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Converting time-temperature modelling into exhumation rates, eroded material fluxes and source-and-sink maps: A semi-quantitative analysis of vertical movements in Morocco and surroundings

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Abstract

This study presents data on the rates of the vertical movements, as documented with time-Temperature (t-T) modelling. All available t-T modelling published results have been digitized and a temperature-to-depth conversion applied. However, t-T modelling studies using the produced low-temperature thermochronology ages as inputs failed to reconstruct a unique time-constrained geological history for the Central Atlantic syn- and post-rift phase at the scale of the Moroccan passive margin. Indeed, modelling results from different publications sometimes show opposite vertical movements in identical areas for the same time interval. To overcome this, a rigorous quality control and discrimination of the data had to be undertaken and applied to the t-T curve dataset based on several conditions. The exhumation and subsidence rates were then used as input for interpolation at the country scale, in order to quantify the volume of rocks that were eroded during the several exhumation episodes.

The results predict high denudation rates, comparable to values typical of rift flank, domal or structural uplifts, in the Anti-Atlas (0.1 km/Myr) during the Early to Middle Jurassic and in the High Atlas (0.1 km/Myr) and Rif (up to 0.5 km/Myr) during the Neogene. During other periods, exhumation rates in the Meseta, High-Atlas, Anti-Atlas, and Reguibat shield are around 0.04±0.02 km/Myr.

Estimates of cumulative eroded volumes from Permian onwards are between ca. 15×10^5 and 2×10^5 km^3 (in the Reguibat Shield and Meseta, respectively). Periods of high rates of denudation in the investigated source areas include the Permian, the Jurassic, the Early Cretaceous (Berriasian to Barremian), and the Neogene.

Ten erosional (quantitative) and depositional (qualitative) “source and sink” maps have been constructed, covering the period between the Variscan Orogeny and the Present-Day (Permian to Neogene). Emphasis is placed on the Jurassic and Cretaceous periods. The maps are based on the

extent of exhumed domains (first part of this study), the integration of data from new geological fieldwork, outcrop spatial distribution, lithofacies from onshore and offshore basin, biostratigraphic data, well data, palaeogeography and depositional environment maps, provenance analysis and calculated exhumation rates. The results illustrate changes in the Permian to Neogene source-to-sink systems and allow for the analysis of the dynamic nature of their components.

We observe several shifts in sedimentary source areas through the investigated period, notably from the Anti-Atlas to the Meseta occurring at the end of the Middle Jurassic and from the Meseta to the Anti-Atlas in the late Early Cretaceous.

Keywords

Time-temperature modelling, Morocco, vertical movements, paleo-reconstruction, exhumation rates

1. Introduction

Source-to-sink studies encompass the investigation of the exhumation history of the hinterland ('source'), the spatial distribution of fluvial and coastal deposits ('to'), and the architecture of continental traps, shallow and deep marine depocenters ('sink'; e.g. Allen, 2008; Sømme et al., 2009; Helland-Hansen et al., 2016). Analyses of this kind take into account geological surface processes, such as erosion, transportation, and deposition. Underlying mechanisms for the onset of source-to-sink systems are controlled by tectonic, eustatic, and/or climatic changes (e.g. Wells et al., 2017). The availability of robust sedimentary, stratigraphic, geochronology, provenance, palaeontology, Low-Temperature Thermochronology (LTT), and numerical analyses allows integration to improve source-to-sink models (e.g. Helland-Hansen et al., 2016).

Source-to-sink studies have limitations, depending on, for instance, the spatial and temporal resolutions of each component, or simply on the existence and quality of the sedimentary record. Moreover, such studies can be done on different temporal scales (sedimentary pulses of annual duration, glacial/non-glacial cycles in kyr, exhumation in Myr, etc…). The creation of relief in the hinterland has sometimes been disregarded (see Helland-Hansen et al., 2016), despite the fact that the vertical motion rate, exposure period, extent, and the erodibility of the source areas are major parameters that significantly impact the sedimentary record in basins.

Continental passive margins and their hinterlands, especially in the Atlantic realm (fig. **1**), are the locus of a significant amount of studies that evidence pre-, syn-, and post-rift episodic km-scale upward (i.e. exhumation) and downward (i.e. subsidence) movements (e.g. Green et al., 2018). Pre-rift exhumation episodes are recorded in the vicinity of the future Atlantic Ocean (e.g. Juez-Larre and Andriessen, 2006; Ruiz et al., 2011; Jelinek et al., 2014; Japsen et al., 2016a). Syn-rift exhumation episodes have been described in the Atlantic rift flanks (e.g. Oukassou et al., 2013; Jelinek et al., 2014;

Wildman et al., 2015; Japsen et al., 2016a, Charton et al., 2018), while syn-rift subsidence episodes in the unstretched continental crust have been documented in fewer places (e.g. Juez-Larre and Andriessen, 2006; Ghorbal et al., 2008). Post-rift km-scale vertical movements have been documented along the North (e.g. Japsen et al., 2006; Japsen et al., 2016a;b), Central (e.g. Frizon de Lamotte et al., 2009; Bertotti and Gouiza, 2012; Amidon et al., 2016) and South (e.g. Jelinek et al., 2014; Wildman et al., 2015) Atlantic margins.

Bertotti and Gouiza (2012) proposed, in the eastern margin of the Central Atlantic, that anomalous vertical movements in the exhuming domain are concurrent to excessive downward movements in the subsiding domain. Exhumation and subsidence episodes occur in regions characterised by both stretched and non-stretched lithosphere, demonstrating that processes other than rifting are at work, or that the effects of the rifting and drifting extend beyond the rifted margin. Several authors have qualitatively tested aspects of these vertical movements with numerical models (e.g. Leroy et al., 2008; Gouiza, 2011; Cloetingh and Burov, 2011; Yamato et al., 2013). However, to better constrain the models, a quantification of these movements over geological time and, more importantly, at the scale of the margin, is required.

Vast regions along Atlantic rifted continental margins are characterised by the exposure of pre-rift rocks (e.g. in Norway, Canada, Greenland, Morocco, Mauritania, Brazil…). There, LTT and time-Temperature (t-T) modelling techniques provided understanding of the thermal history, as this is especially valuable for geologically ill-constrained areas characterised by no or little sedimentary cover (e.g. Gallagher et al., 1998; Ghorbal et al., 2008; Japsen et al., 2009; Teixell et al., 2009; Japsen et al., 2012b; Jelinek et al., 2014). These techniques are commonly selected as proxies to reconstruct vertical movements (e.g. Teixell et al., 2009). Because the LTT ages record the cooling of rock samples, they are linked either to thermal relaxation and/or exhumation (also called denudation; e.g. Pagel et al., 2014). Hence, LTT ages are recorded after magmatic events, during/after processes linked to the creation of topography (e.g. orogenies, shoulder uplift, thermal doming), and/or during processes leading to enhanced erosion (e.g. climatic and sea level changes).

LTT has been used in many regions around the globe, resulting in very dense data sets where not fully constrained mechanisms have generated a variety of landscapes such as elevated continental passive margins (e.g. Japsen et al., 2012a), the Himalaya and Alps mountains. Over thirty LTT and time-Temperature (t-T) modelling published studies have been conducted in Morocco and its surroundings. There, the large majority of the derived LTT ages span the period between the Variscan and Atlas orogenies (ca. 300-40 Ma). These cooling ages were interpreted as resulting from vertical movements, and have sometimes been labelled as km-scale “unexpected” exhumation and “unpredicted” subsidence episodes, with the mechanism to generate this movement remaining enigmatic to-date (e.g. Ghorbal et al., 2008). As a prerequisite to constrain the responsible mechanism(s), vertical movements rates are to be investigate.

Sediment fluxes may be quantified by calculating the amount of deposited sediments in the sink, the erosion rate in the source, or using other techniques that investigate the paleo-drainage system (e.g. Wold and Hay, 1990; Gallagher et al., 1998; Barnes and Heins, 2008; Matenco et al., 2013). Understanding sediment budgets and pathways are crucial for hydrocarbon exploration, to predict reservoir presence and quality and map potential play fairways.

The objectives of this paper are 1) to submit a simple workflow that quantifies eroded material fluxes from basement areas investigated by LTT/t-T studies, 2) to assess the extent of source and sink domains, 3) to provide insights into the post-Variscan paleogeographic evolution of Morocco and its surroundings, and 4) characterise the evolution of sediment delivery pathways and estimate the volume of delivery through time.

This study should be considered as a first framework for future studies investigating source-to-sink systems, creating an opportunity for definition and quantification of sediments pathways and fluxes along the entire Moroccan rifted margin and into the interior of its adjacent continental crust. The aim of these maps is not to precisely define the paleo-drainage systems, as the resolution of our datasets is in all cases too coarse, but to illustrate the dynamic nature of the source-to-sink systems and of their components during the Phanerozoic post-orogenic, syn-rift and post-rift phases.

2. Summary geological history of Morocco

The Central Atlantic continental margins extend from Morocco to Guinea in the east and Canada to the USA to the west (fig. 1; Davison, 2005; Withjack and Schlische, 2005). Morocco is located in Northwest Africa between the Central Atlantic oceanic crust, the West African Craton, and the Atlas orogenic system. The relief (fig. 2A) varies from high mountainous regions (Rif and Atlas belts), elevated plains (Hauts Plateaux and Ouarzazate Basin), high massifs (Central Massif, Rehamna, Jebilets, Massif Ancient, Anti-Atlas, Reguibat Shield, and Ougarta), non-elevated coastal plains (Meseta, Souss Basin, Tarfaya Basin, and Dakhla Basin), and the Saharan domain marked by ergs and sabkhas (salt flats).

The geological history of Morocco (fig. 2B) is punctuated by a number of major events from the Precambrian to the present-day (fig. 2C). Prior to the Central Atlantic rifting period, Morocco was subjected to the Eburnean and Panafrican orogenies during the Paleoproterozoic and Neoproterozoic (Piqué et al., 2006), respectively. These orogenies deformed the oldest sediments and crystalline basement of the Western African Craton, and are exposed in the Reguibat shield, Mauritanides, and in the core of the Anti-Atlas. Marine clastic-dominated sedimentation occurred during the Early Palaeozoic and deposits are preserved and exposed in the Meseta massifs, Anti-Atlas, and Tindouf basin (Michard et al., 2008).

The Late Palaeozoic Variscan orogeny (fig. 2C; basin inversion, crustal folding, intense thrusting, nappe structures, granitic intrusion…) affected the Palaeozoic cover and Precambrian basement of the Meseta, High Atlas, and Anti-Atlas (e.g. Michard et al., 2010). It was followed between Late Permian to Triassic by a post-orogenic collapse, of which terminaison is marked in Morocco by the so-called Variscan (or often ‘Hercynian’) unconformity (e.g. Frizon de Lamotte et al., 2004).

Morocco experienced two partly coeval episodes of rifting during Triassic and Jurassic times: The Central Atlantic (ca. 230-190 Ma; Labails et al., 2010; Frizon de Lamotte et al., 2015) and Atlasic (also called Tethyan; ca. 240-185 Ma, aborted; Piqué et al., 2006; fig. 2C) rifts. The orientation of the Central Atlantic rift was partly inherited from Variscan structures, as rift structures occurred around and parallel to the trend of the Palaeozoic belt. The Atlasic rift belongs to the Tethysian realm and is oriented at ca. 45° to the Central Atlantic rift (fig. 2). In the rift zones, grabens and half graben were filled with continental syn-rift deposits in the Doukkala, Argana/Essaouira-Agadir, Tarfaya coastal basins and High/Middle Atlas basins. At ca. 201 Ma, the Central Atlantic Magmatic Province (CAMP; figs. 2B and C) is characterised by the emplacement of mafic dykes and sills (e.g. Davies et al., 2017), followed by flood basalts dated until ca. 190 Ma (Verati et al., 2007).

The onset of Pangaea break-up marking continental drift and initiation of the proto-Atlantic occurred at the beginning of the Jurassic. The precise age is debated between 190 and 170 Ma (e.g. Labails et al., 2010; Davison, 2005). The development of the Moroccan passive margin during the Jurassic and Early Cretaceous witnessed the accumulation of neritic and deeper marine sediments in the present-day offshore, the coastal basins, the High/Middle Atlas, and in the Meseta basins. The Peri-Atlantic Alkaline Pulse (PAAP) is recorded by plutons and flood basalt in the conjugate margins of the Central and South Atlantic oceans, between 125 and 80 Ma (Matton and Jebrak, 2009; Montero et al., 2016).

The opening of the South Atlantic at ca. 85 Ma led to the African and European plate convergence from the Late Cretaceous to the present-day, and may support far-field intraplate stresses responsible for folding and basin inversion in the High and Middle Atlas and in the Rif chains (Guiraud, 1998). The ongoing Atlas orogenesis that peaked in the Eocene is characterised by the deformation and upheaval of the Rif, the Middle Atlas, and the High Atlas (Michard et al., 2008). Finally, Cenozoic volcanism (Missenard and Cadoux, 2011) and surface uplift, observed along two axes, from the

Canary Islands to the Siroua massif (Anti-Atlas) and from the latter to the Rif belt, have been interpreted as associated to a mantle anomaly (Zeyen et al., 2005; Teixell et al., 2005; Missenard, 2006).

3. Quantifying vertical movements and fluxes of eroded material

3.1. t-T modelling database and t-Depth results

In Morocco and its surroundings, over thirty LTT published studies have been conducted in the last 25 years (see exhaustive list as of March 2018 in Charton, 2018). This provides an extensive database of over 1000 cooling ages in the study area (including (U-Th)/He ages from apatite crystals (AHe), Apatite Fission Track (AFT) ages, (U-Th)/He ages from zircon crystals (ZHe), and Zircon Fission Track (ZFT) ages). The spatial distribution of the samples (fig. 3) highly depends on the lithology, as samples must contain either apatite or zircon crystals/grains. For this reason, only Precambrian crystalline basement rocks, meta-psammites within the otherwise (marine) metapelite dominated Palaeozoic column, Meso-Cenozoic clastic sediments, and dykes/sills of all ages could be analysed for LTT in the studied area.

LTT studies often use the produced cooling ages, fission track density and length as inputs for t-T inverse modelling (e.g. Pagel, 2014). Such modelling allows testing of several t-T paths by guiding the model realisations with user-defined constraints. The method provides a comprehensive illustration of the t-T path of the analysed sample, highlighting cooling and heating event(s).

Amongst the above-mentioned LTT studies, twenty performed t-T modelling, resulting in 117 t-T models (figs. 3 and 4; Appendix A). The programs that were used in these studies for the inverse modelling of LTT data are HeFTy (Ketcham, 2005), AFT Solve (Ketcham et al., 2000), and QTQt (Gallagher, 2012; also, see Vermeesch and Tian (2014) for a comparison of HeFTY and QTQt codes) providing comparable thermal histories. The programs outputs are labelled as ‘acceptable’, ‘good’, ‘best-fit’, or ‘weighted average’ (referring to a goodness of fit) paths for HeFTy/AFTSolve and ‘probability’ range, ‘maximum likelihood’ or ‘expected’ paths for QTQt.

In order to quantify volumes of eroded material on the top of the presently exposed rocks in the study area, we apply a temperature-to-depth conversion on selected t-T results (fig 5; see method and selection in Appendix A).

3.2. Vertical movement rates

Exhumation and subsidence rates (km/Myr; fig. 6) were calculated from the depth-converted t-T curves (fig. 5). We define seven periods of time for these calculations (periods ***a*** to ***g***), resulting in up to seven vertical movement rates for each curves: Permian (***a***; 299-252Ma), Triassic (***b***; 252-201Ma), Early to Middle Jurassic (***c***; 201-163Ma), Late Jurassic to Early Cretaceous (***d***; 163-125Ma), Cretaceous (***e***; 125-66Ma), Palaeogene (***f***; 66-23Ma), and Neogene (***g***; 23-0Ma). The selection of time periods is based on the observed resolution of the t-T results, on recognition of key events in the regional sedimentary record, and on the timing of exhumation and subsidence events as recorded by t-T modelling. The calculated subsidence and exhumation rates range from -0.09 to 0.49 km/Myr.

The first order interpretation gained from this figure is that there were four periods of active and widespread denudation in the studied area: the Permian, Early to Middle Jurassic, Late Jurassic to Early Cretaceous, and Neogene (periods ***a***, ***c***, ***d***, and ***g***, respectively). During the Permian (period ***a***), sampled basement in the Meseta and the Anti-Atlas were strongly exhumed (0 to 0.12 km/Myr), while those of the Reguibat Shield were stable (ca. -0.01 km/Myr). During the Triassic (period ***b***), the exhumation in the Meseta and the Anti-Atlas slows down (0.01 to 0.05 km/Myr). The High Atlas and most of the Meseta and Reguibat samples are subsiding (0 to -0.08 km/Myr). In the Early to Middle Jurassic (period ***c***), the Variscan rocks of the Anti-Atlas are greatly exhumed (0 to 0.16 km/Myr). For this region, we observe an acceleration of the exhumation from the Triassic to the Jurassic, characterised by the highest rates recorded in this study, with the exception of Neogene exhumation rates. Concomitantly, the regions surrounding the Anti-Atlas were mostly subsiding in the north (0 to -0.09 km/Myr) and mildly exhuming in the south (0 to 0.06 km/Myr). The Late Jurassic to Early Cretaceous period (***d***) is marked by the stability or subsidence of the Anti-Atlas (0 to -0.05 km/Myr), whereas the sampled basement of the Meseta, the Reguibat shield, and the High Atlas to some extent, were exhuming (0 to 0.09 km/Myr). During the Cretaceous (period ***e***), the exhumation in the

Meseta, the High Atlas and the Reguibat Shield regions slows down, and all areas are rather stable (weak exhumation and subsidence) with motion rates between ca. 0.03 and -0.03 km/Myr. Exhumation is renewed in the Anti-Atlas during the Palaeogene (period ***f***; 0.01 to 0.03 km/Myr), while other areas remain characterised by rates similar to those of the Late Cretaceous. Finally, the Neogene (**g**) period was characterised by a significant acceleration in exhumation; which increases from a typical value below 0.10 km/Myr, to reach 0.20 km/Myr in the High Atlas and 0.49km/Myr in the Rif belt.

3.3. Exhumation maps and eroded material

Sediment fluxes may be quantified by calculating the amount of deposited sediments in the sink, the erosion rate in the source, or using other techniques that investigate the paleo-drainage system (e.g. Wold and Hay, 1990; Gallagher et al., 1998; Barnes and Heins, 2008; Matenco et al., 2013). Sediment routing is an important parameter in dynamic systems, as it defines where the sediments will be delivered. Understanding sediment budgets and pathways are crucial for hydrocarbon exploration, to predict reservoir presence and quality and map potential play fairways.

In the following section, we estimate the volume of material that has been removed through time in the examined area. We first build seven 'exhumation maps' (fig. 7), using the calculated exhumation rates as recorded by t-T modelling. This takes into account subsidence rates and simplified stratigraphy columns for the Permian to Neogene onshore and offshore basins in the study area (Appendix A3) to define areas undergoing subsidence. Volumes of material removed per million years are then calculated from these maps for the considered regions of Morocco and surroundings.

Volume calculations of eroded material per million years (km^3/Myr; eroded material flux) are performed using Surfer software (Appendix A3). The volumes are also separately calculated, by masking other areas, for three regions of high interest: the Meseta, High Atlas, Anti-Atlas, and the Reguibat Shield (table 1). The eroded material fluxes computed here are an estimation of the amount of removed material, per million years, above of the collected samples. They are not the total terrigeneous sediment fluxes, as LTT data does not take into account the lithology of the overburden, and hence disregard its erodibility (Flowers and Ehlers, 2018). The calculated volume of material removed from the source areas will most-likely be higher than the volume of terrestrial material deposited in the sink areas.

The calculated volumes of eroded material for the seven exhumation maps range from 0.76x10^6 to 0.07x10^6 km^3 /Ma for the Jurassic and Triassic, respectively (fig. 7 and table 1). For the regions of specific interest, the eroded material fluxes are between ca. 600 and 11,000 km^3/Ma for the Reguibat Shield, ca. 700 and 8,000 km^3/Ma for the Anti-Atlas, and ca. 100 and 2,300 km^3/Ma for the Meseta and High Atlas massifs (fig. 7). The descriptions of the exhumation maps and observed patterns are presented below.

4. Source and sink maps

Large scale reconstructions of the Moroccan geological history have been carried out in several studies in the past decades (e.g. Ranke et al., 1982; Le Roy et al., 1997; Nemčok et al., 2005; Sibuet et al., 2012) and this data has been collated and inegrated into our study. The majority of the maps used in this review focused on depositional environments, palaeogeography, tectonic plate reconstruction, and more local structural/stress maps (Appendix B), based on extensive data collections.

Using the knowledge gathered hitherto in the previous part of this study, we construct ten "source and sink" maps, which illustrate the timing, extent, and rate of exhumation episodes documented with LTT and t-T modelling results. Using geological maps, several other databases (well, outcrop, fossil, and provenance data), and previous paleogeography work, we also reconstructed the gross depositional environments. The maps presented illustrate the source, transitional, and sink domains from the Permian to Neogene, within a simplified structural framework.

4.1. Pre-rift: Permian and Triassic maps

During the Permian (fig. 9), erosion occurred in the remnants of the Variscan chain (e.g. Lorenz, 1988; Hmich et al., 2006), located mostly in the Meseta and Western Anti-Atlas. Known Permian basins are the Eastern Meseta, Doukkala and Argana Valley basins. From the interpolated area, we estimate the volume of produced sediments to be about 1.0×10^{6} km^3, of which little is preserved today. Our working hypothesis is that Permian sediments were re-worked during the Triassic and/or that the erosion of the Variscan chain yielded little coarse terrestrial material. Subsiding domains predicted by the t-T modelling results are the Central and Eastern Reguibat Shield.

From the Permian to the Early Triassic (periods ***a*** to ***b***; figs. 9 and 10), the source area shifted from most of the domain affected by the Variscan orogeny to only part of it: The Meseta, the Anti-Atlas, and the eastern Reguibat Shield. The appearance of transitional depositional environments is another important change, resulting from marine incursions from the Tethysian realm as far as the Tarfaya basin (e.g. Ranke et al., 1982; Scotese, 2012; Leleu et al., 2016). The erosion that occurred in the Anti-Atlas during the Triassic is supported by provenance and paleo-current evidence in the Massif Ancien (Brown, 1980; Baudon et al., 2009; Domènech et al., 2018) evidencing a drainage divide perpendicular to the Anti-Atlas trends.

4.2. Syn-rift: Triassic and Early Jurassic maps

During the Triassic (period ***b***; fig. 10), the northern Meseta (estimated volume of eroded material: ca. 6,000 km^3), the Anti-Atlas (ca. 35,000 km^3), and the Reguibat Shield (ca. 30,000 km^3) were being eroded. A large portion of the Meseta shows considerable subsidence (e.g. Ghorbal et al., 2008), which is comparable to Triassic subsidence documented in the Central Atlantic and High Atlas rift zones (e.g. Gouiza et al., 2010; Moragas et al., 2016, respectively). The Central Atlantic and Atlas rift zones were subsiding, except maybe for a part of the Massif Ancien which acted as a major drainage divide as suggested in Domenech et al., 2018 (fig. 10). This massif is indeed described as forming positive structural relief sourcing Triassic sediments to the Argana and Oukaimeden valley (e.g. Baudon et al., 2012). The t-T modelling results do not cover the time before 200 Ma in the Central and Eastern Anti-Atlas (Gouiza et al., 2017), but red clastics overlying Precambrian basement in the northern Central Anti-Atlas are mapped as Triassic. No recent study on these sediments has been conducted, however, basaltic flows covering them have yielded ages of 205.9±7.9 and 207.8±6.5 Ma (Fiechtner et al., 1992), suggesting that these deposits are indeed Triassic. This suggests that while the core of the Anti-Atlas continued to exhume, its northern margin was already subsiding (including the Souss and Ouarzazate basins).

From the Late Triassic to Early Jurassic (periods ***b*** to ***c***; figs. 10 and 11) marine domains progressively covered the Atlas and Central Atlantic rift. The only significant change in source areas is an exhumation event occuring in the western Reguibat Shield and starting in the Early Jurassic (fig. 11). A recent provenance study by Marzoli et al. (2017), using detrital zircon U-Pb ages, shows that sediments interfingering with the CAMP basalts in the western High Atlas have been sourced from the Meseta domain.

4.3. Early Post-rift: Early Jurassic to early Early Cretaceous maps

The Early and Middle Jurassic epochs (period ***c***; figs. 11 and 12) are marked by enhanced erosion in the Anti-Atlas and Reguibat Shield, and to some extent in the Meseta (see volumes of eroded material in table 3). From all the periods defined in this study, period ***c*** is the most active in terms of eroded material flux for the Anti-Atlas. It is likely that the Anti-Atlas formed a topographic swell as calculated exhumation rates are higher in the central part of the belt (e.g. fig. 11). Middle Jurassic redbeds are recorded in the onshore basins north and west of the Anti-Atlas (Tarfaya, Agadir-Essaouira, Central High Atlas, Ifni Margin, and Souss basins; Appendix A). In the basins south and east of the Anti-Atlas, no Jurassic sediments are recognised. This supports the idea of an exhuming Anti-Atlas and Reguibat Shield, linked by an exhuming or stable Tindouf area.

The siliclastic fraction within the overall carbonate sedimentation is abundant in the Central High Atlas during the Early Jurassic and in the Essaouira-Agadir Basin during most of the Early and Middle Jurassic (Duval-Arnould, 2019). Coarse grained clastic sediments are deposited in the Central and Western High Atlas during the Toarcian, and the rest of the Early Jurassic is dominated by carbonate sedimentation with up to 40 % of fine grained siliciclastics (10-20% average). Middle Jurassic rocks are composed of clay to coarse clastics (alluvial plain) and mixed carbonate-siliciclastics in the Western and Central High Atlas, respectively (Malaval, 2016; Joussiaume, 2016). These observations point towards the presence of an active source of clastic sediments in the vicinity of these basins for the Early to Middle Jurassic, matching the results of t-T studies conducted in the Anti-Atlas (e.g. Ruiz et al., 2011; Oukassou et al., 2013; Gouiza et al., 2017).

The Early and Middle Jurassic epochs (period ***c***; figs. 11 and 12) are fairly similar in terms of depositional environments. Moreover, the exhumation patterns are identical on both maps as they originate from the same exhumation map, in this case presented as figure 7C. Provenance studies carried out on Middle Jurassic sediments evidence sedimentary transport from the Meseta to the Middle Atlas (Pratt et al., 2015), and from the Anti-Atlas to the Essaouira-Agadir basin (Stets, 1992). Depositional environments in the Essaouira-Agadir basin change from fluvial to lagoonal during the Early Jurassic, from continental/transitional to shallow marine (dolomites) in the Middle Jurassic, and then remain shallow marine / shelfal during the Late Jurassic (Duval-Arnould, 2019). In the Sidi Ifni area, Arantegui (2018) documented a Bathonian (Middle Jurassic) age for shallow marine and lacustrine deposits exposed along the coast (Charton et al., 2018).

From the Middle to Late Jurassic, our results show a shift in the areas of sediment production, from the Anti-Atlas to the Meseta. The Late Jurassic (period ***d***; fig. 13) shows a major shift in the sediment source areas: the Anti-Atlas is no longer an active source while the Meseta becomes strongly exhumed. A high-resolution clay mineralogy study, carried out in folded Jurassic sediments of the Essaouira-Agadir Basin (Ouajhain et al., 2011), shows a clear shift in either the sediment source lithology or area, between the Middle and Late Jurassic, passing from a chlorite- to an illite-dominated assemblage. It is possible that Middle Jurassic erosion of the Anti-Atlas reached down to the Precambrian, hence cutting through the metamorphosed Palaeozoic series and eventually sourcing basement chlorite to surrounding basins. The Meseta is also a documented source area during the Late Jurassic, as suggested by paleo-currents measured in the western High Atlas (Stets, 1992). The Upper Jurassic was not deposited in the Central High Atlas, but fluvial deposits of Callovian age are recorded, while in the Western High Atlas, the Malm is dominated by carbonate sedimentation interbedded with fine siliciclastics in the Kimmeridgian (Duval-Arnould, 2019).

The transition between the Jurassic and Cretaceous (period ***d***; fig. 13 and 14) was, according to our current dataset at least, fairly quiescent. The coastline shifted towards the north in the Middle Atlas/Rif areas, and towards the west in the Tarfaya basin. The latter change was accompanied by the onset of large Early Cretaceous deltaic systems (Tan-Tan and Boujdour deltas; fig. **14**). The entire Reguibat Shield was an active source of sediments since the Early Jurassic and remains one during the Early Cretaceous. This suggests that an acceleration of the exhumation or a change in source lithology in the Reguibat Shield must have occurred in the earliest Cretaceous, supplying the siliciclastics to the Tan-Tan and Boujdour deltas. It is likely that the erosion in the Reguibat Shield reached the granitic basement at the end of the Jurassic, with removal of the meta-pelites from the overlying Early Palaeozoic basin.

Exhumation of the Meseta massifs (ca. 750 km^3/Ma) from Late Jurassic to Early Cretaceous (period ***d***) was first described in Ghorbal et al. (2008). The preserved onshore basins of the Meseta do not record Upper Jurassic sediments, excepted in the coastal Doukkala basin (fig. **14**). This suggests that a surface larger than that of the presently outcropping basement was being eroded.

In the Late Jurassic and Early Cretaceous, it is unknown if the Tindouf basin was sourcing sediments to the Tarfaya Basin deltas, a transitional sink, or simply stable, as no LTT cooling ages have been measured. Nevertheless, values of vitrinite reflectance from the Silurian (Kuuskraa *et al,* 2013), in the northern Tindouf basin, suggest that these sediments were previously buried deeper and significantly thick overburden is missing, which was deposited and subsequently eroded between the Carboniferous and the Late Cretaceous. As most of the Anti-Atlas and the central Reguibat Shield were subsiding during the Late Jurassic/Early Cretaceous (figs. **14** and **15**), we assume that 1) the missing overburden was deposited during this period in the northern Tindouf Basin, and 2) in the absence of evidence, the basin was fairly stable elsewhere.

A sedimentary provenance study was conducted in the north Tarfafa Basin for Lower Cretaceous to Cenozoic sediments (Ali et al., 2014). Their results showed that the Lower Cretaceous sediments were sourced from the Reguibat Shield, while upper Cretaceous sediments were sourced from both the

Reguibat Shield and the Anti-Atlas (fig. 15). During period ***d***, the Reguibat Shield witnessed substantial erosion (ca. 8,200 km^3/Myr). It appears that the source area of the sediments deposited in the Boujdour and Tan-Tan Lower Cretaceous deltas is the Reguibat Shield (and potentially part of the south Tindouf basin), with over 700,000 km^3 of eroded material.

4.4. Late Post-rift and syn-Atlas kinematics: middle Cretaceous to Neogene maps

The middle Cretaceous (periods ***d*** and ***e***; figs. 14, 15, and 16) is characterised by another shift in source areas. The Anti-Atlas presently outcropping basement, which was subsiding during the Early Cretaceous, is exhumed again from the middle Cretaceous onwards (fig. 15). Meanwhile, the southern massifs of the Meseta underwent subsidence during the middle Cretaceous after a prolongated exhumation episode.

In Morocco, widespread coarse sediments are described from the Early Cretaceous (e.g. Davison, 2005; Frizon de Lamotte et al., 2009, Luber, 2017). In the north Tarfaya basin, Arantegui (2018) has shown that the undifferentiated Lower Cretaceous clastic succession is characterised by fluvial and tidal flat environments, with alluvial fan conglomerates at the base in contact with Cambrian metamorphosed sediments. The study further provides an updated biostratigraphy of Aptian-Albian (middle Cretaceous) transitional to shallow marine deposits exposed along coastal outcrops. The mean paleo-current direction for the fluvial units indicates a local transport direction towards the northwest.

The transition from shallow marine to continental deposition environments occurred between the Early and the middle Cretaceous in the Essaouira-Agadir basin. The continental environment records a general palaeo-current direction towards the west and a significant regression, probably tectonically controlled, during the Latest Barremian to Early Aptian (Luber, 2017). In the Late Aptian and Albian times, the area was drowned once again with the establishment of shallow marine conditions.

Provenance studies suggest that only the Reguibat Shield (including the Mauritanides) were sourcing clastic sediments to the north Tarfaya basin during the Early Cretaceous, while the Anti-Atlas was part of the siliciclastic supply to the coastal basin from Late Cretaceous onwards (Ali et al., 2014).

Pratt et al. (2015) collected Albian sediments deposited in the Rif basin, and traced the provenance to two sources: the Meseta and a presently unknown source area.

A Cenomanian-Turonian carbonate platform with low detrital influx prevailed in the Central High Atlas, while in the Atlantic domain, Turonian organic-matter rich black shales were deposited in fault bounded restricred basins where relatively deeper marine environment prevailed (Wang, 2018).

During the middle Cretaceous, the central Anti-Atlas became an active source area and the Meseta exhumation slowed down significantly. By the end of the Cretaceous, the entire Anti-Atlas s.s. was sourcing sediments to surrounding basins, and most of the Meseta and High Atlas domains were subsiding and progressively drowned.

In the late Early to Late Cretaceous period (period ***e***; fig. 16), subsiding domains are dominant in the study area. This period is characterised by a rise in global sea level (Cenomanian-Turonian transgression; e.g. Piqué et al., 2006), which transgressed into the interior of Morocco and Algeria (e.g. Upper Cretaceous deposits in the Guir Hamada; e.g. Benyoucef et al., 2015). It appears to have partially submerged the Reguibat shield, the Tindouf basin (except its central part), and the borders of the Anti-Atlas. Anti-Atlas erosion (ca. 900 km^3/Ma) is dominated in the centre, and later extends to the eastern and western regions.

Finally, the Palaeogene and the Neogene periods (periods ***f*** and ***g***; fig. 17 and 18) are characterised by the Atlas orogeny, which is expressed by high exhumation rates in the High Atlas and Rif, and to a lesser extent in the Anti-Atlas and Reguibat Shield. We estimate the volume of eroded material from the studied area during the Palaeogene and Neogene to ca. 0.5×10^6 and 0.7×10^6 km^3, respectively.

During the Palaeogene (fig. 17), a large portion of the study area was emerged. Epicontinental basins developed around the exhuming massifs of the Meseta and the High Atlas, and shallow marine setting persisted in the Tarfaya basin. Paleontological evidence comes from remains of fish, lizards and mammals (e.g. whales and turtles; see paleontology references in Appendix B).

The Neogene period (fig. 18) shows only minor differences with the present-day situation, with nearly all of Morocco emergent. Important sediment source areas are the Meseta, the High Atlas, the Anti-Atlas, and the Reguibat Shield. Some shallow marine sinks were developed in the North Tarfaya, southern Settat and Gharb basins, and along the Mediterranean coast in the Rif domain.

5. Discussion

5.1. Prerequistes, advantages, and possible improvements to the proposed workflow

The workflow presented here broadly constrains source-to-sink systems and domains through time, using t-T modelling as the basis for source and sink maps construction. The prerequistes to apply this workflow elsewhere are limited to the availability of dense t-T datasets and prior geological knowledge. Any candidate study area should be characterised by the presence of exposed crystalline basement that has been subjected to LTT/t-T investigation. This workflow requires prior, but not extensive, knowledge about sedimentary basins, palaeo-thermal regimes and paleogeography. In order to construct detailed source and sink maps, published geological data must be obtained, corroborated and interpreted in terms of depositional environments (including borehole data when available). Additionally, in areas where horizontal movements were substantial, exhumation maps should be generated from restored basemaps.

The workflow may be used to test several exhumation scenarios (i.e. exhumation rates, timing, and location) against the stratigraphic record, and may be further validated with sedimentary provenance analyses. Volumes can be calculated without prior information on actual sediment fluxes or budgets, but may be compared with existing results (as exemplified in part 5.4 of this work; Helm, 2009). Provenance studies are also not a requirement to build exhumation maps, but they may facilitate and improve the construction of the source and sink maps. As with all studies, the quality and quantity of available data will improve the results, but this methodology allows exhumation rates and eroded material fluxes to be estimated without the need for new fieldwork campaigns or analyses of samples, making it a powerful tool for evaluating underexplored and fairly remote areas.

These results can be updated and improved as more t-T data points are made available, away from clusters in well-studied basement areas and by gathering subsidence curves from preserved basins or extracting subsidence rates for their interpolation with exhumation rates. It may be subsequently be extended to include landscape evolution modelling, using the vertical movement rates as input, which will help in defining the most-likely sediment entry points into the sinks, as well as providing a first order estimate of the palaeo-altimetry (e.g. Salles et al., 2017).

Finally, this workflow could be greatly improved if associated with a systematic investigation of the contact between t-T modelled basement areas and their sedimentary cover. Indeed, identifying the truncation surfaces where sediments extend onto basement areas, and interpolating these surfaces for the time of deposition, can offer valuable insights, while mapping onlapping features can be used to identify if basement areas were palaeo-highs (topographic or bathymetric).

5.2. Uncertainties of the workflow

Together with the uncertainty inherent in the ranges for the rates and volumes, other uncertainties need to be recognised to fully understand the limitations of the presented workflow. Typically, LTT analyses in Morocco have ~10% error for both (U-Th)/He and FT systems (Charton, 2018). The t-T modelling shows a sustantial temporal and thermal uncertainty associated to all realisations (e.g. good and acceptable envelopes for HeFTy) and this uncertainty increases with age (fig. **4**).

Other factors including the selection of t-T curves and geotherms to model, plus the assumption of a constant surface temperature, impact on the error range. Another source of uncertainty lies in the use of non-restored base maps for the exhumation maps, as some areas may have changed in shape and/or surface (the High Atlas before the Cenozoic orogeny for instance). Further, the use of null vertical movement rates for synthetic points introduces an error, as non-recorded sediments might have been eroded (i.e. subsidence rates should have been used during the assumed time of deposition) or never deposited (i.e. null or exhumation rates). Other potential errors associated with the interpolation method and volume calculations are more difficult to quantify. Overall, we estimate the error for the rates and calculated eroded material fluxes to ~20% for the Permian (periods ***a***), ~15% for the Mesozoic (periods ***b*** to ***e***) and to ~10% for the Cenozoic (periods ***f*** and ***g***).

5.3. Limitations of the source and sink maps

Data quality, data density and temporal resolution are highly variable across the area covered by the source and sink maps. This leads to variable robustness of the presented maps, which complicates the comparisons from one to another. Dating is the primary uncertainty, as several Phanerozoic layers in Morocco and the surrounding area have undifferentiated ages (e.g. Hollard et al., 1985). This is for instance the case for Permo-Triassic, Middle to Late Jurassic, and Early to Middle Cretaceous redbeds (“Continentale Intercalaire”), all three of which are widely mapped accross the study area, but their ages are weakly constrained. These intervals may be intercalated by biostratigraphically marine sequences or radiometrically dated magmatic intrusions, but these biostratigraphic or geochronologic studies are generally local and extrapolation still has to be made to similar but non-constrained facies.

The proposed Permian map is characterised by the less certain dominant depositional environments, as it is constrained with limited data. While the Neogene is a data-rich time interval and the corresponding map is of higher resolution. Another limiting aspect is introduced by the definition of the time-windows that each map covers. The temporal resolution of the Permian and Triassic maps is coarse, as they encompass ca. 50 Myr, compared to the short Middle Jurassic interval (ca. 11 Myr). It is also important to note that the Triassic map is mostly composed of Late Triassic data, as Early and Middle Triassic sediments are rarely documented in the stratigraphy of Morocco. Although much of the Triassic sediments are mapped as undifferentiated, where dated they are mainly Late Triassic and the best dating occurs at the end of the sequence, where CAMP dykes and sills are radiometrically dated at end Triassic in age. However, exhumation rates were calculated for the entire Triassic, which will result in a reduction in overall rate and will have introduced a bias on the map.

Moreover, our source and sink maps use the present-day unrestored geography and geology as base maps. In many areas this is acceptable, however this should be taken into account when using them and discussing implications for areas such as the Atlas and Rif belts, for which Cenozoic upheaval was mostly caused by N-S shortening (e.g. Michard et al., 2008).

5.4. Comparing eroded material flux to terrestrial sedimentation rates

The total estimated eroded volume rates (table 1) can be compared to published sedimentation rates Helm (2009; fig. 19). The study by Helm calculated sedimentation rates for several segments along the offshore west African margin, including the Moroccan segment. The sedimentation rates in the offshore domain and the coastal basins were obtained from nine interpreted seismic profiles perpendicular to the coast, and extended by extrapolation and/or well control to the basin (using DSDP wells). Terrestrial sedimentation rates from the Triassic to the Neogene were then estimated and adjusted to the portion of terrigenous sediments recorded in the used control wells. It is important to note that the age resolution is not identical across Helm (2009) and this study; in other words, the start and end dates of calculated intervals are not systematically concordant. An assumption is that, in an ideal situation, results from the eroded material flux modelling should approximate the terrestrial sedimentation (i.e. disregarding routing of sediment in onshore basins, climate, lithology of the source area or suspension load, and the terrestrial component exiting the system to further offshore).

This comparison shows that the siliciclastic volumes deposited in the offshore/coastal basins and the eroded volume of material from the interpolation grid are, for the most part, of the same order of magnitude (fig. 19). Furthermore, rates are very similar during the Triassic, early Early Cretaceous, Late Cretaceous, Palaeogene, and Neogene. Overall the correlation is good, except for the rates obtained during the Jurassic period. According to our results, between 10,000 to 30,000 km^3/Myr of material were eroded, while the offshore seems to record much lower volumes, about 1000 to 2000 km^3/Myr of siliciclastic sediments. This discrepancy could be explained by considering the eroded lithologies at this time. A hypothesis is that erosion in the Reguibat Shield, Anti-Atlas, Tindouf, and Meseta may have removed fine-grained and/or carbonated meta-sediments from the upper part of the Palaeozoic section. Hence, little coarse terrestrial material would be recorded in the Atlantic basins, were platform limestones are dominant. Additionally, fluvial system pathways could have re-routed sediments to the east.

6. Conclusions

t-T modelling results have been used as a proxy to define and quantify exhumation events from the Permian to the present-day in eastern Morocco and its surroundings. A series of exhumation maps is presented from which erosion patterns and eroded material fluxes have been extracted. This allows analysis of the possible mechanism(s) responsible for these vertical movements. The presented findings have implications for the evolution of the Central Atlantic passive margins and for our understanding of the Permian to Neogene Moroccan source-to-sink systems.

The reconstructed evolution of vertical movements and erosion at the scale of the passive margin can be divided into 3 areas: The Reguibat Shield, the Anti-Atlas, and the High Atlas/Meseta. The Reguibat Shield is marked by subsidence from the Permian to the Triassic, followed by exhumation from the Jurassic onwards (0.01-0.06 km/Myr; ca. 1,400,000 km^3). We infer that the Reguibat shield was the only source of sediments for the Boujdour and the Tan-Tan Cretaceous deltas, offshore Tarfaya basin.

The sampled Anti-Atlas basement rocks were deeply buried in the Permian and were exhumed between the Triassic and the Middle Jurassic (0.01-0.16 km/Myr; ca. 300,000 km^3). Subsidence during the Late Jurassic/Early Cretaceous was followed by a final exhumation from the Late Cretaceous onwards (0.01-0.05 km/Myr; ca. 180,000 km^3).

Presently outcropping Variscan rocks in the High Atlas and Meseta were close to the surface during the Permian/Late Triassic, followed by subsidence until the Middle Jurassic, exhumation in the Late Jurassic/Early Cretaceous (exhumation rates: 0.01-0.09km/Myr; eroded material: ca. 28,000 km^3), renewed subsidence during the Late Cretaceous and a finally exhumation during the Cenozoic (0.01-0.20 km/Myr; ca. 37,000 km^3). The subsidence event was synchronous to Atlantic rifting, and sample analysis indicates rapid burial from close to the surface down to 4 km, suggesting that subsidence associated with the Central Atlantic and/or the High Atlas rift zone(s) extended over nearly the entire Meseta.

This study presents 10 “source and sink” maps, integrating data from palaeo- structural, erosional, and depositional maps for the Permian to the present-day.

During the Permian, terrestrial basins located across the Meseta were sourced with eroded material of the Variscan chain. In the Middle to Late Triassic, widespread rifting allowed more extensive deposition across Morocco. Active sedimentary source areas were the northern Meseta, the western Anti-Atlas, and the central Reguibat Shield. Initially most of Morocco was dominated by continental deposits, with a gradual transgression inland from Tethys to the east and the proto-Atlantic to the west extending terrestrial/transitional marine environments, across the High Atlas, the Meseta, and the Tarfaya basins as well as part of the Reguibat Shield.

Throughout the Jurassic, shallow marine and marine environments dominate, with periods of discrete siliciclastic input. Active sedimentary source areas were the Anti-Atlas, the Reguibat Shield, and the Meseta massifs. A substantial shift of source area was evidenced from the Anti-Atlas to the Meseta/High Atlas at the transition between the Middle and the Late Jurassic (ca. 163 Ma).

In the Early Cretaceous, terrestrial environments cover a substantial portion of the study area, especially between 145 and 125 Ma. Another considerable shift of source area was evidenced from the Meseta/High Atlas to the Anti-Atlas at the transition between the early Early and the middle Cretaceous (ca. 125 Ma). Finally, during the Cenozoic, almost all the presently outcropping basement areas provided source material to the coastal and foreland basins.

The presented workflow enables past large-scale source-to-sink domains to be constrained. The prerequisites, if applied elsewhere, are limited to the availability of t-T datasets and prior geological knowledge. These results may be further improved as more t-T data points are made available and/or if associated with a systematic investigation of the contact between t-T modelled basement areas and their sedimentary cover.

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Captions

Table 1. Eroded material fluxes and surface areas from Permian (**a**) to Neogene (**g**). Preferred scenario for the geotherms is presented in Appendix A. We estimate the error of these fluxes between 20 and 10% (see discussion).

Figure 1. Morphology of the Central Atlantic seafloor and conjugate margins (data: GEBCO_2014_1D). Simplified plate tectonic evolution is after Stampfli and Borel (2002). WAC: Western African Craton.

Figure 2. A) Geography of Morocco and its surroundings (data: GEBCO_2014_1D) with main geological domains, sedimentary basins, and Variscan Massifs superimposed. B) Geological map of Morocco and its surroundings (after Hollard et al., 1985). **CAMP**: Central Atlantic Magmatic Province (Triassic); **PAAP**: Peri-Atlantic Alkaline Province (Cretaceous). C) Tectonic chart of the Atlantic realm and Morocco, see references therein (numerical ages after ICS 2016/12). **LIP**: Large Igneous Province; **CAMP**: Central Atlantic Magmatic Province; **PAAP**: Peri-Atlantic Alkaline Pulse.

Figure 3. Location of samples used for t-T modelling, located in the Rif[1], the Meseta and High Atlas[2], the Anti-Atlas[3], the Reguibat Shield[4], and the western Anti-Atlas and north Tarfaya Basin[5] (see reference details in table A).

Figure 4. Digitized t-T modelling weighted averages, best-fit curves, and acceptable envelopes (grey area) for HeFTy results or expected curves, maximum likelihood curves and limits of 2σ confidence level (grey area) for QTQt results (see references in Appendix A). t-T results for borehole samples from Sehrt (2014), as well as results from El Haimer (2014) and Barbero et al. (2007), for which only envelopes were published, were not included.

Figure 5. Time-depth curves converted from t-T curves shown in figure **4**, assuming geothermal gradients evolving as illustrated in appendix A and assuming a surface temperature of 20°C. The

thicker lines display vertical movement rate calculations; non-selected thiner curves, in the backgrounds, were also converted to depth but were not used in the later study; conditions for result selection are detailed in appendix A. The upper and lower limits (thick dashed lines) are calculated with geothermal gradients of 40 and 20°C/km, respectively.

Figure 6. Exhumation and subsidence rates calculated from the 56 selected depth converted curves of figure **5** using the variable geotherms shown in figure **A1.** The seven defined periods **a** to **g** span between 300 and 0 Ma. The combined uncertainties are extracted from the results of rate calculations using constant geotherms. **Mes**: Meseta; **HA**: High Atlas; **AA**: Anti-Atlas; **CB**: Coastal Mesozoic basins; **RS**: Reguibat Shield. Areas, especially if substantially large, may have experienced both exhumation and subsidence, and must not necessarily be an error from the initial t-T models. North and South are only marked for period **g** because Morocco has been significantly rotated since the Permian (e.g. Scotese, 2012). Note that the x-axis is not time.

Figure 7. Exhumation maps for the seven selected periods (**a-c** on this page and **d-g** on the next one) after geological record (Appendix A) and vertical movement rates (fig. **7**). Three domains are defined on the exhumation maps: a subsiding domain with rates ≤ -0.011 km/Myr, a stable domain characterised by rates between -0.01 and 0.01, and an exhuming domain with rates ≥ 0.011 km/Myr. Note that the western boundary is the Continent-Ocean Boundary (**COB**).

Figure 7. (continued)

Figure 8. Estimated eroded material flux for the three main sediment sources (Meseta/High Atlas, Anti-Atlas, and Reguibat Shield) for the seven defined periods (**a**-**g**). The eroded material flux is obtained with variable geotherms (Appendix A), while the ranges are given by calculations done with two constant geotherms of 20 and 40°C/km.

Figure 9. Permian map (period **a** as defined in the previous part of this work). See list of references used to build this map, and the following ones, in Appendix B. Dominant dep. env.: Dominant depositional environment. **Source-to-sink***: Simplified source-to-sink systems evidenced with provenance study or paleo-currents. **Well data**: full (white) points mean that sediments of that age were preserved; empty (transparent) points illustrate that sediments were not deposited or not preserved. **WAC**: Western African Craton.

Figure 10. Triassic map (period **b**). Illustrated dykes and basalts are from the Central Atlantic Magmatic Province (**CAMP**). See caption of figure 9 for additional information.

Figure 11. Early Jurassic map (period **c**). **CAMP**: Central Atlantic Magmatic Province. See caption of figure 9 for additional information.

Figure 12. Middle Jurassic map (period **c**). See caption of figure 9 for additional information.

Figure 13. Late Jurassic map (period **d**). See caption of figure 9 for additional information.

Figure 14. (early) Early Cretaceous map (period **d**). See caption of figure 9 for additional information.

Figure 15. middle Cretaceous map (period **e**). See caption of figure 9 for additional information.

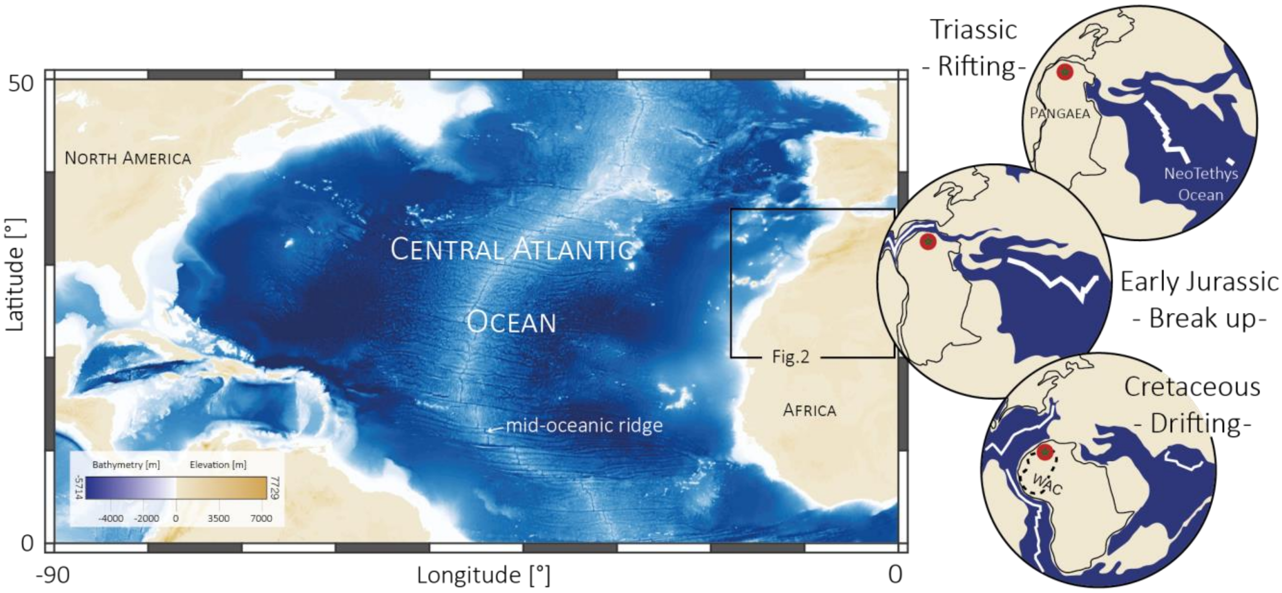
Figure 16. (mid-late) Late Cretaceous map (period **e**). See caption of figure 9 for additional information.

Figure 17. Palaeogene map (period **f**). See caption of figure 9 for additional information.

Figure 18. Neogene map (period g). See caption of figure 9 for additional information.

Figure 19. Comparison of the total eroded material flux to sedimentation rates in Moroccan offshore and coastal basins (after Helm, 2009). Note that it may be expected that the results should not match perfectly, as a proportion of the eroded material would be removed as dissolved carbonate or as

fines that would have long transport distance into the deep oceanic basins (i.e. eroded material flux – red line v terrestrial sedimentation rates - blue).



50
0
-90
0
Latitude [°]
Longitude [°]
North America
Central Atlantic
Ocean
mid-oceanic ridge
Africa
Fig.2
Bathymetry [m]
Elevation [m]
Triassic
- Rifting-
Pangaea
NeoTethys
Ocean
Early Jurassic
- Break up-
Cretaceous
- Drifting-
WAC

Figure 1

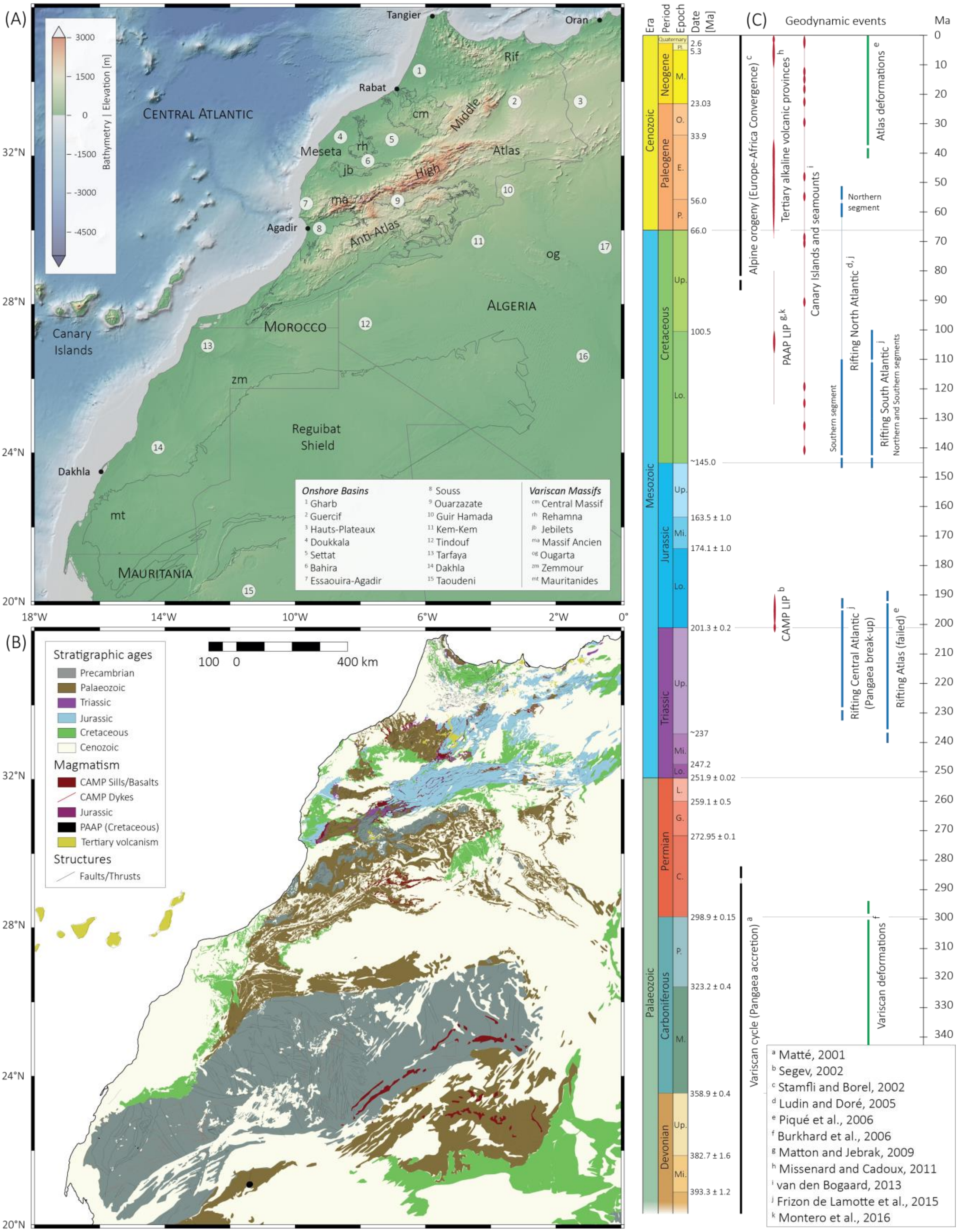
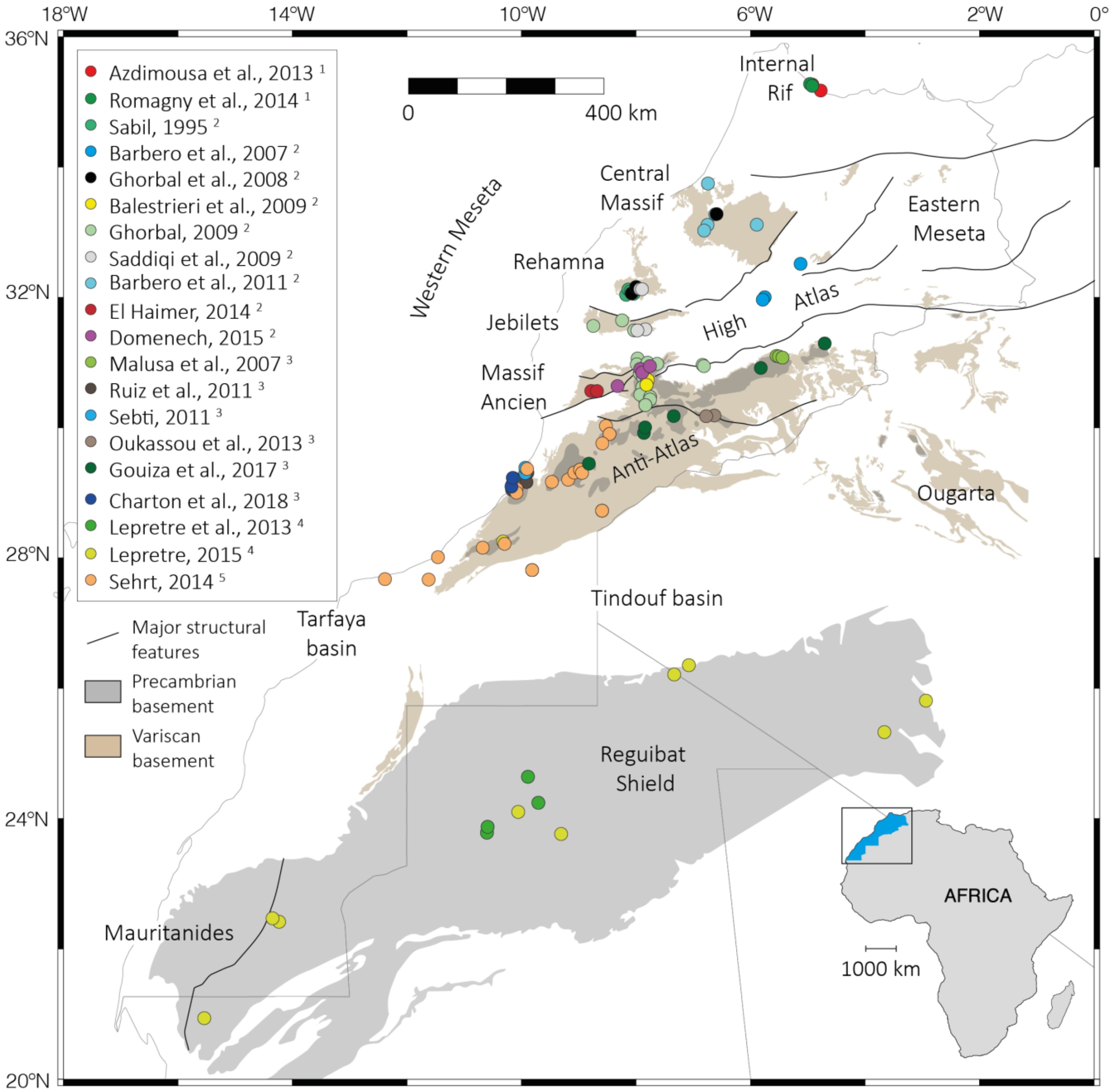


Figure 2



18°W
14°W
10°W
6°W
2°W
0°
36°N
32°N
28°N
24°N
20°N
Azdimousa et al., 2013 1
Romagny et al., 2014 1
Sabil, 1995 2
Barbero et al., 2007 2
Ghorbal et al., 2008 2
Balestrieri et al., 2009 2
Ghorbal, 2009 2
Saddiqi et al., 2009 2
Barbero et al., 2011 2
El Haimer, 2014 2
Domenech, 2015 2
Malusa et al., 2007 3
Ruiz et al., 2011 3
Sebti, 2011 3
Oukassou et al., 2013 3
Gouiza et al., 2017 3
Charton et al., 2018 3
Lepretre et al., 2013 4
Lepretre, 2015 4
Sehrt, 2014 5
Major structural features
Precambrian basement
Variscan basement
0
400 km
Internal Rif
Central Massif
Western Meseta
Rehamna
Jebilets
Massif Ancien
High Atlas
Eastern Meseta
Anti-Atlas
Ougarta
Tindouf basin
Tarfaya basin
Reguibat Shield
Mauritanides
AFRICA
1000 km

Figure 3

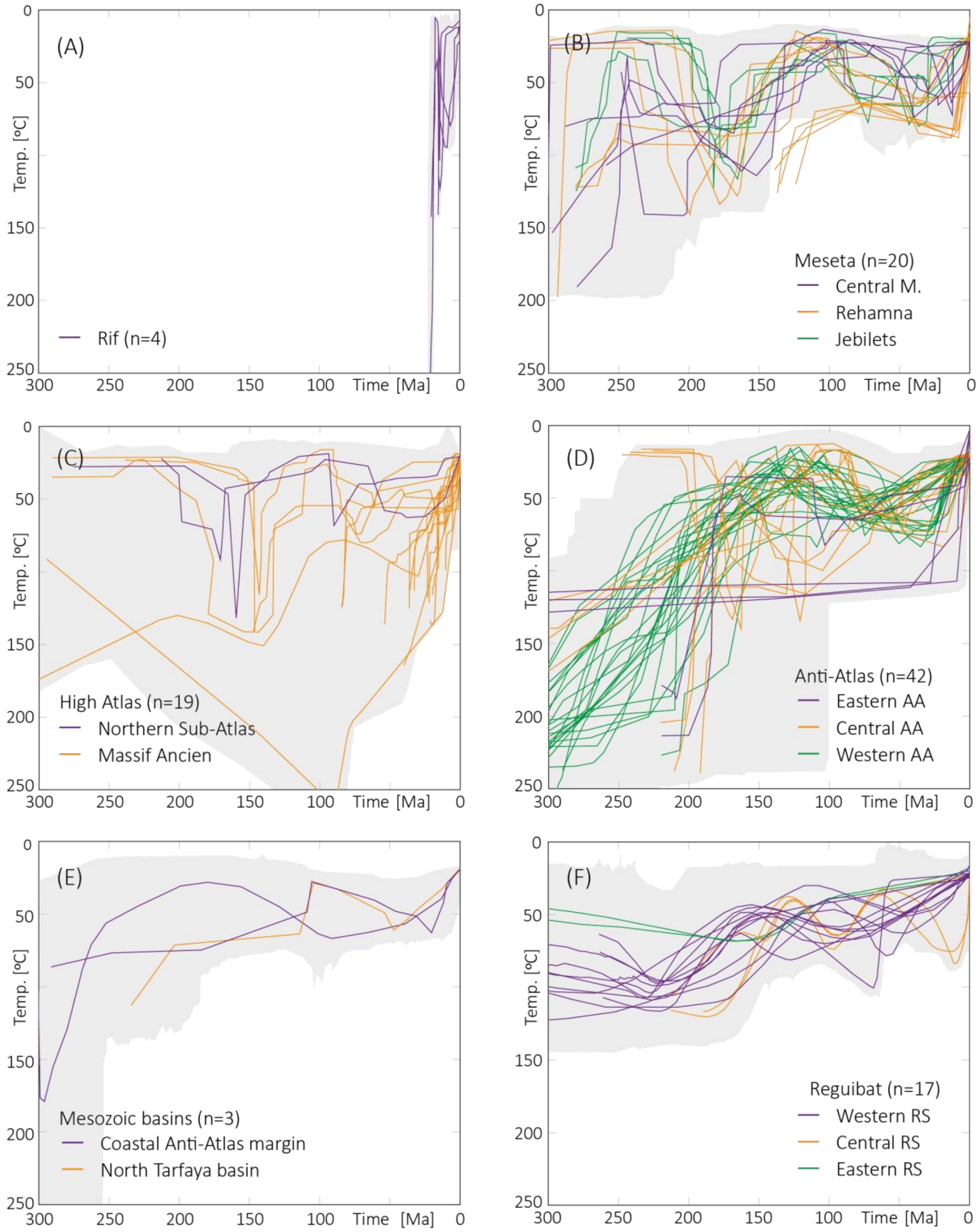

(A)
Rif (n=4)
(B)
Meseta (n=20)
Central M.
Rehamna
Jebilets
(C)
High Atlas (n=19)
Northern Sub-Atlas
Massif Ancien
(D)
Anti-Atlas (n=42)
Eastern AA
Central AA
Western AA
(E)
Mesozoic basins (n=3)
Coastal Anti-Atlas margin
North Tarfaya basin
(F)
Reguibat (n=17)
Western RS
Central RS
Eastern RS
Temp. [ºC]
Time [Ma]
0
50
150
200
250
300
250
200
150
100
0

Figure 4

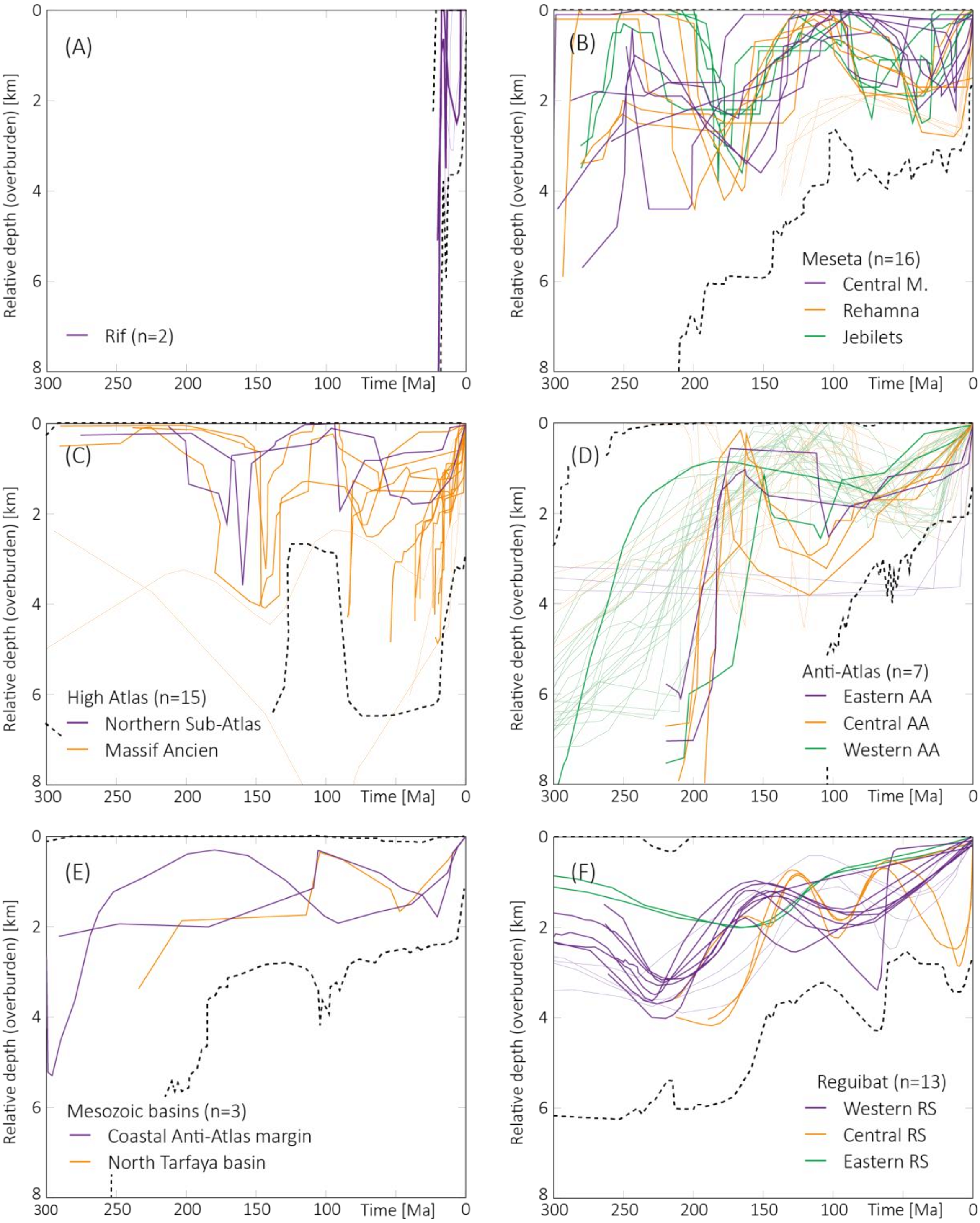
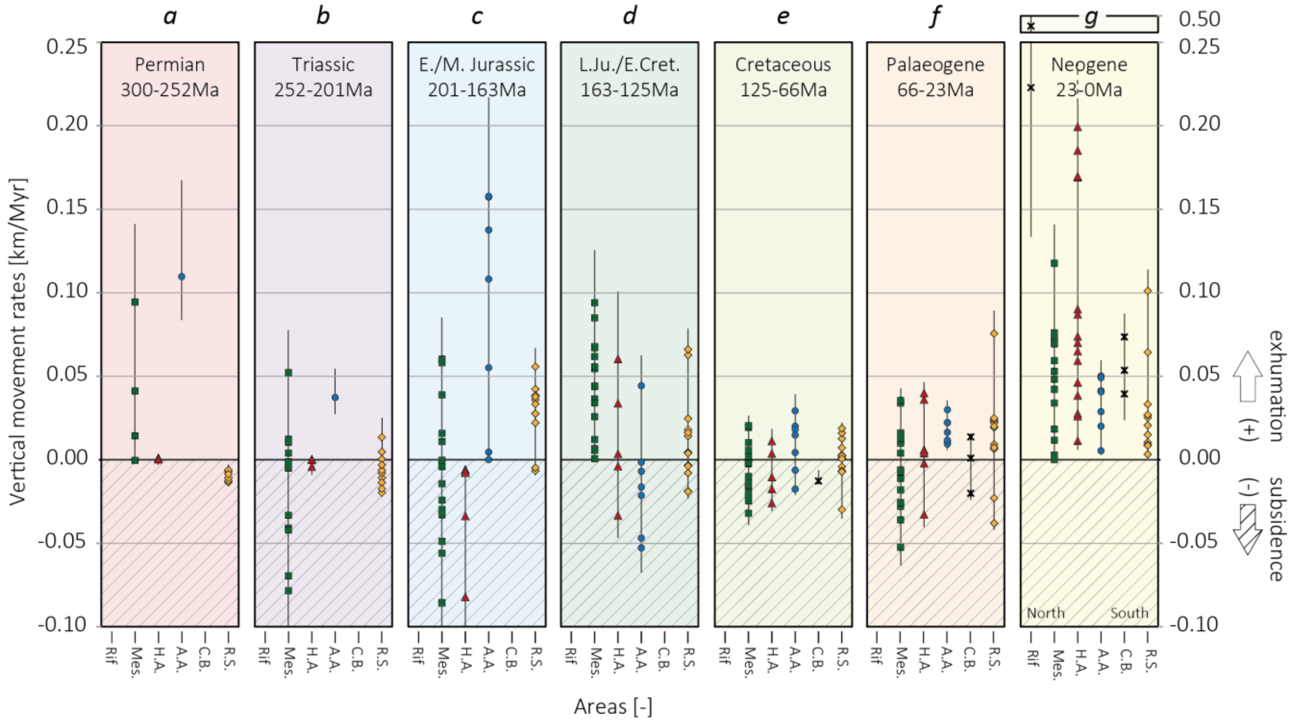

(A)
Rif (n=2)
(B)
Meseta (n=16)
Central M.
Rehamna
Jebilets
(C)
High Atlas (n=15)
Northern Sub-Atlas
Massif Ancien
(D)
Anti-Atlas (n=7)
Eastern AA
Central AA
Western AA
(E)
Mesozoic basins (n=3)
Coastal Anti-Atlas margin
North Tarfaya basin
(F)
Reguibat (n=13)
Western RS
Central RS
Eastern RS
Relative depth (overburden) [km]
Time [Ma]
0
2
4
6
8
300
250
200
150
100
0

Figure 5



a
b
c
d
e
f
g
Permian 300-252Ma
Triassic 252-201Ma
E./M. Jurassic 201-163Ma
L.Ju./E.Cret. 163-125Ma
Cretaceous 125-66Ma
Palaeogene 66-23Ma
Neogene 23-0Ma
Vertical movement rates [km/Myr]
0.50
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
exhumation (+)
(-) subsidence
North
South
Rif
Mes.
H.A.
A.A.
C.B.
R.S.
Areas [-]

Figure 6

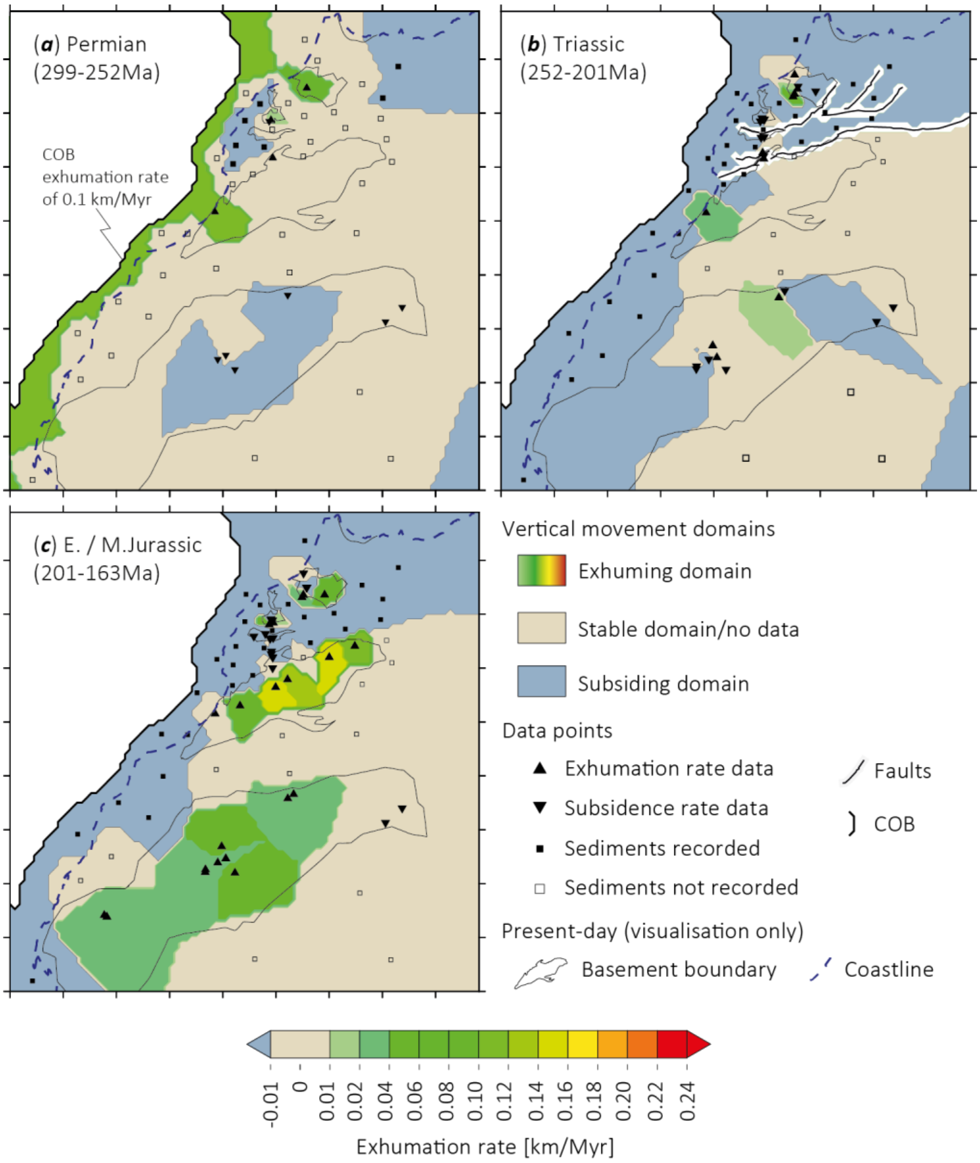

(a) Permian
(299-252Ma)
COB
exhumation rate
of 0.1 km/Myr
(b) Triassic
(252-201Ma)
(c) E. / M.Jurassic
(201-163Ma)
Vertical movement domains
Exhuming domain
Stable domain/no data
Subsiding domain
Data points
Exhumation rate data
Subsidence rate data
Sediments recorded
Sediments not recorded
Faults
COB
Present-day (visualisation only)
Basement boundary
Coastline
-0.01
0
0.01
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
Exhumation rate [km/Myr]

Figure 7

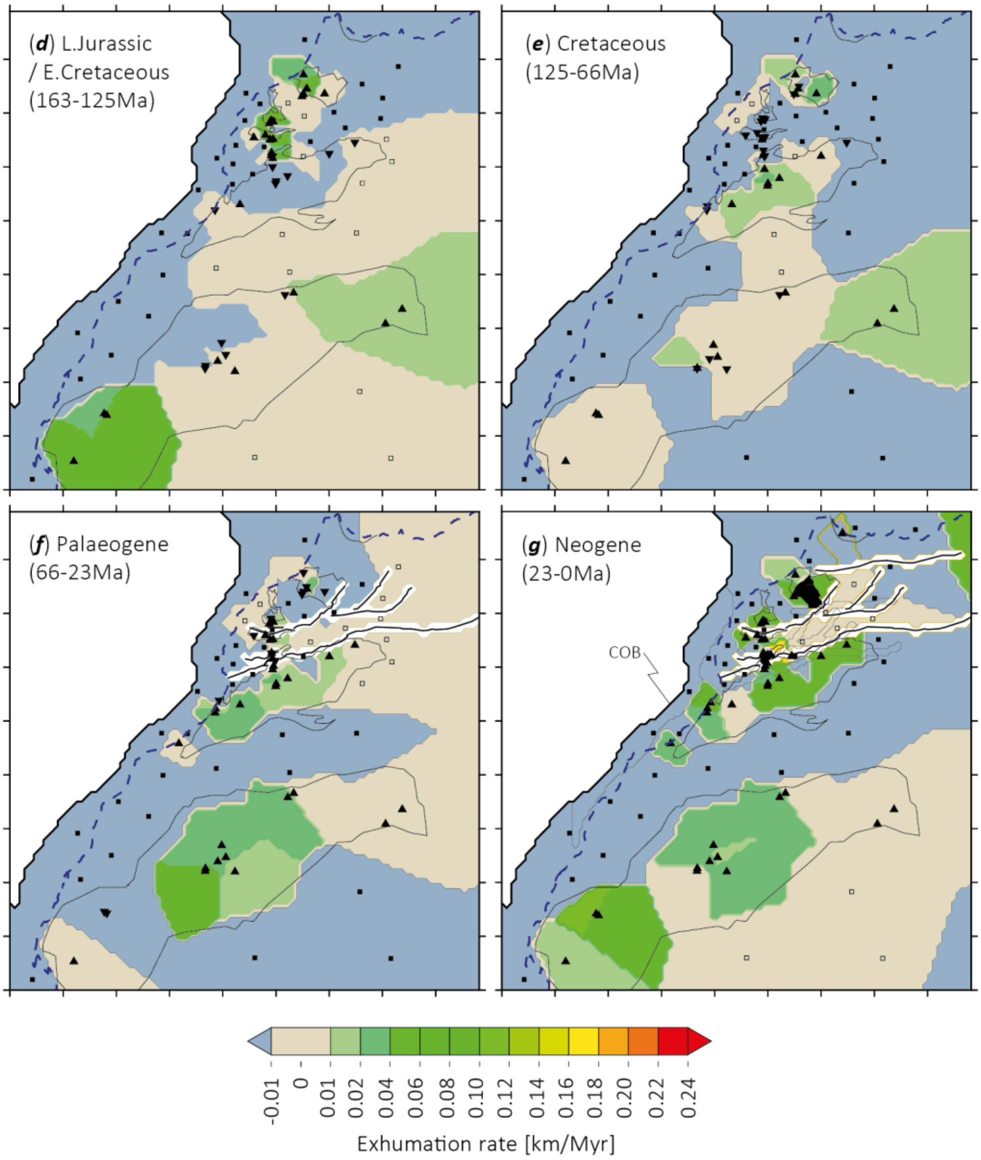


Figure 7 (continued)

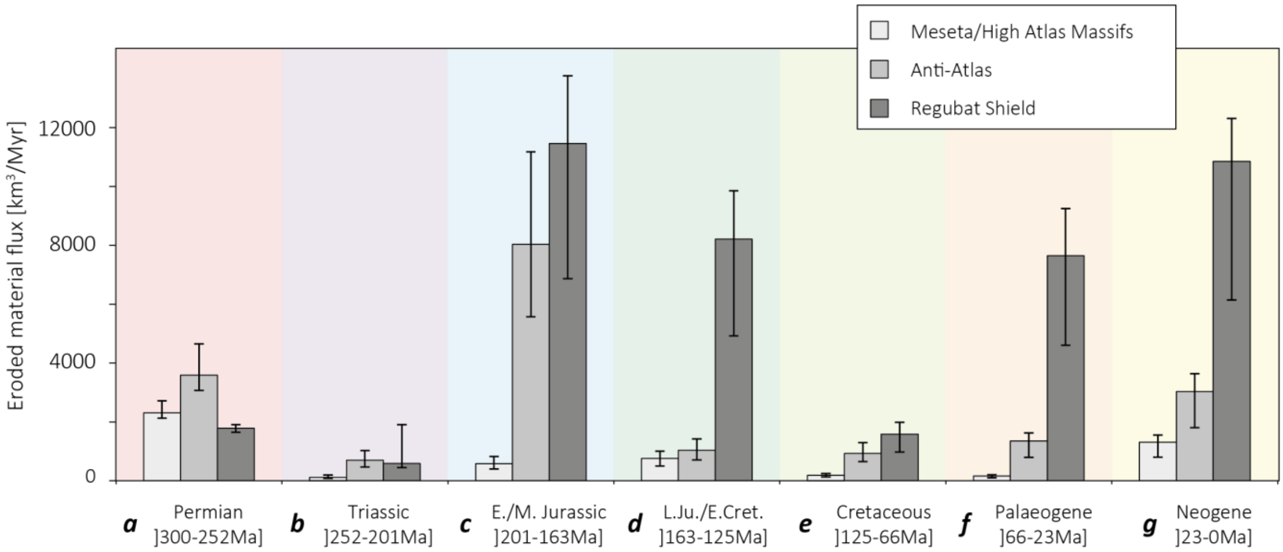

Meseta/High Atlas Massifs
Anti-Atlas
Regubat Shield
Eroded material flux [km³/Myr]
12000
8000
4000
0
a Permian]300-252Ma]
b Triassic]252-201Ma]
c E./M. Jurassic]201-163Ma]
d L.Ju./E.Cret.]163-125Ma]
e Cretaceous]125-66Ma]
f Palaeogene]66-23Ma]
g Neogene]23-0Ma]

Figure 8

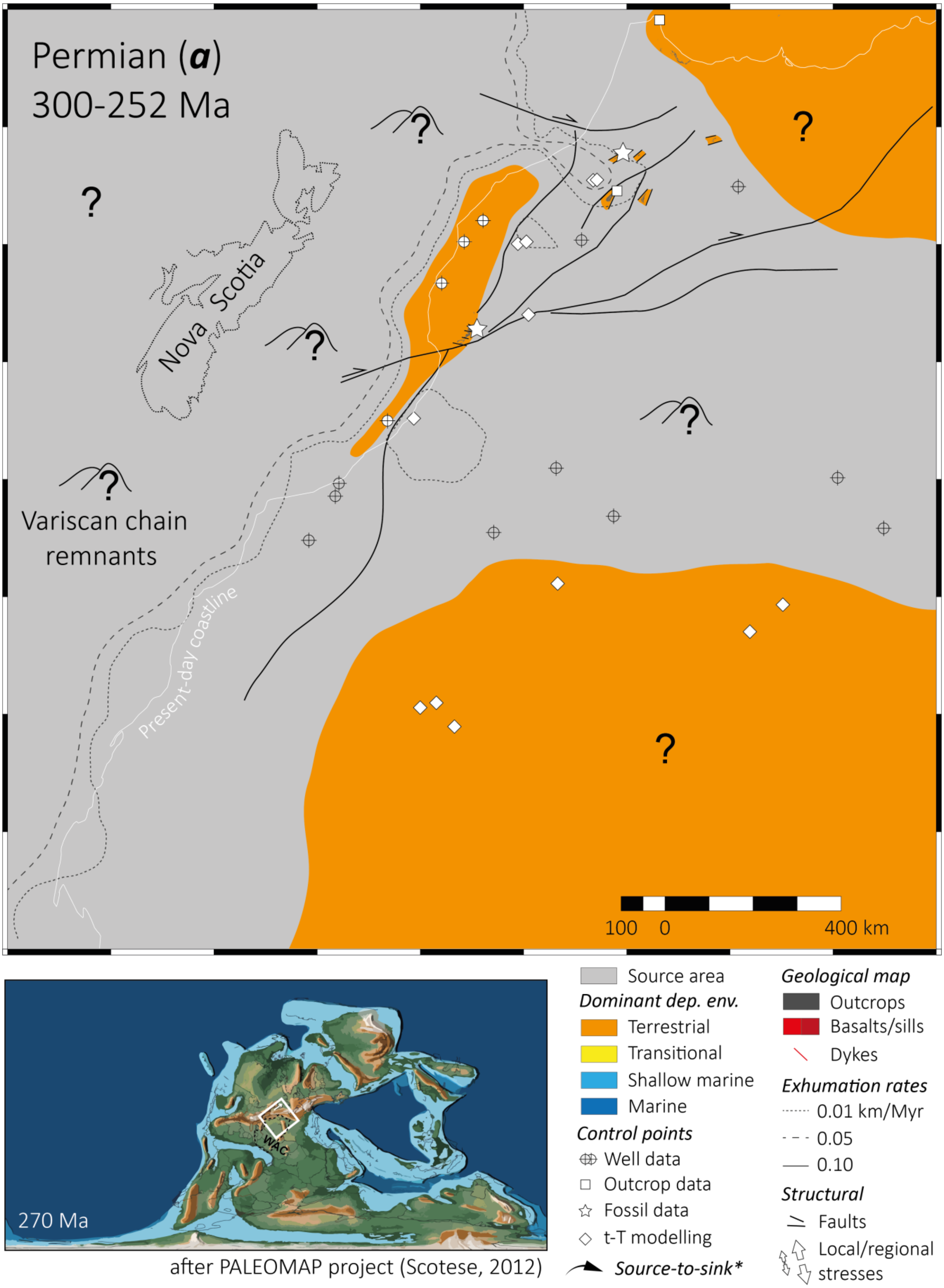
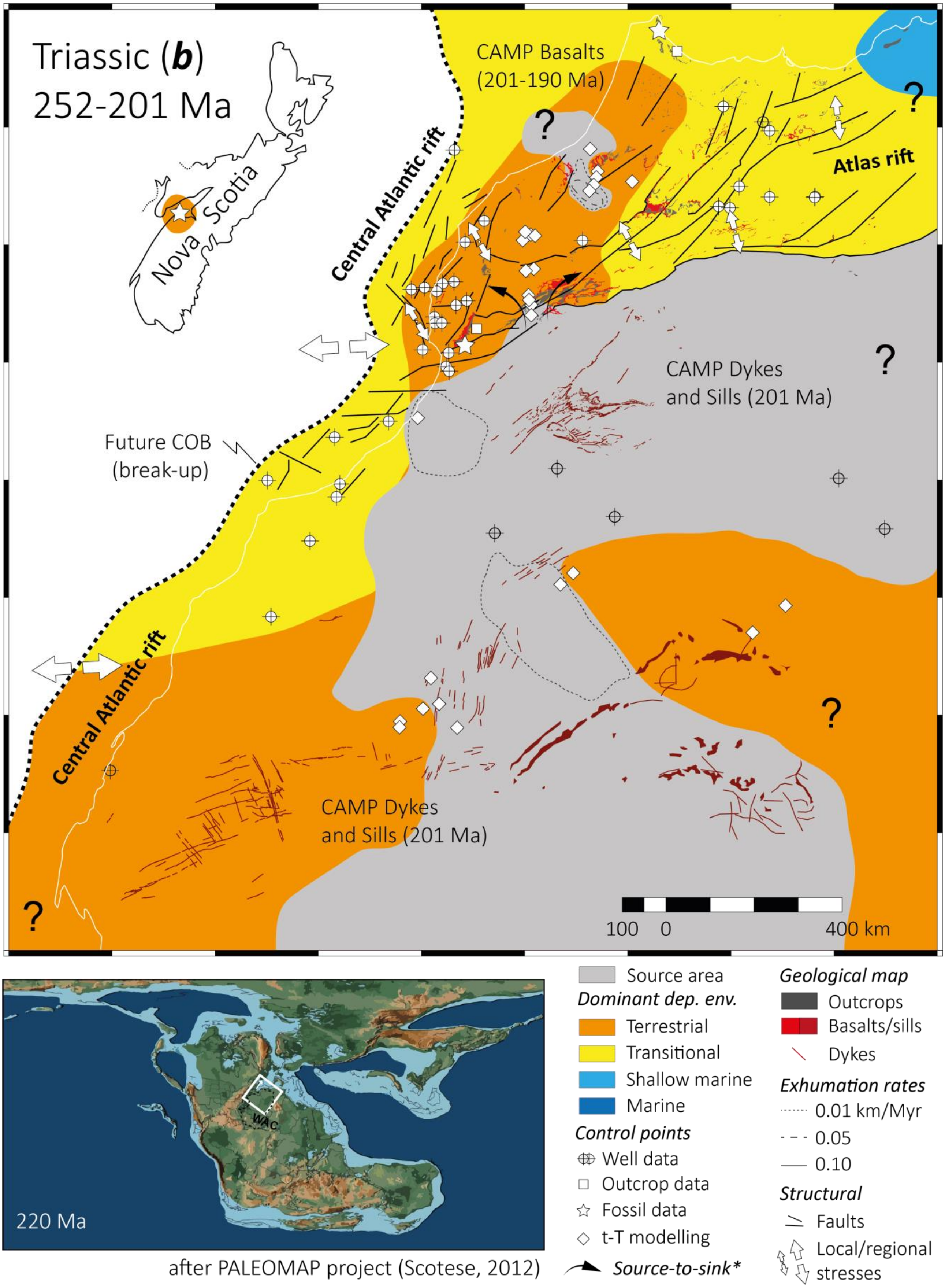
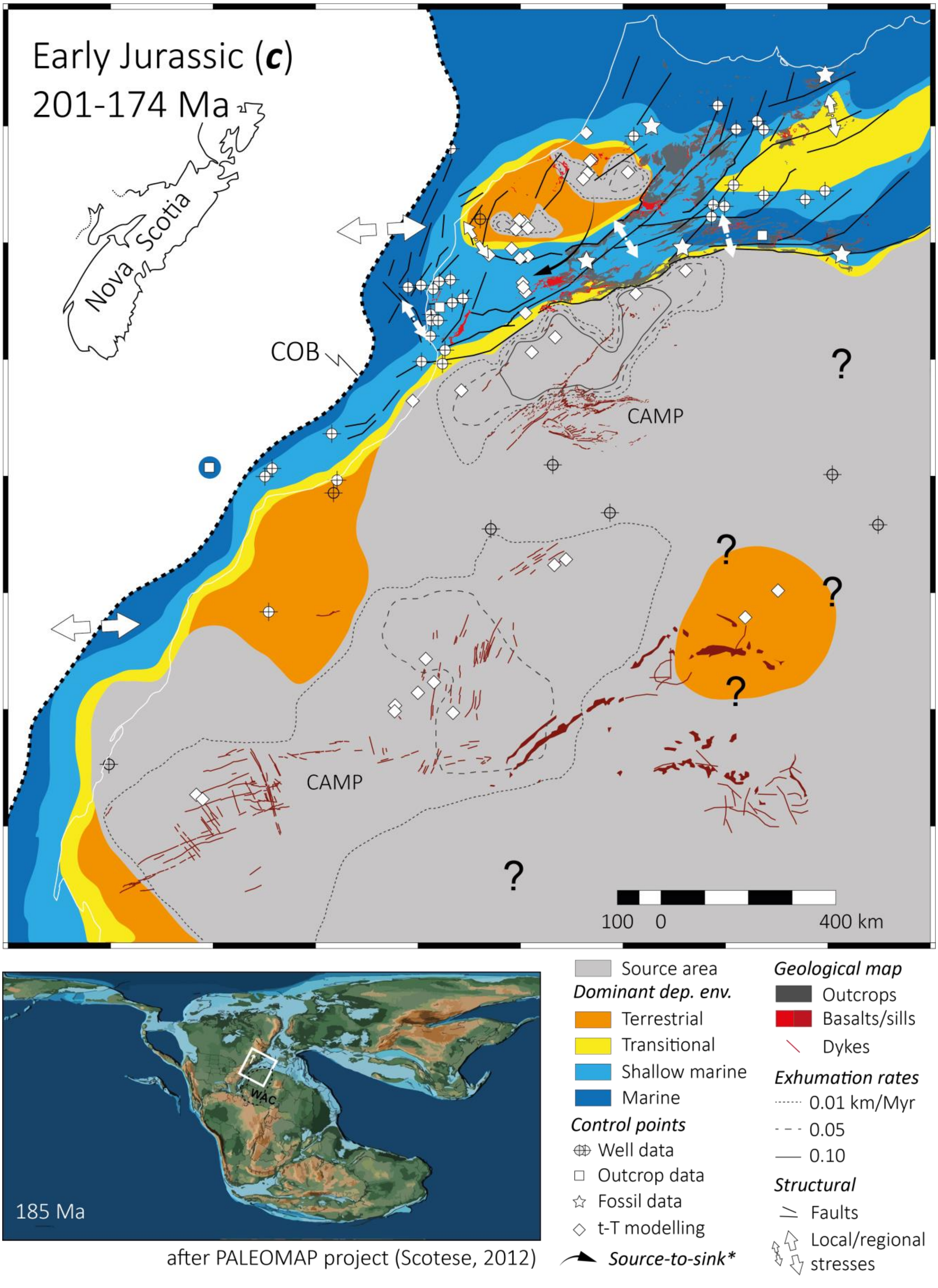

Permian (a)
300-252 Ma
?
Nova Scotia
Variscan chain
remnants
Present-day coastline
100 0 400 km
270 Ma
WAC
after PALEOMAP project (Scotese, 2012)
Source area
Dominant dep. env.
Terrestrial
Transitional
Shallow marine
Marine
Control points
Well data
Outcrop data
Fossil data
t-T modelling
Source-to-sink*
Geological map
Outcrops
Basalts/sills
Dykes
Exhumation rates
0.01 km/Myr
0.05
0.10
Structural
Faults
Local/regional
stresses

Figure 9



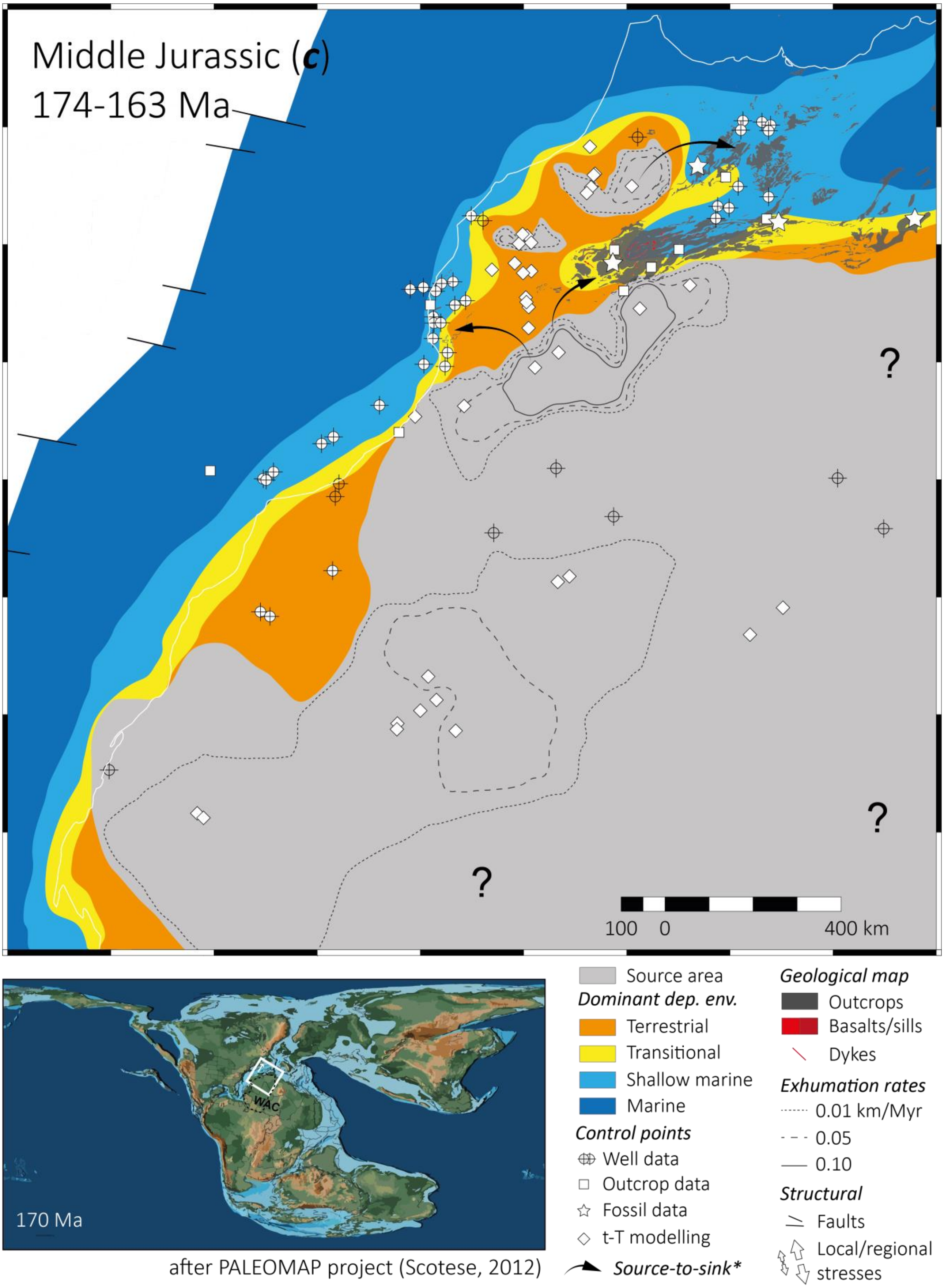
after PALEOMAP project (Scotese, 2012)

Figure 10



after PALEOMAP project (Scotese, 2012)

Figure 11



after PALEOMAP project (Scotese, 2012)

Figure 12

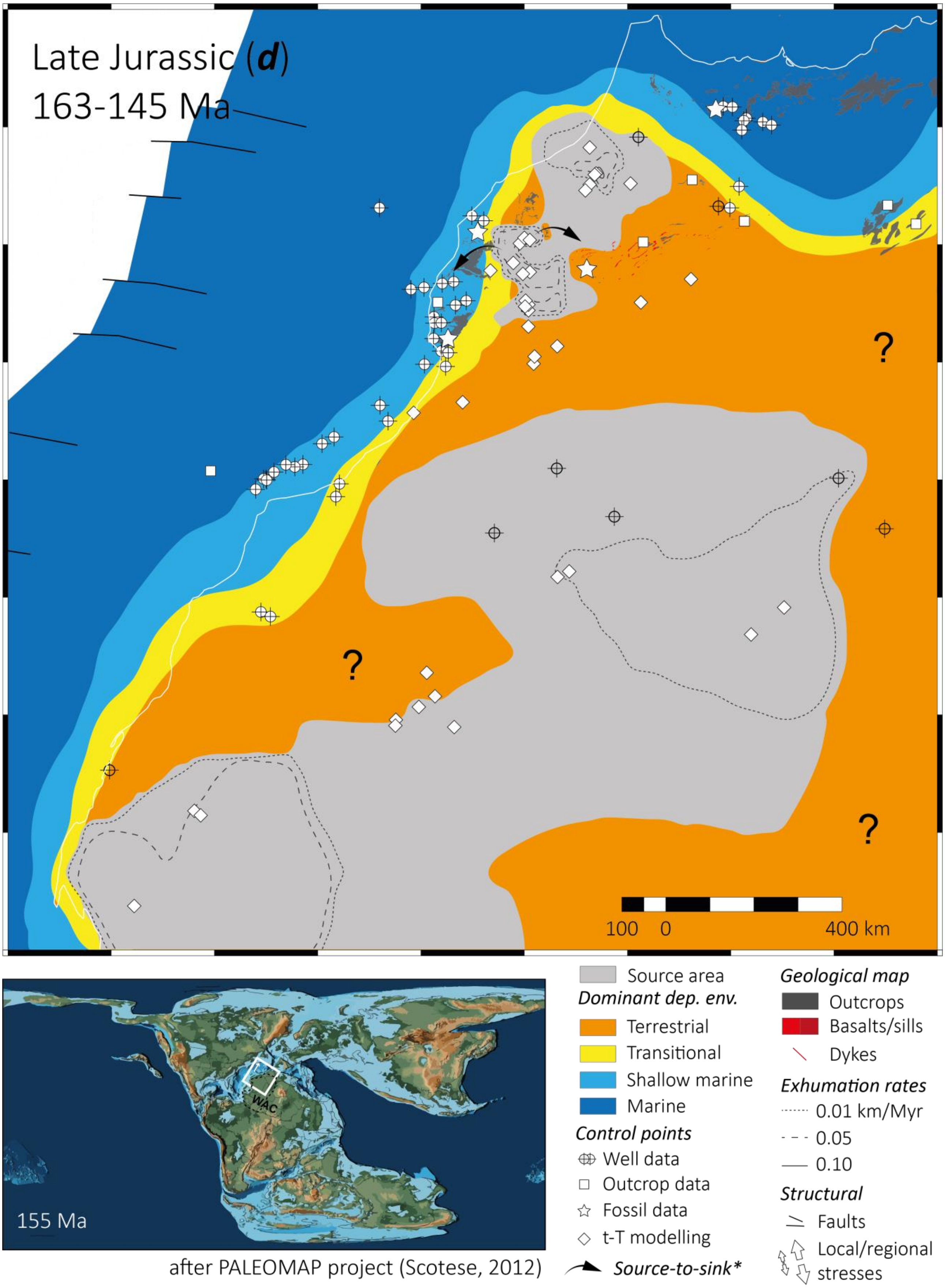
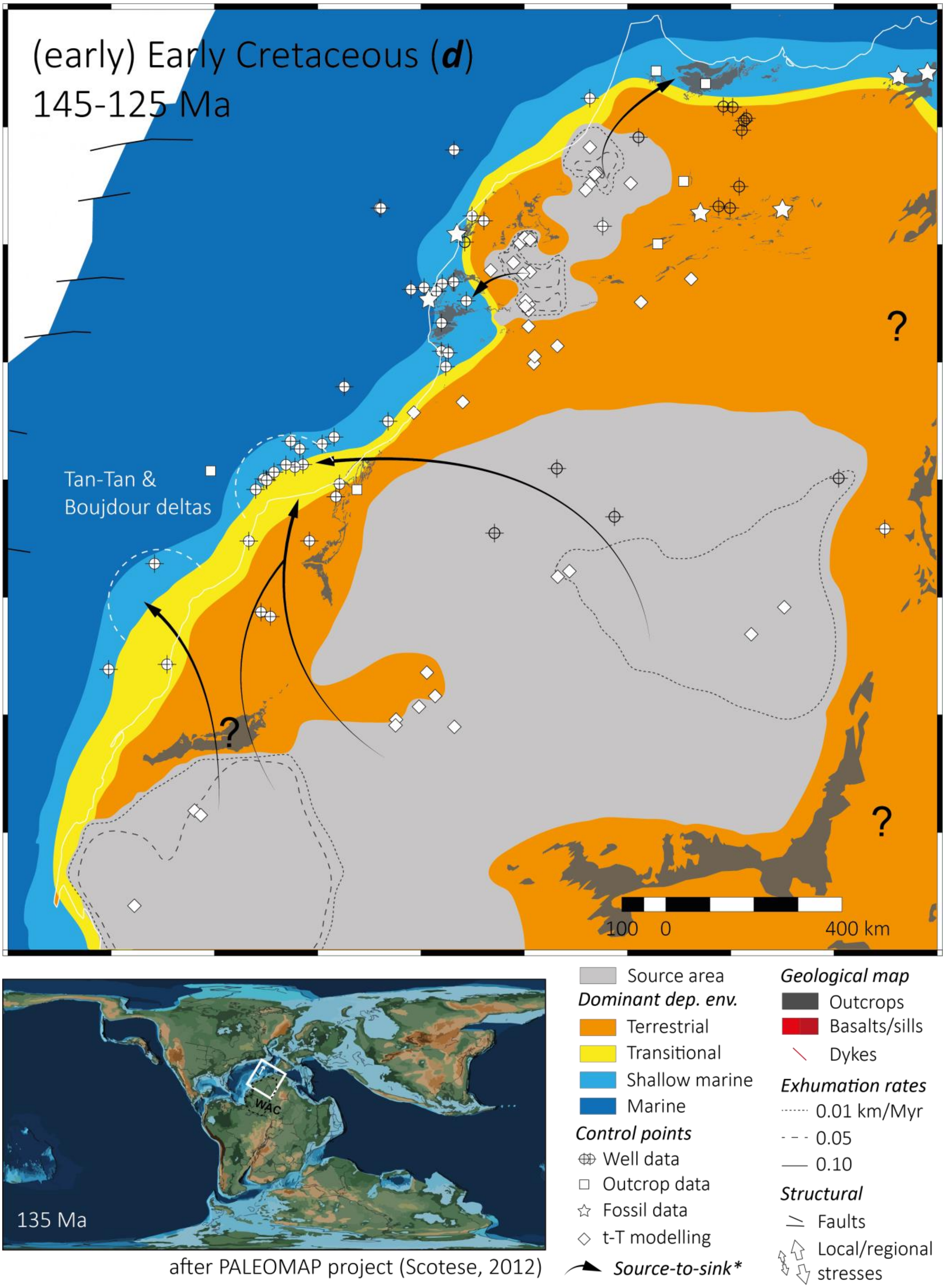
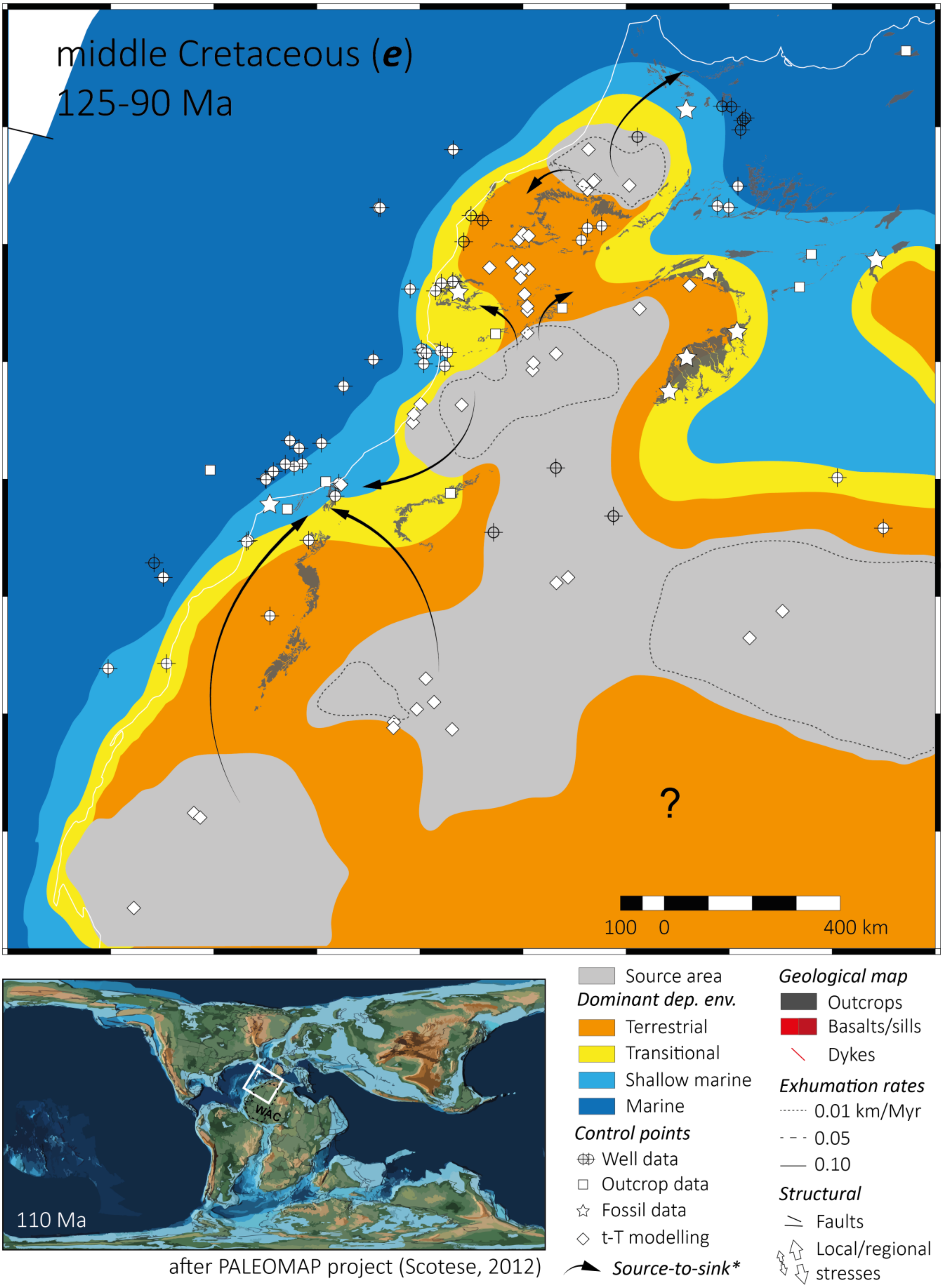

Late Jurassic (*d*)
163-145 Ma
?
?
?
100 0 400 km
155 Ma
WAC
after PALEOMAP project (Scotese, 2012)
Source area
Dominant dep. env.
Terrestrial
Transitional
Shallow marine
Marine
Control points
Well data
Outcrop data
Fossil data
t-T modelling
Source-to-sink*
Geological map
Outcrops
Basalts/sills
Dykes
Exhumation rates
0.01 km/Myr
0.05
0.10
Structural
Faults
Local/regional stresses

Figure 13



(early) Early Cretaceous (d)
145-125 Ma
Tan-Tan &
Boujdour deltas
?
?
?
100 0 400 km
135 Ma
WAC
after PALEOMAP project (Scotese, 2012)
Source area
Dominant dep. env.
Terrestrial
Transitional
Shallow marine
Marine
Control points
Well data
Outcrop data
Fossil data
t-T modelling
Source-to-sink*
Geological map
Outcrops
Basalts/sills
Dykes
Exhumation rates
0.01 km/Myr
0.05
0.10
Structural
Faults
Local/regional
stresses

Figure 14



middle Cretaceous (*e*)
125-90 Ma
?
100 0 400 km
110 Ma
WAC
after PALEOMAP project (Scotese, 2012)
Source area
Dominant dep. env.
Terrestrial
Transitional
Shallow marine
Marine
Control points
Well data
Outcrop data
Fossil data
t-T modelling
Source-to-sink*
Geological map
Outcrops
Basalts/sills
Dykes
Exhumation rates
0.01 km/Myr
0.05
0.10
Structural
Faults
Local/regional stresses

Figure 15

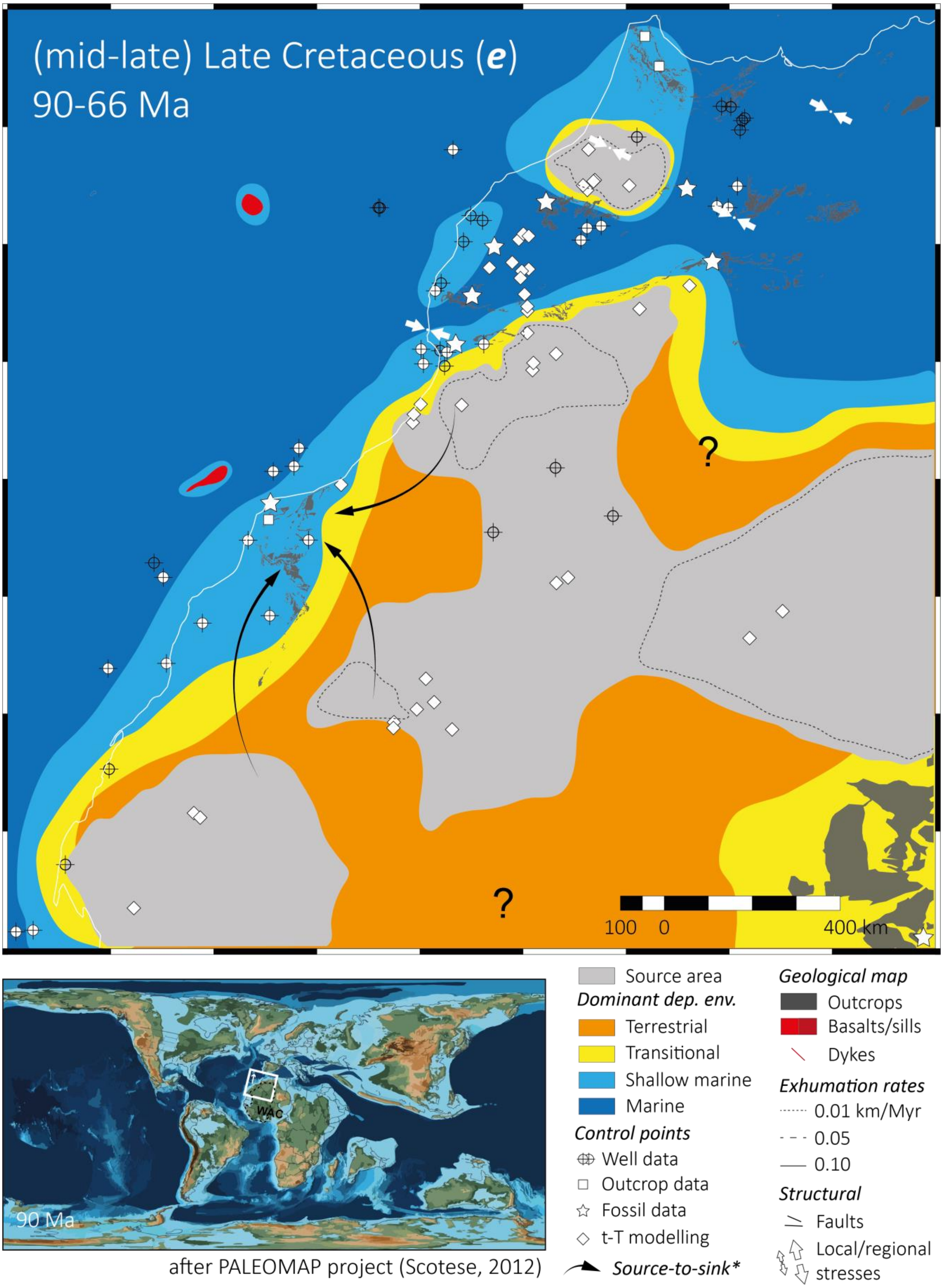
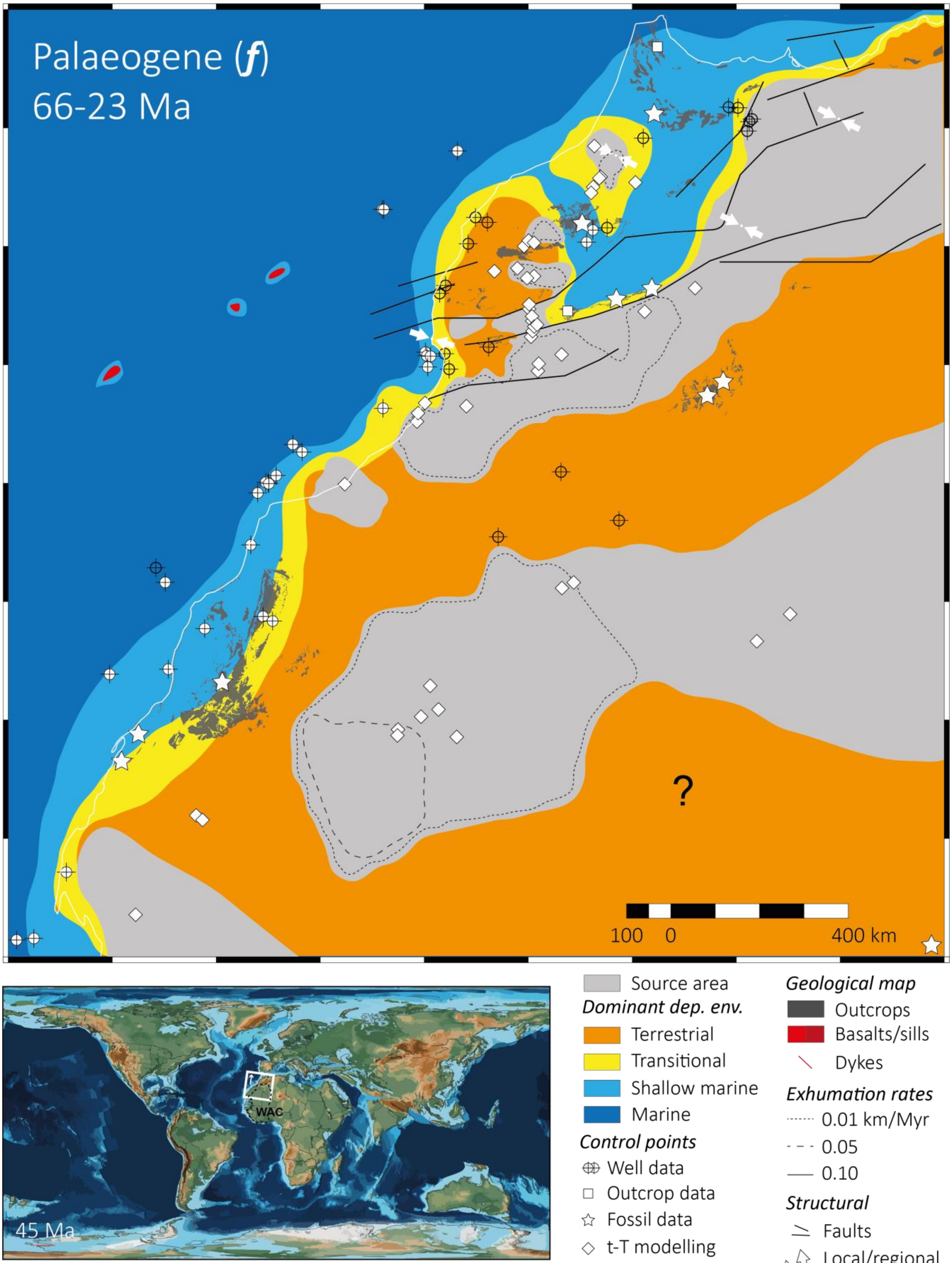
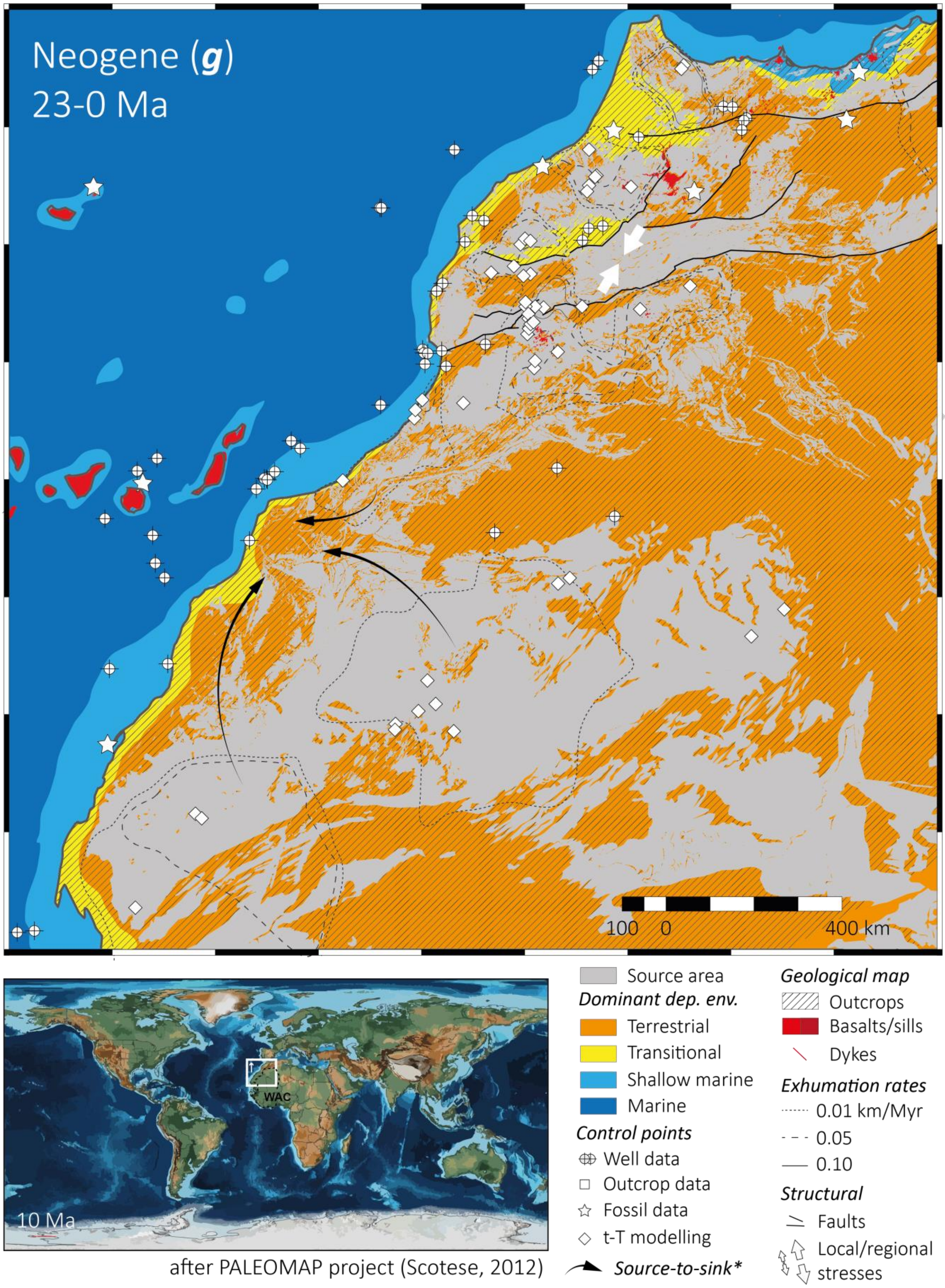

(mid-late) Late Cretaceous (e)
90-66 Ma
?
?
100 0 400 km
90 Ma
WAC
after PALEOMAP project (Scotese, 2012)
Source area
Dominant dep. env.
Terrestrial
Transitional
Shallow marine
Marine
Control points
Well data
Outcrop data
Fossil data
t-T modelling
Source-to-sink*
Geological map
Outcrops
Basalts/sills
Dykes
Exhumation rates
0.01 km/Myr
0.05
0.10
Structural
Faults
Local/regional stresses

Figure 16



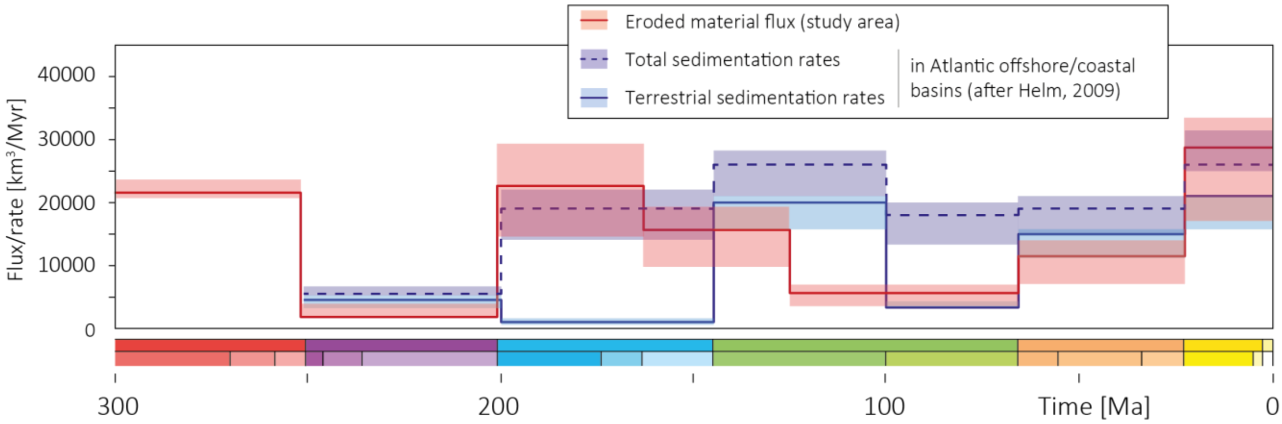
after PALEOMAP project (Scotese, 2012)

Figure 17



after PALEOMAP project (Scotese, 2012)

Figure 18



Eroded material flux (study area)
Total sedimentation rates
Terrestrial sedimentation rates
in Atlantic offshore/coastal basins (after Helm, 2009)
Flux/rate [km³/Myr]
40000
30000
20000
10000
0
300
200
100
Time [Ma]
0

Figure 20

Appendix A: From time-Temperature models to eroded material fluxes

A.1. The use of geological and radiometric t-T model constraints in Morocco and surroundings

The conclusion reached in nearly all t-T studies, conducted in Morocco and surroundings, including our previous work (e.g. Bertotti and Gouiza, 2012; Charton et al., 2018), is that samples with cooling ages younger than their stratigraphic ages record vertical movements. This allows cooling and heating events to be translated into exhumation and subsidence, respectively. The exceptions to this general conclusion are the results from samples collected in the Canary Islands (Wipf et al., 2010) and in the Siroua massif (e.g. Ghorbal, 2009), for which a Cenozoic thermal event is assumed to reset the LTT ages.

The age depth/temperature geological constraints added to t-T modelling between 300 and 0 Ma are discussed in this Appendix. In the study area, two types of geological constraints are used: 1) sediments are overlying the sampled basement, with or without an erosion gap, provide a constraint to surface temperatures (ca. 10-40°C) for the estimated time of deposition. In the case of detrital thermochronology, the stratigraphic age of the sampled sediments is used as a constraint, also at surface temperatures. 2) when the age and temperatures of emplacement or metamorphism of the sampled basement are known, a corresponding radiometric constraint is implemented.

In the Rif belt, Pliocene sediments and Miocene $^{40}Ar/^{39}Ar$ and K-Ar radiometric dating were used as constraints (Romagny et al., 2014; Azdimousa et al., 2013). In the Meseta, constraints based on the Variscan granite emplacement and Permian, Triassic, and Cenomanian sedimentary record in the basins surroundings the Variscan massifs were added to the t-T modelling (Saddiqi et al., 2009, Ghorbal et al., 2008; Barbero et al., 2011). In the Variscan High Atlas (Massif Ancien), Triassic and poorly dated Early Cretaceous sediments overlying Precambrian basement rocks permitted authors to add surface-temperature constraints to the models (Ghorbal, 2009; Balestrieri *et al* 2008; Barbero et al., 2007; Domenech et al., 2016). In the central Anti-Atlas, emplacement data from the Jurassic intrusive rocks served as a constraint (Barbero et al., 2007). In the Tarfaya basin, Sehrt et al. (2017b) used the Aptian and Albian stratigraphic age of sampled sediments for the t-T modelling. In the Reguibat Shield, a geological constraint at surface temperatures was defined for the Early/Middle Cretaceous, as sediments (poorly dated) are exposed in the Tarfaya and Tindouf basins (Leprêtre et al., 2013; 2015; 2017). In the eastern Reguibat Shield, the poorly dated Upper Cretaceous sediments of the Reggane basin were used to guide t-T models (Leprêtre et al., 2017). Overall, these studies used t-T model constraints fairly consistently.

The Variscan metamorphism (Ruiz et al., 2011, Charton et al., 2018, Malusà et al., 2007) and the emplacement of the CAMP dykes (see Gouiza et al., 2017) were used as geological constraints. The Triassic sediments in the north of the belt (Ghorbal, 2009), Middle Jurassic sediments (Charton et al., 2018), poorly dated terrestrial Infra-Cenomanian sediments in the western, central, and eastern Anti-Atlas (e.g. Ruiz et al., 2011; Oukassou et al., 2013) and Cenomanian fluvial sediments overlying the Variscan basement on the eastern Anti-Atlas (Gouiza et al., 2017) were used as evidence of the presently outcropping Anti-Atlas basement rocks being close to surface temperatures.

However, comparison between t-T models of the Anti-Atlas suggests major discrepancies (Gouiza et al., 2017; fig. 4D). One of the aspects of the modelling, to which these discrepancies can be attributed, is the use of different t-T modelling constraints. Despite the established use of an Early Cretaceous modelling constraint in the Anti-Atlas (Ruiz et al., 2011; Oukassou et al., 2013; Sehrt et al., 2017a), re-dating means less and less of the terrestrial beds around the belt are still considered as Lower Cretaceous (reviewed in Gouiza et al., 2017; Charton et al, 2018). In the eastern part of the belt, extensive paleontological work conducted by Benyoucef and co-authors showed that the red beds are Cenomanian (e.g. Benyoucef et al., 2015). In the central Anti-Atlas, no recent study on the local undifferentiated clastics has been conducted, but a time constraint is the Cenomanian limestones positioned higher in the stratigraphic column (e.g. Fetah et al., 1990). The clastics could hence be Cenomanian in age, similarly to the sediments in eastern Anti-Atlas. Finally, in the western Anti-Atlas, recent work by Arantegui (2018) presents new biostratigraphic data that conclusively dates the local redbeds, also mapped as Lower Cretaceous, as Bathonian (Middle Jurassic) or older (most-likely Triassic or Liassic). Overall, this invalidates the use of an Early Cretaceous constraint that was previously used to guide basement rock surface temperatures in the Anti-Atlas close. In this work, we consider as valid all of the abovementioned new modelling constraints used for the Anti-Atlas, and disregard the previous Early Cretaceous surface temperatures geological constraint.

A.2. Data selection and temperature-to-depth conversion

Weighted average/expected curves were digitized when available (else the best-fit/maximum likelihood curves) using WebPlotDigitizer (Ankit Rohatgi; https://automeris.io/WebPlotDigitizer/). We applied five conditions to select representative and valid t-T curves, resulting in a total of 56 selected t-T curves (detailed in table A1). We consider that modelling results have to i) start before 20 Ma (about the extent of youngest considered period), ii) be based on HeFty, AFT solve or QTQt results, iii) if different models using the same LTT data exist, be from the most recent realizations (e.g. in Leprêtre et al., 2013 and Leprêtre, 2015), iv) should be based on one sample and not several as for vertical profiles (justified by the fact that we are use punctual measurements allowing for spatial interpolation), and v) be compatible with the geological history of each region as discussed in the previous paragraphs.

To achieve the temperature-to-depth conversion (fig. 5), different geotherms were used based on the location of the selected t-T curves (fig. A2) and keeping the surface temperature constant at 20°C. The considered geothermal gradients are based on several studies, which serve as analogues for the past geodynamic setting in Morocco. Luth and Willingshofer (2008; see references therein) obtained geothermal gradients of 23-35°C/km for the Alps. Based on these values, we considered an average geotherm of 29°C/km for the Variscan orogeny. The geotherm in the rift zone of the East African Rift system is ca. 40°C/km (van der Beek et al., 1998) and between 25 and 32°C/km in the Rio Gande Rift (Bridwell, 1976). We consider a geotherm of 34°C/km as representative for the High Atlas Rift zone. The flanks of the East African Rift systems display geothermal gradients between 25 and 30°C/km (van der Beek et al., 1998) and we use 27°C/km as an analogue for the Central Atlantic/High Atlas rift flanks.

Lastly, Zarhloule (2004) obtained present-day values from Moroccan Passive margin of 20 to 35°C/km. As an analogue for the post-rift Moroccan passive margin at 80 Ma (mature passive margin) and for intra-continental domain of the Reguibat Shield, we considered a geotherm of 24°C/km. The selected geotherms take into account the thermal relaxation that follows after the rift-related heating phase.

To estimate the range of depth-converted results, we used two constant geotherms of 20 and 40°C/km. Both values are realistic, given the present-day values of geothermal gradients in Morocco, and are consider in this case as end-member values. The low and high constant geotherms, applied to the digitized temperature envelopes, consistently yield the maximum and minimum depths throughout the considered period of time, respectively (cf. dashed lines in figure 6).

A.3. Exhumation maps and eroded material fluxes

Data points for of the exhumation maps consist of the exhumation and subsidence rates calculated using the variable geotherms. For the computation of volume ranges, we use rates obtained by using the previously defined constant geotherms of 20 and 40°/km temperature range converted to depth.

The dataset, composed of vertical movement rates, is characterised by dense data (basement massifs in Meseta/Anti-Atlas) and sparse data areas (Reguibat Shield). Data clusters are separated by preserved basins for which no LTT/t-T results are available. To add geological meaning to the exhumation maps, by including documented subsiding areas, we added synthetic points on the basis of computed stratigraphic columns, which are compiled in figure **B**. For each preserved sedimentary basin, up to four points were created depending on the extent of the area. If sediments were deposited during one of the selected periods and are still preserved in a basin, we attribute a negative rate to all the synthetic points of this basin. When sediments are not recorded in a basin, because they were not deposited or not preserved, we attribute to synthetic points a rate of 0 km/Myr.

More synthetic points are needed away from the present day coastline, in order to guide the interpolation while retaining geological meaning. To this end, the Continental-Ocean Boundary (COB; Miles et al., 2012) is used as a boundary to yield synthetic exhumation/subsidence rates. Prior to the Jurassic, there was oceanic crust being generated, and therefore no COB. Nevertheless, for the Permian and Triassic (periods ***a*** and ***b***), we consider a similar position for the boundary location in order to yield synthetic rates. For the Permian, the COB line is attributed an exhumation rate of 0.1 km/Myr. This is to account for the collapse (peneplain) of the Variscan chain, which is documented in Morocco as occurring somewhere between the Carboniferous and the Triassic (e.g. Michard et al., 2008). Exhumation rates during post-orogenic collapse have been used in other published models and documented between 0.15 and 0.7 km/Myr (e.g. Clift et al., 2004; Mazzoli et al., 2010; Casini et al., 2015). We consider in this study a lower exhumation rate of 0.1 km/Myr, comparable to the highest rate we calculated for the Permian (period ***a***). From the Triassic onwards (periods ***b*** to ***g***), we attributed a subsidence rate to the COB of -0.011 km/Myr. This is equivalent to adding a number of synthetic points with subsiding rates, as above-defined, in the slope or basinal domains. These values are not necessarily realistic, but acceptable as this area is not the focus of study.

For the interpolation of the vertical movement rates, we use the nearest neighbour algorithm (available in Surfer version 8; Golden Software, Inc.). This algorithm is simple to implement, with an interpolation grid that can be extended across the entire study area, and allows for the addition of faults. The interpolation grid extends from 0 to -18°W and 20 to 36°N (112x100 lines with fixed spacing) and ends at the COB in the west. For the Triassic, Palaeogene, and Neogene periods (***b***, ***f***, and ***g***, respectively), the Atlas system faults (whether they were normal or inverse faults) are added as boundaries for the interpolation (after geological map in Frizon de Lamotte et al., 2004).

The "Nearest Neighbor" is a fairly simple approach, but it has some limitations as it gives better results with regularly spaced data points. In addition, the algorithm does not extrapolate the rates above and below input values. The interpolated rates are calculated from the closest data/synthetic points. When located exactly in the middle, between two points, the lowest value will be attributed to the interpolated rates, which is most-likely responsible for artefacts observed in the exhumation maps (fig. 7). These artefacts are illustrated by narrow zones with important changes of rates over short distances.

Volume calculations of eroded material per million years (km^3/Myr; eroded material flux) are performed with the Surfer software between the interpolated surface and a plane characterised by a null motion rate (0 km/Myr). The volumes are also separately calculated, by masking other areas, for three regions of substantial interest: the Meseta, the High Atlas, the Anti-Atlas, and the Reguibat Shield.

Table A1. Selection of t-T models for temperature-to-depth conversion and for exhumation and subsidence rate calculations. Conditions: The t-T modelling results had to i) start before 20Ma, ii) be based on HeFty, AFT solve or QTQt results, iii) for different models based on the same LTT data, be from the most recent and published realizations, iv) should be based on one sample (as opposed to vertical profiles), and v) be compatible with the geological evidences discussed in the text.

Figure A1. Geothermal gradients used for the depth conversion of the t-T curves. ***Geotherms****: Geothermal gradients documented in literature, from present-day or recent settings similar to ones in Moroccan geological past. See description of the geotherms considered as analogues in the text of Appendix A.*

*Figure A2. Simplified stratigraphic columns. The hatched parts highlight continental facies and/or coarse to very coarse clastic deposits. The name of the corresponding Variscan/Precambrian basement is shown below the unconformity surfaces (****MS****: Meseta,* ***HA****: High Atlas,* ***AA****: Anti-Atlas, and* ***RS****: Reguibat shield basements). The seven selected periods (****a*** *to* ***g****) are shown on the left. *Late Cretaceous in the Tindouf basin is present in the eastern and western parts, but not in its central part (Hollard et al., 1985).*

t-T modelling studies	Locations	Stratigraphic age (sample)	t-T modelling software	t-T models (n=117)	Failed to meet conditions					t-depth models (n=56)
					i	ii	iii	iv	v	
Sabil, 1995	Meseta	Palaeozoic	Gallagher et al. (1993)	4	.	4	.	.	.	0
Barbero *et al.,* 2007	High Atlas	Pal-Meso-Ceno	AFT-Solve	3						
Malusa *et al.,* 2007	Anti-Atlas	PC-Pal	HeFTy	3	.	.	.	.	3	0
Ghorbal *et al.,* 2008	Meseta	Palaeozoic	HeFTy	4	.	.	.	.	.	4
Balestrieri *et al.,* 2009	Anti-Atlas	Precambrian	HeFTy	2	.	.	.	.	2	0
Ghorbal , 2009	High Atlas	Pc-Pal-Meso	HeFTy	23	1	.	.	.	4	18
Saddiqi *et al.,* 2009	Meseta	Palaeozoic	AFT-Solve	4	.	.	.	.	.	4
Barbero *et al.,* 2011	Meseta	Palaeozoic	HeFTy	5	.	.	.	.	.	5
Ruiz *et al.,* 2011	Anti-Atlas	Precambrian	HeFTy	5	.	.	.	.	5	0
Sebti, 2011	Anti-Atlas	Precambrian	HeFTy	4	.	.	.	.	4	0
Azdimousa *et al.,* 2013	Rif	Palaeozoic	HeFTy	2	1	.	.	.	.	1
Lepretre *et al.,* 2013	Reguibat Shield	Precambrian	HeFTy	4	.	.	4	.	.	0
Oukassou *et al.,* 2013	Anti-Atlas	Precambrian	HeFTy	2	.	.	.	.	2	0
ElHaimer, 2014	Massif Ancien	Palaeozoic	HeFTy	1						
Romagny *et al.,* 2014	Rif	Palaeozoic	QTQt	2	1	.	.	.	.	1
Sehrt, 2014	Tarfaya and Anti-Atlas	Meso-Ceno and Precambrian	HeFTy	24	.	.	.	.	14	2
Domenech, 2015	Massif Ancien	PC-Pal	QTQt	3	.	.	.	3	.	0
Lepretre, 2015	Reguibat Shield	Precambrian	QTQt	14	.	.	.	.	1	13
Gouiza *et al.,* 2017	Anti-Atlas	Precambrian	HeFTy	6	.	.	.	.	.	6
Charton *et al.,* 2018	Anti-Atlas	PC-Meso	HeFTy	2	.	.	.	.	.	2

Table A

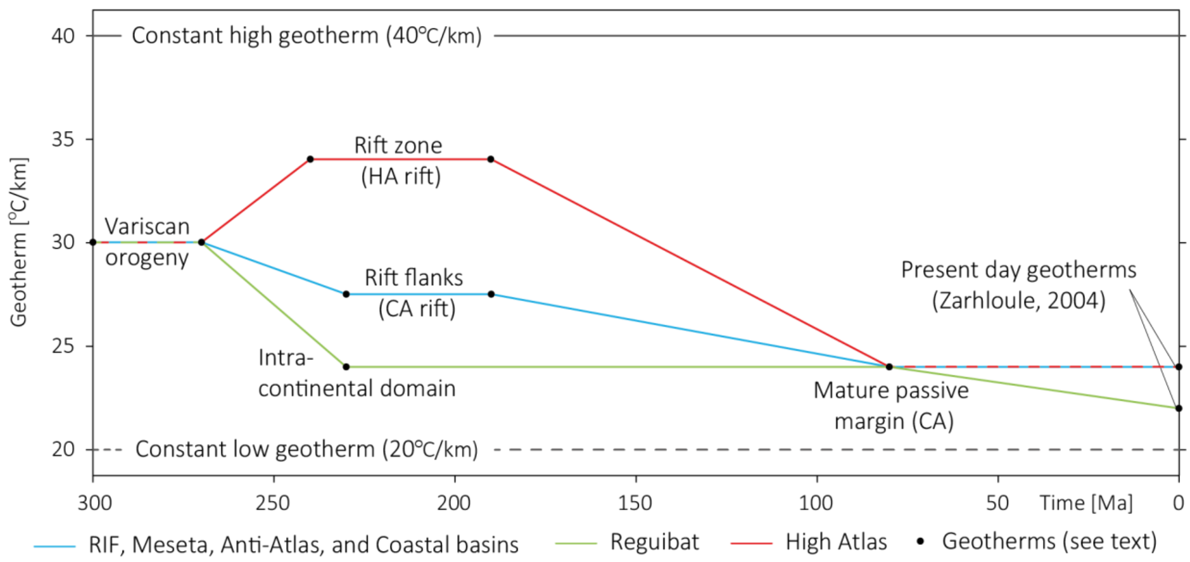
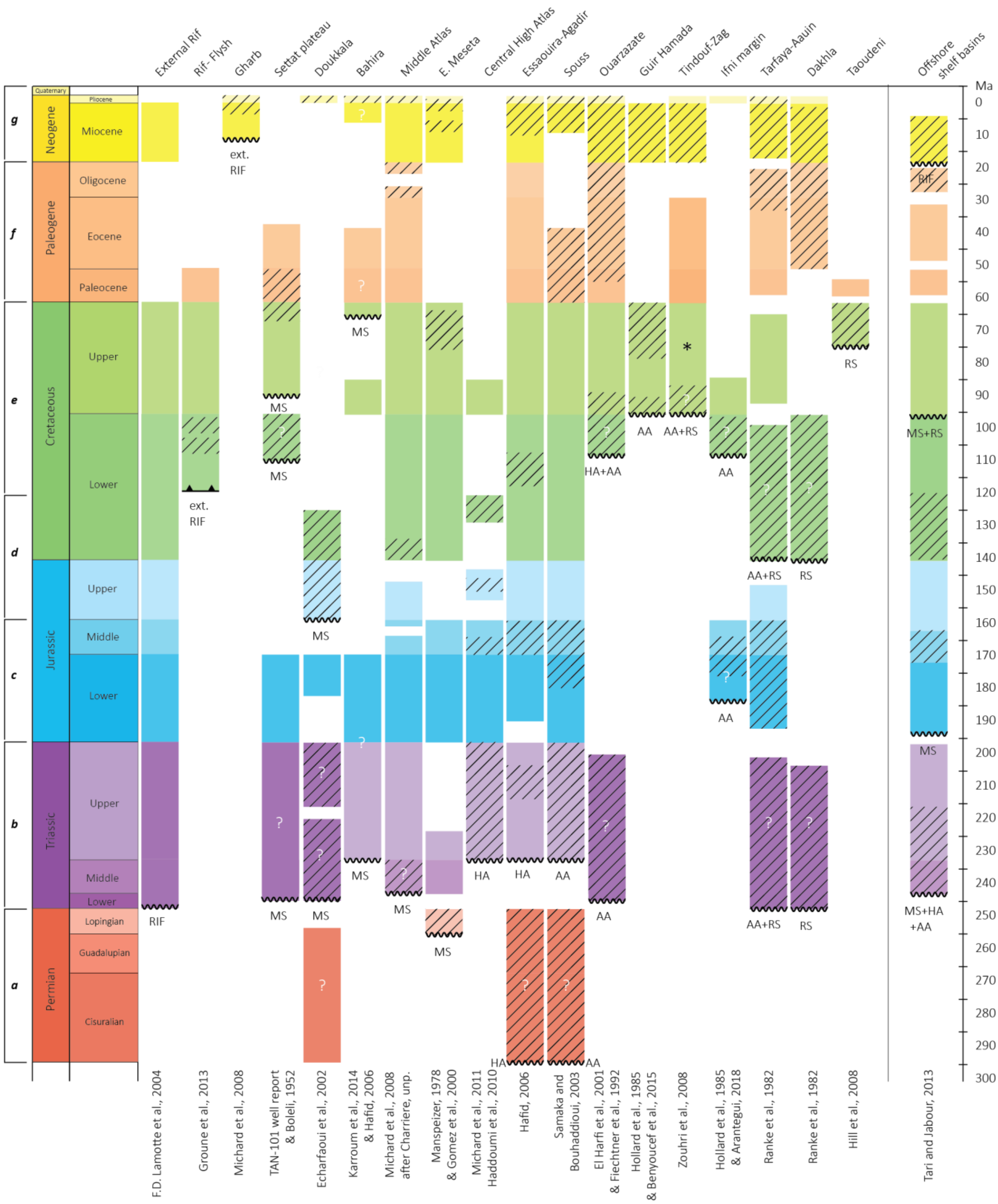

Constant high geotherm (40°C/km)
Rift zone
(HA rift)
Variscan
orogeny
Rift flanks
(CA rift)
Present day geotherms
(Zarhloule, 2004)
Intra-
continental domain
Mature passive
margin (CA)
Constant low geotherm (20°C/km)
Geotherm [°C/km]
40
35
30
25
20
300
250
200
150
100
50
Time [Ma]
0
RIF, Meseta, Anti-Atlas, and Coastal basins
Reguibat
High Atlas
Geotherms (see text)

Figure A1



External Rif
Rif- Flysh
Gharb
Settat plateau
Doukkala
Bahira
Middle Atlas
E. Meseta
Central High Atlas
Essaouira-Agadir
Souss
Ouarzazate
Guir Hamada
Tindouf-Zag
Ifni margin
Tarfaya-Aauin
Dakhla
Taoudeni
Offshore shelf basins
Ma
Quaternary
Pliocene
Neogene
Miocene
Paleogene
Oligocene
Eocene
Paleocene
Cretaceous
Upper
Lower
Jurassic
Upper
Middle
Lower
Triassic
Upper
Middle
Lower
Permian
Lopingian
Guadalupian
Cisuralian
g
f
e
d
c
b
a
ext. RIF
MS
AA
AA+RS
HA+AA
MS+RS
AA+RS
RS
HA
AA
MS+HA +AA
RIF
F.D. Lamotte et al., 2004
Groune et al., 2013
Michard et al., 2008
TAN-101 well report & Boleli, 1952
Echarfaoui et al., 2002
Karroum et al., 2014 & Hafid, 2006
Michard et al., 2008 after Charriere, unp.
Manspeizer, 1978 & Gomez et al., 2000
Michard et al., 2011 Haddoumi et al., 2010
Hafid, 2006
Samaka and Bouhaddioui, 2003
El Harfi et al., 2001 & Fiechtner et al., 1992
Hollard et al., 1985 & Benyoucef et al., 2015
Zouhri et al., 2008
Hollard et al., 1985 & Arantegui, 2018
Ranke et al., 1982
Ranke et al., 1982
Hill et al., 2008
Tari and Jabour, 2013

Figure A2

Appendix B: Building the source and sink maps

B.1. Data collection

Initially we digitized the geological map of Morocco at 1:1,000,000 (Hollard et al., 1985; fig **2B**). For neighbouring regions not covered by the Moroccan map, we digitized the map of NW Africa compiled by the UNESCO in 1990. It provided widespread control points for our maps, with the exception of the Permian, for which there are few penetrations in the basins and even less exposed at outcrop. Several "modifications" of the stratigraphy were added to this map, based on new fieldwork or new published data, especially around the Anti-Atlas (see details in Gouiza et al., 2017; Charton et al., 2018; Arantegui et al., 2019) and in the Central High-Atlas. In the latter, the so-called "Couches Rouges" terrestrial redbeds are found associated with Middle Jurassic and middle Cretaceous (Aptian) marine carbonates (Charrière and Haddoumi, 2016) have historically been attributed a Middle and Late Jurassic age (Hollard et al., 1985). Recent biostratigraphy work constrained the ages of the redbeds more precisely to the Middle and Late Jurassic, but also to the Barremian (Early Cretaceous; reviewed in Charrière and Haddoumi, 2016).

The outcrop and fossil data in Morocco is extensive, as suggested by the title of the recent special edition on Morocco from the journal "Geologues" (Number 194, septembre 2017): "Le Maroc, paradis des geologues", providing a wealth of outcrop and fossil data (table **B**).

The well database (fig. **B**) is composed of DSDP and IODP well reports, confidential oil exploration well reports and completion logs accessed from the "Office National des Hydrocarbures et des Mines" (ONHYM). Detailed well data from published works (notably Michard et al., 2008), and limited well data such as total depth, reached formation, or stratigraphy in published studies or company reports was also used.

Several types of paleo-reconstructions were used as the basis for depositional environments and general tectonic regime. In some cases, we modified them according to new evidence (outcrop, fossil, and/or well data). Sedimentary provenance analysis conducted in Morocco and surroundings for the Permian to Neogene periods are scarce; three recent works investigated the provenance with detrital zircon U-Pb (Pratt et al., 2015; Marzoli et al., 2017; Domènech et al., 2018), one study used traced elements and radiogenic Nd-Sr isotopes (Ali et al., 2014), and one produced detrital LTT ages (Sehrt, 2014). A few studies have also documented paleo-current directions in fluvial systems (e.g. Brown, 1980; Baudon et al., 2009, Fabuel-Perez et al 2009, Mader et al., 2017). Finally, we use the previously presented exhumation maps to constrain the source domains, while modifying their extent based on the control points described above.

B.2. Construction of the maps

The presented maps are defined according to the geological time chart division (with a strong focus on the Cretaceous and Jurassic periods). The time-windows covered by the maps are as follow: Permian (300 to 252 Ma; fig. **9**), Triassic (252 to 201 Ma; fig. **10**), Early Jurassic (201 to 174 Ma; fig. **11**), Middle Jurassic (174 to 163 Ma; fig. **12**), Late Jurassic (163 to 145 Ma; fig. **13**), (early) Early Cretaceous (145 to 125 Ma; fig. **14**), middle Cretaceous (125 to 90 Ma; fig. **15**), (mid-late) Late Cretaceous (90 to 66 Ma; fig. **16**), Palaeogene (66 to 23 Ma; fig. **17**), and Neogene (23 to 0 Ma; fig. **18**).

Four types of depositional environments are described in this study: terrestrial, transitional, shallow marine, and marine. For most of the map control points, the depositional environments were already interpreted in the associated study (table B). In other instances, we interpreted the depositional environment based on lithology and/or fossil data. The transitional environments presently suggest a coastal situation, but may account for areas characterised by fluctuation(s) between shallow marine and terrestrial environments.

Although most vertical movement rates are negative in the Anti-Atlas (i.e. subsidence rates), one of them is positive in the western part of the belt (fig. 7D). This could be due to a t-T modelling inconsistency or it could be a remnant, non-structural, relief from the previous period. A sedimentary provenance study conducted in the north Tarfafa Basin (Ali et al., 2014) for Lower Cretaceous sediments showed they were sourced from the Reguibat Shield only. It suggests that the one positive vertical movement rate calculated for the western Anti-Atlas for period ***d*** should be discarded, and that the t-T modelling results for that specific sample are inconsistent. We therefore considered no active source area in the western Anti-Atlas during the Late Jurassic in the corresponding source and sink map (fig. 16).

Table B. References used in this review to construct the source and sink maps.

*Table B (continued). * Including paleogeography, depositional environment, and stress / structural maps.*

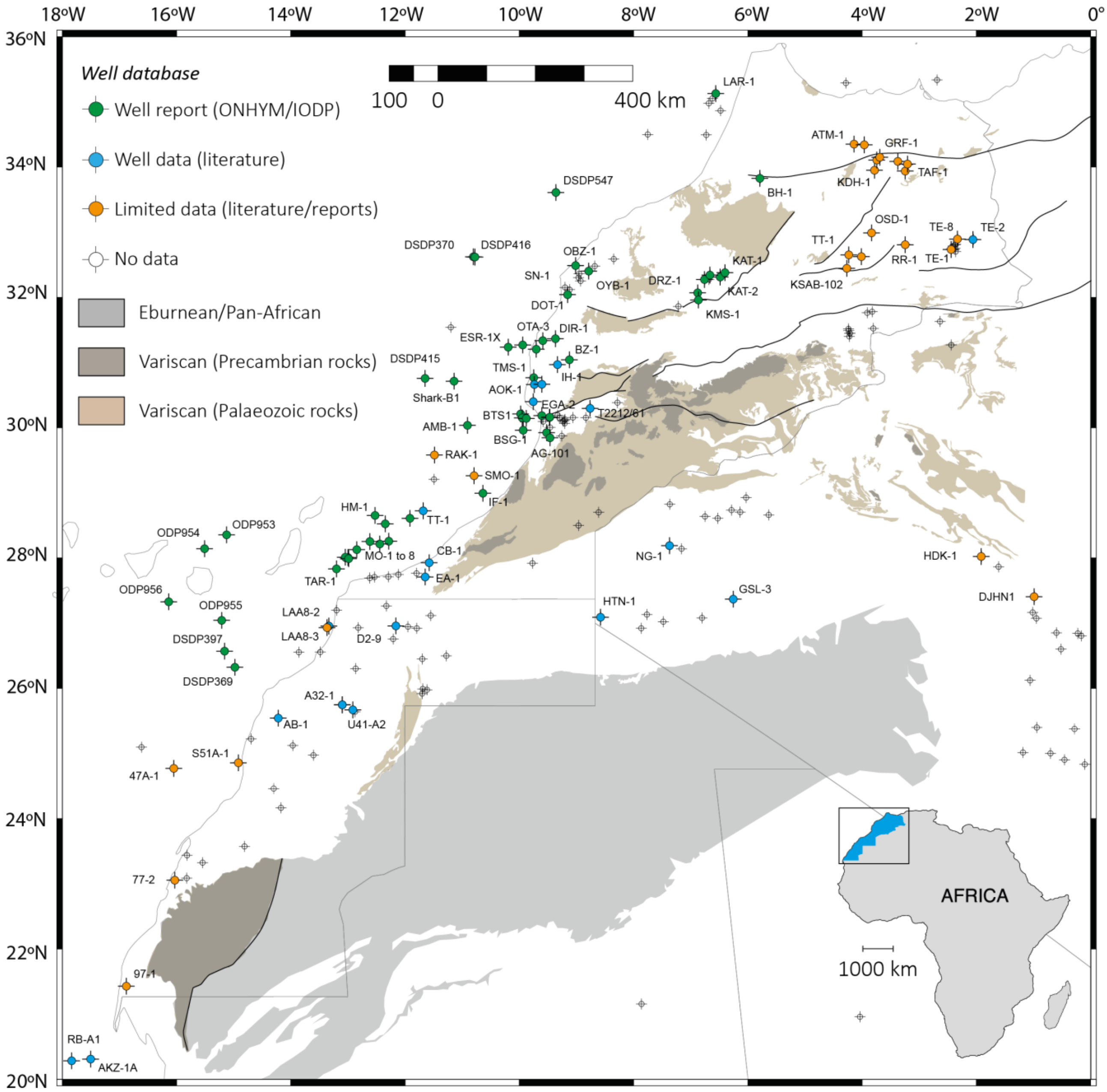
Figure B. Location of boreholes in Morocco and surrounding NW African countries (non-exhaustive). Color-coded wells were used in the construction of the source and sink maps.

Map	Outcrop Data	Fossil data
Permian (fig. 10)	Wrtiti et al., 1990 | Central Massif Chalouan et al., 2008 | Rif basin	Doubinger, 1956 | Central Massif Broutin et al., 1989 | Argana valley
Triassic (fig. 11)	Brown, 1980 | Argana valley Chalouan et al., 2008 | Rif basin	Chalouan et al., 2008 | Rif basin Kammerer et al., 2011 | Argana valley Lagnaoui et al., 2016 | Argana valley
Early Jurassic (fig. 12)	Steiner et al., 1998 | Canary Islands Sanders et al., 2015 | Rif basin Merino-Tome et al., 2017 | Eastern High Atlas	Jenny and Jossen, 1982 | Central High Atlas Lee, 1983 |Central High Atlas Beauvais, 1986 | Eastern High Atlas Bourillot et al., 2008 | Central High Atlas
Middle Jurassic (fig. 13)	Ouajhain et al., 2011 | Essaouira-Agadir basin Charriere and Haddoumi, 2016 | Central High Atlas Merino-Tome et al., 2017 | Central High Atlas Benvenuti et al., 2017 | Ouarzazate basin	Monbaron and Taquet, 1981 | Central High Atlas Mahammed et al., 2005 | Eastern High Atlas Haddoumi et al., 2015 | Central High Atlas Oukassou et al., 2016 |Middle Atlas
Late Jurassic (fig. 14)	Steiner et al., 1998 | Canary Islands Mekahli and Benhamou, 2004 | Eastern High Atlas Ouajhain et al., 2011 | Essaouira-Agadir basin Charrière and Haddoumi, 2016 | Central High Atlas Benvenuti et al., 2017 | Ouarzazate basin	Ourribane et al., 2000 | Essaouira-Agadir basin Nouri et al., 2011 | Central High Atlas Hssaida et al., 2014 | Rif basin
(early) Early Cretaceous (fig. 15)	Steiner et al., 1998 | Canary Islands Ali et al., 2014 | Tarfaya basin Charrière and Haddoumi, 2016 | Central High Atlas Benzaggagh, 2016 | Rif basin	Monbaron, 1978 | Middle Atlas Middlemiss, 1980 | Essaouira-Agadir basin Benest, 1985 | Rif basin Ettachfini et al., 1998 | Doukkala basin
middle Cretaceous (fig. 16)	Steiner et al., 1998 | Canary Islands Aquit et al., 2013 | Tarfaya basin Benyoucef et al., 2015 | Guir Hamada	Dhondt et al., 1999 | Tarfaya basin Ait Boughrous et al., 2007 | Guir Hamada Cavin et al., 2010 | Kem Kem beds Ibrahim et al., 2014 | Kem Kem beds Benzaggagh et al., 2017 | Rif basin
(mid-late) Late Cretaceous (fig. 17)	Choubert et al., 1966 | Tindouf basin Chalouan et al., 2008 | Rif basin Aquit et al., 2013 | Tarfaya basin Arab et al., 2015 | Rif basin	Andreu and Tronchetti, 1994 | Middle Atlas Dhondt et al., 1999 | Tarfaya basin Ambroggi and Lapparent, 1954 | Essaouira-Agadir basin Mulder et al., 2000 | Essaouira-Agadir basin Rage and Wouters, 1979 | Settat basin Hill et al., 2008 | Taoudeni basin
Palaeogene (fig. 18)	Trappe, 1991 | Ouarzazate basin Chalouan et al., 2008 | Rif basin	Tabuce et al., 2005 | Ouarzazate basin Jouve et al., 2005 | Settat basin Gaffney et al., 2006 | Rif basin Adaci et al., 2007 | Kem Kem beds Hill et al., 2008 | Taoudeni basin Zouhri et al., 2014 | Dakhla basin Gingerich and Zouhri, 2015 | Tarfaya basin Marivaux et al., 2017 | Dakhla basin
Neogene (fig. 19)	-	Dartevelle and Schwetz, 1937 | Canary Islands Ennouchi, 1954 | Rif Chevalier and Choubert, 1962 | Safi basin Koeniguer, 1967 | Dakhla Rage, 1976 | Middle Atlas Best and Boekschoten, 1981 | Porto Santo Saint Martin, 1990 | Rif Blain et al., 2013 | Hauts Plateaux

Table B

Map	Paleo-reconstruction*	Provenance strudy
Permian (fig. 10)	Broutin et al., 1998 | Meseta Ellouz et al., 2003 | Atlas Systems Chopin et al., 2014 | Atlas Systems	-
Triassic (fig. 11)	Ranke et al., 1982 | Tarfaya basin Le Roy, 1997 | Atlantic Shelf Brahim et al., 2002 | Atlas Systems Leleu et al., 2016 | Morocco Benvenuti et al., 2017 | Massif Ancien	Baudon et al., 2009 | Massif Ancien Domenech et al., 2018 | Massif Ancien
Early Jurassic (fig. 12)	Laville and Pique, 1992 | Atlantic Ellouz et al., 2003 | Atlas Systems Elmi et al., 2009 | Rif basin Sibuet et al., 2012 | Atlantic	Domenech et al., 2018 | Western High Atlas
Middle Jurassic (fig. 13)	Ellouz et al., 2003 | Atlas Systems Nemčok et al., 2005 | Morocco	Stets, 1992 | Massif Ancien Pratt et al., 2015 | Middle Atlas
Late Jurassic (fig. 14)	Ranke et al., 1982 | Tarfaya basin Ellouz et al., 2003 | Atlas Systems Nemčok et al., 2005 | Morocco Sibuet et al., 2012 | Atlantic	Stets, 1992 | Rehamna
(early) Early Cretaceous (fig. 15)	Sibuet et al., 2012 | Atlantic Aloui et al., 2012 | Algeria Ye et al., 2017 | Reguibat Shield Luber, 2018 | Essaouira-Agadir basin	Ali et al., 2014 | Tarfaya basin Leprêtre, 2015 | Reguibat Shield Pratt et al., 2015 | Rif basin Luber, 2018 | Essaouira-Agadir basin
middle Cretaceous (fig. 16)	Ye et al., 2017 | Reguibat Shield	Ali et al., 2014 | Tarfaya basin Pratt et al., 2015 | Rif basin Essafraoui et al., 2015 | Massif Ancien Meister et al., 2016 | Kem Kem beds
(mid-late) Late Cretaceous (fig. 17)	Ranke et al., 1982 | Tarfaya basin Brahim et al., 2002 | Atlas Systems Sibuet et al., 2012 | Atlantic van den Bogaard, 2013 | Canary Islands Ye et al., 2017 | Reguibat Shield	Ali et al., 2014 | Tarfaya basin
Palaeogene (fig. 18)	Ranke et al., 1982 | Tarfaya basin Brahim et al., 2002 | Atlas Systems van den Bogaard, 2013 | Canary Islands	-
Neogene (fig. 5.11)	Ranke et al., 1982 | Tarfaya basin	Ali et al., 2014 | Tarfaya basin

Table B (continued)



Well database
Well report (ONHYM/IODP)
Well data (literature)
Limited data (literature/reports)
No data
Eburnean/Pan-African
Variscan (Precambrian rocks)
Variscan (Palaeozoic rocks)
100 0 400 km
AFRICA
1000 km

Figure B