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Multi-phase reactivations and inversions of Paleozoic-Mesozoic extensional basins during the Wilson Cycle: case studies from the North Sea (UK) and central Apennines (Italy)

--Manuscript Draft--

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Full Title:	Multi-phase reactivations and inversions of Paleozoic-Mesozoic extensional basins during the Wilson Cycle: case studies from the North Sea (UK) and central Apennines (Italy)
Short Title:	Reactivation of Late Palaeozoic-Mesozoic extensional basins
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	David Iacopini (Writing – review & editing: Supporting)
Abstract:	The Caledonian-Variscan orogens in Northern Europe and the Alpine-age Apennine range of Italy are classical examples of thrust belts that were developed at the expense of formerly rifted, passive continental margins and that experienced various degrees of post-orogenic collapse. Portions of these settings comprise the outer zones of orogenic belts and their adjoining foreland domains, where the effects of superposed deformations are mild-to-very mild, making it possible to recognise and separate structures produced at different times and to correctly establish their chronology and relationships. In this paper we integrate subsurface data (2- and 3D seismic reflection and well-logs), mainly from the North Sea, and structural field evidence, mainly from the Apennines, with the aim to reconstruct and refine the structural evolution of these two provinces that, in spite of their different ages and present-day structural framework, share repeated pulses of alternating extension and compression. The main outcome of this investigation is that in both scenarios, during repeated episodes of inversion that are a characteristic feature of the Wilson Cycle, inherited basement structures were effective in controlling stress localisation along faults affecting younger sedimentary cover rocks.
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Ref.: *Ms. No. GSLSpecPub17-232*

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From: *Dr. Vittorio Scisciani,*
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To the attention of Woody Wilson, Ken McCaffrey, Tony Doré, Greg Houseman and Wiki Royden
Guest Editors of the Volume: Tectonic evolution: 50 years of the Wilson Cycle concept

Dear Woody, Ken, Tony, Greg and Wiki,

we are hereby forwarding the revised version of our manuscript titled "Multi-phase reactivations and inversions of Paleozoic-Mesozoic extensional basins during the Wilson Cycle: case studies from the North Sea (UK) and northern Apennines (Italy)" (the working title was: "Modes of reactivation of Late Paleozoic-Mesozoic extensional basins during the Wilson Cycle: case studies from the North Sea (UK) and central Apennines (Italy)").

This manuscript was submitted for publication on the Geological Society of London Special Publication titled "Tectonic evolution: 50 years of the Wilson Cycle concept".

The original version of the manuscript was carefully reviewed in the light of the referees (Thomas Phillips and Stuart Archer) and corresponding editor' (Woody Wilson) comments. Following their suggestions, the new version has been re-structured, reduced in length (from 215000 to less than 10,000 words) and made more fluent, simplifying redundant descriptions and details of the regional geology of the two study areas. The regional setting was simplified and an integrated description of the evolution of the two study area has been treated in the chapter entitled "Supra-regional evolution of Western Europe" (correlated with Figure 2 and the new Figure 3). Finally, the discussion was significantly shortened and rearranged in order to make the description of modes of structural reactivation and inversion patterns more homogeneous for the two areas; a new figure (Fig. 20) has been added to highlight the analogies in multiphase reactivation in the East Shetland Platform and Northern Apennines. In a specific paragraph of the discussion, the common controlling factors of multi-phase reactivations were emphasized.

We think that the new version of the manuscript has been significantly improved with respect to the previous form and we hope it is now fully suitable to contribute to the success of the outcoming volume of the GSL Special Publication.

We hope to hear back from your editorial decision soon, and we take this opportunity to thank you very much for your advice, and the reviewers for their constructive comments and suggestions.

On behalf of all my co-authors, I send you my best wishes and remain

Yours truly,

Vittorio Scisciani

Ref.: *Ms. No. GSLSpecPub17-232*

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Contribution type: *Original Research Paper*

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Previous Working Title: *Modes of reactivation of Late Paleozoic-Mesozoic extensional basins during the Wilson Cycle: case studies from the North Sea (UK) and central Apennines (Italy) ""*

Short title: *Reactivation of Late Palaeozoic-Mesozoic extensional basins*

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Response to the reviewers' comments

The manuscript has undergone to the revision in the lights of the scientific comments of the referees (Thomas Phillips and Stuart Archer) and the corresponding editor (Woody Wilson). Following their suggestions we restructured and shortened the manuscript, removing a great amount of details on the regional evolution of the two study areas and integrating the regional settings and the teconic evolution in single common chapters (i.e., "Geological setting of the East Shetland Platform (ESP) and Northern Apennines (NA)" and "Supra-regional evolution of Western Europe"). Moreover, we added two new figures; the first (new Fig. 3 - including previous Figs. 4 and 13) is to help readers to follow the main plate and intra-plate Wilson cycles occurred during the evolution of the study areas and the second (Fig. 20) to make a comparison of the role played by the inherited structures during positive and negative reactivation in both the study areas.

Based on the general comments of the reviewers the following corrections have been carried out:

i) distinction between the work done in previous studies (included in the chapters #2 and #3) and our contribute (chapters #4-8);

ii) addiction of a further figure (i.e., the new Fig. 20) to make more explicit the link between the inherited structures and the subsequent positive and negative reactivation in both the study areas and relative description in the text;

iii) enhanced integration between the study areas in the chapters #2 and #3;

iv) specific description and discussion of the influence of the inherited structures on the subsequent reactivation processes with comparison between the two study areas (third paragraph in the discussion).

v) tightening of the narrative and shorten of the the word count;

vi) improvement of the English langiage and grammar

As regards the general comments and concerns of the reviewer #1 (Thomas Phillips) and #2 (Stuart Archer), our responses (text in italic) are listed as follow:

Reviewer #1 comment: Throughout the manuscript the authors refer to “inherited structures emanating from basement” (Line 34), or “Caledonian basement grain structures” (Line74) – it is unclear what these structures are and what their geometry is. It is also difficult to see the relationship between the basement structures and the later faults, in particular on the figures, where the faults and inherited basement structures are not shown on the same fig.

In all the seismic cross-section there are now annotations, and similarly this is now decribed at length in captions and in the main text. We highlight faults with different age of activity (and re-activations), ranging *from Caledonian thrusts and normal faults, Devonian normal faults, Variscan inversion, Permo-Triassic normal faults, Mid Cimmerian inversion, Late Jurassic normal faults, Alpine-age inversion etc.*

Reviewer #1 comment: The geological setting of the East Shetland Platform area, and of the wider North Sea is incredibly detailed. Some of the observations made in this section (i.e. lines 108-112) would benefit from being shown in a cross-section. However, it is often unclear how some of the information given in this section is relevant to the overall study. Some of this information could be streamlined in order to reduce the length of the study and to give more impact to the main results

In the revised version of the manuscript the geological setting of the East Shetland Platform area was simplified and streamlined; the Lines 108-112 were deleted.

Reviewer #1 comment: Currently, the descriptions of the main plate cycles, without any explicit reference to figures, reduce the impact of the overall results and observations later in the paper.

This suggestion has been followed and the revised version includes the new Figure 3 with plate reconstructions that illustrate the main evolutionary stages of the two study areas.

Reviewer #1 comment: Currently, some of the later results repeat points made in the geological setting. I would suggest streamlining the geological setting section to give more impact to the results later.

In the revised version of the manuscript the geological setting of the East Shetland Platform area was simplified and streamlined.

Reviewer #1 comment: Line 132-134 – The authors define a complete plate cycle as where oceanic spreading and continental collision has taken place, and an intra-plate cycle where extension and compression occur, without the requirement of oceanic crust. However, the authors then state that plate cycle (2), the Devonian-Variscan cycle (Line 200-241) is a plate-cycle, although no seafloor was generated during Devonian orogenic collapse. This should be referred to as an 'intra-plate cycle.'

In the revised version of the manuscript we re-defined the "classical/complete" and "foreland/incomplete" Wilson cycles occurred in the two study area during the Iapetus-Caledonian/Rheic-Variscan (lines 171- 180) and Permian-Present (lines 251-259) plate and intraplate cycles.

Reviewer #1 comment: Some of the information when describing the different plate and intra-plate cycles appears to be extraneous with regards to the main aim of the paper, which is to identify reactivation within Wilson cycles. For example, much of the stratigraphic information (e.g. Lines 147-160) could be removed to streamline the paper without influencing the overall message.

This part of the text in the previous version manuscript has been deleted.

Reviewer #1 comment: Line 194-198 – more information needs to be given on the geometry of the lineaments if available?

Some of the implications of the observations stated in the results are unclear as to how they fit in with the overall paper

This part of the text in the previous version manuscript has been deleted.

Reviewer #1 comment: Line 473-479 – could you use potential field data, or older studies to shed some light onto the extent of the granite in this area?

As far as we know the Bressay granite has not really been discussed in previous studies (e.g., stephenson et al., 1999).

Reviewer #1 comment: Line 498 – Where are the offshore continuations of the Great Glen fault and the axis of the Iapetus ocean? Although these soceatructures are shown in Figure 3, these structures are not immediately clear relative to the main study area and are also not referenced in the text.

A recostruction of the basement units in the northern North Sea and surrounding areas has been included in Fig 4C where the offshore prosecution of the Great Glen fault and Iapetus oceanic units are illustrated.

Reviewer #1 comment: Line 499-501 – more evidence is required to invoke inheritance for the similarities in strikes of these faults, and the links to the onshore Caledonide structures need to be shown. This is not shown in map view and therefore it is difficult to make the link between these pre-existing lines of weakness and the later faults. Evidence for the relationship between the lineaments and the later phases of activity is currently lacking. No figures are referred to throughout this section.

The Tertiary positive inversion of the NNE-SSW Devonian master fault illustrated in Figures 10 and 11 has been described (e.g., lines 310-320); in addiction, this Devonian normal fault is one of the extensional structures developed during the Devonian-age extensional collapse of the Caledonian Orogeny. In the text we argued that the attitude of the reactivated master faults, which shows a NNE-SSW strike, resembles the orientation of the main lineaments associated to the Caledonian Orogeny (e.g., lines 345-352).

Reviewer #1 comment: More integration needs to be made at the beginning as to why both the North Sea and the Apennines are included in this study, and how they link together. Currently it seems that these form almost two separate papers that are stuck together. One suggestion could be to have a much shorter geological setting for both the North Sea and the Apennines at the beginning of the manuscript followed by two sections on the findings of this study. I feel that this would greatly improve the flow of the manuscript.....

In the revised version of the manuscript we followed overall these suggestions.

Reviewer #1 comment: The descriptions of the plate cycles within the Apennines (e.g. lines 529-571), are hard to follow without reference to figures that state where these structures and locations are relative to one another, particularly for people not familiar with the area. In addition, at this point it is also unclear how some of this information is related to the individual plate cycle, these descriptions should be simplified or at least located on a map.

The description of the plate cycles within the Apennines has been rearranged in the chapter #3 ("Supra-regional evolution of Western Europe") and illustrated in the new Figure 3.

Reviewer #1 comment: The section 'Field geology of the central Apennines' should potentially appear before the descriptions of the plate cycles, to serve as an introduction to the region.

The section concerning the field geology of the Northern Apennines has been streamlinined and the descriptions in the text are now limited to the results of fieldwork carried out to calibrate the seismic profile.

Reviewer #1 comment: Line 668-670 – this is setting up this part of the study, which should have been set up prior to the descriptions of the plate cycles in the Apennines. In places it appear that some sections of the manuscript do no link to the others. This section does not link to the overall aim of the paper

The section concerning the field geology of the Northern Apennines has been streamlininged and combined to the seismic interpretation; the descriptions in the text are now limited to the results of fieldwork carried out to calibrate stratigraphy and structures imaged in the seismic profile.

Reviewer #1 comments: The presence of the lineaments and inherited structures is not referred to throughout the text (eg. Line 729) even though this forms one of the main conclusions stated in the abstract.

Line 753 – very detailed descriptions of the seismic section and the imaged stratigraphy, but still unclear as to how this fits into the Wilson cycle story. Some good information occurs later (line 822 onwards, but some of the earlier information does not add to the main points.

Line 908-909 – The definition and identification of the structural grains can be made clearer

Line 921-937 – this seems partly repeated from earlier during the descriptions of the plate and intra-plate cycles.

These parts of the manuscript were removed in the new version.

Reviewer #2 comment: One minor point of consistency is that the reviewers of this SP will need to decide early whether to use Wilson cycle or Wilson Cycle – the use of upper versus lower case C is inconsistently applied.

The term Wilson Cycle has been used throughout the manuscript.

Reviewer #2 comment: I am unsure if the Mid Cimmerian Thermal doming event in the Central North Sea can be seen in the context of the Wilson cycle as it is neither part of an open closing nor ocean opening event. As we all know, the North Sea is a failed passive margin and the thermal dome probably represents the response to a transient plume event in an intra-plate setting.

We treated the Mid Cimmerian event as a likely mantle plume erosion (Underhill & Prtington 1993) occurred in an intraplate setting.

Reviewer #2 comment: The two topics co-exist unsatisfactorily in the current manuscript rather than being weaved into an elegant compare and contrast type discussion.

The discussion section has been reorganized and more analogies and comparisons between the complete and incomplete Wilson Cycles have been argue.

Reviewer #2 comment: One obvious problem with a section is Fig 17 where the quality of the seismic line does not (to my eye at least) allow the interpretation of all the detail below. If this is supported by outcrop observations then I suggest that you add an intermediate step – a cross section showing the outcrop control points and projecting the structural dip into the subsurface. In this way a basic line drawing might act as a stepping stone to the final interpretation.

The new Fig. 16 includes a larger and better quality image of the seismic reflection profile. In particular in the new version, the two reflectors (corresponding to the base of siliciclastic turbidites and the Fucoidi Marls), that have been tied with a geological cross-section derived from fieldwork and have been used to control the subsurface interpretation, are now clearly imaged on the seismic profile.

In addiction, the revised version of the manuscript takes into account of every specific point listed by the reviewers (points in the list and in the annotated version of the submitted manuscript of the reviewer #1 and #2, respectively)

Multi-phase reactivations and inversions of Paleozoic-Mesozoic extensional basins during the Wilson Cycle: case studies from the North Sea (UK) and central Apennines (Italy)

Short abstract

The Caledonian-Variscan orogens in Northern Europe and the Alpine-age Apennine range of Italy are classical examples of thrust belts that were developed at the expense of formerly rifted, passive continental margins and that experienced various degrees of post-orogenic collapse. Portions of these settings comprise the outer zones of orogenic belts and their adjoining foreland domains, where the effects of superposed deformations are mild-to-very mild, making it possible to recognise and separate structures produced at different times and to correctly establish their chronology and relationships. In this paper we integrate subsurface data (2- and 3D seismic reflection and well-logs), mainly from the North Sea, and structural field evidence, mainly from the Apennines, with the aim to reconstruct and refine the structural evolution of these two provinces that, in spite of their different ages and present-day structural framework, share repeated pulses of alternating extension and compression. The main outcome of this investigation is that in both scenarios, during repeated episodes of inversion that are a characteristic feature of the Wilson Cycle, inherited basement structures were effective in controlling stress localisation along faults affecting younger sedimentary cover rocks.

Introduction

In orogenic belts the coexistence of deformed portions of oceanic crust and passive margin successions, in turn pulled-apart by subsequent continental breakup is often ascribed to the Wilson Cycle context (Wilson, 1966; Vauchez et al., 1997). Within these orogens formed by continental collision following the closure of ancient oceanic basins the pre-existing rifting discontinuities are commonly reactivated during subsequent compressional episodes in the context of positive inversion tectonics (e.g., Williams et al., 1989). Similarly, during post-collisional reworking of orogens a fundamental role has been recognised to be exerted by pre-existing anisotropies, such as reverse faults and compressive fabrics on younger extensional structures (Ring, 1994; Vauchez et al., 1997; Korme et al., 2004).

Although several separate examples of positive or negative inversion tectonics occurred in disparate times and across diverse structural settings (Harding, 1985; Cooper and Williams, 1989; Buchanan and Buchanan, 1995), few of these testify a complete Wilson Cycle from the initial rift phase to the final collisional and post-collisional stages.

In his seminal paper, Wilson (1966) first proposed the closure of a proto-Atlantic Ocean developed in early Paleozoic times followed by the assembly of the Gondwana supercontinent (known as Appalachian-Caledonian orogeny), its break-up, and re-opening of the Mesozoic-Cenozoic Atlantic Ocean. He also speculated that a similar but more recent event occurred along the present-day Asian and circum-Mediterranean mountain belts following the total and partial closure of the Tethys Ocean.

Following the pioneering approach by Wilson, both the Caledonian orogen in Northern Europe and the Apennines fold-and-thrust belt of Italy were recognised as key areas to study the effects of the Wilson Cycle with repeated episodes of opening and closing of ocean and extensional basins along similar structural trends (e.g., Butler et al., 2006).

In the present work, we have selected two continental margins where regional geology, field structural evidence and subsurface data all point out to at least a complete Wilson Cycle (Figs. 1-3), with long-term preservation of structural grain and reactivation of pre-existing structures within both the suture zones and the foreland domains. The two study areas comprise the East Shetland Platform (ESP) in the UK North Sea (NS) and the south-eastern portion of the Northern Apennines (NA) of Italy, including the Umbria-Marche Apennine Ridge (UMAR) (Figs. 1, 4-5).

The results of our investigation indicate that the Wilson Cycle concept, useful for the description of the tectonic evolution of the NS and UMAR, may also be successfully applied in the study of other analogue foreland settings flanking the zones where multiple cyclical events that switch, from extension to compression and vice-versa, have occurred.

Geological setting of the East Shetland Platform (ESP) and Northern Apennines (NA)

The ESP is a large (≈62,000 km^2) Jurassic-Recent offshore platform in the UK North Sea (NS), bounded by the Orkney and Shetland Islands to the west, and by several Jurassic structural lows (e.g., East Shetland Basin, Viking Graben, Outer Moray Firth, Witch Ground Graben) to the east and south (Figs. 1 and 4).

The outer half of the ESP hosts an expanded and weakly deformed Tertiary succession (1.0-2.0 seconds two-way traveltime or TWT), usually resting on a thin horizontal veneer of Upper Cretaceous carbonate-rich Chalk Group sediments, which in turn overlies a highly tectonized 1.0-3.0 TWT seconds thick Devonian-age unit (Platt, 1995; Platt and Cartwright, 1998; Zanella and Coward, 2003; Patruno et al., in press). An angular unconformity separates the tilted and eroded Devonian unit and the sub-horizontal Cretaceous-Tertiary cover. Permo-Triassic intra-platform extensional basin fills are locally present (e.g., Richardson et al., 2005; Patruno and Reid, 2016; 2017). A series of widespread hiatuses and unconformities are partitioned by expanded seismic-stratigraphic units, directly linked to a succession of regional inversion tectonic events that have taken place in the last 850 million years (Patruno et al., in press; Figs. 2-3).

The Apennines of Italy is a prominent mountain range within the central Mediterranean region (Figs. 1 and 5). In particular, the NA are an arc-shaped east to north-east verging fold-and-thrust belt developed during Cenozoic times (Malinverno and Ryan, 1986; Carmignani and Kligfield, 1990). The NA continental margin forms a tectonic stack of thick-skinned thrust sheets with a tectonic pile including: i) fragments of ophiolites derived from the Mesozoic Ligurian Ocean and flysch units; ii) a metamorphic core (Apuane Units) with basement imprinted by the previous Alpine and Variscan orogeny; iii) a foreland fold-and-thrust belt mainly composed of pre-Alpine Mesozoic-Palaeogene carbonates and syn-orogenic Miocene flysch and juxtaposed towards the E-NE onto the Adriatic foreland. Starting from the Miocene, the inner sector of the chain was also dissected by post-orogenic extension and magmatism (Carmignani and Kligfield, 1990; Carmignani et al., 1994; Calamita et al., 2000; Pizzi and Scisciani, 2000; D'Agostino et al., 2001).

These thrust sheets outcrop in the NA mountain belt and are buried underneath Pliocene-Quaternary syn-orogenic sediments in the Po Plain and Adriatic foreland. The highest topography zone of the NA (c. 3000 m) consists of two NW-SE trending carbonate mountain ridges (i.e., the Umbria-Marche and Lazio-Abruzzo ridges – UMAR and LAR, respectively) separated by the NNE-SSW trending Olevano-Antrodoco-Sibillini oblique thrust ramp (OAMS - Fig. 5). These ridges are composed by Triassic-Miocene syn-rift and passive-margin succession of the thinned Adriatic crust and their prominent structural elevation is testified by some of the oldest rocks (Late Triassic-Early Jurassic) exposures in the highest mountains of the entire Apennines belt (e.g., the Vettore Mt. and Corno Grande - Fig. 5).

Supra-regional evolution of Western Europe

The geological evolution of the two study areas is here set within a framework of repeated mega-regional Wilson Cycles (with both complete and incomplete cycles), which are readily identifiable throughout Western Europe.

The ESP and NA study areas were subject to two very similar Proterozoic-Paleozoic plate cycles (albeit not completely overlapping and with different chronological duration), namely the *Iapetus-Caledonian Cycle* and the *Rheic-Variscan Cycle*. Following the Variscan Orogeny, both areas have been subject to cyclical reactivations and inversions of pre-existing structures. These reactivations took place in an intra-plate setting in the case of the NS (with at least two incomplete Meso-Cenozoic intra-plate extension-compression cycles), while in the NA a new "complete" orogeny-rifting-drifting-orogeny Wilson Cycle took place in Permian-Recent times (Figs 2-3).

Iapetus-Caledonian (ca. 850-405 Ma) and Rheic-Variscan (ca. 480-300 Ma) plate cycles

In the Late NeoProterozoic and Cambrian, the paleogeography of Western Europe was dominated by the north-trending Iapetus Ocean, opened between the continental blocks of Laurentia, Baltica and Gondwana (Mac Niocaill et al., 1997- Fig. 3a). Since the Cambrian, Gondwana and Baltica had been in turns separated by the west-trending Tornquist seaway (Glennie and Underhill, 1998; Toghill, 2002).

In the Grampian Highlands of Scotland, set on the southern Laurentian continental margins, an early NeoProterozoic to Cambrian rifting event that preceded the opening of the Iapetus Ocean is recorded by up to 25 km of metamorphosed sedimentary rocks belonging to the "Dalradian Supergroup" (Strachan et al., 2002; Toghill, 2002; Stephenson et al., 2013). This succession has been interpreted as a subsiding submarine shelf, evolving into a deeper basin and finally leading to ocean-floor spreading (Stephenson et al., 2013). The last stage is documented by the late NeoProterozoic submarine Tayvallich basalts outcropping in western Scotland (Stephenson and Gould, 1995; Macdonald and Fettes 2007; Fettes et al., 2011).

The Dalradian Supergroup is interposed between the Great Glen Fault to the north and the Highland Boundary Fault to the south (Ziegler, 1988; 1990; Glennie and Underhill, 1998; Coward et al., 1989; 2003). These deep-seated and long-lived northeast-trending tectonic lineaments, associated to the complete subduction and suturing of the Iapetus Ocean during the Caledonian Orogeny, can be expected to continue offshore towards the ESP area (Figs. 3a and 4d).

Avalonia was a small continental fragment which detached in the Early Ordovician from the northern Gondwanan margin by a new widening east-trending ocean, known as the Rheic Ocean (Fig. 3a; Strachan, 2000; Nance et al., 2010, 2012). During Ordovician-Silurian times, the fast seafloor spreading of the Rheic Ocean lead to the passive drifting of Avalonia northwards, and initiated the progressive three-plate convergence between Avalonia, Baltica and Laurentia in and around the present-day NS and Scottish-Norwegian regions (McKerrow et al., 2000a; Bluck, 2001; Mendum, 2012; Coward et al., 2003; Nance et al., 2010; 2012 - Fig. 3a). The Iapetus and Tornquist oceans were eventually closed in Silurian times, leading to the Acadian-Grampian-Caledonian Orogeny (Trench and Torsvik, 1992; McKerrow et al., 2000a; Mendum, 2012) and to the final assemblage of a larger continent in the Early Devonian (Laurussia or Old Red Continent - Ziegler, 1988; 2012; Scotese and McKerrow, 1990; McKerrow et al., 2000b; Dalziel et al., 1994).

The assembly of the Caledonian Orogen was quickly followed, during Devonian times, by the extensional collapse of its thickened crust (e.g., McClay et al., 1986; Coward et al., 1989; Seranne, 1992; Ziegler, 1992; Marshall and Hewett, 2003; Wilson et al., 2010 - Figs. 1 and 2). This post-orogenic extension produced many quickly-subsiding half-grabens throughout Laurussia, with accompanied lower Devonian volcanism and granitic intrusions identified both onshore Scotland and in the NS (e.g., Utsira High, Halibut and Bressay granites). These fast-subsiding Devonian extensional basins hosted the deposition of thick continental clastic successions (Old Red Group - Glennie and Underhill, 1998).

The Devono-Carboniferous extensional phase was eventually cut short, because the Late Carboniferous continental plates switched motion, leading to the subduction of the Rheic Ocean and the subsequent continental collision between Laurussia, Gondwana, and several intervening microplates (Variscan Orogeny), with the Early Permian assemblage of the Pangea mega-continent (Fig. 3b).

Remnants of the Caledonian Orogenic belt span northern Britain and Norway, with Lower Paleozoic crystalline rocks (or “Caledonian basement”) thought to underlie the entirety of the present-day NS Basin (Abramovitz and Thybo, 2000; Scheck et al., 2002; Coward, 1990; Coward et al., 2003; Zanella and Coward, 2003; Bassett, 2003). On the contrary, the Variscan metamorphic core belts today straddle the ancient plate margin of Laurussia and Gondwana, from the eastern U.S. and Newfoundland to Morocco, Iberia, France, Germany and the Ural Mountains. In particular, the northern, approximately east-trending front of the Variscan orogenic belt spans south-western

England, Wales and Ireland (Fig. 3b; Leveridge and Hartley, 2006). In southern Europe, the Paleozoic basement of Sardinia along with the scattered outcrops in the NA, Western Alps and Calabria is the result of the Variscan continental collision between the northern Gondwanan margin and the Armorica micro-plate (Fig. 3b; Carmignani et al., 1994; Franceschelli et al., 2005; Giacomini et al., 2006; von Raumer and Stampfli, 2008; Rossi et al., 2009). As a consequence, the Variscan belt is expected to transect underneath the NA mountain belt (Vai, 2001; Doglioni and Flores, 1996).

Caledonian and Variscan orogenic belt "core complexes" are therefore present over the Greater NS area and part of central-southern Europe (including the NA), respectively. Conversely, the NS and much of southern Europe (including the NA) represented part of the foreland of the far-field Variscan and Caledonian orogenies, respectively. Nevertheless, large-scale Caledonian-age uplift/erosion and local folding (Sardic deformation) took place in Sardinia and Iberia (Fig. 2 - Carmignani et al., 1994; Romão et al., 2005). Similarly, episodes of Variscan-age intra-plate compression and uplift/erosion leading to the partial inversion of Devonian-Carboniferous sedimentary basins, have been identified in Britain and the NS (e.g., Fraser and Gawthorpe, 1990; Corfield et al., 1996; Thomson and Underhill, 1993; Hay et al., 2005), including the ESP (Patruno et al., in press; Figs. 3 and 4). The end of the Variscan foreland compressional phase in the NS is marked by a regional peneplanation surface, usually referred to as "Base Permian Unconformity".

In the NS and northern Britain, the Iapetus-Caledonian plate cycle therefore corresponds to a "classical/complete" Wilson Cycle (from likely pre-Iapetus compression to Iapetus extension and ocean spreading and back to Caledonian compression), while the Rheic-Variscan plate cycle can be described as a "foreland/incomplete Wilson Cycle" (from Caledonian orogeny to a Devonian extension which does not culminate in ocean spreading and back to foreland Variscan compression). The opposite is true for the NA and southern Europe. Here, the Iapetus-Caledonian cycle is a foreland/incomplete Wilson Cycle (no Iapetus-equivalent ocean formation in this region and far-field Caledonian compression), while the Rheic-Variscan plate cycle represents a classical/complete Wilson Cycle (from likely pre-Rheic compression to Rheic extension and ocean spreading and back to Variscan compression).

Permian-Present plate and intraplate cycles (ca. 280/260-0 Ma)

Following the Variscan orogeny the NS and NA areas suffered multiple Permian-Jurassic rifting episodes, associated to the breakup of Pangea (Decourt et al., 1993; Stampfli and Borel, 2002). In southern Europe this extensional processes resulted in the opening of three distinct oceanic arms (Figs. 2-3c), including: i) the Permian-Triassic Ionian-East Mediterranean ocean (Finetti and Del Ben, 2005); ii) the Middle Triassic North-Western Tethys (Hallstatt-Meliata and Vardar oceans; Kozur, 1991); and iii) the latest Triassic-Middle Jurassic Alpine Tethys (including the Ligurian-Piedmont Ocean; Stampfli and Borel, 2002). The two oldest oceans formed the western termination of the Neo-Tethys whereas the last was an eastward ramification of the central Atlantic opening.

On the contrary, in the NS/ESP, the whole post-Variscan Permian-Recent evolution took place in an intra-plate setting (Figs. 2-3c-e). In the NS, the initial Permo-Triassic rifting is often related to the reactivation and inversion of old Caledonide lines of weakness (Ziegler, 1988; 1990; 1992; Glennie and Underhill, 1998; Wilson et al., 2010; Patruno et al., in press). In general, two main Permo-Triassic phases of crustal thinning occurred (rift I and rift II in Fig. 2). In the NS/ESP these two syn-rift units correspond to expanded middle Permian clastics and volcanics (Rotliegend Group) and to lower Triassic clastics, often confined within syn-depositional half-grabens and grabens (Færseth and Råvnas, 1998; Stemmerik et al., 2000; Richardson et al., 2005; Patruno and Reid, 2017; Patruno and Lampart, 2018; Patruno et al., in press). These two units are separated by upper Permian evaporitic cycles of the Zechstein Group, which were deposited in largely post-rift thermal relaxation basins (Glennie et al., 2003; Ziegler, 1988; 1990; Ziegler et al., 2004; 2006; Peryt et al., 2010; Patruno et al., in press). In the NA, there are extensional basins infilled by two distinct sedimentary cycles, respectively of Permian to Early Triassic and of Middle Triassic to Early Jurassic age – e.g., Martini et al., 1986; Ciarapica and Passeri, 2005; Fantoni and Franciosi, 2010).

After the Permo-Triassic phase, active rifting mainly occurred in Lower and Late Jurassic in the NA and NS/ESP, respectively (Figs. 2-3C).

In the NA, this rifting lead, in the Early Jurassic, to the partial drowning of the widespread carbonate platforms in the NA (Ciarapica and Passeri, 2002; Scisciani and Esestime, 2017). During the Late Jurassic-Early Cretaceous, the NA Jurassic rifting evolved into the definitive oceanization of the Ligurian-Piedmont Ocean (Alpine Tethys in Fig. 3c – Stampfli and Borel, 2002; Bortolotti and Principi, 2005).

Meanwhile, prior to the Late Jurassic rifting, in the NS Aalenian thermal doming caused a new phase of regional uplift/erosion (Fig. 2), linked to the development of a transient mantle-plume head and leading to the extrusion of the Rattray Series and the Forties Igneous Province in the Central NS (Ziegler, 1992; Underhill and Partington, 1993; 1994; Davies et al., 1999; Coward et al., 2003; Hendrie et al., 2003; Husmo et al., 2003). The erosional truncation associated to this uplifting event is known as Mid Cimmerian Unconformity (e.g., Patruno and Reid, 2016). Renewed active extension in the NS began with a diffuse Bajocian-Bathonian proto-rifting which evolved in the Late Jurassic-?Ryazanian main and last rifting event of this region (Færseth and Ravnås, 1998; Glennie and Underhill, 1998; Nøttvedt et al., 2000; Ziegler, 1990; 1992; Steel, 1993; Coward et al., 2003; Fraser et al., 2003; Patruno et al., 2015a,b,c; Patruno, 2017; Turner et al., 2018). The areas to the footwall of the border faults of the three main rift-related regional lows (i.e., Viking Graben, Moray Firth and Central Graben), including the ESP, became relatively stable Jurassic-Recent platforms (Figs. 3c, 4-5). As with the Permo-Triassic extension, and unlike the Jurassic rifting-drifting in the NA, the Late Jurassic rifting in the NS was aborted before ocean floor formation.

A new switch in relative plate motion in the "Mid Cretaceous" triggered the progressive convergence between the Eurasian/Corsica-Sardinian and African-Adriatic continental margins, which lead to the closure of the interposed Penninic-Piedmont-Ligurian Ocean and the Eocene-Recent Alpine/Apennine continental collision (Malinverno and Ryan, 1986; Dewey et al., 1989; Carmignani and Kligfield, 1990; Calamita et al., 2007) (Figs. 2, 3d-e). The onset of this plate convergence was possibly reflected by the abrupt lithostratigraphic transition in the NA from typical passive-margin pelagic limestones to Aptian-Albian marlstones (Patruno et al., 2015d; Unida and Patruno, 2016).

During this Eocene-Recent collisional stage (Fig. 3d,e), the NA consisted of an eastward to north-eastward migration of compressive fronts, coupled by foredeep development ahead of the advancing thrust-belt (Ricci Lucchi, 1986; Patacca and Scandone, 1989; Boccaletti et al., 1990).

These Neogene thrust structures have subsequently been affected by arrays of post-orogenic normal faults (Fig. 5), showing maximum fault-throws of 600-1500 meters and trending roughly parallel to the previous compressive structures (Calamita et al., 2000; Pizzi and Scisciani, 2000; Pizzi and Galadini, 2009). Several hangingwall-related intermontane basins infilled with thick ?Pliocene-Quaternary continental deposits (e.g., Galli et al., 2008) are associated to the occurrence of moderate magnitude (M≤7) historical and instrumental earthquakes (e.g., Calamita et al., 2000).

In the NS/ESP, the propagation of weak and localized intra-plate Alpine-age compressions interrupted the Cretaceous-Tertiary regional thermal subsidence (Figs. 1, 3d and 4; Alberts and Underhill, 1991; Butler, 1998; Patruno et al., in press). Furthermore, a post-Paleocene easterly tilting affected the whole U.K. NS. As a consequence, on the western portion of the ESP, we observe Paleozoic sediments outcropping to the seafloor (Underhill, 1991; Hillis et al., 1994; Patruno et al., in press; BGS 250k Marine Bedrock Map), while in the eastern portion of the ESP, the Paleozoic is overburdened by 2000 m of Cenozoic clastic sediments.

In summary, in the post-Variscan, the two study area shows the following regional geology differences.

- The NA is constructed through a new “classical/complete” Wilson Cycle (from Variscan compression to Permian-Jurassic Western Tethys extension and ocean spreading and back to Cretaceous-Recent Alpine/Apennine orogenesis). Post-orogenic Plio-Quaternary extensional collapse may in fact be interpreted as the early onset of a new cycle.
- The NS/ESP region instead underwent through at least two “foreland/incomplete” Wilson Cycles in an intra-plate setting: (1) from Variscan compression to Permo-Triassic rifting, and back to Mid Cimmerian uplift; (2) from Mid Cimmerian uplift to Late Jurassic rifting, interrupted by Cretaceous-Palaeogene thermal subsidence, and then partly inverted by far-field Alpine inversion and, close to the coastlines, by Neogene regional uplift.

Seismic interpretation of the ESP

The analysis of recently-acquired 3D seismic surveys over the outer ESP, coupled with the available stratigraphic well information, revealed significant traces of repeated tectonic inversion events.

On the basis of well data alone (e.g., the regional well correlation panel shown in Fig. 6), discrete regional unconformities can be inferred, corresponding in age to the regional uplift and erosion events discussed in the previous chapter. These are the following:

1) Base Tertiary Unconformity - identified locally by an erosional top Chalk contact, and possibly related to mantle plume related epirogenetic uplift.
2) Intra-Cretaceous Unconformity - possibly related to early Alpine age uplift, with a direct contact between upper Chalk and Cromer Knoll groups.
3) Base Cretaceous Unconformity (or BCU) - situated at the base of the preserved Cromer Knoll Gp. and representing the end of rift unconformity.
4) Mid Cimmerian Unconformity (MCU or BJU = Base Jurassic Unconformity) - hiatus/truncation at the base of the preserved Jurassic package, highlighted by the direct contact between upper-middle Jurassic units (e.g., Pentland, Heather or Kimmeridge Clay formations) with lower Triassic or, on structural highs, even older units.
5) The top and base of the lower Permian Rotliegend Group, if preserved, corresponds to two discrete erosional surfaces associated with the Variscan Orogeny. However, these and possible deeper Caledonian unconformities are not well documented, as most wells have shallower TDs.

Each of these erosional surfaces is also visible across several seismic lines as time-equivalent angular unconformities. In particular, in Figure 7b a Devonian to lower Carboniferous package has been tilted and truncated by the Base Permian unconformity. A thin Zechstein to Triassic package is subject to a lower amount of tilt and is truncated by the BJU. Finally an upper Jurassic package shows an even lower amount of tilt and is truncated by the BCU. The stratal packages bounded by these unconformities are characterized by increased tectonic subsidence rates (Fig. 7c), particularly in relationship with the Devonian post-orogenic collapse event and the post-Variscan Permo-Triassic rift-related mini-basins (Figs. 7c-7d).

Discrete unconformity surfaces can be identified only in intra-platform depocentral areas characterized by maximum stratigraphic preservation of Carboniferous-Cretaceous units, which are normally absent elsewhere on the ESP (e.g., Piper Shelf in Figs. 6-7 and Crawford-Skipper Basin in Fig. 8; Patruno and Reid, 2017; Patruno and Lampart, 2018; Patruno et al., in press). The unconformities instead merge together towards persistent structural highs (e.g., Kraken High, Fladen Ground Spur and Halibut Horst in Figs. 7-9). Intra-platform Carboniferous-Jurassic depocentres and persistent structural highs are also characterized by very different fault density (Fig. 9). Main age of fault activity ranges from Devonian, Permo-Carboniferous, Triassic and Jurassic-Cretaceous, and each fault age population shows a characteristic strike trend (Fig. 9; Patruno et al., in press). In particular, both east-trending well correlation panels and seismic lines across the Piper Shelf – Fladen Ground Spur areas (Figs. 6 and 7) reveal several sub-BCU extensional faults, with different timing of activity. Fault 6 in Figure 7a for example is associated to a partly inverted Rotliegend syn-rift wedge, whilst Fault 9 relates to both upper Jurassic and Permo-Triassic syn-rift wedges (also see backstripped evolution along a similar transect in Patruno, 2017). The Rotliegend syn-rift wedge bounded by Fault 6 and the Jurassic-Early Paleocene reflectors lying on it are subject to late inversion, highlighted by a gentle anticlinal folding of these reflectors, against which later Palaeogene reflectors onlap (Fig. 7a). An Eo-Alpine and Mid Cimmerian inversion age was proposed for this structure by Patruno and Reid (2018).

This inverted sedimentary wedge corresponds to one of the Carboniferous-Permian mini-basins highlighted by the time-thickness map (Fig. 7d).

Further north, relatively minor Late Cretaceous and Paleocene compressional inversion phases are revealed by: (1) the gentle folding of the ?Carboniferous-Paleocene reflectors in the Crawford-Skipper Basin (Fig. 8; also see Patruno and Reid, 2017); (2) the larger-scale antiformal folding of the Fladen Ground Spur, with Late Cretaceous strata becoming progressively thinner towards the antiformal culmination of this area and Paleocene reflectors onlapping against it (Fig. 8); (3) the minor reverse reactivation event for a major Devonian master-fault on the Kraken High, with an associated fault-related anticline formed by the overlying Paleocene reflectors, forming the structural closure for the Kraken oil field. (Fig. 10). This half-graben is associated to an expanded (up to 2.0 seconds TWT) hangingwall Devonian succession, including possible syn-rift wedge geometries (Figs. 8, 10). This is just one of the several extensional structures developed during the Devonian-age extensional collapse of the Caledonian Orogeny.

A few km to the north of Kraken, a prominent Devonian syncline is related to the same syn-depositional master-fault (Fig. 11). Below the Devonian reflectors (Units 1-2 in Fig. 11), a distinctly opaque seismic stratigraphic unit is tentatively identified as metamorphic basement (Units 3-4). This unit is about 1.0 second (TWT) thick, and do not contains any visible reflectors. Below this seismically opaque "basement" a second more highly reflective strata (Unit 5) is observed overlying a third more opaque seismic package. Fazlikhani et al. (2017) showed that a very similar tripartite sub-division of the basement seismic facies can be observed throughout the rest of the northern NS.

The Devonian successions in this area range from thick shale and sandstone intercalations in the main syncline, to conglomerates and breccias away from it (e.g., wells A and B). The ?Early Devonian, characterized by granite wash grading to granite in Well C ("Bressay Granite") could either be an intrusion localized in a small area surrounding the well (e.g., Unit 3 in Fig. 11) or could be interpreted as an acoustically transparent "basement" (Unit 4). Unfortunately, the regional extent and thickness of the intrusions is unknown and unconstrained by further data (Stephenson et al., 1999)

The highly reflective Unit 5 underneath the seismically transparent basement is fortuitously penetrated by Well D, drilled across the ESP/Viking Graben border fault. According to the analysis of this well, this unit is composed of gneiss/schists rich in hornblend and biotite, with an Early Devonian radiometric metamorphic cooling (Bassett, 2003). As a consequence Unit 5 possibly represents a transition between different compositions of crystalline rocks, likely to give rise to a significant contrast in acoustic impedance (e.g., acidic granites over basic gneiss?).

We interpret Unit 5 as possible pre-Devonian Caledonides or shear zones (e.g., Seismic Facies 2 of Fazlikhani et al., 2017) based on: (1) the lower Devonian metamorphic cooling age, and (2) the presence of likely north-westerly verging compressional compressive structures (at least in the south-eastern half of the line). In the north-western half of the line, the presence of likely extensional structures inside the same "Caledonide" package is counterintuitive. A possible explanation is that the north-western half of the line may represent a foreland area of the Caledonian Orogeny. The frontal Caledonian thrust was possibly situated in proximity of the previously mentioned Devonian master-fault, which can be mapped laterally for several tens of km (thick red fault on Kraken High in Fig. 9). This Devonian master-fault and other deeper faults that cut Unit 5 all show a NNE-SSW strike resembling the main lineaments associated to the Caledonian Orogeny (e.g., the Great Glen Fault and its offshore continuation), and to the likely orientation of the axis of the Iapetus Ocean (Figs. 3a, 4 and 9; Patruno et al., in press). This suggests a long-term preservation of the structural grain from the Caledonian compression to the Devonian extension up until the Alpine-age inversion (Figs. 9 and 12; Patruno et al., in press).

Field geology of the NA

In this section, seismic and outcrop data in the UMAR are tied, with the aim to reconstruct a balanced crustal geological cross-section of the outer NA. Moreover, due to the low resolution of vintage seismics, a detailed structural fieldwork has been carried out along some key regional-scale thrust zones, in order to define the field-scale geometric structural-stratigraphic relationships.

The UMAR comprises a series of east/north-east-verging folds, with 5-8 km wavelength, gentle backlimbs and near vertical-to-overturned forelimbs (Calamita et al., 2012). Thrust planes commonly truncate the east/north-eastern limbs of the folds (Fig. 13) with a shortening of c. 1-3 km achieved by each thrust and the related fold.

The eastern UMAR comprises four thrust-related anticlines, in which the more continuous corresponds to the Igno Mt.-Valnerina Anticline (Fig. 13). Some of these folds are displaced by NW-SE trending Quaternary normal faults, juxtaposing recent continental deposits in the hanging-wall to Jurassic-Miocene carbonates in the footwall, and responsible for recent destructive earthquakes (Calamita et al., 2000).

A detailed structural fieldwork has been carried out in the Igno Mt. Anticline area (Fig. 14). This anticline shows an overturned forelimb with Jurassic-Cretaceous strata overlaying gently SW-dipping Cretaceous-Miocene beds (Calamita et al., 1993). The anticline is cored by a Jurassic condensed pelagic succession, while the back-limb is affected by a set of WSW-dipping normal faults (Fig. 14). The presence of a thick and complete Mesozoic pelagic succession in the downthrown block indicates a Jurassic syn-sedimentary activity for these normal faults. A Miocene reactivation of these structures is suggested by Miocene channelized conglomerates cutting into their footwall. Clear Quaternary activity indicators (like fault scarps and triangular facets) are missing, suggesting a pre-thrusting foreland flexural-induced extension (cf., Scisciani et al., 2000b). The normal fault pre-thrusting activity and the thrust hangingwall ramp onto footwall ramp relationship observed in the field constrained the balanced geological cross-section for the Igno Mt.-Valnerina thrust, allowing estimating a shortening of about 1.7 km (Fig. 14b).

North-eastward to Igno Mt. the Camerino Basin has been interpreted as a Miocene normal fault-controlled basin, filled by Miocene turbidites (Scisciani et al., 2000b). This area was affected by the 2016 Visso-Norcia-Amatrice normal-faulting seismic sequence (Emergeo Working Group, 2016).

The eastern margin of the Camerino basin corresponds to the gently dipping back-limb of the Sibillini Mts. Anticline (Fig. 13). The regionally-extensive Sibillini Mts. thrust and thrust-related fold shows a curved geometry expressed by two segments, respectively trending NW-SE (northern sector) and NNE-SSW (Vettore Mt. apical central sector, with maximum shortening and structural elevation), that continue southward into the north-trending Olevano-Antrodoco thrust (Fig. 13). At least the central part of the Sibillini Mts-Olevano-Antrodoco thrust coincides with an inherited NNE-trending lineament (Ancona-Anzio line in Castellarin et al., 1982) separating the persistent Mesozoic Apulian (Lazio-Abruzzi) carbonate platform to the east from the time-equivalent Umbria-Marche pelagic basin to the west, and its arcuate shape has been commonly interpreted to be controlled by this structural inheritance (Alberti et al., 1996; Butler et al., 2006; Calamita et al., 2011; Pace et al., 2011; Scisciani and Esestime, 2017).

The best exposures of the main thrusts crop-out along the Fiastrone Valley (along the NW-trending thrust segment), located few kilometres southward to the trace of the seismic line (Figs. 13 and 15), where the Jurassic-Cretaceous carbonate succession (including Lower Jurassic Calcare Massiccio Fm.) form a thrust-related anticline emplaced onto Paleogene strata. The steeply dipping-to-overturned forelimb describes a hanging-wall ramp superimposed onto a footwall flat.

A balanced cross-section reconstructed by the collected surface geological data indicates a shortening of c. 4.0 km (Fig. 15). A shortening of c. 2.0 km was estimated more to the north (Mazzoli et al., 2005), and close to the seismic line trace (Fig. 13) documenting a reduction of the orogenic contraction away from the apex of the salient (Vettore Mt. area).

Subsurface geology of the outer NA

In this work, we selected a recently released seismic reflection profile transecting the UMAR from the inner Umbria Valley to the outer Laga Basin, through the intervening Camerino and Colfiorito basins (Figs. 5, 13-16). Key reflectors were correlated through: (a) geological fieldwork in proximity of the seismic trace; and (b) direct ties between well-log stratigraphy and seismic by using check-shot or synthetic seismograms of deep wells drilled close to the seismic profile.

The reconstructed seismic stratigraphy is consistent with previous studies (Bally et al., 1986; Mirabella et al., 2008; Scisciani and Montefalcone, 2005; Scisciani et al., 2014), and consists of eight units with distinctive seismic facies and bounding reflectors (Fig. 16). Units 3-7 have been drilled in the Massicci Perugini ridge-Tiber Valley (about 10.0 km to the north-west of the seismic line) and show a good correlation along the profile. Conversely, in the eastern sector, the older intervals (Units 6-8) are unconstrained due to the shallow penetration of exploration wells. Nevertheless, the results of combined gravimetric and magnetic modelling indicate homogenous characteristics of the deeper intervals along the entire seismic profile (Scisciani et al., 2014).

The seismic profile displays an overall westwards thinning of the Liassic-Miocene pre-orogenic succession, which is in agreement with the outcropping geology (Deiana and Pialli, 1994; Scisciani et al., 2010).

The Pliocene-Quaternary continental deposits (Unit 1) are restricted to the hanging-wall of west-dipping normal faults in the Umbria Valley and Colfiorito Basin (Fig. 16), where they unconformably overlie the older and deformed units. The Miocene siliciclastic deposits (Unit 2) correspond to poorly reflective seismic facies with respect to the underlying Unit 3, and are confined to the Umbria Valley, Camerino Basin and Laga Basin - Fig 16).

The Marne a Fucoidi reflector at the base of Unit 3 (EK in Fig. 16) overlies a very reflective package which terminates downward into a reflection-free interval, corresponding to the massive and monotonous Liassic shallow-water carbonates (Calcare Massiccio Formation). The Marne a Fucoidi and Top Calcare Massiccio reflectors are therefore distinctive and can be confidentially traced regionally, illustrating the deep geometry of outcropping structures. The three large wavelength (5-10 km) folds in the seismic section correspond to the Subasio Mt., Igno Mt.-Valnerina and Sibillini Mts. thrust-related anticlines. Clear reflector terminations against the thrust faults are visible in both hanging-wall and foot-wall blocks. The resulting hanging- and foot-wall ramp geometry let the thrusts achieve a limited amount of shortening: about 4.0 km for the principal and regional Sibillini Mts. thrust and lower for the others.

Underneath the core of the large-scale UMAR ridge, the ?Paleozoic-Triassic interval (Units 6-7) is significantly thicker (maximum TWT-thickness of 3.8 s) than in the areas underneath the Umbria Valley and the footwall of the Sibillini Mts. Thrust (about 1.2 and 1.8 s, respectively). These lateral thickness variations are also preserved after performing time-to-depth conversion of the seismic profile, suggesting that they are not artifacts.

In particular, Unit 7 has been correlated with the slightly metamorphosed Verrucano facies in adjacent wells (Scisciani and Esestime, 2017). This unit shows a wedge-shaped geometry in the hangingwall of normal faults at depth (Fig. 16). Some of these faults show a variation of the offset with depth that is typical of positive inversion tectonics: faults have a normal offset at depth that changes to reverse up-dip (e.g., Williams et al., 1989), with a mild degree of inversion (*sensu* Cooper and Williams, 1989). The geometry of the lower part of Unit 6 (presumably corresponding to the Late Triassic evaporites) clearly depicts the vertical extrusion of the over-thickened Mesozoic syn-rift basin infill. The thick wedge of lower Unit 6 at depth corresponds at surface with the long-wavelength exhumed carbonate ridge and with the region of highest topographical elevation (Fig. 16).

At shallow depth in the seismic profile, several high-angle faults terminate against low-angle thrusts (e.g., SP1600-1800, 2080-2130, and 2150-2420 in Fig. 16). Some of these high-angle faults show a good correlation with outcropping Jurassic and Miocene normal faults that commonly occur in the core and back-limb of anticlines. This setting corresponds to short-cut geometries that are typical of positive inversion tectonics where a thrust fault truncates across the footwall of a pre-existing inverted normal fault (e.g., Figs. 15-16; Cooper and Williams, 1989; Coward, 1994).

The west-dipping Quaternary Colfiorito normal fault system merges downward into a previous Neogene thrust plane, as suggested by the continuity of the gently -dipping fault plane reflections at 1.0-2.0 seconds (TWT) of depth (SP1400-1500 in Fig. 16). Conversely, the Quaternary Subasio Mt. normal fault system is likely associated with a décollement layer within the Triassic evaporites, as suggested by: (a) the fault down-throw apparently decreasing down-dip; and (b) the top phyllites reflector being only moderately offset (SP200-500 in Fig. 16).

Integrated fieldwork and seismic interpretation: positive and negative inversions in the NA

The interpretation and time-to-depth conversion of the seismic line in Figure 16 has been used to constrain a regional balanced and restored geological cross-section across the outer sector of the NA (Fig. 17). The basement geometry is characterized by a structural depression located underneath the UMAR salient. The adjoining basement highs are placed beneath the Umbria Valley and Laga Basin. The inferred basement physiography highlights a large pre-existing basin filled with Triassic and probably late Paleozoic sediments. The resulting structural style appears strictly controlled by the inversion and vertical extrusion of this deep Paleozoic-Triassic extensional basin.

The UMAR separates two thick siliciclastic turbiditic wedges infilled during the Burdigalian-Serravalian (Marnoso-Areancea Fm.) and Messinian (Laga Formation) times. These wedges are 2000-5000 m thick (e.g., Boccaletti et al., 1990) and their present-day transversal extension is at least of 60 km. In the interposed ridge, the siliciclastic turbidites are generally lacking or extremely reduced in thickness with the exception of few NNW-SSE trending confined basins delimited by normal faults (e.g., the Camerino Basin in Fig. 5 and 13; Scisciani et al., 2001). Analogous extensional basins infilled by siliciclastic foredeep sediments have been found both in the eastern (Belforte basin and Cingoli area) and western sector (Gubbio basin) of the UMAR (e.g., Scisciani et al., 2002; Mirabella et al., 2004 - Figs. 5 and 13). The syn-sedimentary normal faults trend NNW-SSE to N-S, are both E- and W-dipping and show a range of throw from about 100 to 800m. Thick turbiditic successions are concentrated in the basin depocentres, with synsedimentary slumps, slide scars and coarse grained deposits sourced by steep paleo-scarps created by the synsedimentary normal faults. The evident increase in conglomerates and coarse grained sandstones close to the paleoscarps suggest the synsedimentary control exerted by the normal fault in the development of these confined basins (Ricci Lucchi, 1986). By contrast the structural highs are capped by thin and condensed sequences of hemipelagic shales or are deeply eroded. Detailed stratigraphic studies indicate that the extensional faults were active and controlled the deposition of Late Miocene foredeep turbidites included in the Marnosa-Arenacea (Burdigallian-Tortonian), Camerino sandstones (Tortonian-early Messinian) and Laga (early Messinian) Formations. Moreover, several of these normal faults frequently reactivated pre-existing extensional structures, including Jurassic and Cretaceous pre-orogenic faults. The Miocene normal faults are commonly deformed or truncated by subsequent folds and thrust faults developed during the Apennines compressive tectonics.

Prevailing thrust hangingwall ramp onto footwall ramp geometric relationships have been constrained through both fieldwork and seismic interpretation. The total shortening associated with the Neogene compressive deformation is about 7.7 km (i.e., c. 10% of the total section length), with each thrust and related fold realizing a maximum shortening of 4.0 km (e.g., for the Sibillini Mts. thrust).

The common occurrence in the anticline backlimbs of high-angle WSW-dipping normal faults truncated by Neogene thrusts propagated with a short-cut geometry highlights the key role played by positive inversion tectonics in the Apennines orogeny. Another relevant feature is the negative reactivation of low-angle thrust fault segments by recent active normal faults, including the WSW-dipping Colfiorito and Visso-Norcia normal fault systems (indicated with "X" and "Y" in Fig. 16, respectively). These fault systems were responsible for two strong recent seismic sequences with main-shocks of Mw 6.0 (1997 in Colfiorito) and Mw 6.5 (2016 in Visso-Norcia), respectively. The dense network of seismic stations installed during these recent earthquakes clearly imaged the deep active fault geometry (Barba and Basili, 2000; Chiaraluce et al., 2017). Two evident SSW-dipping areas with densely concentrated aftershock locations are consistent with the geometry of the normal fault systems reconstructed by both field data and seismic interpretation. All these methodologies suggest that the active normal faults negatively reactivate preceding thrust segments.

Discussion

Structural reactivation and inversion patterns in the ESP

A lateral transition between compressional belt, foredeep and mainly extensional foreland structural domains can be clearly interpreted for a young and relatively well-preserved orogeny like the Apennines (e.g., Finetti et al., 2005). Instead it is much more challenging to reconstruct the structural setting for older collisional belts such as the Caledonian Orogen where subsequent high-pressure metamorphic core complex formation and widespread phases of erosional truncation often obliterated the remnants of earlier structural configurations. However, as the offshore ESP was likely subject to a lower degree of metamorphic obliteration of the Caledonian belt configuration than in the onshore it was possible to observe and highlight the coexistence of Caledonian-age normal faults and compressional structures (Fig. 11). These offshore structures have been mapped in 3D, revealing an overall north-trending strike-orientation that is virtually undistinguishable from the Devonian-Jurassic structural grain of this area, and the hypothesized offshore trend of the Iapetus Suture (Fig. 3a). It can therefore be inferred that these possible Caledonian-age extensional structures were formed in the palaeo-foreland of the evolving Caledonian orogen. Moreover, the Devonian normal master-fault that underlies the Kraken area might have coincided with the front of the Caledonian belt, as no trace of deep-seated compressional deformation is observed beyond it.

Irrespective of kinematic and age of activity, all mapped Caledonian, Devonian, Permo-Triassic and Jurassic-Cretaceous faults share similar trends (Fig. 9). Two areas can be identified in the outer

ESP, one with structural grain parallel to the north-trending Viking Graben, the other with conjugate fault trends mirroring the east-trending Witch Ground Graben. This long-term preservation of structural grains and the reconstructed polyphase history of tectonic inversion and reactivation of the same structural zones of weakness highlights the profound impact of structural inheritance in the NS/ESP (e.g., Fig. 12; Johnson and Dingwall, 1981; Bartholomew et al., 1993; Glennie and Underhill, 1998).

During this polyphase post-Devonian inversion history, the multiple intra-plate compressional phases lead to the deposition of up to five main regional erosional unconformities: (1) Saalian (Variscan orogeny); (2) Mid Cimmerian (Mid North Sea Doming); (3) Late Cimmerian (BCU); (4) Intra-Cretaceous (Eo-Alpine); (5) Base Tertiary and Paleocene Alpine unconformities (Fig. 2). These events correspond to "peaks of absence" of the time-equivalent rocks from >75% of the ESP wells (Patruno et al., in press).

In particular, the Late Carboniferous Variscan compression lead to extensive foreland-type uplift and erosions (Figs. 6 and 7d), which were significant over certain portions of the ESP, such as the Fladen Ground Spur and Kraken High. These areas became permanently inverted into long-lasting positive features, with erosional processes which started sourcing sediments to the adjacent relative depocentres (Freer et al., 1996; Fig. 12). We suggest that, consistently with the main supra-regional Variscan kinematic (Fig. 3b), the local maximum compression vectors were oriented roughly north-south (Fig. 12b). A number of Devonian reflector folds (e.g., Figs. 7-8) were possibly due to Variscan intra-plate compressional stress propagation.

Although the Late Triassic to Aalenian hiatus has been recorded by nearly all the ESP wells (Patruno and Reid, 2017; Figs. 6 and 7d), evidence of significant Aalenian uplift is particularly strong in the vicinity of the South Viking Graben 'triple junction', where the focus of regional thermal doming and erosion was situated (Underhill and Partington, 1993; Coward et al., 2003). In particular, an overall Early-Middle Jurassic tectonic uplift has been highlighted by the burial history modeling of Well 15/6-1 (Fig. 7c; Patruno and Reid, 2018). Furthermore, the Devonian-Carboniferous succession between Fault 6 and Anticline A in Figure 7a underwent an initial Variscan tilting and a successive Mid Cimmerian uplifting-related tilting, which had an increasingly greater magnitude towards the proto-Viking Graben. As a consequence, these reflectors are now characterized by a greater overall easterly tilt (ca. 83 ms/km) than the overlying Permo-Triassic over the same area (ca. 35 ms/km), which was only affected by the Mid Cimmerian tilting.

Minor Early Alpine compression events are highlighted by the gentle anticlinal folding of the entire ?Carboniferous-Top Cretaceous succession over inverted Permo-Triassic extensional basins, with lower Paleocene strata progressively onlapping against the antiformal culmination (e.g., Fig. 7, 8 and 12). These compressional events are probably Late Cretaceous in age, as highlighted by Chalk strata becoming anomalously thin towards the antiformal culmination, which corresponds to the Permo-Triassic hangingwall depocentres (Figs. 7a-8). The inversion of the Devonian extensional master-fault on the Kraken High (Figs. 10 and 12) highlights a slightly posterior, Late Paleocene compressional event.

The Permo-Triassic and Late Jurassic rifting events left behind a number of syn-depositional fault-driven intra-platform tectonic depocentres, such as several half-grabens on the Piper Shelf (Figs. 7a, 7d and 9) and the Crawford-Skipper Basin (Figs. 8-9 and 12; Patruno and Reid, 2017). The mini-basins on the Piper Shelf were mostly filled with Rotliegend sediments (e.g., the Fault 6 half-graben in Fig. 7a), suggesting a main Permian-age for the post-Variscan rift development over this area, with minor Triassic and Jurassic reactivations. Both Permian and Triassic faults are present on the Crawford-Skipper Basin: they share a mean north-northeast orientation which is parallel to the border faults of the nearby Viking Graben (Fig. 9), but show negligible Late Jurassic reactivation, suggesting that in the Jurassic the entire extensional strain had been transferred to the incipient Viking Graben border faults (Figs. 9 and 12).

Structural reactivation and inversion patterns in the NA

Following the Variscan Orogeny, the basement of the NA underwent repeated episodes of extension during the Late Paleozoic-Mesozoic times. Our subsurface interpretation suggest that, presumably starting from the Late Paleozoic and Triassic, in the study area a prominent extensional basin developed and was infilled by at least 5 km of syn-tectonic sediments (Figs. 16-17). Comparable extensional basins were also reconstructed further east in the Montagna dei Fiori area and in the Central Adriatic (Fig. 18). The subsequent Jurassic-Cretaceous extensional event was less severe and achieved an overall reduced amount of down-throw (Fig. 17). The shallower and high-frequency setting of Jurassic normal faults with respect to previous structures suggest that the thick Triassic evaporitic interval acted as decollement level during the extension, influencing fault vertical growth and transversal spacing.

The pre-orogenic configuration of basement and Triassic decollement strongly controlled the style of compressive structures during the Apennines inversion tectonics. The low-wavelength folds are commonly related to minor thrusts propagated from shallow detachments and following short-cut trajectories with respect to the pre-existing Jurassic normal faults. Conversely, the large-wavelength anticlines forming the prominent mountain fronts and delimited by regional thrusts (e.g., the Sibillini Mts thrust) correspond to main thick skinned structures emanating from basement (Figs. 18 and 19). Fieldwork and seismic interpretation typically indicate thrusts cross-cutting through hanging- and foot-wall ramps; these geometric relationships imply a reduced shortening amount with respect to previous thin-skinned reconstructions (e.g., Bally et al., 1986).

Normal fault networks were widely observed in several foreland basins all over the world (e.g., Sinclair, 1997) and have also been described in the NA/UMAR foredeep basins. Syn-orogenic normal faults developed in a foreland tectonics context before the onset of contractional deformation and generated structural highs near-parallel to the flexure axis and to the subsequent compressive structures, therefore controlling the thickness, dispersal and facies distribution of the syn-tectonic foredeep deposits (Tavarnelli et al., 1998; Tavarnelli and Peacock, 1999; Scisciani et al., 2000a; 2001; 2002; Mazzoli et al., 2002; Calamita et al., 2003). Several of these normal faults frequently reactivated pre-existing extensional structures, including Jurassic and Cretaceous pre-orogenic faults (Calamita et al., 2011), as observed in similar settings where foreland down-warping resulted in the reactivation of inherited passive-margin structures (Frankowicz and McClay, 2010; Langhi et al., 2011; Saqab and Bourget, 2015).

In general the strong subsidence recorded in foredeep basins is triggered by the flexure of the foreland plate due to the load exerted by the adjacent growing orogenic wedge (Cross, 1986). The foreland flexure is locally accommodated by pre-orogenic extension affecting the shallow brittle crust ("flexural extension" - Turcotte and Schubert, 1982; Doglioni, 1995). The syn-orogenic normal faults in the Apennines were also classically interpreted in term of flexural bending extension (e.g., Boccaletti et al., 1990); however, the normal faults within the UMAR and in adjacent NA sectors show distinctive architectural characteristics that differ with respect to those of typical flexural bending settings (Fig. 19). In the NA, Miocene normal faults are commonly foreland-dipping and are located in the inner edges of foredeep basins (e.g., in the eastern sector of the Sibillini Mts). In the proposed reconstruction (Fig. 19), the Late Miocene UMAR is interpreted as an embryonic large wavelength (about 40 km in width) uplift developed in proximity of the advancing Apennines thrust front. This suggests that during the Late Miocene the Adriatic foreland underwent foreland flexure accompanied by normal faulting, prior to large-wavelength (about 40 km) uplift, with reactivation at shallow levels of the pre-existing normal faults. The large-scale uplifted "peripheral bulge" almost corresponds to the whole UMAR, suggesting a large-scale basin inversion, with embryonic vertical extrusion by positive inversion of the Late Paleizoic-Mesozoic extensional basin at depth, possibly promoted by mechanical weakening of the NA foreland lithosphere due to flexural normal faulting.

The controlling factor of multi-phase reactivations and inversions

Although the ESP and the NA underwent different tectonic evolutions within distinct settings, they both show evidence of cyclic reactivation of faults and structural grains, with alternating extension and compression (Fig. 20). Therefore, these areas are expected to be characterized by some of the geological elements that, in past studies, have been suggested to promote this sort of recurring reactivations, at scales ranging from a single fault plane to an entire basin or chain, as predicted by the Wilson Cycle concept. The main reported factors include: (1) nature and composition of sedimentary cover and crust, (2) thermal conditions, (3) crustal thickness, (4) amount/rate and direction of deformation, (5) frequency, orientation and mechanical/petrophysical characteristics of fractures and shear zones, (6) fluid occurrence and relative pressure, and (7) amount/rate of sedimentation/erosion (Sibson, 1985; Williams et al., 1989; Butler et al., 1997; Turner and Williams, 2004; Morley et al., 2008; Buiter et al., 2009; Bonini et al., 2012; Lafosse et al., 2016).

Both analysed areas rest onto a relatively attenuated continental lithosphere (Zanella et al., 2003; Artemieva, 2007; Molinari and Morelli, 2011). In particular, in the far undeformed Adriatic foreland, where crustal thickness was preserved by the Cenozoic contractional and extensional tectonics, the Moho is relatively shallow (about 30-35 km in depth) (Finetti et al., 2005; Miller and Piana Agostinetti, 2012). Under present-day onshore Scotland and Greenland Caledonian core complexes, the Moho is also at relatively shallow depths (c. 50 km - Snyder, 1991) for a fully collisional orogen. The thickness of the crust in the NS was probably reduced to 30-40 km at the end of the Devonian extensional collapse (Schlindwein and Jokat, 1999) and is currently 10-30 km, which are typical values for rift basins (Zanella et al., 2003).

Elevated geo-thermal gradient and inherited basement grain are "classical" drivers for long-term lithosphere weakening, consequently favouring the cyclical reactivation of the former rifted structural grain during the compressional and extensional collapse parts of a Wilson Cycle (Krabbendam, 2001).

Previous numerical modelling studies have demonstrated that a short time-interval between rifting-related crustal thinning and the subsequent compression prevents the basin and the underlying mantle from cooling, favouring positive basin inversion (Burov and Diament, 1995; Buiter et al., 2009). This however is in direct contrast to our Apennines case study, where the post-rift phase lasted 140-190 Myr.

In our interpretation, instead, the mechanical weakening of the foreland lithosphere due to pre-inversion flexural normal faulting, tectono-magmatic phases and frequently reactivation of inherited discontinuities, accompanied by possible crustal hydration, is the key to explain the observed polyphase basin inversions in the two study areas.

In relatively old and cold basins, numerical modelling indicates that small amounts of strain softening are required to promote basin inversion by reactivation of inherited fault zones. In particular, the weakening mechanism of shear zones or the cyclic re-utilization of pre-existing discontinuities are thought to be long-lived driving processes (e.g., Butler et al., 1995; Imber et al., 1997; Hatcher, 2001; Thomson and Underhill, 1993; Holdsworth et al., 2001; Scisciani, 2009). Shear zone weakening is enhanced by high fluid pressures, clay-scale gouge and phyllosilicate-rich foliated fault rocks (e.g., Collettini et al., 2009). Several of these key-elements have been clearly documented in several reactivated faults in both the NA and the NS, as further explained below.

The main positive inversion stages affecting the NS/ESP foreland were preceded by relevant tectono-magmatic phases (Fig. 2) during the Carboniferous to Lower Permian and middle Jurassic, associated to the development of large wavelength erosional unconformities. The NS Mid Cimmerian Unconformity, in particular, causes Aalenian to upper Triassic interval to be missing in wells even in relative structural depocentres (e.g., the Piper Shelf) (Fig. 7; Patruno and Reid, 2017), and is associated with the extrusion of the Rattray Series and the Forties Igneous Province (Ziegler, 1992; Underhill and Partington, 1993; 1994). This widespread erosion is the result of the impingement of a broad-based (>1250 km diameter) transient plume head at the base of the lithosphere ("Mid North Sea Doming" event, *sensu* Underhill and Partington, 1993). Analogously, in the NA Adriatic foreland, a Palaeogene regional uplift and extensive erosion is associated with the near-complete absence of Paleogene sediments in wellbores, and Miocene deposits unconformably locally resting onto Lower Cretaceous carbonates (Rusciadelli et al., 2003; Satolli et al., 2014). This regional uplift was also concomitant with an extensive Paleogene anorogenic intra-plate magmatism that affected the

Adriatic foreland, associated to intrusive and effusive ultra-mafic products sourced by the mantle (Bell et al., 2013).

The overall reduction of the mechanical resistance of the rocks in the study areas was thus likely favored by: (a) the magmatic-related increase in heat-flow and geothermal fluids; and (b) the diagenetic processes associated with the development of several long-lasting, erosional and compound erosional surfaces. Stress localization subsequently took place within the thermally-weakened portions of the crust and multi-phase reactivations of pre-existing lineaments ensued (Kusznir and Park, 1987).

In relation to this, it is interesting noting the very quick transition in the Viking Graben from high-magnitude Aalenian uplift to Bajocian-Bathonian proto-rifting and Callovian-Berriasian main rift (Patruno, 2017). Also, the locus of maximum Aalenian uplift quickly became the 'triple junction' between the axes of the three main Late Jurassic rift systems of the NS (the Viking Graben, Central Graben and Moray Firth).

In addition, the existence of foreland units affected by syn-orogenic normal faults has several implications on fluid circulation and mechanical characteristics of the foreland plate. Pre-orogenic formations in the foreland are commonly overlain by a veneer of hemipelagic shales and marls which predates the deposition of thick coarse grained turbidites, acting as a fluid barrier (Ricci Lucchi, 1986). However, when this confining layer is offset and breached by syn-orogenic normal faults, the deep reservoir becomes hydraulically interconnected to the shallow one. Consequently, deep and light fluids leak-off (hydrocarbons, Co2 and hot water) while cold and dense saltwater may intrude into the deep carbonate reservoir recharging or enhancing the deep circulation. Analogously, in uplifted forelands the direct exposure of eroded and in places karstified carbonates promotes the meteoric water infiltration along the fracture network into the crust and recharge the ground-water circulations (Mindszenty et al., 1995; Allen et al., 2001; O'Brien et al., 1999). In the NA foreland, an increase in salinity of migrating fluids caused diffuse dolomitization of carbonates along Jurassic normal faults reactivated during Miocene syn-orogenic foreland tectonics (Ronchi et al., 2003). Further evidence of ascending hydrocarbon-charged fluids through a pathway composed of syn-orogenic fractures and faults network (Scisciani et al., 2000a) in the Late Miocene NA foreland is testified by the occurrence of cold-seep carbonate build-ups, authigenic patches and carbonate breccias (Iadanza et al., 2013).

Analogously, in the Norwegian Northern NS, reverse fault slippage and gas leakage along sections of previously sealing reservoir-bounding faults occurred in recent times due to a combination of increase in compressional stress associated with postglacial rebound and locally elevated pore pressure due to the local presence of natural gas in fault footwalls (Wiprut and Zoback, 2000; 2002). It is arguable that similar mechanisms acted on the ESP, where several Alpine-age reverse-fault reactivations have been identified (e.g., Figs. 4d and 7) and where there are multiple evidence of hydrocarbon seepage (Richardson et al., 2005; Patruno and Reid, 2016; 2017) and possible fluid leakage (Patruno et al., in press).

Moreover, the infiltration of aqueous fluids my lead to the formation of clay minerals, often leading to important changes in mechanical behaviour of the fault zones, such as local anisotropy enhancement and the bulk shear strength reduction, and increased fluid pressures during shearing (Warr and Cox, 2001).

Summary and Conclusions

The Caledonian-Variscan orogens in Northern-Central Europe and in the Apennines range of Italy are classical examples of thrust belts developed at the expense of former passive margins that underwent multiple events of extension and compression. Both settings represent key regions to study the effects of how a complete Wilson Cycle is achieved and preserved in the geological record.

In the present work, we have selected two study areas set in the above-mentioned regions, where field structural data and subsurface data allow the recognition of at least one "classical/complete" Wilson Cycle along with several "foreland/incomplete" Wilson Cycles, with long-term preservation of structural grain and polyphase reactivation of pre-existing structures. These two study areas are the offshore East Shetland Platform (ESP) in the UK North Sea and the onshore Northern Apennines (NA) of Italy. Regional geology, structural field evidence and subsurface data (2D and 3D seismic reflection and well-logs) have been here integrated with the aim to reconstruct the tectonic evolution and the common features that were significant in controlling the stress localisation along inherited zones of weakness that suffered repeated reactivation.

In the ESP, the relatively shallow Palaeozoic-Tertiary sedimentary cover, combined with a remarkable penetration depth of recently acquired 3D broadband seismic reflection data revealed several events of compression and extension that have been taking place since the Caledonian Orogeny. We interpret multiple reactivation of the Caledonian basement structures during both negative (e.g., the Devonian post-collision collapse, Permian-Triassic and Middle-Late Jurassic rifting events) and positive inversion tectonics (e.g., from far-field Variscan and Alpine orogenic phases).

Similarly in the NA, due to exceptional outcrop exposures and availability of abundant subsurface data (e.g., exploration wells and seismic profiles), we have been able to recognize repeated rifting and mountain building processes. This area underwent: i) compression during the Variscan Orogeny; ii) extension during the Late Paleozoic-Early Mesozoic rifting and Jurassic Alpine Tethys ocean opening; iii) Apenninic compression in Cenozoic times; and iv) late/post-orogenic extension in the Miocene to Recent.

The outcomes of this study indicate that inherited normal faults related to pre-orogenic rifting phases promoted multiple, deep-rooted, basement-involved positive basin inversion, with different amounts and rates of vertical extrusion of previous wedge-shaped graben. In turn, normal faults produced by negative inversion and post-orogenic extensional collapse were also strongly influenced by the location of precursor compressional discontinuities (e.g., thrust ramps). In the NA this has resulted in distinct patterns and segmentation of the recent post-orogenic normal faults that are responsible for the present-day seismicity.

In the two study areas, pre-inversion thermal softening and fault weakening of the foreland lithosphere, particularly if accompanied by possible crustal hydration and tectono-magmatic phases, are suggested to represent the main controlling factors that promote cyclical structural reactivations, during both full Wilson Cycles and far-field foreland inversions.

This study, moreover, illustrates how the structural signature of a complete Wilson Cycle is best preserved in foreland domains flanking orogenic systems and produced at the expenses of pre-orogenic rifted margins. In these settings, earlier lineaments are not completely obscured by later deformations, but are still legible in the structural record, thus enabling us to investigate the role, degree and intensity of structural inheritance phenomena. Foreland domains may, therefore, be regarded as ideal settings to study the factors controlling crustal reactivation processes during both positive and negative inversion histories.

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Figure captions

Figure 1: Location map of the study area including (a) the East Shetland Platform in the UK offshore and (b) the Northern Apennines of Italy.

Figure 2: Synoptic scheme showing the main tectonic, stratigraphic and magmatic events that occurred in the East Shetland Platform and Northern Apennines (pre-mid Permian evolution derived from Sardinia). The ESP and NA were subject to two Proterozoic-Paleozoic plate cycles, albeit not completely overlapping and with different chronological duration, namely the *Iapetus-Caledonian Cycle* and the *Rheic-Variscan Cycle* (see the text). Following the Variscan Orogeny, the NA underwent a further complete plate cycle whereas the NS have been subject to at least two incomplete Meso-Cenozoic intra-plate extension-compression cycles in an intra-plate setting.

Figure 3: Paleogeographic reconstructions during the Ordovician (a), Late Carboniferous (b), Late Jurassic (c) Paloecene (d) and Early Oligocene (e); compiled from different authors (Decourt et al., 2000; Stamply and Borel, 2002; Coward et al., 2003; Scisciani and Montefalcone, 2006; Nance et al., 2010;). The figures illustrate the plate configuration during the Iapetus-Caledonian (a), Rheic-Variscan (b) and Alpine-Apennines (c-d-e) plate cycles (see the text for the discussion).

Figure 4: (A) Central and Northern North Sea location map, showing the East Shetland Platform and the Greater East Shetland Platform (sensu Patruno and Reid, 2016) with location of the PGS seismic surveys. (B) East Shetland Platform location map, including the position of the main hydrocarbon fields, the wells with the Devonian interval, and the relationships between the Devonian Orcadian Basin and the Late Jurassic platform tectonic elements (modified after Patruno & Reid, 2017). The position of the seismic lines discussed in the present work, as well as the PGS 3D MultiClient GeoStreamer surveys, is shown. (C) Onshore outcrop and offshore Permian subcrop map of the East Shetland Platform, West of Shetlands and Moray Firth areas (modified after Patruno et al., in press). The main tectonic lineaments, the igneous intrusions and the extent of the Zechstein-age halokinetic salt are also shown (A, B and C modified after Patruno, 2017). (D) Sketch map of basement units in the northern North Sea and surrounding areas (modified from Lundmark et al., 2014); the Dalradian basement of the ESP is delimited to the ENE by the Walls Boundary Fault, corresponding to the offshore prosecution of the Great Glen Fault, and to the SE by the continuation offshore of the Iapetus oceanic units with an interposed volcanic arc basement (e.g., Utsira High and East Shetland Basin Basement).

Figure 5: Structural sketch map of Central and Northern Apennines; upper left inset for location.

Figure 6: West-to-east oriented well correlation panel spanning the southern margins of the East Shetland Platform, from the Halibut Horst, through the Piper Shelf and the Fladen Ground Spur (UKCS Quadrants 14, 15 and 16) to the western edge of the South Viking Graben. Modified after Patruno et al. (in press).

Figure 7: Figure showing the complex multi-phase inversion tectonics in the southern East Shetland Platform (UKCS Quadrants 15-16), near the transition between the Platform and the Witch Ground Graben (ca. 36 km further south) and the South Viking Graben (right-hand side in section A). This figure includes the following parts: (A) Interpreted seismic cross-section (PGS GeoStreamer® MC3D-Q15-2014 3D seismic survey), along a similar transect as the correlation panel in Figure 6; (B) Close-up of the interpretation of Section A (C) total subsidence curve below present-day sea level and tectonic subsidence rate graphs from Well 15/6-1 (backstripping method of Allen and Allen, 2005); (D) TWT thickness map of the Permian to Carboniferous interval.LC = Late Cretaceous; EC = Early Cretacoues; LJ = Late Jurassic; MJ = Middle Jurassic (post-Aalenian); Tr = Triassic (mostly Early Triassic); Z = Zechstein Group (latest Permian); Ro = Rotliegend Group (Late Permian); C = Carboniferous. This figure has been modified after Reid and Patruno (2015), Patruno and Reid (2018) and Patruno et al. (in press).

Figure 8: Regional N-S seismic reflection line straddling the western edge of the East Shetland Platform, parallel to the Viking Graben. The Kraken High and the Fladen Ground Spur are two prominent ?Variscan structural highs, where a thin Chalk/Jurassic veneer is the only stratigraphic unit that separates a thick Devonian and Tertiary successions. Between these highs, the Crawford-Skipper Basin (sensu Patruno and Reid, 2017) is an area hosting a much more complete Carboniferous-Cretaceous succession. Figure modified after Patruno and Reid (2017) and Patruno et al. (in press).

Figure 9: Map showing 633 different faults on the East Shetland Platform area constrained by 3D seismic coverage. The faults have been mapped in 3D and classified according to their kinematic and main age of activity. The predominance of N-striking faults parallel to the Viking Graben and overall E-striking faults parallel to the Witch Ground Graben, despite the wide variation in activity age, suggests long-term structural inheritance. Figure modified after Patruno (2017). For a full statistical appraisal of these structures see Patruno et al. (in press).

Figure 10: Northwest-southeast trending seismic line across the Paleocene Kraken Oil field, highlighting an expanded Devonian succession in the hangingwall of a likely lower Devonian masterfault, successively subject to a partial Palaeogene-age inversion, leading to the formation of a fault-related anticline in the Paleocene section (i.e., the structural closure of the Kraken Field itself). Figure modified after Patruno and Reid (2017) and Patruno et al. (in press).

Figure 11: Overall northwest-to-southeast arbitrary line to the north of the Kraken Field, displaying again the Devonian syncline (Units 1 and 2) within the ESP associated with the partly inverted masterfault shown in Figure 10. Below the Devonian reflectors there are opaque seismic-stratigraphic units (Units 3 and 4), characterized by no visible reflector, followed by another unit with high-amplitude reflectors (Units 5 and 7), highlighting both compressional (south-eastern sector) and extensional deep-seated structures. Unit 3: inferred granitic intrusion. Also see Patruno et al. (2017) for further details.

Figure 12: Schematic reconstruction of the structural and stratigraphic evolution of the regional N-S line (Fig. 8). These cartoons were reconstructed based on: stratal geometries; inferred depositional thickness trends (seismic and wells); backstripping analyses; facies variations in the wells. Also see Patruno and Reid (2017) for further details.

Fig. 13: Simplified geological and structural map of the south-eastern sector of the Northern Apennines (modified from Scisciani et al., 2014) transected by the arc-shaped Umbria-Marche Apennine Ridge (UMAR); upper left inset for location. Dotted and continuous lines mark the location of the seismic reflection profile (A-A') of Fig. 16 and geological cross-section (B-B') of Fig. 17, respectively.

Fig. 14 (a) Structural map of the Igno Mt. area (location in Fig. 13 - modified from Scisciani et al., 2014); (b) Geological cross-section (trace in (a)), and restored template across the Igno Mt.-Valnerina thrust system.

Fig. 15: (a) Simplified geological map of the Sibillini Mts thrust eroded and exposed along the Fiastrone Valley; (b) exposure of the overturned thrust-related anticline in the hangingwall block of the Sibillini Mts thrust along the northern flank of the Fiastrone Valley; (c) geological cross-section showing the overturned anticline and the ramp trajectory of the thrust fault across the Lower Jurassic strata (CM: Calcare Massiccio Fm.) and the steeply dipping forelimb in the hangingwall block; and (d) restored template showing the shortcut trajectory of the future Sibillini Mountains thrust with respect to the pre-thrusting normal faults.

Fig. 16: Geological interpretation of a regional seismic reflection profile across the UMAR; trace location in Figs. 5 and 13.

Fig. 17: Balanced crustal geological cross-section (a) across the UMAR reconstructed by integrating the results of surface geology and seismic interpretation (trace in Figs. 5 and 13). The restored template (b) illustrates the geometry of the late Paleozoic-Triassic extensional basin that was inverted and extruded during Miocene.

Fig. 18: Regional geological cross-section (a) and simplified restoration (b) across the Northern Apennines from the Umbria Valley to the Plio-Quaternary Adriatic basin (trace in Fig. 5). The transect derives from the present study (C-D segment) and previous reconstructions (E-F-G segment - modified from Scisciani and Montefalcone, 2006; Scisciani, 2009; Pace et al., 2015).

Fig. 19: a) Sketch map illustrating the reconstructed distribution of thickness and facies of late Tortonian-Messinian pre-gypsum deposits. b) Schematic cross-section showing the embryonic growth of the UMAR that was interposed between the thrust front of the Apennines chain and depocentre of the Messinian Laga Basin.

Fig. 20: Examples of fault reactivation in positive and negative inversion tectonic setting in the ESP and NA: a) positive reactivation during the Alpine foreland tectonics (late Cretaceous-Paleocene) of a Devonian and Triassic normal fault flanking to the west the Crawford Spur in the ESP; b) Pliocene-Quaternary positive reactivation of a Triassic-Early Jurassic

normal fault in the Adriatic basin in front of the Northern Apennines (seismic line location in Fig. 19 - modified from Pace et al., 2015); c) positive inversion of a synsedimentary Devonian normal fault (note the divergent Du syn-rift wedge in the hangingwall of the NW-dipping extensional fault) in the ESP (modified from Platt and Cartwright, 1998); the south-eastward thinning of the basal Devonian unit (Dl) towards the inverted fault is also consistent with the negative reactivation of an early reverse fault; d) portion of the seismic line of Fig. 16 showing the negative inversion of a Neogene thrust fault by the Quaternary SW-dipping normal faults (Colfiorito Basin boundary faults). Normal faults = tick black lines with black arrow; thrust and reverse faults = red lines with red arrow; double arrow (black and red arrow labelled with "i") = inverted faults; Tb = Top basement; Dl = Devonian lower unit; Du = Devonian upper unit; Do = onlap surface.

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figure 01

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Fig. 1

figure 02

Click here to access/download;figure;Fig02_Chronotecto_magmatic scheme.jpg

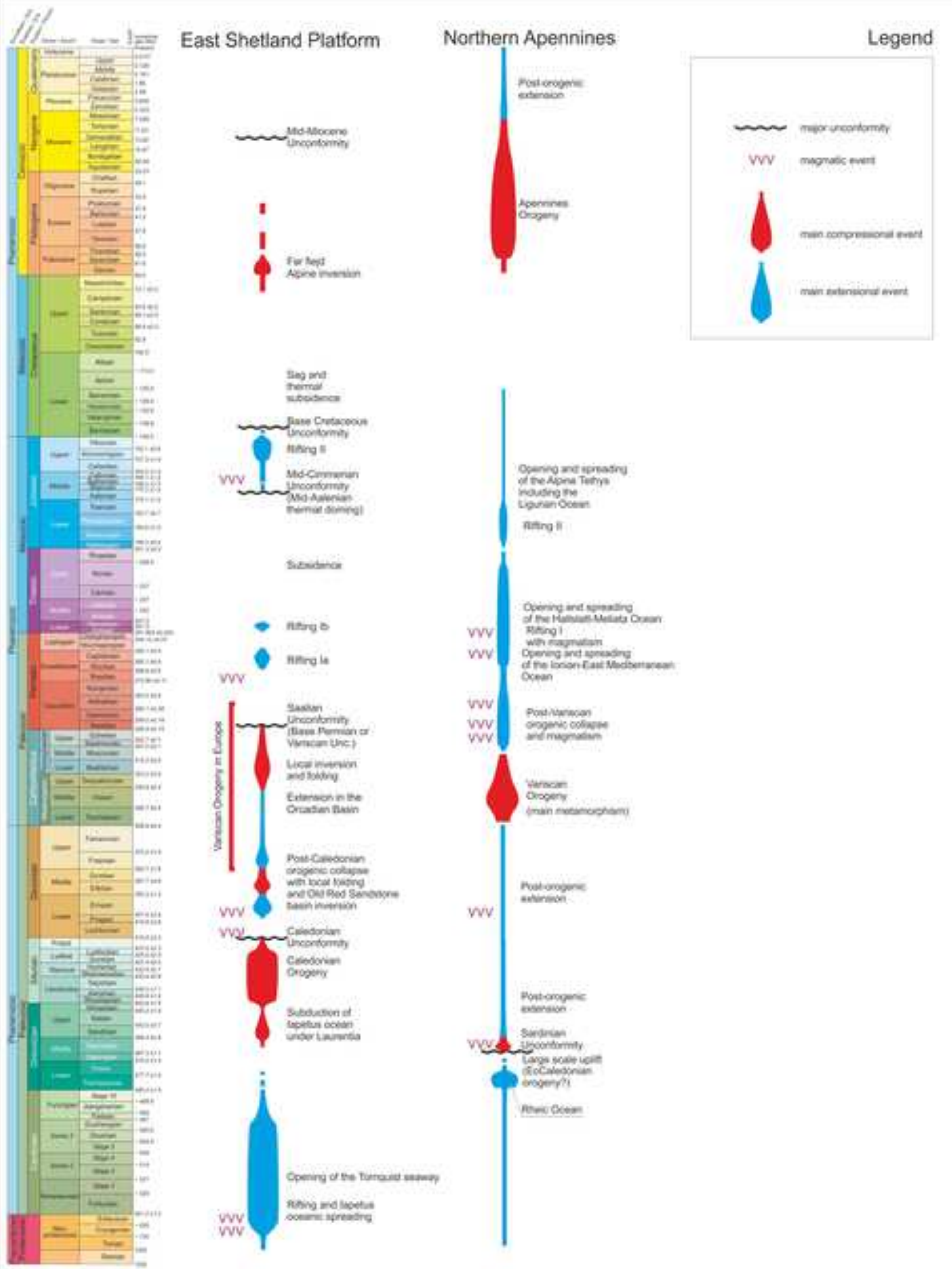

Fig. 2

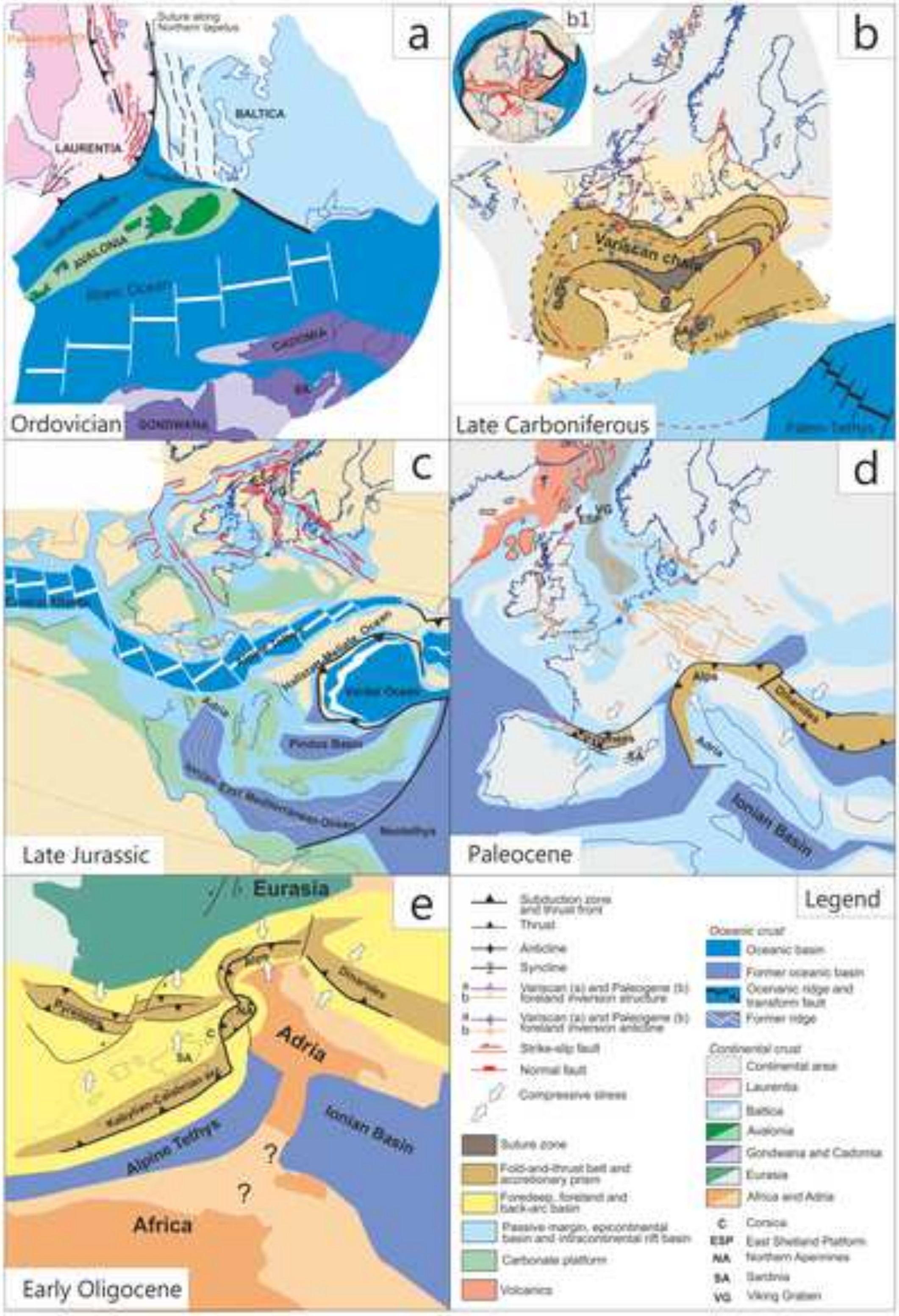
a
LAURENTIA
BALTICA
AVALONIA
CADOMIA
GONDWANA
Ordovician
b1
b
Variscan chain
Late Carboniferous
c
Pindos Basin
Late Jurassic
d
Alps
Dinarides
Adria
SA
Ionian Basin
Paleocene
e
Eurasia
Pyrenees
Alps
Dinarides
Adria
SA
Ionian Basin
Alpine Tethys
Africa
?
?
Early Oligocene
Legend
Subduction zone and thrust front
Thrust
Anticline
Syncline
Variscan (a) and Paleogene (b) foreland inversion structure
Variscan (a) and Paleogene (b) foreland inversion anticline
Strike-slip fault
Normal fault
Compressive stress
Suture zone
Fold-and-thrust belt and accretionary prism
Foredeep, foreland and back-arc basin
Passive margin, epicontinental basin and intracontinental rift basin
Carbonate platform
Volcanics
Oceanic crust
Oceanic basin
Former oceanic basin
Oceanic ridge and transform fault
Former ridge
Continental crust
Continental area
Laurentia
Baltica
Avalonia
Gondwana and Cadomia
Eurasia
Africa and Adria
C Corsica
ESP East Shetland Platform
NA Northern Apennines
SA Sardinia
VG Viking Graben

Fig. 3

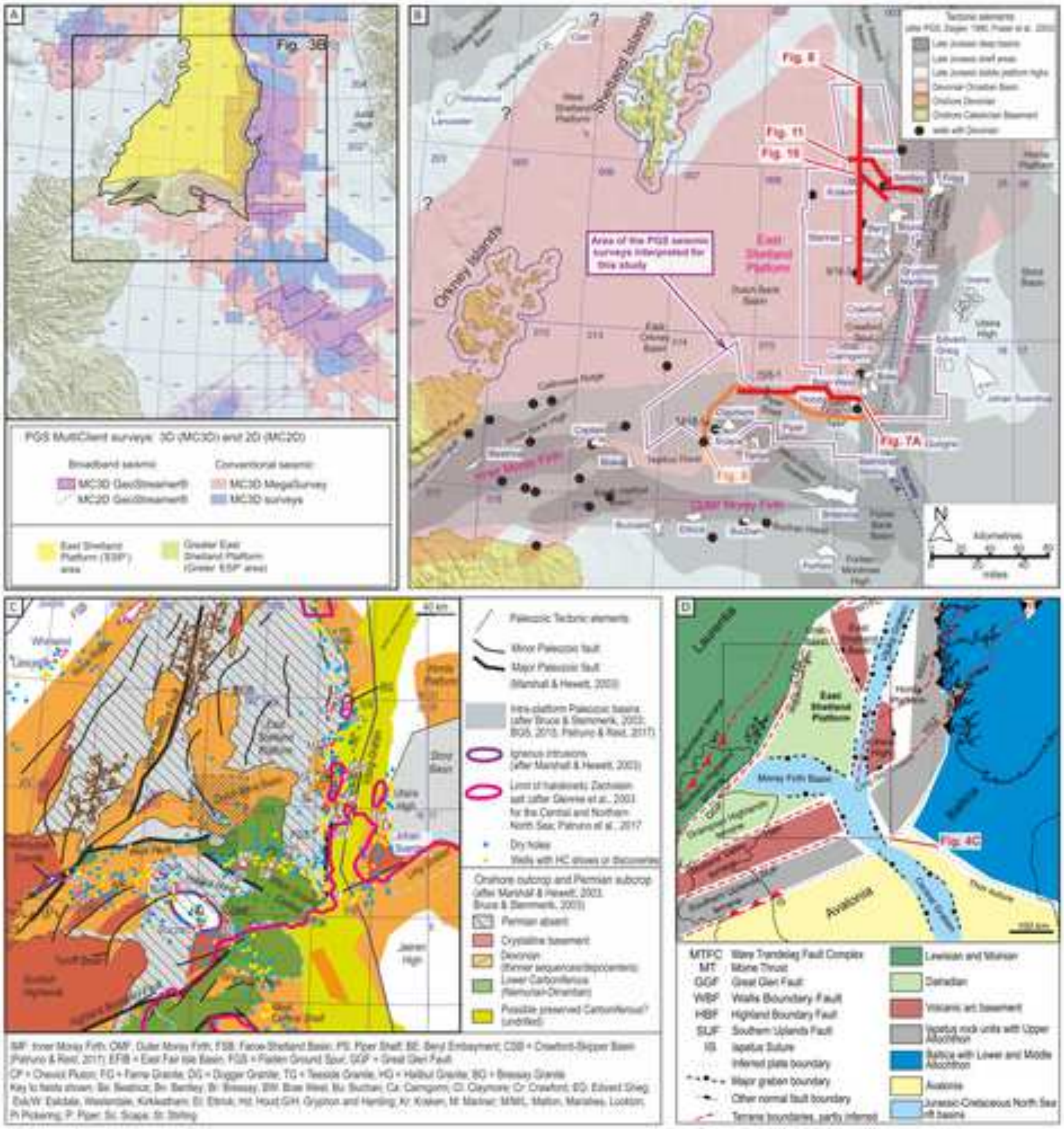
A
Fig. 3B
B
Shetland Islands
Orkney Islands
East Shetland Platform
Fig. 8
Fig. 11
Fig. 7A
C
D
Laurentia
Avalonia
Baltica
Fig. 4C

Fig. 4

figure 05

Click here to access/download;figure;Fig05_NA Structural scheme.jpg

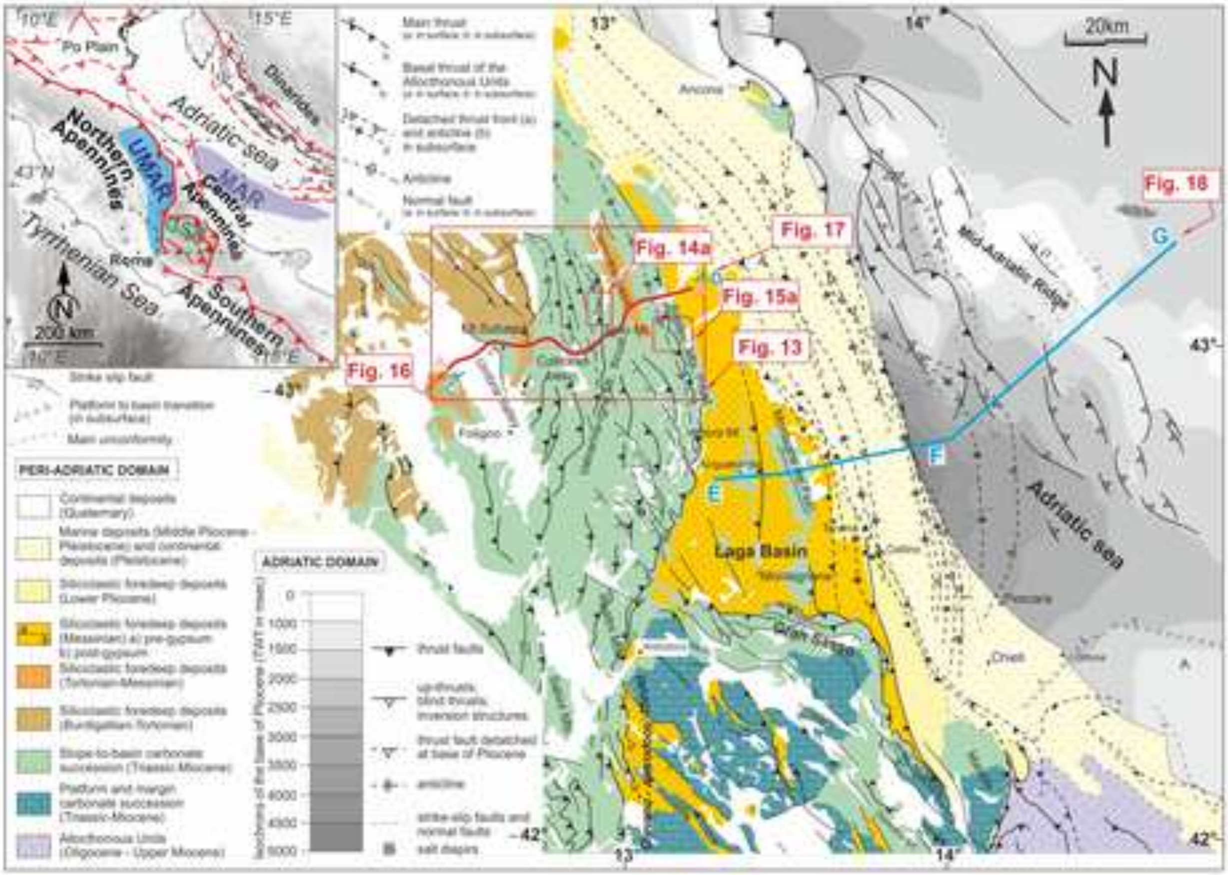

Fig. 5

figure 06

Click here to access/download;figure;Fig06_NPR wells correlation .jpg

Fig. 6

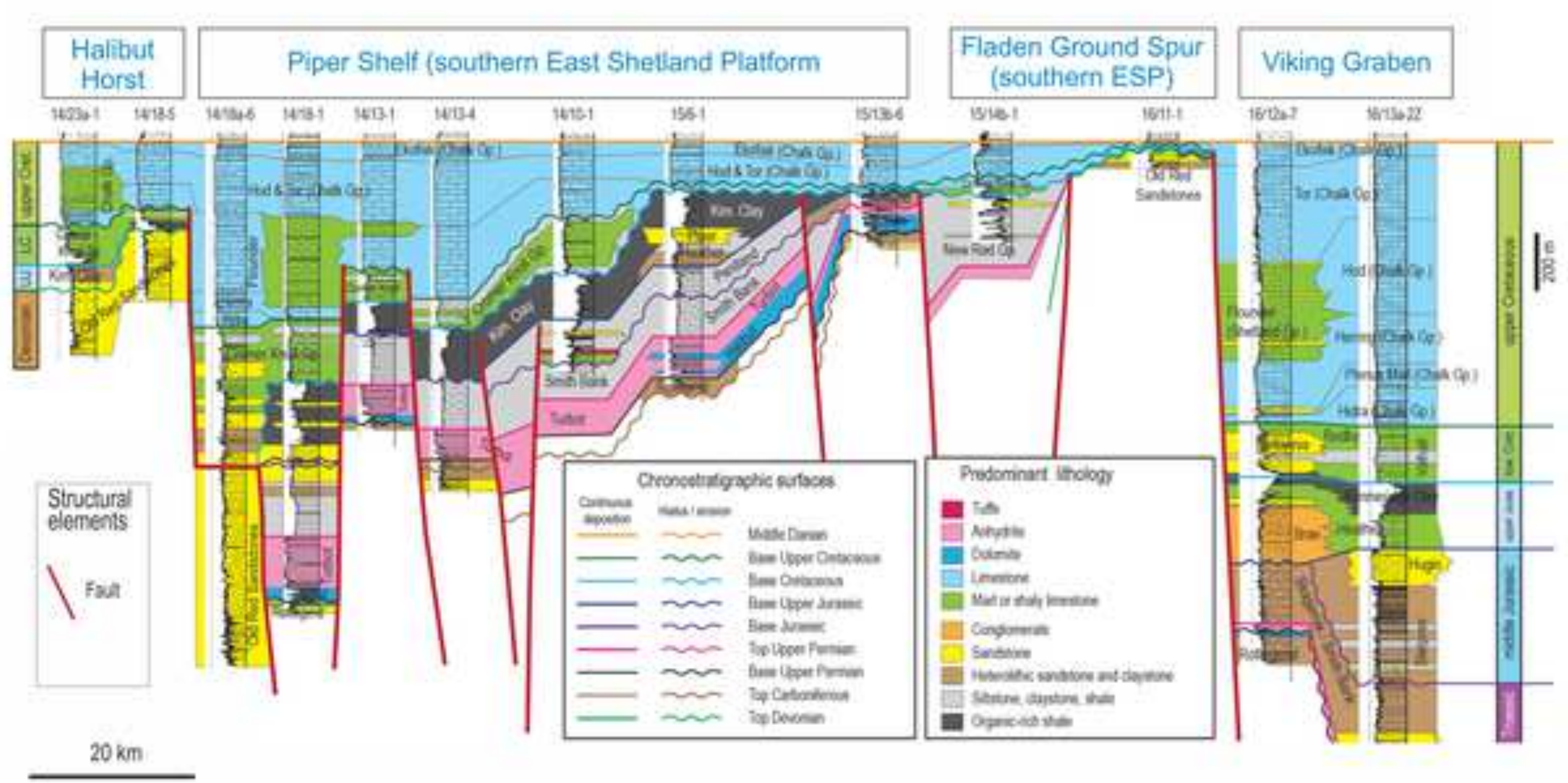

figure 07

Click here to access/download;figure;Fig07_ESP E-W line.jpg

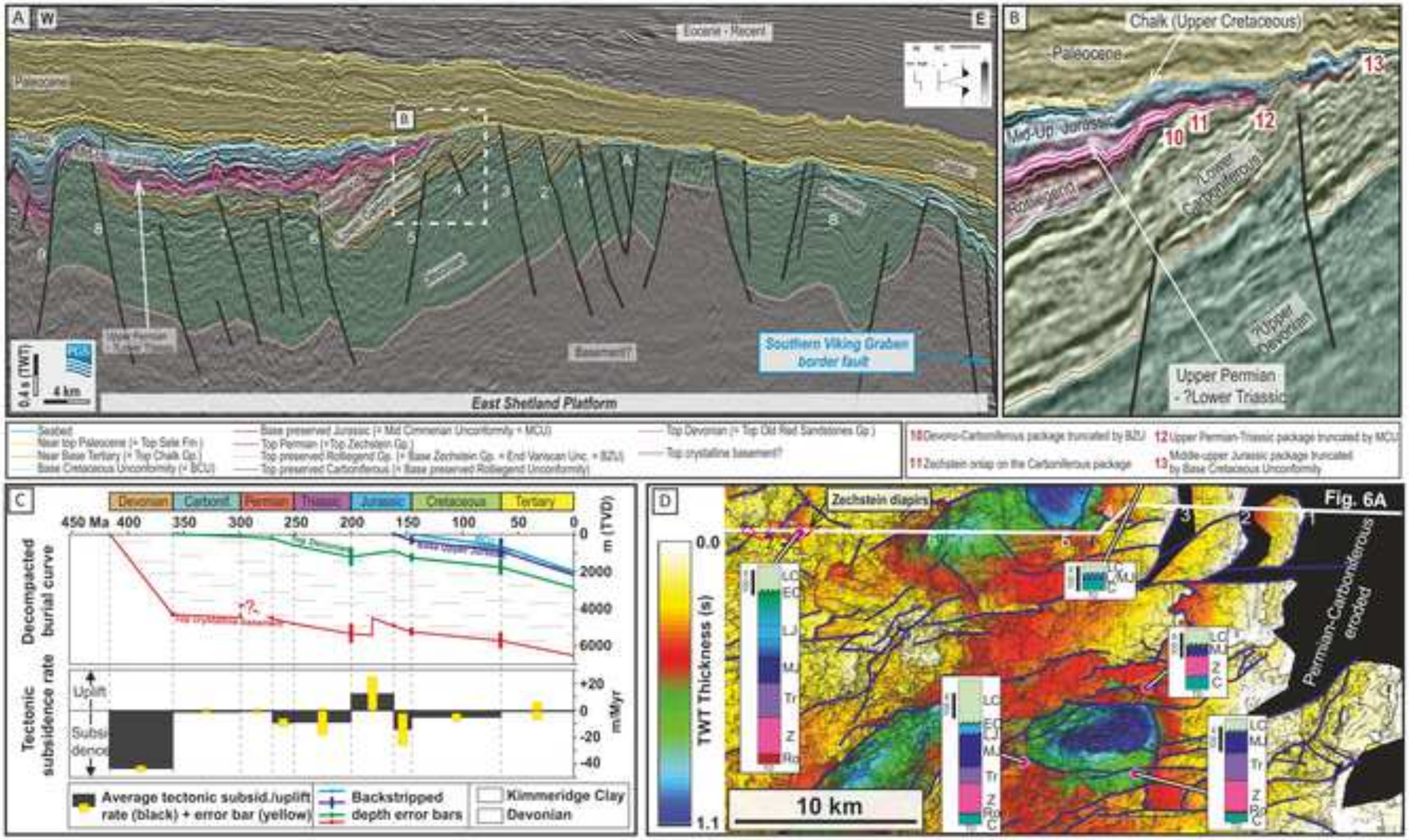

Fig. 7

figure 08

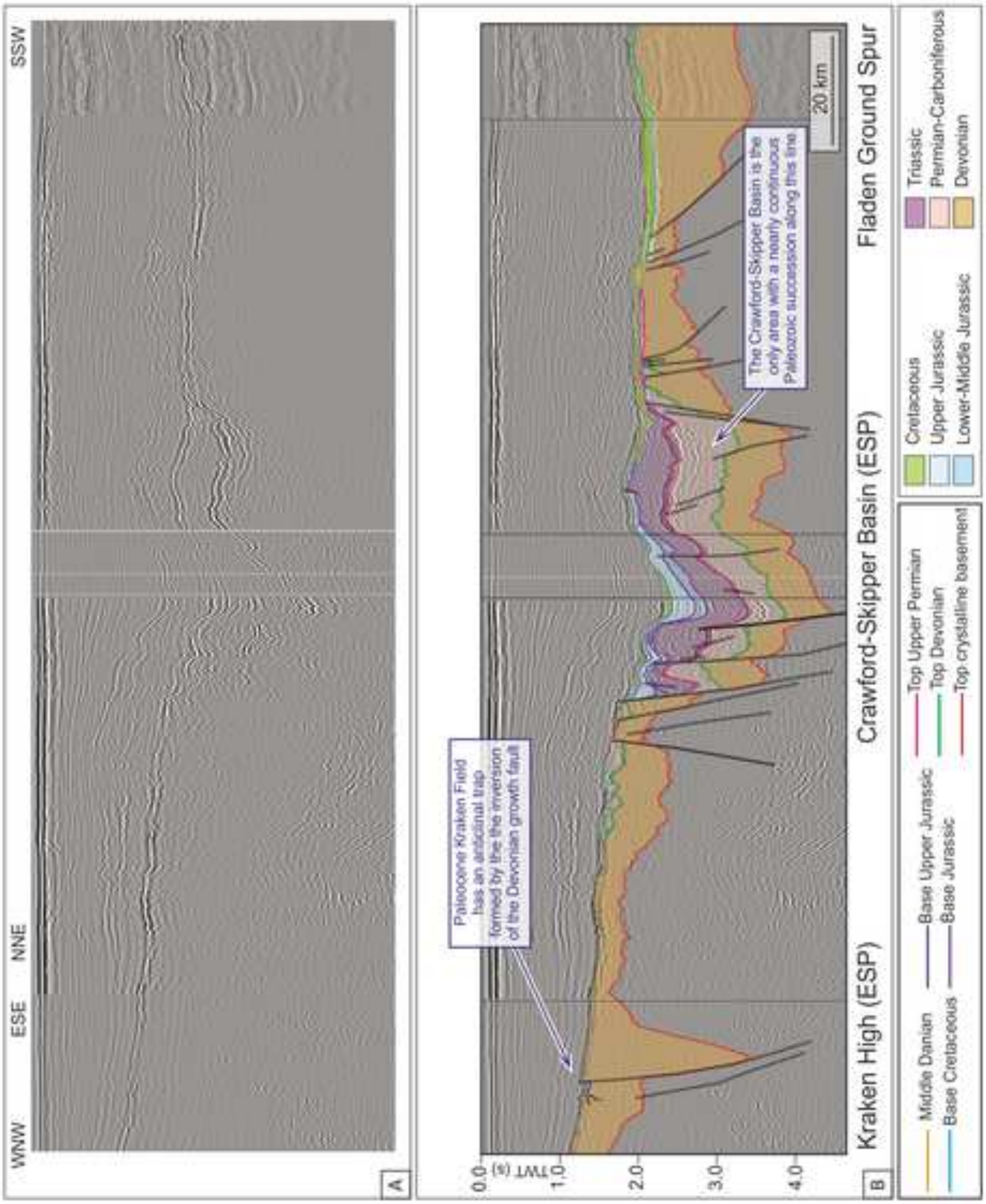

Fig. 8

figure 09

Click here to access/download;figure;Fig09_fault ages_new2.jpg

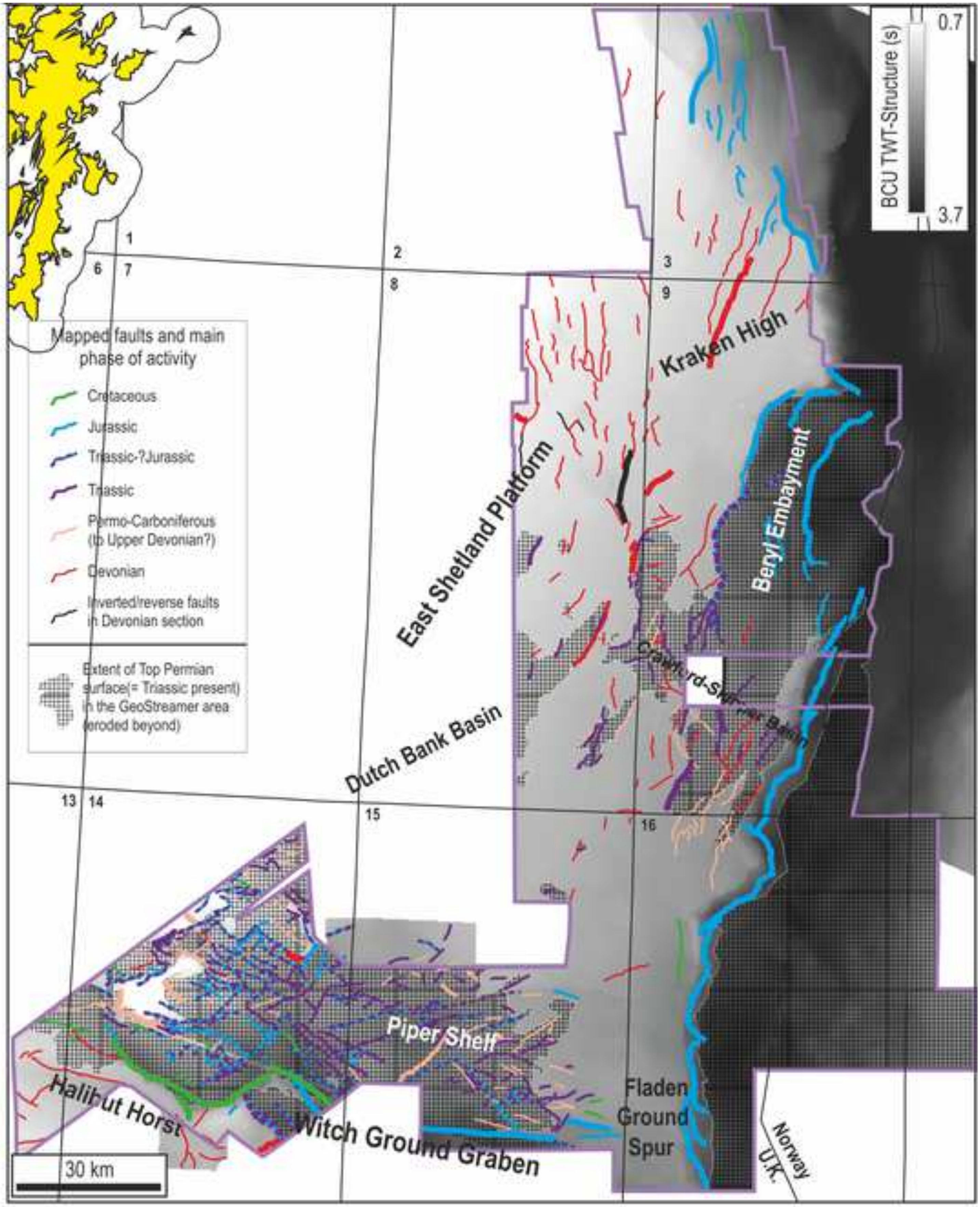

Fig. 9

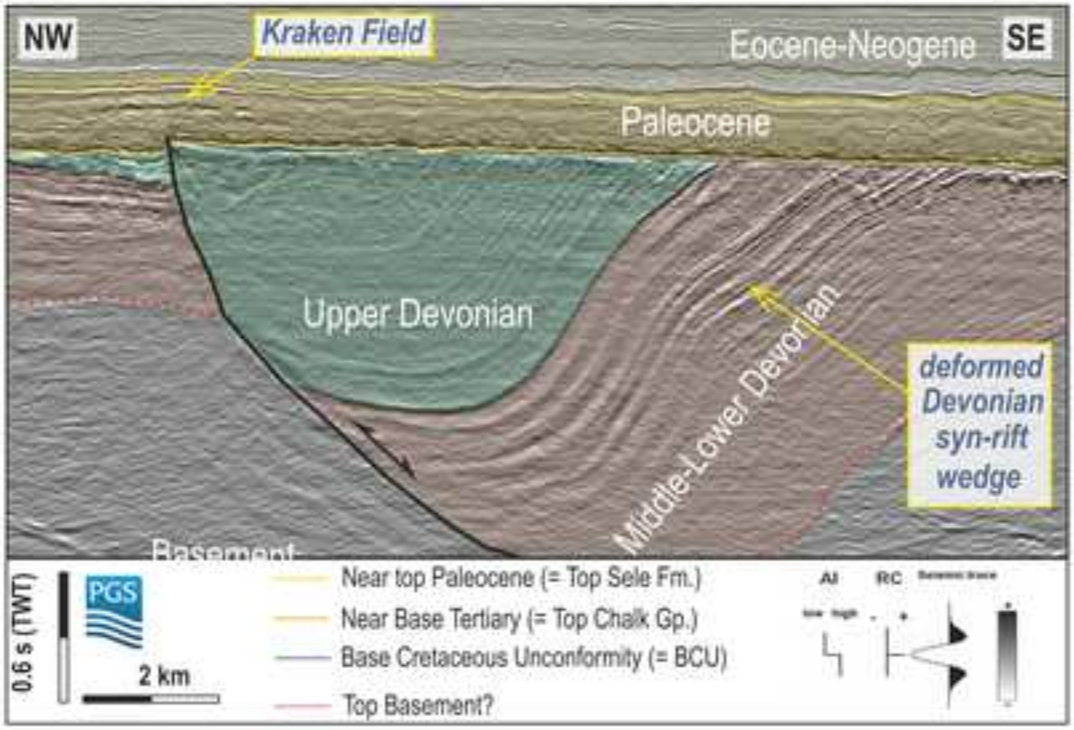
NW
Kraken Field
Eocene-Neogene
SE
Paleocene
Upper Devonian
Middle-Lower Devonian
deformed Devonian syn-rift wedge
Basement
0.6 s (TWT)
PGS
2 km
Near top Paleocene (= Top Sele Fm.)
Near Base Tertiary (= Top Chalk Gp.)
Base Cretaceous Unconformity (= BCU)
Top Basement?
AI
RC

Fig. 10

figure 11

Click here to access/download;figure;Fig11_Deep Seismic Facies transect_P.jpg

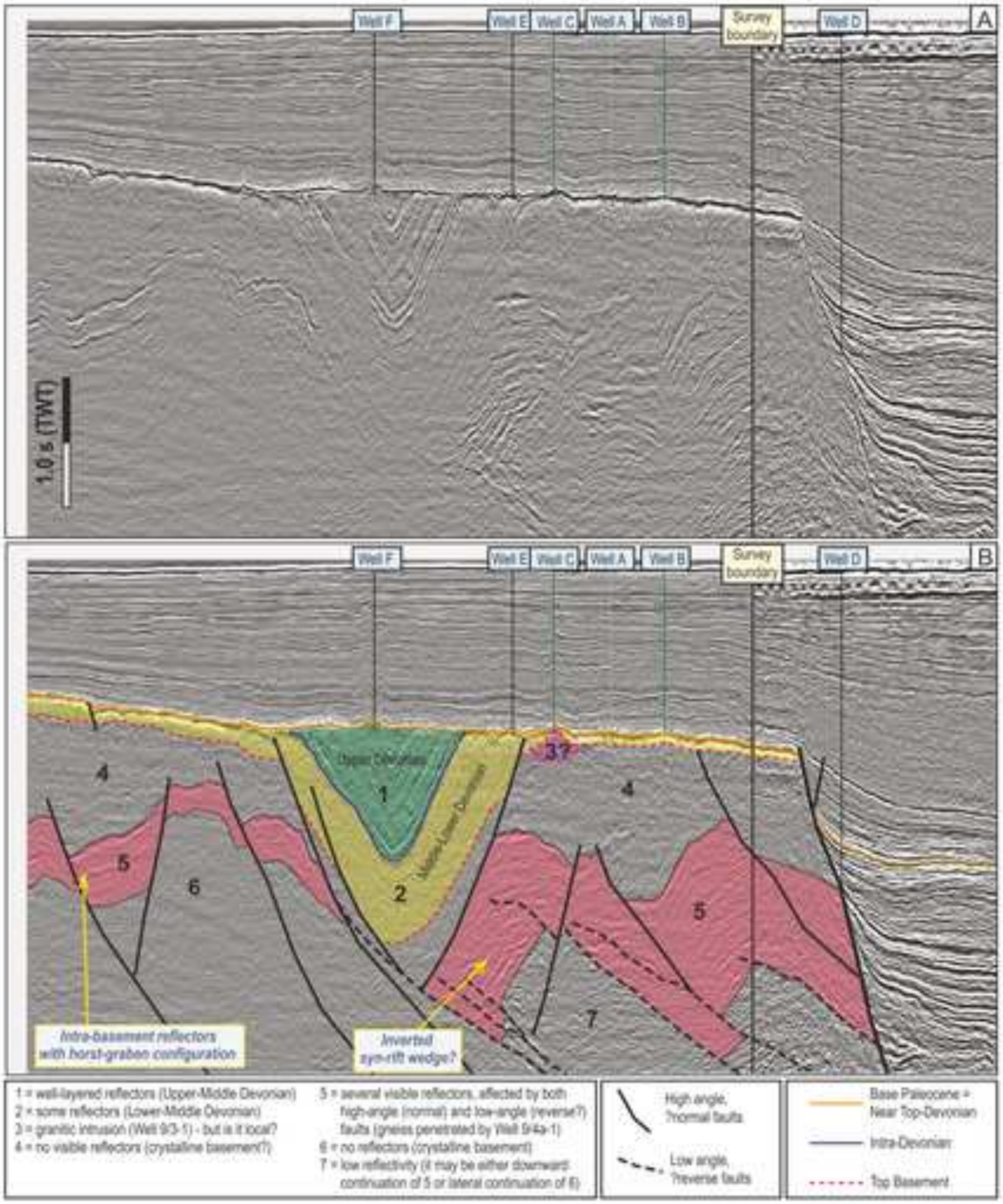

Fig. 11

figure 12 Click here to access/download;figure;Fig12_evolution.jpg

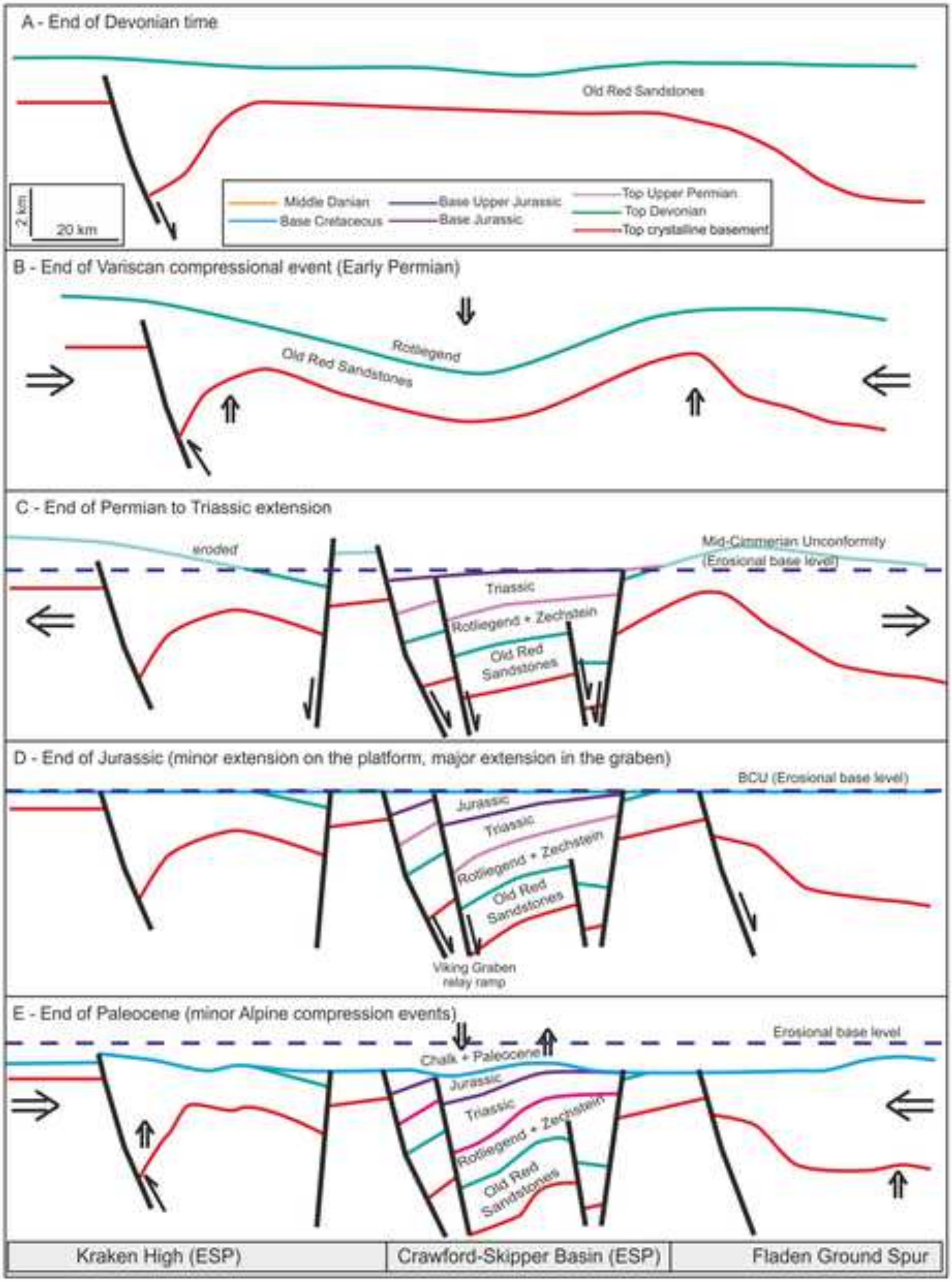

Fig. 12

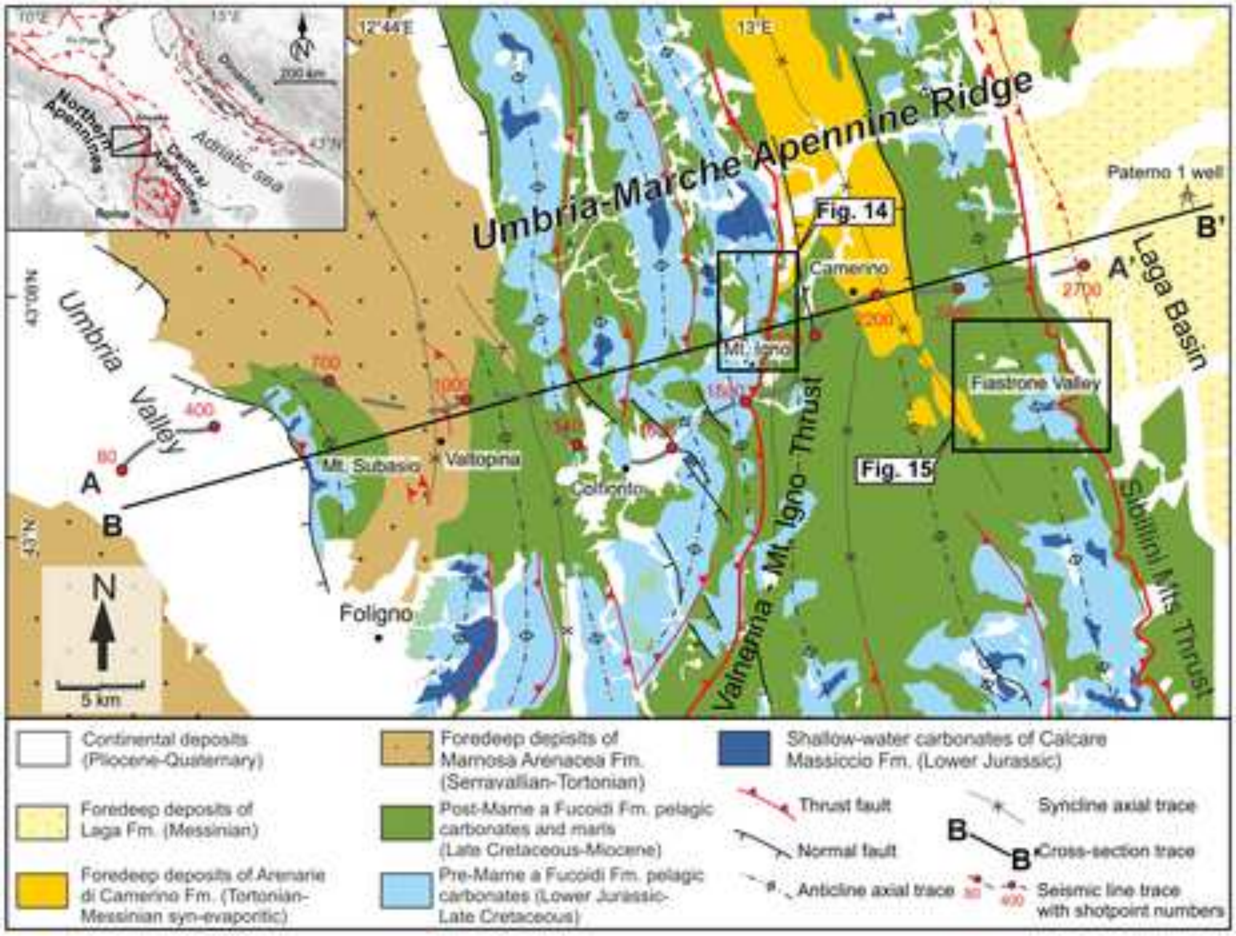
Umbria-Marche Apennine Ridge
12°44'E
13°E
43°08'N
43°N
Northern Apennines
Central Apennines
Adriatic sea
200 km
N
Umbria Valley
Laga Basin
Paterno 1 well
Camerino
Mt. Igno
Fig. 14
Fig. 15
Fiastrone Valley
Mt. Subasio
Valtopina
Colfiorito
Foligno
Valnerina - Mt. Igno Thrust
Sibillini Mts Thrust
A
B
A'
B'
80
400
700
1000
1500
2200
2700
5 km
Continental deposits (Pliocene-Quaternary)
Foredeep deposits of Laga Fm. (Messinian)
Foredeep deposits of Arenarie di Camerino Fm. (Tortonian-Messinian syn-evaporitic)
Foredeep deposits of Marnosa Arenacea Fm. (Serravallian-Tortonian)
Post-Marne a Fucoidi Fm. pelagic carbonates and marls (Late Cretaceous-Miocene)
Pre-Marne a Fucoidi Fm. pelagic carbonates (Lower Jurassic-Late Cretaceous)
Shallow-water carbonates of Calcare Massiccio Fm. (Lower Jurassic)
Thrust fault
Normal fault
Anticline axial trace
Syncline axial trace
Cross-section trace
Seismic line trace with shotpoint numbers

Fig. 13

figure 14

Click here to access/download;figure;Fig14_Igno Mt thrust.jpg

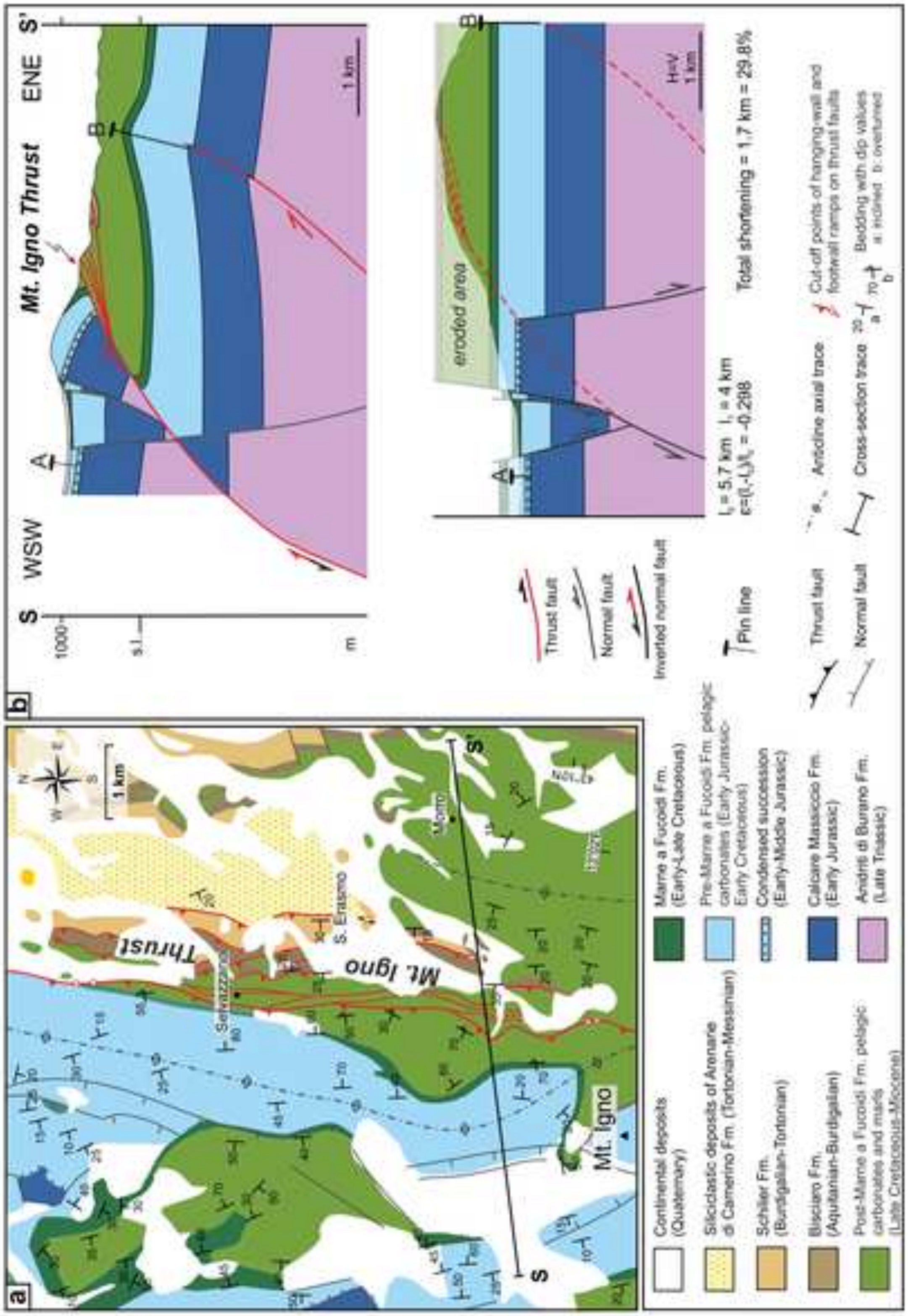

Fig. 14

figure 15

Click here to access/download;figure;Fig15_Sibillini thrust_new04.jpg

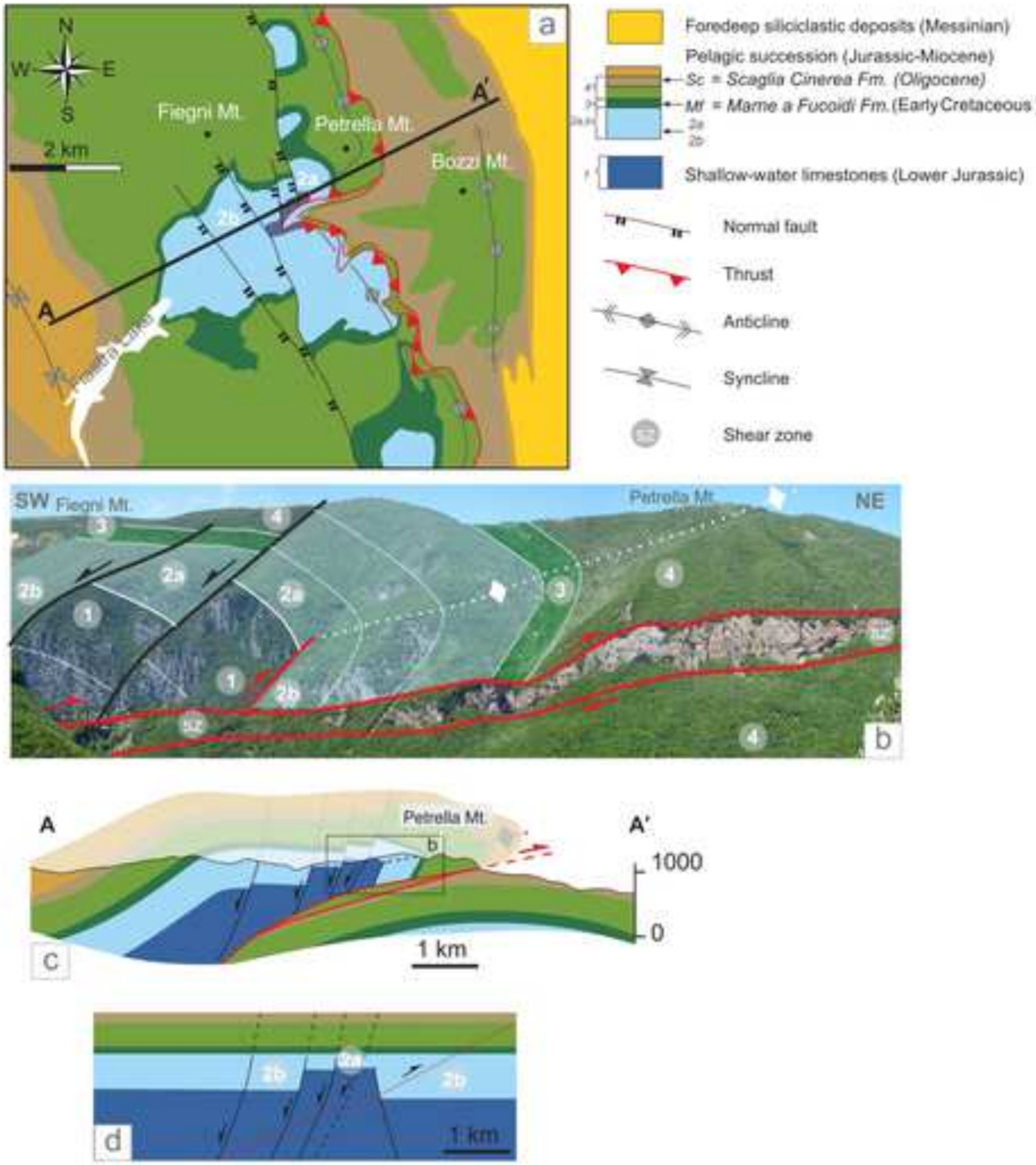

Fig. 15

figure 16 Click here to access/download;figure;Fig16_NA seismic_two fold_LRE.jpg

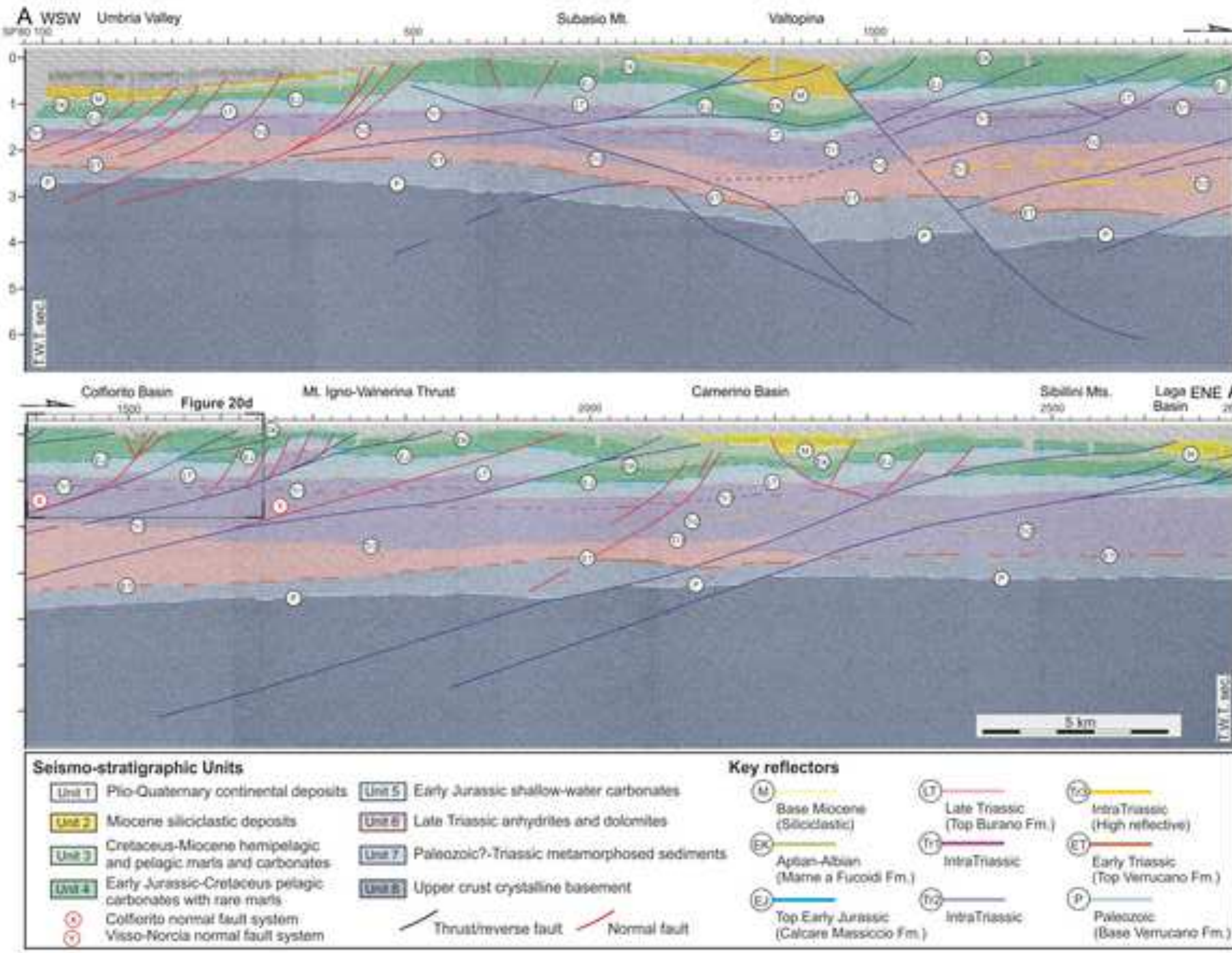

Fig. 16

figure 17

Click here to access/download;figure;Fig17_NA_restored section_stp.jpg

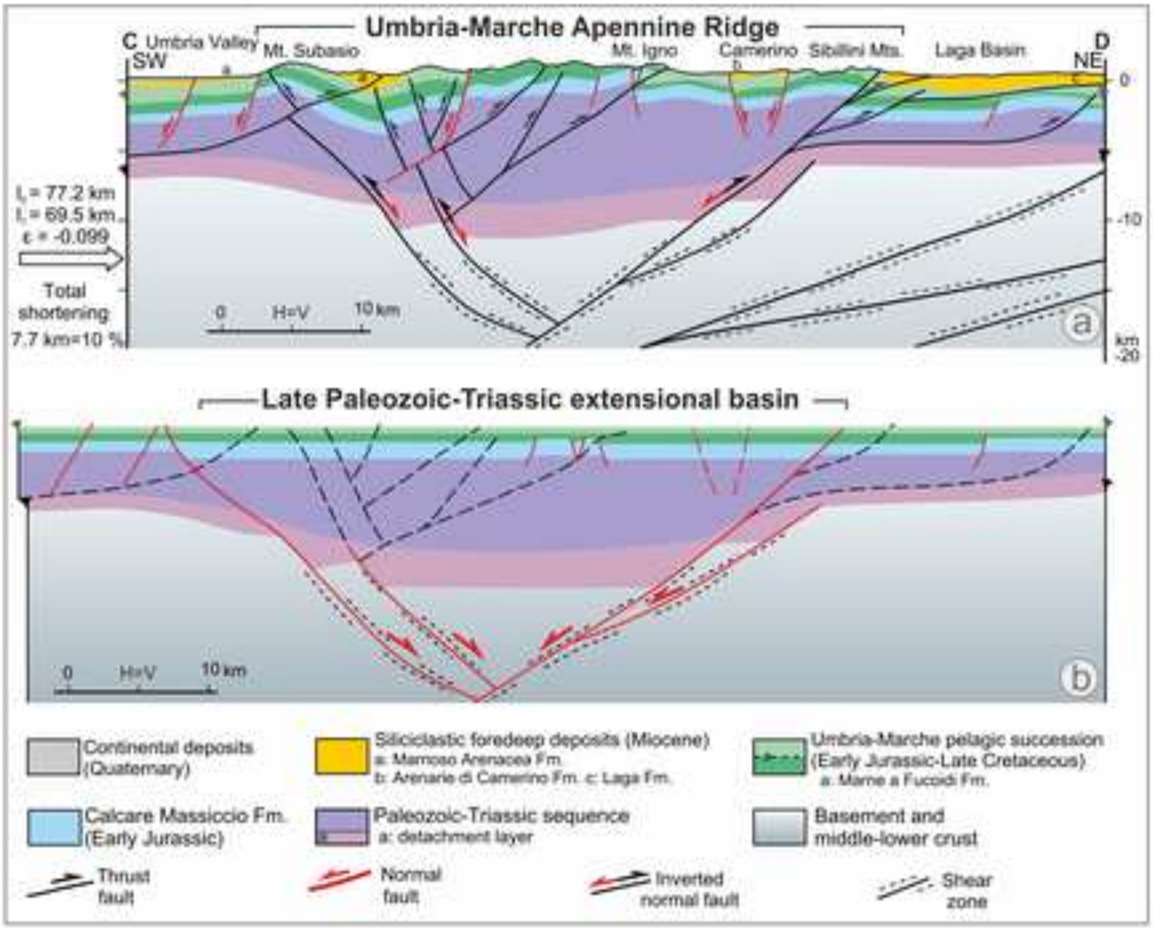

Fig. 17

figure 18

Click here to access/download;figure;Fig18_Na-Adriatic section4.jpg

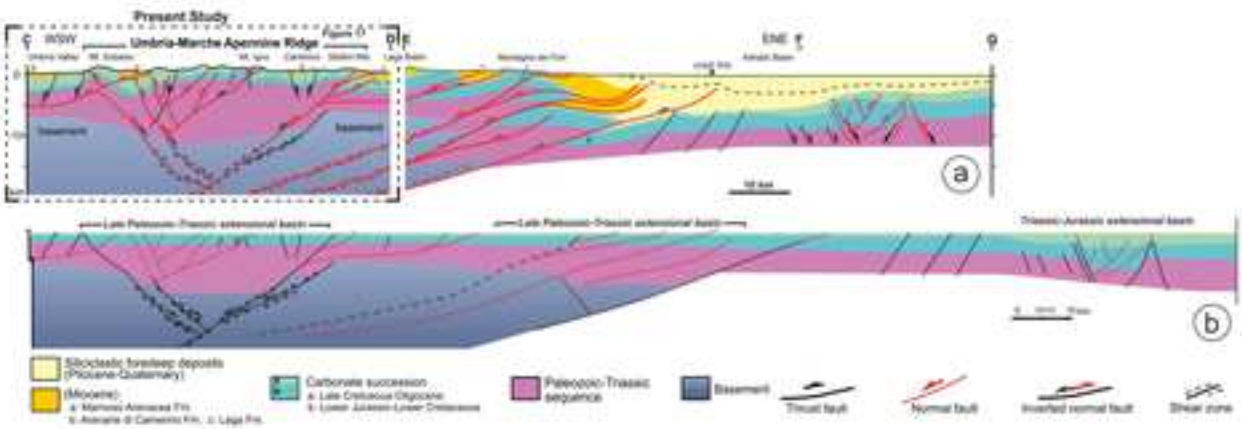

Fig. 18

figure 19

Click here to access/download;figure;Fig19_foredeep & UMAR.jpg

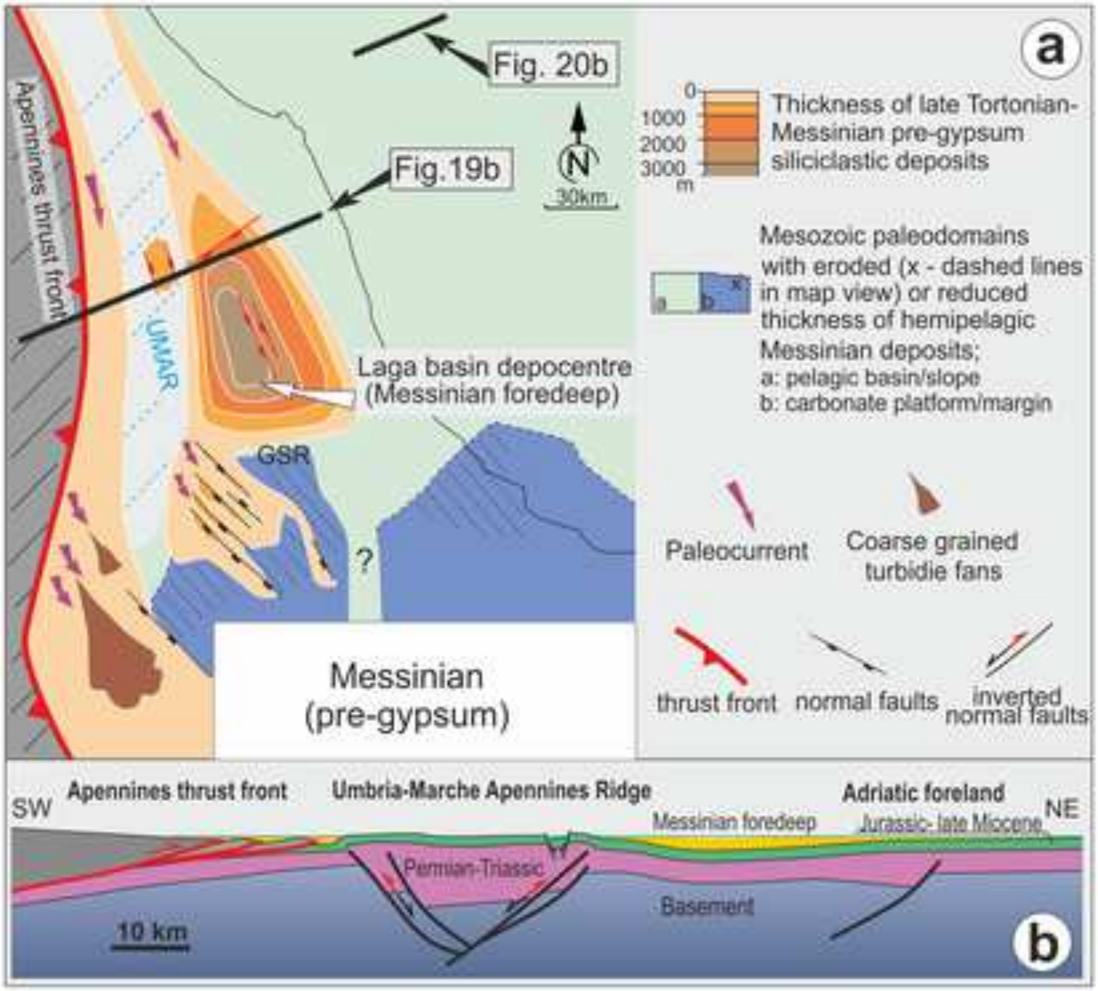

Fig. 19

figure 20

Click here to access/download;figure;Fig20_Inversion ESP&NA.jpg

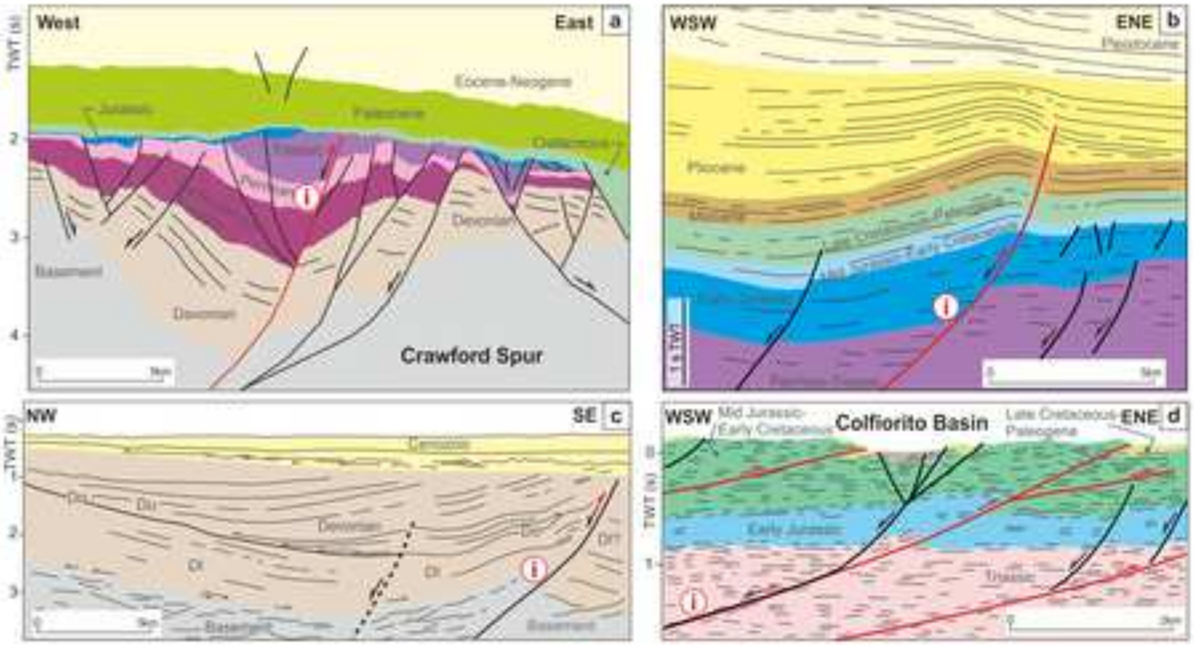

Fig. 20