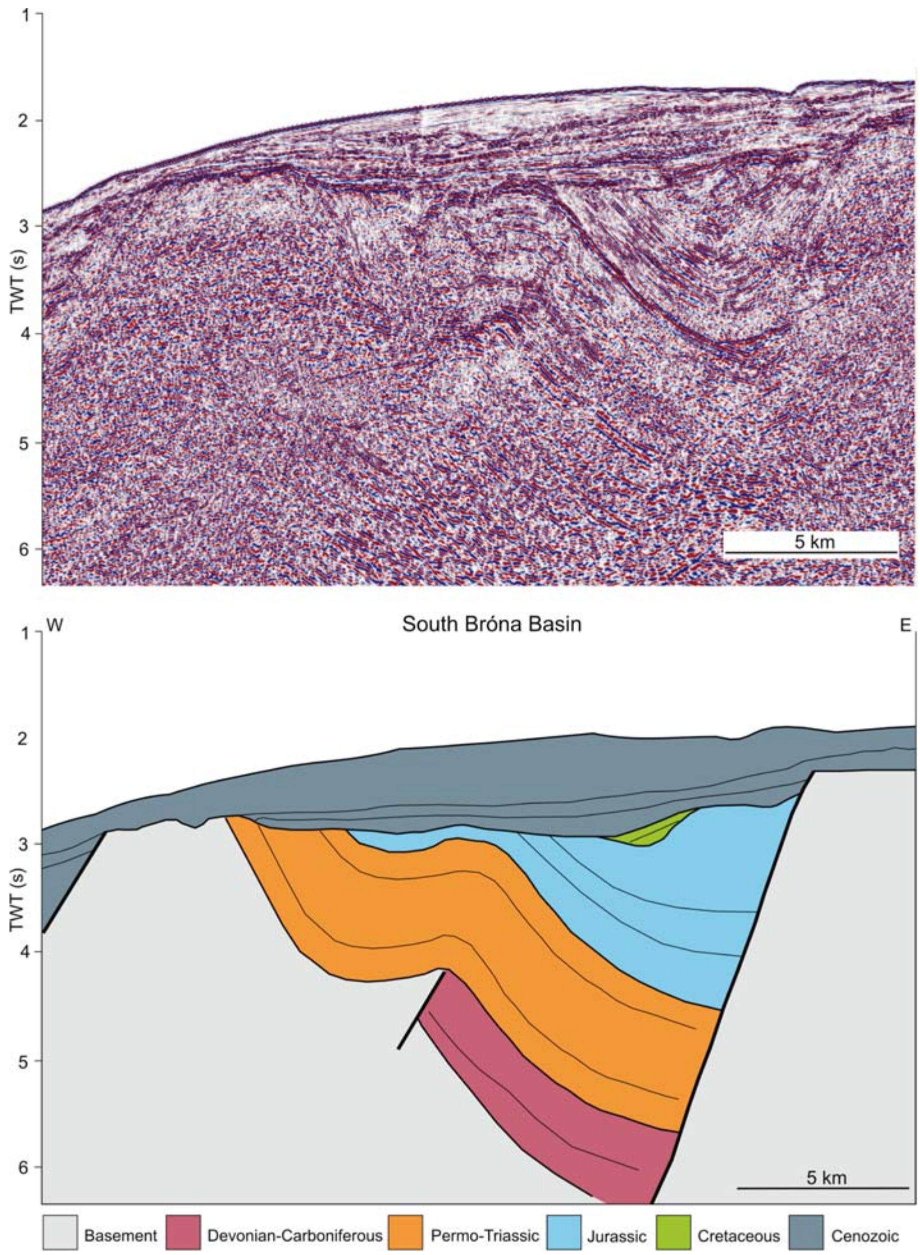

Fig. 5. Seismic profile and geoseismic profile across the South Bróna Basin on the SE flank of the large Rockall Basin. The preserved basin, incised by later faulting and erosion, had a larger depositional extent as evidenced by the absence of any evidence of thickness variations towards the bounding fault to the east or the basement block to the west. It is interpreted as an example of a wide-rift basin.

north, as typified by the Slyne Basin, basins NW of Scotland, and the Froan Basin on the Trøndelag Platform, the Permian succession is significantly thicker. The thin succession resting unconformably upon the interpreted Permian strata in the south of the region is suggested to be of Late Triassic age, while in the Norwegian region a complete Triassic succession is commonly proven by well data. This suggests that rifting commenced in the Norwegian region in Permian times, synchronous with intermontane localized Variscan collapse basins further south. Regional Triassic sedimentation did not take place in the south until later in the Triassic, when deposition was of regional extent, with wide rift processes dominating in this region.

Structural style/evolution: evidence from outcrop: Morocco

The Permo-Triassic Central High Atlas and Argana basins in Morocco (Fig. 7) are 100 km apart, separated by the Palaeozoic and Pre-Cambrian rocks of the 'Massif Ancien'. The exceptional exposures provide information on contrasting structural style, and the geodynamic response to North Atlantic and Tethyan tectonics. The basin types are similar to those documented from regional seismic, and outcrop analysis provides an analogue study to detail the fault geometries and impact of tectonics on local sedimentation and reservoir development. The outcrop evidence builds upon the regional picture and elucidates in more detail the semi-regional to reservoir scale tectonostratigraphic features of the successions.

The Oukaimeden–Ourika Valley, part of the broader Central High Atlas Basin, comprises an ENE-elongated rift basin bounded by extensionally reactivated Variscan structures. Although the present-day outcrop pattern reflects inversion due to the Alpine compression that led to major uplift in the High Atlas and subsequent erosion, it is possible to reconstruct the basin's earlier structural history. Both the ENE–WSW and NNE–SSW striking sets of normal faults show evidence for syn-sedimentary

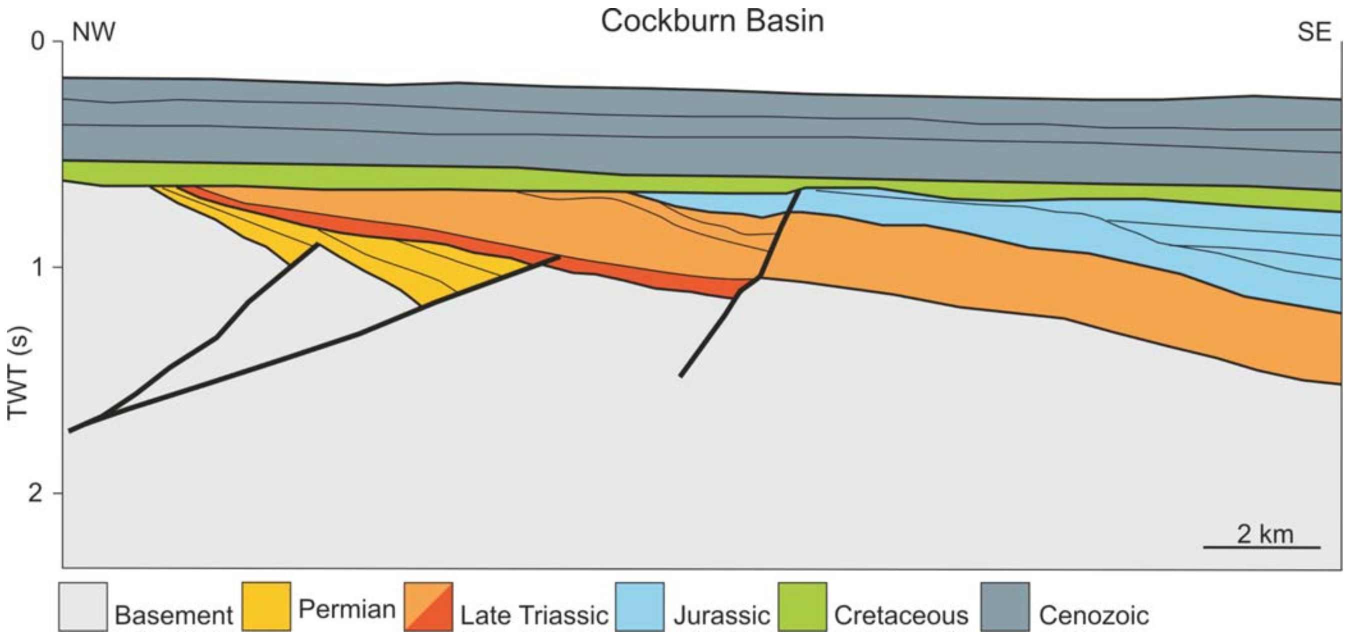

Fig. 6. Geoseismic profile from the Cockburn Basin. Interpreted Permian strata are developed in small half-graben controlled by early extensional collapse of the thick Variscan crust along reactivated thrusts. These sediments are unconformably overlain by late Triassic strata showing as relatively uniform, with subtle thickness variations, interpreted as the product of wide-rift extension. The planar nature of the unconformity, with no evidence of residual topography, suggests a significant hiatus between the two sedimentary sequences.

movement, displaying stratigraphic thickening into growth faults and associated progressive change in dip of the bedding (Fig. 8). The ENE–WSW faults are deep rooted and controlled the geographical extent of the basin, providing the accommodation for sediment deposition within a typical narrow half-graben basin geometry following NW–SE extension during the Late Triassic. The direction of extension is nearly parallel to the dip on NE to NNE striking faults, illustrated by striations. ENE trending structures display left-lateral movement, with a strong normal component.

Close to the bounding fault the main sandstone units have a higher net to gross ratio (N:G), consistent with a tectonic control on reservoir development. Increased accommodation on the downthrown side of the main faults resulted in river capture, and detailed sedimentary logging (Fabuel-Perez & Redfern 2009) shows that the main fluvial system flowed parallel to the controlling faults. More mudstone-rich overbank deposits become the dominant facies as the section thins away from the main fault-controlled depocentres (Fig. 8). The presence of thick locally derived conglomerates adjacent to the main bounding faults, with palaeocurrents oblique to the dominant axial trends for the main fluvial system (Figs 7 & 8), record alluvial fans derived from erosion of the main fault scarp during tectonic activity (Fabuel-Perez & Redfern 2009).

Smaller NE to NNE oriented faults are interpreted to be contemporaneous to the main fault set and are compatible with NW–SE extension. However, these faults have a small throw and are interpreted to have a limited influence on sediment deposition.

The second area of study in the Argana Basin, on the western margin of the High Atlas, contains exceptionally exposed Permian and Triassic red beds. This is the SE extension of the Essaouira Basin (Fig. 7). Permian and Upper Triassic beds strike approximately parallel to the NNE trend of the valley and dip 5–30° towards the NW. The Upper Permian sediments consist predominantly of conglomerates interpreted to be deposited within alluvial fans, grading vertically and laterally into sandstones deposited in fluvial channels and as floodplain deposits. A major unconformity separates the Permian from the overlying Upper Triassic sediments that mainly consist of siltstones and mudstones deposited in floodplain or playa environments, alternating with coarse alluvial conglomerates and continental fluvial or aeolian sandstones (Tixeront 1973; Brown 1980; Mader 2005).

Several models have been proposed to explain the structural evolution of the basin and the structural control on sedimentation (Tixeront 1973; Brown 1980; Medina 1988, 1991; Hofmann *et al.* 2000). Episodic movement of east–west trending fault blocks tilted towards the north was initially suggested to control the deposition of the whole Permo-Triassic sequence (Brown 1980). Other studies recognized two main phases of syn-sedimentary extension characterized by the two sets of normal-faults, striking east–west and NE to NNE (Laville & Petit 1984; Medina 1988, 1991, 1995). Both these interpretations attribute the evolution of Mesozoic basins in the High Atlas of Morocco to pull-apart extensional mechanism along the ENE–WSW trending fractures (Manspeizer 1982; Laville & Petit 1984).

Recently analysed field data as part of this study are modifying this interpretation. It is suggested that the large east–west striking-faults do not significantly influence Triassic deposition. The thick Permian conglomerates, deposited as large alluvial fans, were sourced mainly from the uplifted Ancien Massif (Baudon *et al.* 2009). These conglomeratic units are cut by, but not sourced from, the east–west faults. The Upper Permian sequence was tilted towards the NW prior to Upper Triassic sedimentation producing a marked angular inconformity. Upper Triassic sedimentation in the Argana Valley does not show significant lateral variation in thickness or facies, which suggests the east–west and smaller NNE trending normal faults were not significantly active. The main basin-bounding fault is speculated to be a sub-surface extensional fault located to the west of the valley, now masked by later Jurassic and Cretaceous cover. This is parallel to faults producing similar half-graben structures identified further NW in the Essaouira Basin (Hafid 2000; Le Roy & Pique 2001). This fault probably controlled the regional tilt of the beds. In contrast to the Ourika Basin, deposition in the Argana Basin is interpreted to have been part of the much broader Essaouira Basin, with limited local fault control on sedimentation. This pattern of uniformly thick sediments, with subtle fault-controlled thickness variations, is comparable to that observed in the seismic study from the North Atlantic,

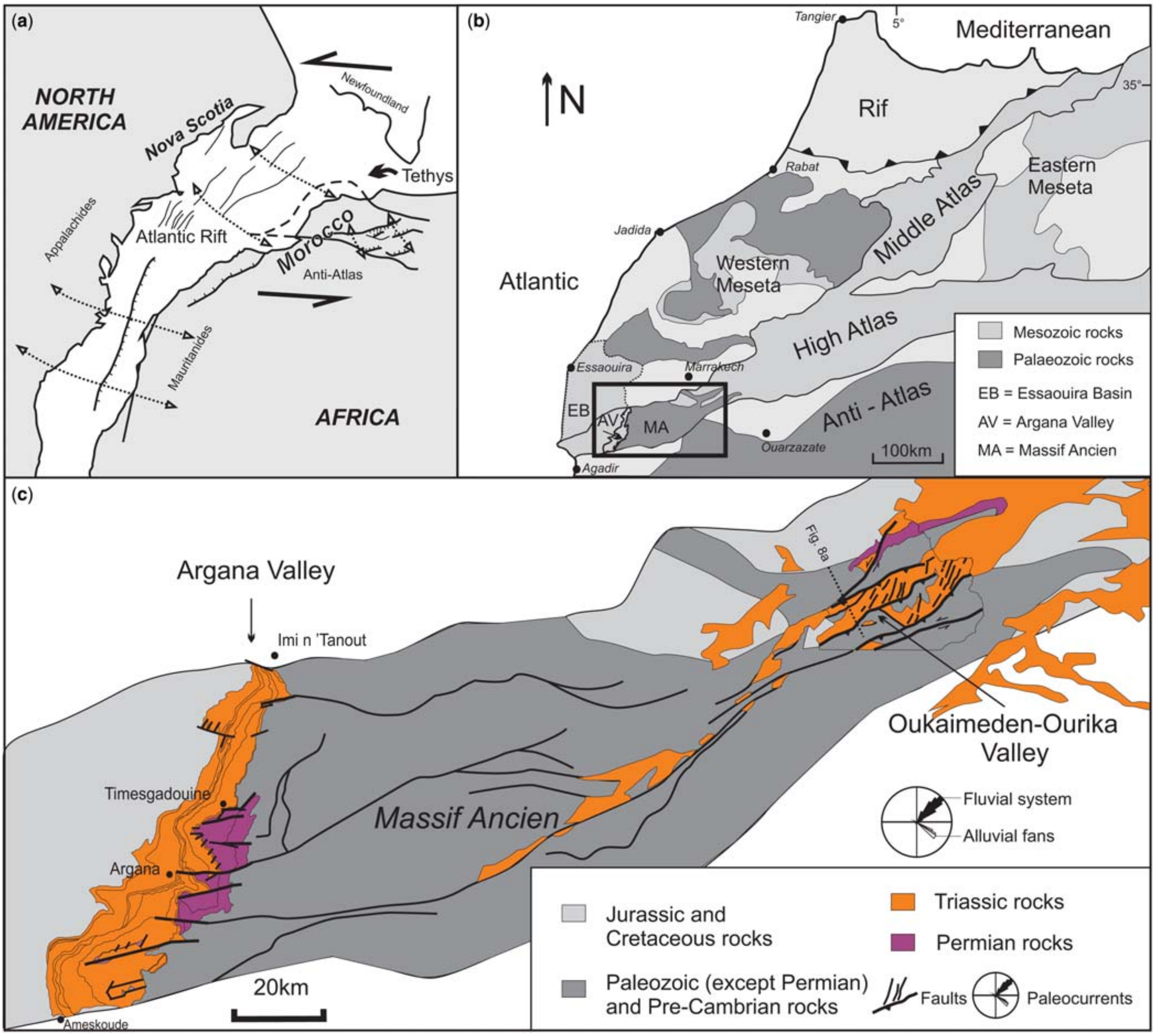

Fig. 7. (**a**) Palaeogeographic map of Morocco at Triassic time (modified from Laville & Piqué 1991). (**b**) Present-day structure summary map of Morocco (modified from Ellouz *et al.* 2003). The box denotes the location of the study area. (**c**) Close-up of study area showing the main structures. The Permian and Triassic outcrops in the Oukaimeden–Ourika Valley (modified after Taj-Eddine & Pignone 2005) and Argana Valley (modified after Tixeront 1973) are highlighted with respect to the Massif Ancien. Palaeocurrents in the Ourika Valley for the F5 Unit from Fabuel-Perez & Redfern (2009).

suggesting this Moroccan section provides a good outcrop analogue for subsurface exploration in the Atlantic borderland area.

Provenance studies: tracking Triassic sand dispersal on the NW European margin

The Moroccan outcrops described in the previous section illustrate the interplay of tectonics and sedimentation at regional and local scale and the resulting complexity of the depositional system. To better understand reservoir sand dispersal within such complex systems a novel provenance tool was utilized as part of the integrated analysis, illustrated by results from the Atlantic Margin basins west of Ireland and the UK.

Recent studies have demonstrated the utility of the Pb isotopic composition of detrital K-feldspar as a sand provenance tool, particularly when applied on a regional scale (Tyrrell *et al.* 2006, 2007; Clift *et al.* 2008). Common Pb isotopes vary in the crust on a sub-orogenic scale and it has been shown that detrital K-feldspar can retain the signature of its source despite erosion, transport and diagenesis (Tyrrell *et al.* 2006). The Pb isotopic signature of individual K-feldspar sand grains can be analysed *in situ* using laser ablation multicollector inductively-coupled plasma mass spectrometry (LA-MC-ICPMS). Imaging prior to analysis highlights heterogeneities which then can be avoided during laser ablation. The use of ion counters to measure Pb ion beams means that data can be retrieved at a spatial resolution (*c.* 20 μm laser spot sizes) similar to that achievable using ion microprobe techniques but with reduced analytical uncertainty (Tyrrell *et al.* 2009).

One of the major advantages of the Pb K-feldspar tool is that, in contrast to provenance approaches that utilize signals in robust grains (e.g. U–Pb zircon), it provides a means of assessing first-cycle sand-grain provenance. As detrital K-feldspar is unlikely to survive more than one sedimentary cycle, these grains can be tracked back directly to their basement source, allowing the scale and geometry of the drainage system to be constrained. These types of insights can aid in more accurate prediction of reservoir sandstone distribution and quality in the subsurface.

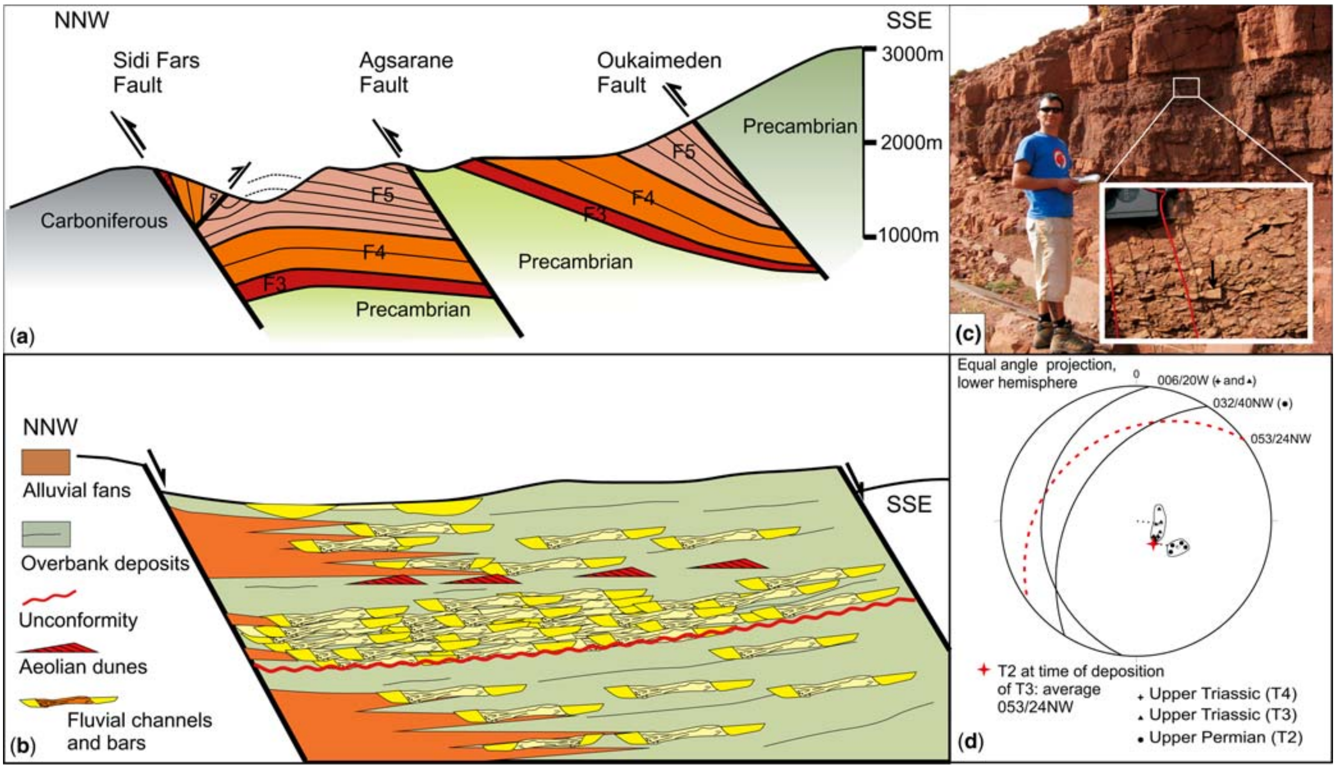

Fig. 8. (**a**) Structural cross-section across the Oukaimeden Valley showing the main ENE striking faults. Location of cross-section shows on Figure 6*c*. (**b**) Schematic model of the structural control on sedimentation, showing alluvial fans shed from the footwall highs, and the axial river system preferentially captured close to the main fault. (**c**) Photograph of the alluvial fan breccias, with close up of clasts. (**d**) Stereonet plot illustrating the angular unconformity between the Permian and Triassic bedding in the Argana Valley.

The Pb K-feldspar provenance tool is particularly appropriate in an investigation of Triassic sand dispersal in the NE Atlantic margin basins, given the abundance of arkosic and sub-arkosic sandstones in these successions. Recently published provenance data have shed new light on the nature and origin of these sandstones. Data from K-feldspar from Lower Triassic sandstones in the Slyne Basin (including the Corrib Gasfield), offshore west of Ireland, define two distinct Pb populations (Fig. 9), which are likely to have been sourced from Archaean and Proterozoic crust to the north and west (Tyrrell *et al.* 2007; McKie & Williams 2009).

Pb K-feldspar data from Permo-Triassic sandstones in the Rockall Basin (Dooish gas condensate discovery, Well 12/2-1z; Fig. 9) appear to have been derived from the north and NE, probably from elements of the Lewisian Complex (Fig. 9; Tyrrell *et al.* 2010). In basins west of Shetland (Fig. 9), new Pb K-feldspar data (Fig. 10; McKie & Williams 2009; Tyrrell *et al.* 2009) from Middle–Upper Triassic Foula Formation sandstones (part of the Strathmore Field) indicate derivation from Archaean– Palaeoproterozoic rocks on the margins of the rift basin (Nagssugtoqidian Mobile Belt of East Greenland and/or the Lewisian Complex of NW Scotland and equivalents), although whether the derivation is from the east- or west-rift margins, or from a northern axial source, cannot be distinguished. Here, the Pb K-feldspar data are in broad agreement with U–Pb detrital zircon geochronology (Morton *et al.* 2007).

The Pb K-feldspar data from Atlantic margin basins consistently preclude Irish Massif, the UK Mainland south of the Moine Thrust and the remnant Variscan Uplands to the far south as sources for Triassic sand (Fig. 10). This indicates no linkage between the drainage systems supplying these Atlantic margin basins and those delivering sand to onshore UK, the East Irish Sea Basin and the Central and Southern North Sea. The sedimentary contribution of non-radiogenic Archaean and Palaeoproterozoic Pb sources appears to increase in basins further to the north. The data indicate that palaeodrainage evolution in these marginal Triassic basins was strongly influenced by uplifted Archaean–Palaeoproterozoic basement highs, and not Variscan Uplands to the south, with consequent implications for potential reservoir sandstone distribution in these areas (e.g. Tyrrell *et al.* 2010). These studies reveal the value and effectiveness of the Pb K-feldspar provenance tool in investigations of both ancient and modern broad-scale drainage systems.

Developing analogue depositional and reservoir models

Building upon the work defining the basin architecture and provenance, detailed sedimentological analysis is improving our understanding of basin development, basin-scale depositional systems and producing analogue reservoir models. Correlations within the Central Atlantic domain have been attempted by Olsen (1997) and Olsen *et al.* (2000) from the Fundy Basin to Morocco. This is based on limited biostratigraphic data and often poorly defined unconformities. Because of the low resolution of biostratigraphy with red bed deposits, the only synchronous marker beds that can confidently be picked are the radiometrically dated CAMP basalt and the palynological turnover of the Rhaetian/Jurassic boundary located a few metres below the basalt. Biostratigraphical correlations across the Triassic basins of Morocco have been assessed recently by El Arabi *et al.* (2006) while the biostratigraphy in the Fundy Basin is still relatively poorly constrained. The stratigraphy from the Fundy Basin, Canada and the Argana and Central High Atlas basins in Morocco is compared in Figure 11. Triassic rift basins along the Central and North Atlantic margins display a similar sedimentary evolution characterized by an initial phase of

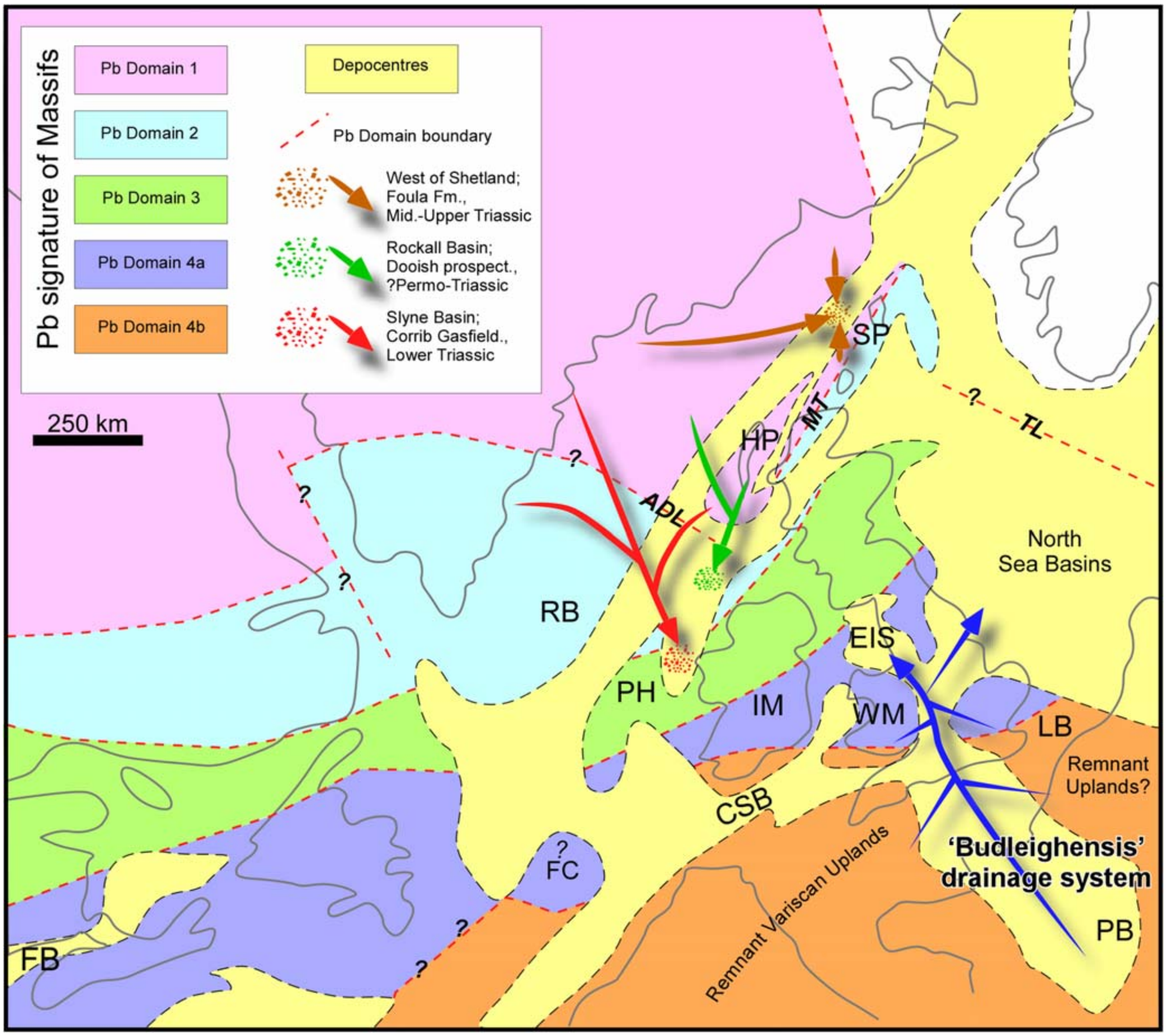

Fig. 9. Schematic Triassic palaeogeographic reconstruction of the circum-North Atlantic region (after Torsvik *et al.* 2001; Eide 2002; Scotese 2002) showing the configuration of massifs and depocentres. The massifs are colour-coded to reflect their broad Pb isotopic signature (after Tyrrell *et al.* 2007 and references therein). The 'Budleighensis' drainage system is also shown (blue). Directional arrows (red, green, brown) show likely derivation directions for sandstones from the marginal basins, based on the Pb isotopic composition of individual K-feldspar sand grains. ADL, Anton Dorhn Lineament; CSB, Celtic Sea basins; EIS, East Irish Sea Basin; FB, Fundy Basin; FC, Flemish Cap; HP, Hebridean Platform; IM, Irish Massif; LB, London–Brabant Massif; MT, Moine Thrust; PB, Paris Basin; PH, Porcupine High; RB, Rockall Bank; SP, Shetlands Platform; TL, Tornqvist Line; WM, Welsh Massif.

alluvial fan and fluvial sedimentation and a later playa/lacustrine dominated phase. Although the sedimentological evolution of these basins is similar, the timing and duration of the phases of fluvial and playa deposition vary within and between the basins. In order to understand the basin-fill evolution, and in particular the depositional systems, the sedimentology of two broadly co-eval Permo-Triassic basins is reviewed in this paper: the Minas Basin (Nova Scotia) and the Central High Atlas Basin (Morocco). These formed at different palaeolatitudes and now lie on different sides of the Atlantic passive margin.

In the Fundy Basin, detailed analysis of laterally extensive coastal outcrops allows definition of basin-scale sedimentary architecture and assessment of basin development. A comparable Moroccan section provides equally extensive sections, offering another analogue for the subsurface basins, and using innovative LiDaR (Laser Detection and Ranging) analysis, detailed sedimentary and reservoir models have been produced (Fabuel-Perez *et al.* 2009).

Fundy Basin, Nova Scotia, Canada

The Fundy Basin, one of a series of early Mesozoic rift basins developed along the NW Atlantic margin, contains 6–12 km of Anisian to basal Hettangian non-marine clastic sediments (Olsen *et al.* 1989; Wade *et al.* 1996; Leleu *et al.* 2009). It represents a large complex Triassic half-graben (Wade *et al.* 1996) with a strike-slip component of movement (Olsen & Schlische 1990; Withjack *et al.* 1995, 2009) and is subdivided into three sub-basins; amongst them the easternmost Minas sub-basin shows the most extensive outcrops and preservation of sequences (Fig. 12).

The Triassic succession in the Minas sub-basin comprises the Wolfville (<800 m) and the overlying Blomidon (<250 m) formations (Fig. 12). The Wolfville Formation is Carnian in age (Olsen *et al.* 1989), and lies unconformably on Carboniferous and older rocks, forming the earliest syn-rift unit in the basin (Wade *et al.* 1996). The Wolfville Formation comprises coarse- and fine-grained fluvial sandstones (Klein 1962; Hubert & Forlenza 1988;

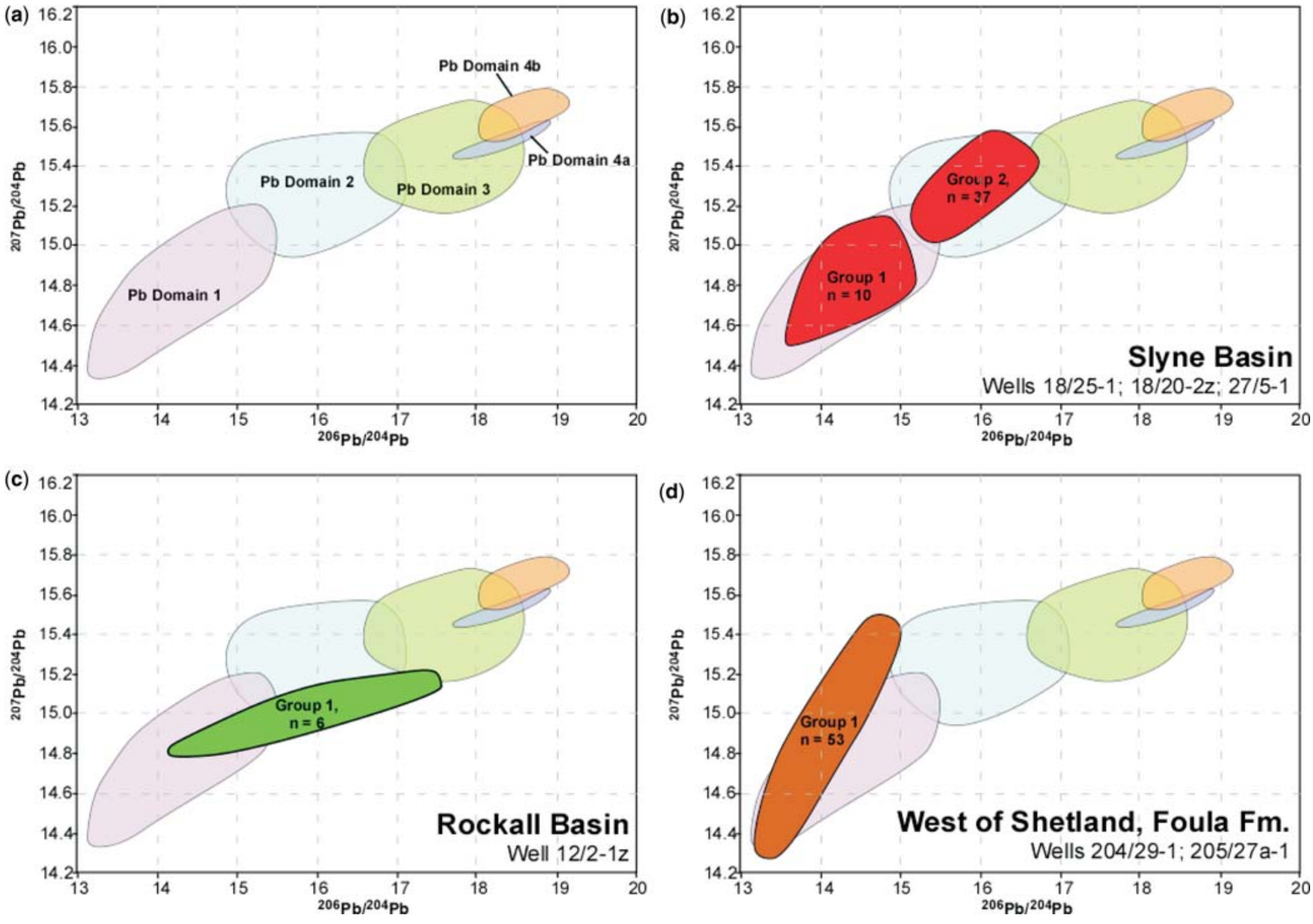

Fig. 10. Plot of $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ lead space (after Tyrrell *et al.* 2007 and references therein) illustrating (**a**) the isotopic composition of Pb basement domains in the circum-North Atlantic (Fig. 8); (**b**) the Pb isotopic range of K-feldspar from Lower Triassic sandstones in the Slyne Basin; (**c**) the Pb isotopic range of K-feldspar from Permo-Triassic sandstones in the Rockall Basin (Dooish gas condensate discovery); (**d**) the Pb isotopic range of K-feldspar in Foula Formation sandstones from basins west of Shetland.

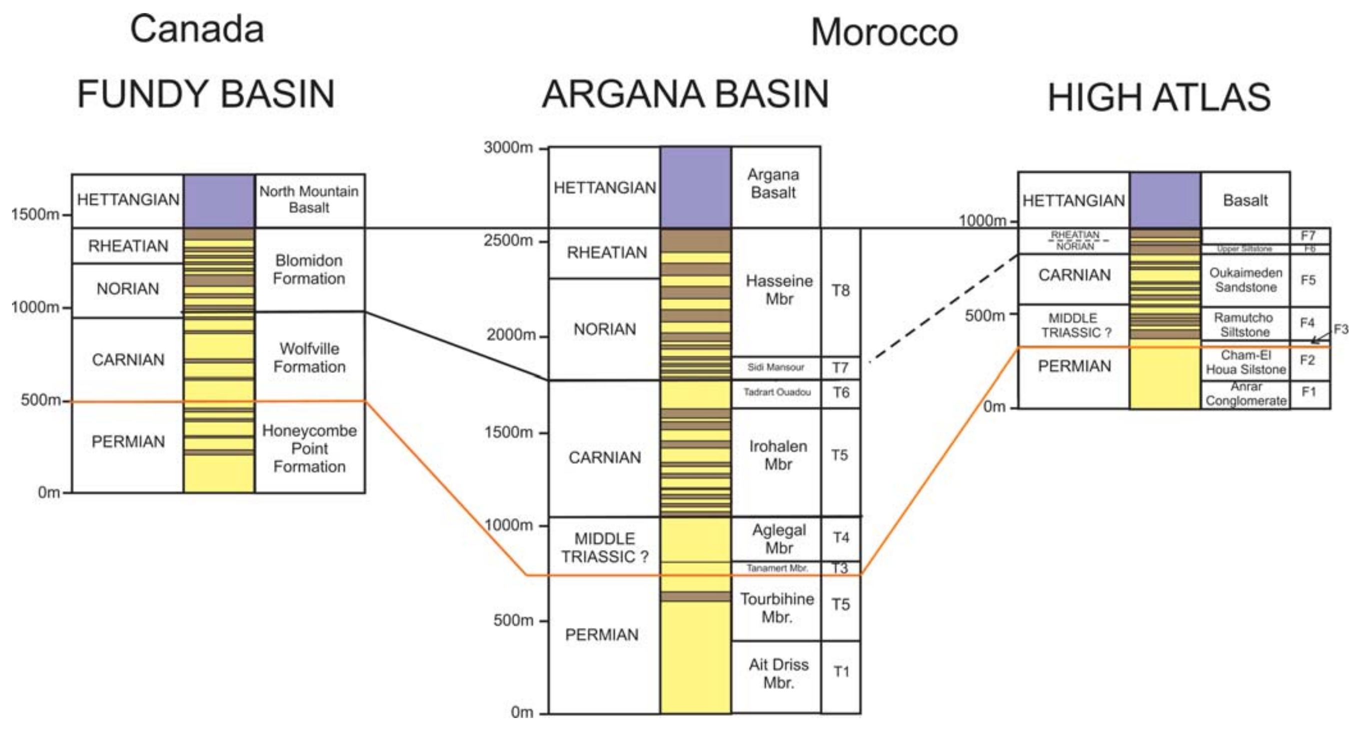

Fig. 11. Simplified stratigraphy comparing the Permian and Triassic sections in the Fundy Basin, Nova Scotia, and the Argana and Central High Atlas basins in Morocco. Modified from Olsen *et al.* (2000).

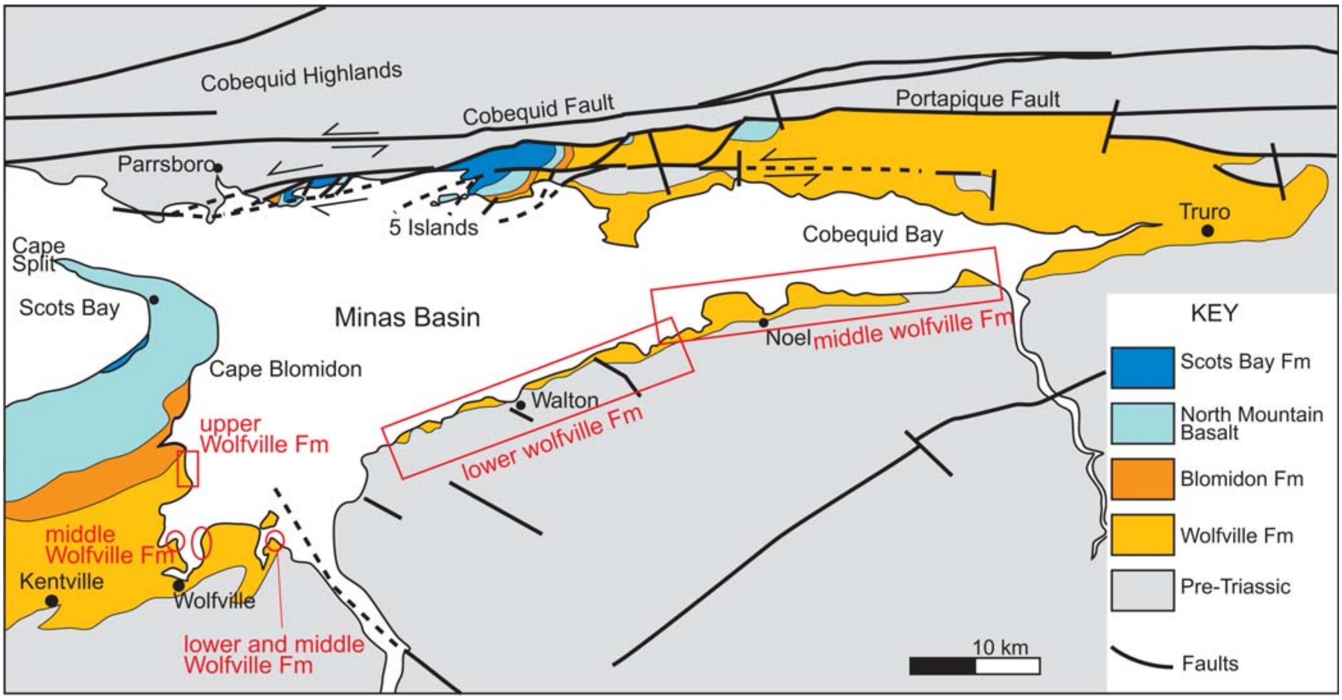

Fig. 12. Location of the Minas Basin in Nova Scotia, Canada, showing the studied Triassic outcrops.

Leleu *et al.* 2009) and subordinate aeolian dune deposits (Hubert & Mertz 1980, 1984) and alluvial fan sediments (Hubert & Mertz 1984). The contact between the formations corresponds to a major change in facies architecture to mud-rich playa margin deposits containing evaporites and ephemeral fluvial sheet-sandstones (Hubert & Hyde 1982; Mertz & Hubert 1990; Gould 2001). The extensive North Mountain Basalt, part of the Central Atlantic Magmatic Province event (McHone 2000), overlies the Blomidon Formation, and straddles the Triassic–Jurassic boundary (Olsen *et al.* 1989; Olsen 1997).

Within the Wolfville fluvial succession three distinguishable packages with very different characteristics of grain size and stacking patterns have been observed. The lower Wolfville Formation (110 m thick) is dominated by coarse-grained fluvial deposits (Fig. 12) which filled remnant palaeotopography. It comprises four mega-units and 13 smaller scale high-resolution fining-upwards cycles of pebbly conglomerates to sandstones (Fig. 13). The bounding surfaces can be correlated regionally over a distance of between 10 and 27 km (Leleu *et al.* 2009), thereby providing effective basin-scale stratigraphic correlation. The overall succession has a sheet-like geometry comprising stacked, erosion-dominated, multi-storey channel bodies with a drainage system that evolves to the north and NE. An individual high-resolution cycle records braid-plain development and is interpreted as a multi-storey channel belt. However, the width of the active channel belt is unknown. Recognition of key surfaces across a 10–20 km section (Fig. 14), provides criteria for correlation of these continental facies, barren of biostratigraphic markers (Leleu *et al.* 2009).

The middle Wolfville Formation abruptly overlies the lower Wolfville Formation (Fig. 12). It is a well sorted sandy bedload fluvial system (< 350 m thick) and consists of 15 repetitive units. These comprise stacked channel bodies forming channel belt complexes that are intercalated with upward thickening floodplain deposits. Application of LiDaR digital outcrop analysis aids the definition of detailed architecture (van Lanen *et al.* 2009). Large-scale sequences have been defined based on grain size evolution that encompasses several channel belt complexes. The grain size variation reveals a climatic control which influences the bedload transport capacity of the river, while smaller scale repetitive channels and channel belt migration/avulsion possibly result from autocyclic processes. The larger scale architectural evolution including the development of the channel belt architecture, channel body dimensions and the increased upwards preservation of greater floodplain units result from allocyclic processes which may reflect a tectonic control producing increased accommodation.

The upper Wolfville Formation (240 m thick) occurs beneath the lacustrine/playa deposits of the Blomidon Formation (Fig. 12). It displays repetitive packages of channelized and unconfined fluvial facies and playa deposits together with occasional aeolian dune deposits. Grain size varies from pebbly coarse sand and medium to coarse sand in the channelized facies to well sorted medium to fine sand in the unconfined facies and aeolian deposits. Development of the playa margin environment in the basin during Blomidon Formation deposition records retrogradation of the fluvial profile within the drainage basin, and the extension of the playa and playa margin towards the catchment. Retrogradation suggests a major decrease in water and sediment supply. This major shift could be interpreted as the result of climate change. However, although all Triassic basins along the Atlantic margins show a similar sedimentological evolution from fluvial to playa depositional phases, the transition occurs at different times and with variable duration. This suggests that basin development governs the large-scale basin-fill and the shift from fluvial to playa depositional phase (Schlische & Olsen 1990; Smoot 1991). In particular, because the transition from fluvial to playa/lacustrine conditions takes place at different times, it indicates that climate may not be the critical controlling factor. The transition is interpreted to be associated with a progressive decrease in source area relief related to a decline in fault-generated topography towards the end of the syn-rift phase of basin development.

The Central High Atlas Basin, Morocco

Previous work in Morocco (Petit & Beauchamp 1986; Mattis 1977; Benaouiss *et al.* 1996; Tourani *et al.* 2000) provided an overview

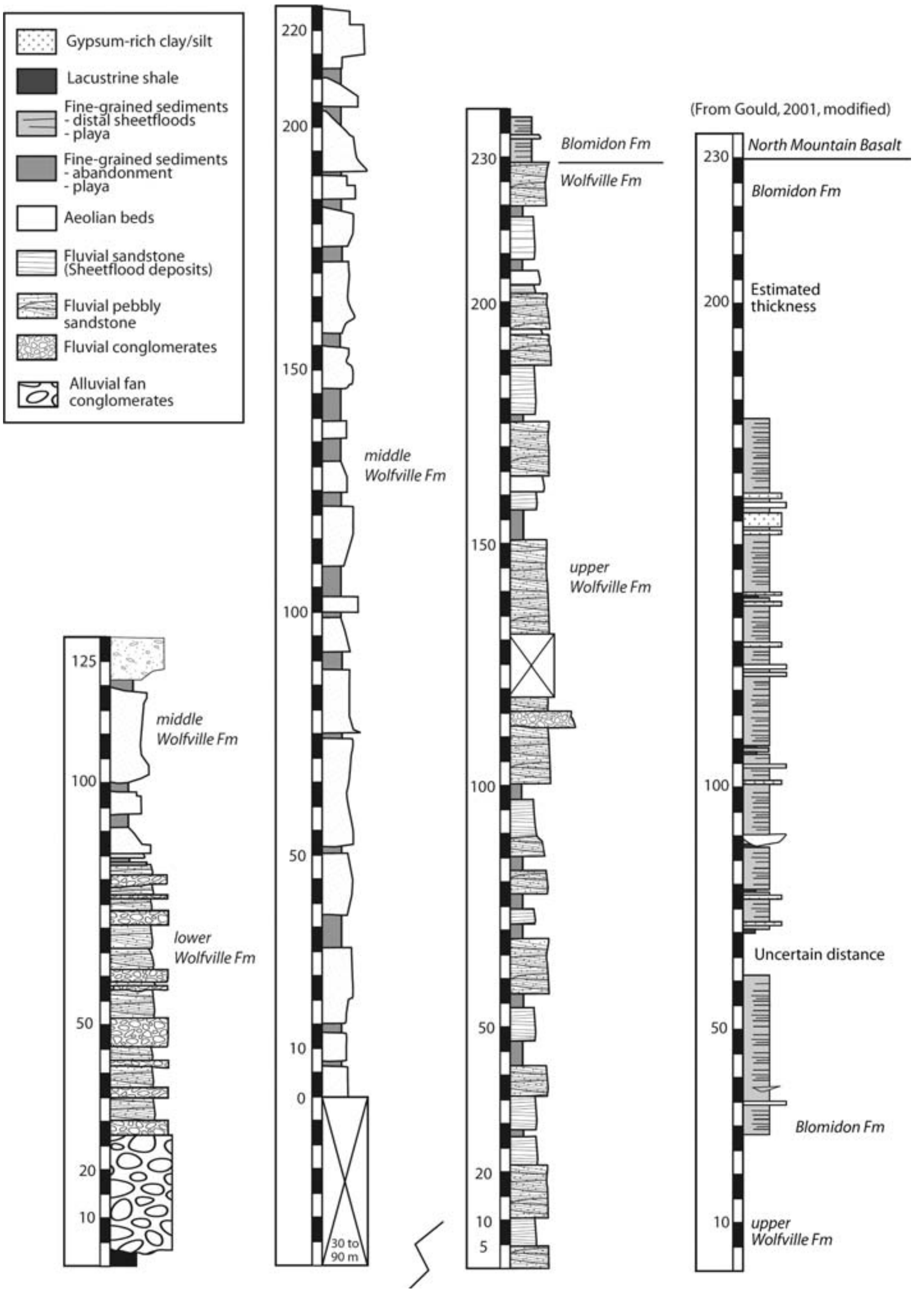

Fig. 13. Two summary sedimentary logs through the Triassic succession in the Minas sub-basin comprising the Wolfville (<800 m) and the overlying Blomidon (<250 m) formations. The Wolfville Formation is Carnian in age (Olsen *et al.* 1989), and lies unconformably on Carboniferous and older rocks.

of the broad depositional setting and stratigraphy for the Permian and Triassic section in the Central High Atlas (Fig. 11). Fabuel-Perez & Redfern (2009), as part of this research project, recently revised the sedimentological interpretation of the Oukaimeden Sandstone Formation in the Oukaimeden–Ourika valley area (Fig. 7). Detailed sedimentary models were produced using LiDaR for digital outcrop analysis, and a reservoir model was developed (Fabuel-Perez & Redfern 2009; Fabuel-Perez *et al.* 2009).

Within the Oukaimeden Sandstone Formation five major facies associations have been identified (Fig. 15). Changes in the distribution of facies associations, identification of key boundaries, surfaces and variation in the architectural style through time have been used to subdivide the Oukaimeden Sandstone Formation into three major members (Fig. 15): (a) a lower member comprising channels and bars (Facies Association 1) alternating with floodplain mudstone units (Facies Association 2); (b) a middle member, characterized by vertically stacked amalgamated channels and bars and a significant decrease in the amount of preserved mudstone units; and (c) an upper member showing a similar style to the one observed in the lower member with the first occurrence of aeolian facies (Facies Association 3) and tidally influenced sandstones (Facies Association 4).

Using a process-based depositional facies model based on genetically related packages (Fabuel-Perez & Redfern 2009), the Lower Oukaimeden Member is interpreted to record deposition from large axial ephemeral river systems. The Middle Oukaimeden displays a change in depositional style to perennial fluvial conditions. This is interpreted to record the rejuvenation of the fluvial regime related to a change in climate to more humid conditions and subsequent increased run-off. The Upper Oukaimeden is interpreted to record a change in fluvial conditions from perennial back to ephemeral combined with the presence of aeolian dunes (Facies Association 3) which reflect climatic variations shifting

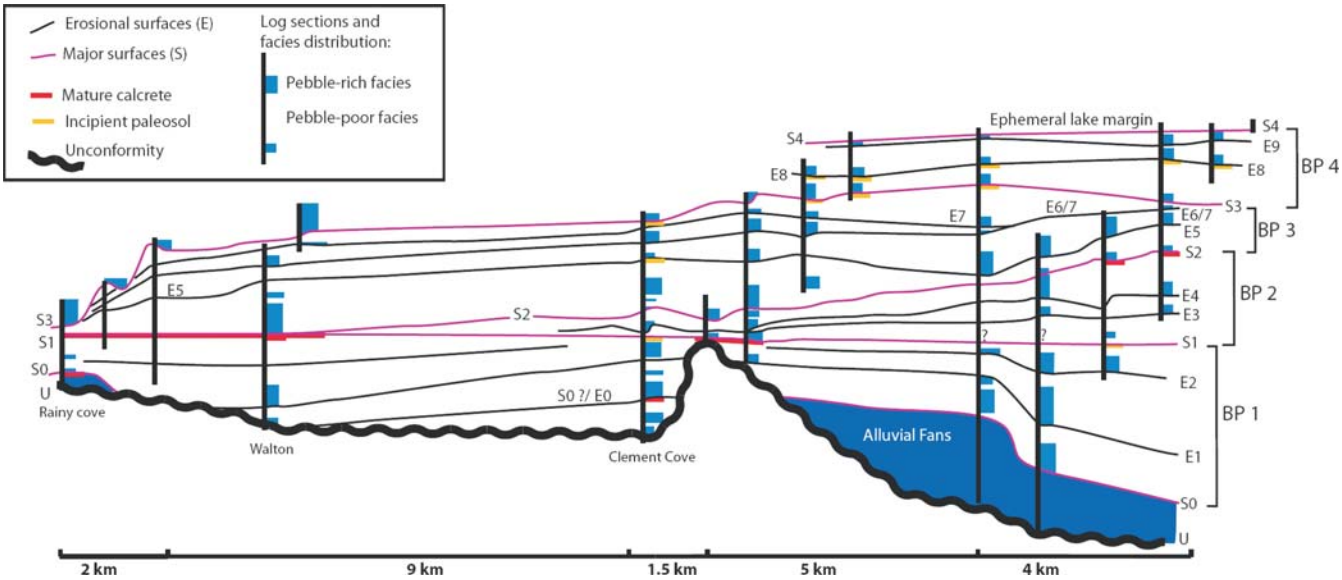

Fig. 14. Summary correlation of the lower Wolfville Formation (110 m thick). It comprises multi-storey channel bodies arranged as four mega-units bounded by ‘S’ surfaces and 13 smaller scale high-resolution fining-upwards cycles of pebbly conglomerate to sandstone, bounded by ‘E’ (or ‘S’) surfaces which can be correlated regionally between 10 and 27 km (Leleu *et al.* 2009).

towards more arid conditions. The top of the Oukaimeden Sandstone is characterized by the presence of tidally influenced facies recording the first marine incursion into the basin.

In the lower and upper member, alluvial fans were deposited in response to footwall uplift erosion of the controlling Sidi Fars fault. These alluvial fans, which pinchout towards the SW, are interpreted to force the axial rivers away from the controlling fault. The lack of alluvial fan deposits in the middle member could be due to ‘toe cutting’ of the alluvial fan by the axial rivers due to their increased size and switch to perennial conditions of the river system as a consequence of a climatic change (Leeder & Mack 2001).

Evidence is seen of a tectonic control on deposition and changes in architectural style. Preferred orientation of palaeocurrents in Facies Association 1 is towards the ENE. This is interpreted to be related to the palaeogeography of the basin (ENE–WSW orientated), which was tectonically controlled by the orientation of the syn-sedimentary Sidi Fars fault. Alluvial fans have a preferred palaeocurrent orientation towards the SE, normal to the ENE–WSW orientation of the Sidi Fars fault, indicating a sediment source from the uplifted footwall. N:G ratio decreases away from the fault, indicative of capture of the axial river system close in the depocentre. The morphology of the contacts also varies with distance from the controlling fault, with a sharp erosive contact

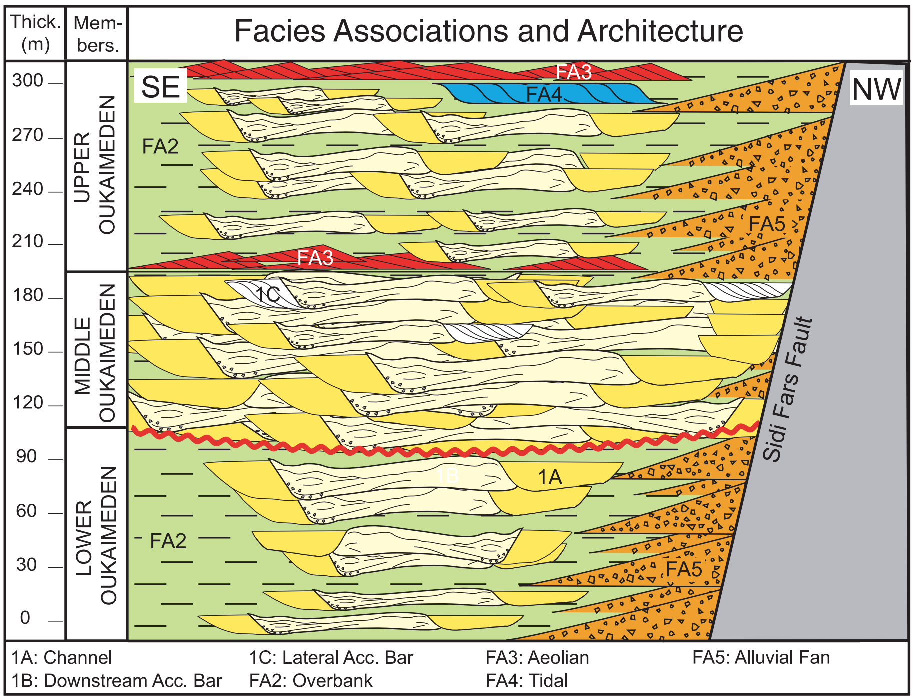

Fig. 15. Composite log summarizing the gross distribution of facies associations in the Ouikamaiden Sandstone, key surfaces used to define the three members and the changing architectural style through time.

near the fault due to successive erosional events by downcutting channels, and more gradation contact on the basin margin.

The sections in Morocco record both the tectonic and climatic influence on depositional architecture and reservoir distribution. The contact between Lower and Middle Oukaimeden is interpreted to record possible tectonic reactivation in the hinterland magnified by a concurrent change in climate towards more humid conditions. Increasing run-off and input of coarse sediment into the basin produced a change in architectural style, and a switch from ephemeral to perennial conditions. In the Upper Oukaimeden, a return to ephemeral conditions, combined with the presence of aeolian facies, suggests a climatic change back towards more arid conditions. Similar gross facies shifts, also interpreted as a response to climatic change, are observed in the Argana Basin. Improved dating and more detailed correlation are required to corroborate these as regionally correlatable events.

Conclusions

(1) An improved understanding of basin and sedimentary evolution, provided by multidisciplinary analysis, is illustrated by this regional study of the Atlantic margin Permo-Triassic basins. This addresses basin and outcrop to pore scales, across three orders of magnitude. Regional seismic scale allows analysis of a number of structurally linked basins, imaging the large-scale structure, in order to understand overall basin architecture and identify mega-sequences. Outcrop analysis provides ground-truth information to refine the seismic-scale structural interpretations and the resolution to model reservoir architecture at sequence scale, with definition of depositional systems and key correlation surfaces. Provenance analysis has the potential to test regional structural models and predict source to sink fairways, improving reservoir characterization by identifying provenance sources and sediment transport directions.

(2) A range of basin geometries are identified in the Permo-Triassic Atlantic margin basins, using both seismic (offshore, NE Atlantic) and outcrop (onshore, Morocco) studies. These include post-orogenic collapse basins, focused narrow rifts and wide, low-magnitude multiple extension depocentres. The shape and evolution of the basins were influenced by both Atlantic and Tethyan tectonic regimes, with significant control from inherited basement structures and structural fabrics.

(3) The basin fill, characterized in detail by examining the onshore Permo-Triassic outcrops in both Morocco and Nova Scotia, is dominated by continental red beds. They comprise braided fluvial, alluvial fan, aeolian, floodplain and lacustrine facies, and display a cyclicity in fluvial deposits from major ephemeral to perennial fluvial systems. Detailed outcrop analysis has identified key marker horizons and sequence boundaries that can be used to provide constraints for the delineation of laterally correlatable cycles. The depositional architecture at high-resolution outcrop scale is complex, controlled by the interplay of local and regional tectonic and climatic factors, as well as autocyclic processes. At basin scale, sedimentation records climatic changes, but the low-resolution basin fill evolution is mainly controlled by tectonically induced basin development. This has implications for reservoir distribution and quality on a regional and field scale.

(4) Application of a new Pb in K-feldspar provenance technique to determine the source of Triassic sandstones offers new and robust controls on sediment dispersal patterns in the North Atlantic. Results indicate that the regional palaeodrainage evolution of the basins was predominantly controlled by uplifted Archaean–Palaeoproterozoic basement highs to the north and NW and not, as hitherto assumed, by the Variscan uplands to the south. In addition to providing information on likely reservoir quality, the technique also has applications as a test for the robustness of large-scale structural basin tectonics and timing.

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