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Revisiting orogens during the OROGEN project: tectonic maturity, a key element to understand orogenic variability

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Abstract – By demonstrating that extensional inheritance plays a decisive role in the formation of orogens, recent studies have questioned the ability of a unique, complete Wilson cycle model to explain the diversity of collisional orogens. For 5 years, the OROGEN Research Project had therefore the ambition to challenge this classical Wilson cycle model. By focusing on the diffuse Africa-Europe plate boundary in the Biscay-Pyrenean-Western Mediterranean system, the project questioned the preconceived "Orogen singularity" assumption and investigated the role of divergent and convergent maturities in orogenic and post-orogenic processes. This work led us to rethink the development of collisional orogens in a genetic (or process-driven) way and to propose an updated version of the " classical Wilson cycle", the Wilson Cycle 2.0, and the ORO-Genic ID concept presented in this paper. The particularity of the Wilson Cycle 2.0 is to take into account the divergence and convergence maturity reached during extensional and orogenic processes in proposing different tectonic tracks associated with different ORO-Genic ID numbers. The ORO-Genic ID is composed of a letter (or track), corresponding to the maturity of divergence reached and a number corresponding to the maturity of convergence reached during the formation of the orogen. This new concept relies on the observed pre- and syn- convergent tectono- stratigraphic and magmatic record and deformation history and can be identified in using diagnostic criteria presented in this paper. It represents therefore a powerful tool that can be used to characterize the evolution and the architectural type of an orogenic system. Moreover, as a mappable concept, it can be easily used worldwide and can help us to explain differences in the style of deformation at crustal scale between orogens.

Keywords: Wilson cycle / orogenesis / rifting inheritances / tectonic maturity / Africa-Europe plate boundary / Bay of Biscay-Pyrenean system

Résumé – En démontrant que l'héritage extensional joue un rôle décisif dans la formation des orogènes, des études récentes ont remis en question le cycle de Wilson et sa capacité, en tant que modèle unique, à expliquer la diversité des orogènes collisionnels. Pendant 5 ans, le projet de recherche OROGEN s'est donc donné pour ambition de questionner ce modèle classique du cycle de Wilson. En se concentrant sur la frontière diffuse entre les plaques Afrique-Europe dans le système Golfe de Gascogne-Pyrénées-Méditerranée occidentale, le projet a remis en cause l'hypothèse préconçue de la « singularité orogénique » et a exploré le rôle de la maturité divergente et de la maturité convergente dans les processus orogéniques et post-orogéniques. Ce travail nous a amenés à repenser le développement des orogènes collisionnels d'un

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point de vue génétique (ou axé sur les processus) et nous a amené à proposer une version actualisée du « cycle de Wilson classique », appelée Cycle de Wilson 2.0 et le concept d'ID ORO-génique présenté dans cet article. La particularité du Cycle de Wilson 2.0 est de prendre en compte la maturité de la divergence et la maturité de la convergence atteinte au cours des processus d'extension et d'orogénèse, en proposant différents parcours tectoniques associés à différents numéros d'identité ORO-génique. Le numéro d'identité ORO-génique est composé d'une lettre (ou d'un parcours), correspondant à la maturité de la divergence atteinte, et d'un numéro correspondant à la maturité de la convergence atteinte lors de la formation de l'orogène. Ce nouveau concept repose sur l'enregistrement tectono-stratigraphique et magmatique avant et pendant la phase de convergence, ainsi que sur l'histoire de la déformation observée, et peut être identifié en utilisant les critères diagnostiques présentés dans cet article. Il constitue donc un outil puissant pouvant être utilisé pour caractériser l'évolution et le type architectural d'un système orogénique. De plus, en tant que concept cartographiable, il peut être facilement utilisé dans le monde entier et nous aider à expliquer les différences de style de déformation à l'échelle crustale entre les orogènes.

Mots clés : Cycle de Wilson / orogénèse / héritage extensif / maturité tectonique / limite de plaque Afrique-Europe / système du Golfe de Gascogne et des Pyrénées

1 Preamble

Orogens display a large variability of size, relief, lithotypes, along- and across-strike structures, as well as in their tectono-stratigraphic and metamorphic records, suggesting that each orogen is unique. What controls this apparent diversity remains an open question: does it relate to a variability in the orogenic processes at work during convergence? Or does it relate to a variability in the characteristics of the oceanic/rift system involved, which we refer to as "divergence inheritance" or to a combination of both? The OROGEN research project, an academic-industry joint-venture involving more than one hundred geoscientists, was set up to answer these questions. Over 5 years, 30 PhD and post-doctoral projects handled by young talents, to whom this paper is dedicated, have challenged the preconceived "orogen singularity" assumption. The study area chosen for the project was the diffuse Africa-Europe plate boundary in the Biscay-Pyrenean-Western Mediterranean system because it provides a present- day access to different evolutionary steps of a Wilson Cycle spatially (un-shortened rift, early orogen, evolved collisional orogen, post-orogenic rift).

Based on new seismic imaging methods, focused multidisciplinary field studies, and innovative analytical and simulation methods, a new observation-driven, holistic understanding of orogenic processes has emerged. Never conceptualized before as such, it evaluates each tectonic stage with respect of its precursors including pre-convergence records. Although the Biscay-Pyrenean system is one of the best documented orogenic systems in the world, the new approach developed in the OROGEN project has achieved a new level in the detailed description of the architecture of this orogenic system and in the understanding of its evolution.

The results of the OROGEN Research Project have been published in around a hundred papers, within and outside this special volume. The main results, concepts and interpretations have been summarized in five review papers that build the backbone of the special volume. They are respectively about: (1) a geophysical passive seismic imaging techniques (Chevrot *et al.*, 2022); (2) the key role of pre-orogenic inheritance with a specific focus on rift inheritance (Manatschal *et al.*, 2021); (3) the tectono-sedimentary record and how it can help unravel the link between relief and basin genesis from pre- to post-orogenic stages (Ford *et al.*, 2022); (4) the impact of near- versus far-field interactions on orogenesis (Mouthereau *et al.*, 2021); and (5) the role of the subducting slab dynamics in syn- and post-orogenic records (Jolivet *et al.*, 2021).

The following contribution builds on the results of the OROGEN Research Project and on the five aforementioned review papers. It certainly cannot compile all of the individual outcomes of the OROGEN project, but we hereby aim to introduce, provide examples, and discuss the concept of "tectonic maturity", which has emerged from extensive discussions among the OROGEN researchers. The "tectonic maturity" concept aims to integrate the variability of the re-, syn- and post-orogenic settings considering that each stage of the Wilson cycle (divergence and convergence) can continue until its most mature evolutionary stage or can stop prematurely if the driving forces cease. This requires us therefore to look at a given final orogenic product as the result of the interactions between "inheritances" and convergence-induced processes. This approach contrasts with the traditional view, which considers that an orogen is primarily controlled by convergence-induced processes and a partially inherited mechanical stratigraphic template. In this view, each orogen is unique and cannot be understood in a genetic way and time-space geological prediction strictly relies on a regional expertise.

2 Introduction

In the 1960s, scientists started to understand that orogens are part of the plate tectonic process that became known as the Wilson Cycle (Wilson, 1966; Dewey and Bird, 1970). The Wilson Cycle was quickly accepted, and rapidly became a paradigm and a starting point in plate tectonic reconstructions. The main assumption was that orogens went through the same life-cycle including rifting, seafloor spreading, oceanic subduction, continental collision and post-orogenic collapse and that diversity amongst orogens resulted from unique geological processes and different boundary conditions rather than from differences in their life-cycle. Recent studies in the Pyrenees and the Alps, both belonging to the best studied orogens world-wide, have raised questions about the role of pre-orogenic structures during early collision, formation of internal parts of these orogens and the control that an orogen segment can have on adjacent segments as a boundary condition. In both alpine and pyrenean orogens, the observations of preserved remnants of distal margins within their inner (internal) units suggest that some of the present-day complexities may be inherited from the pre-orogenic rifting phase. More generally, Chenin *et al.* (2017) and Vasey *et al.* (2024), suggest that orogens resulting from the closure of narrow oceans and essentially controlled by crustal-deformation processes (Vlaar and Cloetingh, 1984; Pognante *et al.*, 1986; Rosenbaum and Lister, 2005; Mohn *et al.*, 2010) differ from orogens resulting from the closure of wide oceans and subduction-induced processes (Uyeda, 1981; Willett *et al.*, 1993; Ernst, 2005; Handy *et al.*, 2010). By demonstrating that extensional inheritance plays a decisive role in the formation of orogens, these results pave the way to new interpretations of the internal parts of collisional orogens and generate a new genetic way (meaning process-driven way in this paper) to classify them as a function of divergent and convergent maturities. This in turn challenges the ability of a unique, complete Wilson cycle model to explain the diversity of collisional orogens.

No study prior to the OROGEN project has explored in such a systematic way the architecture of a wide area preserving different evolutionary steps of the Wilson Cycle, as observed along the diffuse Africa-Europe plate boundary in the Biscay-Pyrenean-Western Mediterranean system. The work of more than one hundred Earth scientists involved in the project did not only produce new seismic images of the subsurface, new mapping of critical structures and new analytical data, including chronological and dynamic models, but also a new observation-driven, holistic understanding of orogenic processes, from the pre- to the post-orogenic stage. The OROGEN community developed the new concept of “tectonic maturity”, which can integrate so-called immature extensional systems (*i.e.*, extensional systems devoid of wide oceanic domains or hyperextended distal margins) in a Wilson Cycle and thus proposes an updated version of the Wilson Cycle. As it is, the classical Wilson cycle represents only orogen resulting of the closure of wide oceanic domain and subsequent collision of margins. On the contrary, the updated model, referred to as Wilson Cycle 2.0, has been developed to integrate the different degrees of maturity that can be reached in magma-poor divergent settings and how these divergence templates interact with convergence. The conceptual model, as well as examples and applications are presented in Sections 3 and 4. As a disclaimer, it is important to note that the concept has been developed based on observation made in Western European Orogens built on failed rift and/or narrow oceans. Its applicability to Himalayan and Andean systems remains to be investigated.

3 The concept of tectonic maturity and the Wilson Cycle 2.0

The Wilson Cycle 2.0 (WC 2.0), like the traditional version, is a representation of successive divergent and convergent tectonic stages that can be reached through time as stable continents diverge and converge (see Fig. 1). However, the WC 2.0, allows, in contrast to the original version, for possible “shortcuts” that depend on the tectonic maturity reached during divergence. Indeed, the WC 2.0’s main assumption is that the fate of convergent systems depends partly on the degree of maturity reached during divergence. To integrate possible shortcuts in the WC 2.0, we associate divergent maturity levels (A, B, C, or D) to convergent maturity levels (1, 2, 3 or 4) within an orogenic life-cycle, referred to as tectonic tracks. For clarity, the different possible tectonic tracks (A, B, C and D) are fully represented in supplementary material (see Figures A1, A2, A3 and A4). Note that “impossible domains”, indicated in grey in Fig. 1 and supplementary material, correspond to the shortcuts in the track, which depend on the final maturity reached during divergence (*i.e.* function of when continents stop separating). For example, without the formation of a wide ocean, no mature oceanic subduction associated with a volcanic arc can form as it cannot give birth to a subducting plate with sufficient negative buoyancy (Chenin *et al.*, 2017). A key point in the new approach is to be able to define the degree of divergent and convergent maturity reached in a track, based on first order geological observations and clear diagnostic criteria (see Tabs. 1 and 2). Rigorous application of the diagnostic criteria allows the definition of the so-called Orogenic-Genetic Identification number (ORO-Genic ID). This code corresponds to a letter and a number corresponding to the maximum maturity reached during a track (for instance D1 for a full, classical Wilson cycle). The ORO-Genic ID can express the evolution of an orogenic system but can also be used to map domains that result from different tracks (see Sect. 4).

It is important to note that some ORO-Genic IDs do not exist as shown with the grey areas in Figure 1. Examples are A1, A2, and A3 along track A (Fig. A1), or B1 and B2 along track B (Fig. A2). The main reason is that the formation of an oceanic subduction system requires, to initiate and be sustainable, a wide oceanic domain. In the case of track C (immature, narrow oceanic domain, Fig. A3), a subduction can initiate (ORO-Genic ID C1), however, continents start to interact (stage 3) before the negative buoyancy of the slab reaches the critical value leading to a mature, self-sustained subduction (slab-pull efficient enough to sustain the subduction) (Chenin *et al.*, 2017). Such systems will therefore take a short cut and evolve, if not abandoned, to early orogenesis (ORO-Genic ID C3) and collision (ORO-Genic ID C4) without creating a mature subduction (impossible ORO-Genic ID C2) (Fig. 1).

Defining the respective degree of divergent and convergent maturity and therefore the ORO-Genic ID requires distinctive and clear criteria, based on rigorous geological or geophysical observations, and can result in a mapping approach as shown in Section 4. Similar approaches have been used in the Alps and are described in McCarthy *et al.* (2021). In the following paragraphs we define the diagnostic criteria and the approach used to define divergent and convergent maturity stages.

3.1 Divergent maturity

In the WC 2.0, we define 4 stages of increasing divergent maturity that can be characterized as follow (see Tab. 1):

– Early Rift (A): This stage shows only local and very limited crustal thinning and extension ($ß < 1.5$), with top and base

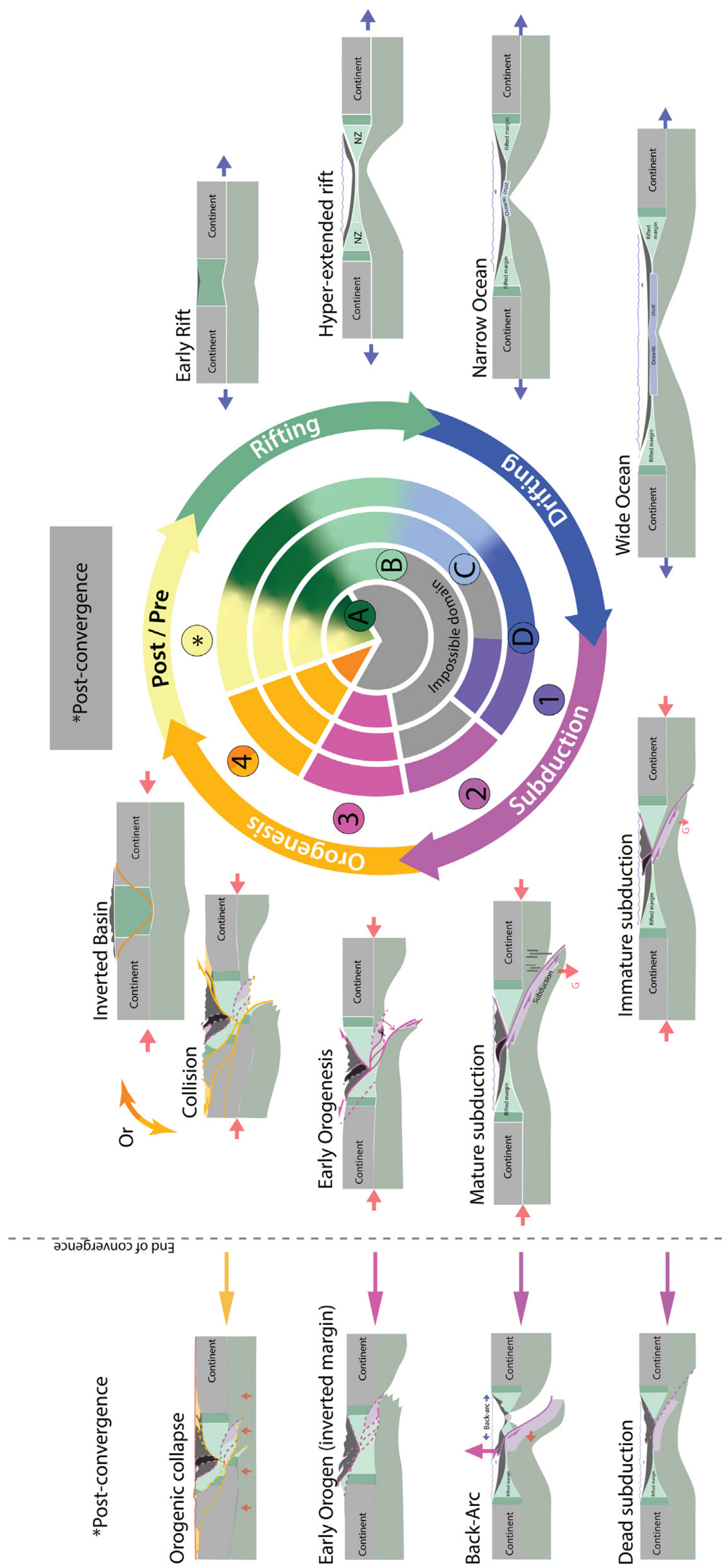

Fig. 1. On the right : Wilson cycle updated representing the 4 maturity stages of divergence (A, B, C and D) and the 4 maturity stages of convergence (1, 2, 3 and 4). Both the divergent and convergent cycle are predated and follow by pre and post deformation phases (*i.e.* stable continent and inactive ocean basin). In the case of the end of convergence, different post-convergent scenarios are possible depending of the maturity stage of the convergence. Those scenarios are illustrated on the left side of the figure.

Table 1. The diagnostic criteria summarizing the key observations that are characteristics of each maturity stage of divergence.

	Divergent Maturity Level		**A: Early Rift**			
			B: Hyperextended Rift			
			C: Narrow Ocean			
			D: Wide Ocean			
	Rifted domain		***Proximal domain***	***Hyperextended and OCT domain***	***Oceanic domain***	
Diagnostic criteria	**Crustal architecture**		Tabular and thick continental crust with disconnected and distributed basins	Tapering and / or hyper-thinned crust with exhumed mantle domain	Transitional from continental to oceanic crust	
	Structural record	**Low-β rift features**	High angle syn-rift normal faults		Possible occurrence of high angle normal faults	
		High-β rift features		Occurrence of syn-rift detachment faults	Occurrence of detachment faults	
	Basement record		No tectonic exhumation of deep pre-rift crustal levels and mantle rocks	Tectonic exhumation of pre-rift continental crustal levels (mid to lower crust) and possibly serpentinized mantle	Tectonic exhumation of serpentinized mantle and occurrence of ophicalcites	Magmatic accretion
	Magmatic record		Not significant	Possible syn-rift magmatic intrusion and post-rift magma	Magmatic addition with alkaline to T-MOR composition	MORB magmatism (gabbro, basaltic dykes or pillows)
	Sedimentary record	**Syn-tectonic sequence**	Local thickness or facies variations due to syn-rift relationship with fault bounded local basins	Local derived clastic sedimentation and tectono-sedimentary breccias overlain by sequences that show a general deepening	Deep marine detrital, pelagic, and locally derived breccias interleaved with pelagic to hemipelagic material	Deep marine and mainly showing passive infill
		Post-tectonic sequence	Shallow marine passive infill	Deep water sedimentation	Deep water sedimentation	
	Type of subsidence		Syn-kinematic, fault-controlled local subsidence [(1)]	Crustal thinning-related subsidence and thermal subsidence increasing basinward	Thermal subsidence [(2)]	
	Relation with convergence		Not consumable by subduction	Consumable by subduction implying HP-metamorphism	Consumable by subduction but too small to generate a steady-state subduction	Consumable by subduction and prone to develop a steady-state subduction
ORO-Genic questions	**Q_{D1}: Did rifting stop before necking?**		Yes	No	No	No
	Q_{D2}: did rifting result in crustal separation and formation of a proto-oceanic domain?		-	No	Yes	Yes
	Q_{D3}: Did seafloor spreading result in a wide/mature oceanic domain that could give birth to a mature subduction?		-	-	No	Yes

[(1)] Mc Kenzie (1978); [(2)] Stein and stein (1992)

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Table 2. The diagnostic criteria summarizing the key observations that are characteristics of each maturity stage of convergence.

	Convergent Maturity Level		1: Immature Subduction	2: Mature Subduction	3: Early Orogenesis	4: Mature Collision/Inverted Basin
Diagnostic criteria	**Crustal architecture**		Short "slab" made of underthrust oceanic or proto-oceanic lithosphere	Long "slab" made of oceanic lithosphere	Limited crustal thickening (no root)	Major crustal thickening (orogenic root formation)
	Relief record		Controlled by the mechanics of accretionary wedge	Controlled by the mechanics of accretionary wedge and magmatic activity in the arc	Low-relief formation controlled by inverted rift structure	High-relief formation controlled by crustal thickening
	Magmatic record		Limited and boninitic if hydrated minerals are subducted	calc-alkaline magmatism in the upper plate arc	none	none
	Structural record	**lower plate or pro-wedge**	Thin-skinned deformation in accretionary prism	Thin-skinned deformation in accretionary prism	The front of the thick-skinned deformation remains in between the necking lines	The front of the thick-skinned deformation propagates outside the necking domain forming nappe-stacks and classical foreland basin
		upper plate or retro-wedge	Thin-skinned to limited thick-skinned	Thin-skinned to limited thick-skinned		
	Relation with divergence		Oceanic, proto-oceanic or distal rifted domains consumed only	Oceanic domains consumed only	Distal rifted domains are consumed but shortening of the proximal margin is absent as deformation remains within the necking lines	Proximal rifted and / or unrifted domains shortened
ORO Genic questions	**Q_{C1a}: Did an oceanic subduction/slab form?**		Yes	Yes	No	No
	Q_{C1b}: Did the subduction reach steady state?		No	Yes	-	-
	Q_{C2}: Does the front of the thick-skinned deformation go beyond the necking line?		No	No	No	Yes

crust remaining tabular at a crustal scale. Rift basins are high-angle normal fault controlled (limited crustal-scale subsidence due to crustal thinning), distributed and often later- ally disconnected (distributed strain). Faults are high-angle and sole out at mid-crustal ductile levels. Syn-rift sediments can either show high thickness and/or facies variations over short distances (fault- controlled), whereas post-rift sediments show, over wide areas, little accommodation (km) and limited regional thermal subsidence.

- Hyperextended rift (B): This stage is characterized by a proximal domain where the crust is weakly extended (similar to the rift domain formed in A) and a distal hyperextended crust (<10 km thick, ß > 2) with deep, wide and long segmented basins. The proximal and distal domains are limited by a crustal necking zone where the crust tapers across variable distances. Extension is accommodated by long-offset normal faults / detachment faults that first thin the crust (necking faults) and then exhume the mantle underneath a progressively embrittled, hydrated and tapering continental crust. This structural style reflects strain localization rifting by comparison with early rifting and efficiently forms horizontal space by exhuming new surfaces. Mantle-decoupled hyper-extension ultimately leads to exhumation of lower crust beneath supra-detachment basins whereas mantle-coupled hyper-extension leads to juxtaposition of sediments with mantle rocks. As faults are long-offset (high strain) and cross the entire crust, fluids efficiently circulate leading to hydrated crustal and mantle rocks (*i.e.* serpentinization). Note that magmatic processes also interact with rifting and can range between N-MORB and alkaline. Syn-rift accommodation space is maximum within a wide and highly subsiding rift basin. Syn-rift sediments can therefore be up to 10 km-thick for fully-filled basins but generally show deepening depositional environments to abyssal environments if syn-rift sedimentation rates are low. Post-rift sediments are also generally deep-marine but can be in extreme cases (*e.g.* front of large deltas) shallow marine/continental but with kilometric thicknesses.
- Narrow Oceanic basin (C): This stage includes, in addition to the aforementioned characteristics, an OCT (Oceanic-Continent Transition) domain (with exhumed mantle and/ or magmatic additions ranging from alkaline to T-MOR compositions) and an embryonic oceanic lithosphere made of exhumed subcontinental mantle. We consider an oceanic system as "narrow" or "immature" when it is too narrow and not dense enough (density being composition and/or age-dependent) to create a slab able to generate and sustain a subduction by negative buoyancy (*i.e.* slab pull) only.
- Wide Ocean (D): This stage is related to the formation of a wide oceanic lithosphere between diverging continents. Mantle and magmatic rocks are genetically linked and expected to be N-MORB except if a plume is present. We consider the ocean as "wide" or "mature" if it can generate a sustainable (*i.e.*, slab-pull controlled) subduction. Note that Chenin *et al.* (2017) proposed that oceans wider than 300 km can be considered as "wide oceans". However, as subduction is a consequence of the negative buoyancy of a slab, the age and the composition of the slab should be also considered at the onset of convergence.

While the divergent maturity stages A to D are easy to define at present day rifted margins using seismic data (see rift-domain concept of Tugend *et al.* (2014)), in orogenic systems their recognition is more difficult and based mainly on diagnostic criteria (see 1). A major challenge in orogenic systems is also that parts of the divergent system and especially wide oceans have been subducted, and, therefore, must be recognized by indirect criteria, such as the occurrence of arc signatures or by tomographic mapping of detached slabs in the underlying mantle. In contrast, distal parts of magma-poor margins, including the serpentinized mantle, either commonly escape subduction or are subducted and then exhumed and emplaced as high-pressure rocks in internal units of collisional orogens. Magma-rich margins are likely to be subducted and therefore not to be present in collisional orogens (see Gómez-Romeu *et al.* (2023); Ganade *et al.* (2023)).

In a more applied way, and as explained previously, in the ORO-Genic ID (see Fig. 1 and Tab. 1), it is important to identify the highest stage of divergent maturity reached prior to convergence, which can be done by answering, in a consecutive way, the following three questions.

Q_{D1}: Did rifting stop before necking, *i.e.*, before thinning the crust to less than 20 km thickness?

Q_{D2}: Did rifting result in crustal separation and formation of a proto-oceanic domain?

Q_{D3}: Did seafloor spreading result in a wide/mature oceanic domain that could give birth to a mature subduction?

A "yes" to QD1 points to stage A (Early Rift), while a "no" to QD1 and QD2 is characteristic of stage B (Hyperextended Rift); a "yes" to QD2 and a "no" to QD3 points to stage C (Narrow Oceanic basin), and finally, a "yes" to QD3 is compatible with stage D (Wide Ocean). Answering QD1, QD2 and QD3 requires the use of diagnostic criteria listed in Table 1. An example of how to apply this new concept is presented in Section 4 using the focus area of the OROGEN project.

3.2 Convergent maturity

In the WC 2.0, we define 4 stages of convergent maturity labelled as 1, 2, 3 and 4 in Figure 1 that can be characterized as follow:

- Immature Subduction (1): In this stage, most of the deformation is localized along the subducting slab made either of mature or proto-oceanic lithosphere. Structurally, this results in thin-skinned dominated deformation in the accretionary wedge with limited deformation involving the basement in the retro-wedge. Subduction-related magmatism may be in an embryonic stage or simply absent. If far-field driven convergence stops, the gravity-driven forces (slab-pull) are as yet insufficient to counteract the buoyancy of the slab and therefore subduction fails and freezes (see dead subduction system in Fig. 1).
- Mature Subduction (2): In this convergence stage, deformation is still localized along the subducting slab and results mostly in thin-skinned deformation in the accretionary wedge mostly involving oceanic sediments. Calc-alkaline magmatism is expected in the upper plate forming a mature arc, but can be inhibited by the magma-poor nature of the oceanic lithosphere (McCarthy *et al.*, 2018). If far-field driven convergence stops, the negative

buoyancy of the subducted oceanic slab (slab-pull) remains dominant. As a result, the subduction cannot stop, leading to the retreat of the slab and the development of a back-arc basin in the upper plate (see back-arc system in post convergence situation in Fig. 1). Note that a decrease in plate convergence can lead to a similar record.

- Early Orogenesis (3): In this stage, most of the deformation is concentrated in the inverting hyperextended domain. Reactivation occurs in the presence of flysch type (deep-water syn-orogenic turbidite) sedimentation and if previously present, arc-type magmatic activity stops in the upper plate as continental material enters the subduction zone (so called "continental subduction"). The front of thick-skinned deformation (or deformation involving the basement) remains in between the necking lines (see Fig. 2b) implying that at this stage only former distal (hyperextended) parts of the rifted margin are consumed and rift/post-rift sedimentation deforms within the accretionary wedge. The distal parts of the down going crustal taper in the lower plate can reach HP to UHP conditions (>15 kbars) prior to being exhumed back in the subduction channel, leading to a prograde-retrograde metamorphic record. If convergence stops, an early orogen involving only inversion of the hyperextended domain is formed (see early orogen system in post convergence situation in Fig. 1). If this early orogenesis stage follows a mature subduction (track D, see Fig. A4), the hanging wall contains former arc material. In addition, the underthrusting of the hyperextended domain made of low-density crustal material increases slab buoyancy and plays against the slab-pull force. The subduction can stop, and the slab can detach (*e.g.*, slab breakoff of Davies and von Blanckenburg (1995)). Alternatively, if early orogenesis follows an immature subduction (track C, see Fig. A3), the hanging wall is formed by the former conjugate margin without former arc activity. The slab can reach high-pressure conditions but may not be exhumed. Slab breakoff is not necessarily expected. The slab is therefore preserved at depth and visible in tomographic data section which can explain the lack of exhumation of high-pressure rocks.
- Mature Collision or Inverted Basin (4): In this convergence stage, deformation migrates out over previously weakly thinned crust (crust >20 km thick) and propagates outside the necking domain in the pro-wedge side. Thick-skinned structural shortcuts are formed and the orogen develops into a double- vergent geometry (Fig. 2c). Two contrasting cases can be envisaged. Either a former Early Rift (stage A) is inverted, resulting in an inverted basin (ORO-Genic ID A1, see Fig. A1), a process that is local and involves limited shortening, often triggered by far field stresses to deform thick crust. A second, and very different case, is the formation of a collisional belt that deforms crust that followed tracks B, C and D. During the collision stage, the classical fold-and-thrust belts form, including thin- and thick-skinned nappe-stacking. Crustal thickening, resulting in the formation of isostatically induced high topography often between external (former proximal) and internal (former distal) domains at the location of the former necking zone. The nature of the internal parts of the orogen will strongly differ depending on the maturity reached during the divergent stage (see Figs. A2, A3 and A4). While arc material can be expected for track D, ophiolites including subcontinental mantle, remnants of crustal blocks including pre-rift lower crustal rocks, associated with deep water sediments can be expected for track B and C, with in addition T-MOR and alkaline magmas for track C, to more classical N-MORB for track D. Outside the necking zones, in the former proximal margin above a >20 km thick crust, flexural foreland basins are formed due to the increasing load of the forming collisional belt. Pro and retro-foreland basins are filled by molasse type (syn-orogenic marine and continental) sedimentary sequences. The nature of this domain seems to be independent of the previous convergent history (see Fig. 2c) and is controlled more by an interplay between an inherited mechanical stratigraphy (specific to local pre-rift geological record and therefore not predictable genetically), erosion and sedimentation. The vergence of the belt has also consequences for the respective dynamics of pro- and retro-foreland basins. The prowedge accommodates high shortening by horizontal propagation of deformation (lower plate), whereas the retrowedge accommodates considerably less shortening above the orogenic buttress (less propagational, see details in Ford *et al.* (2022) and references therein). When convergence stops in a mature collisional orogen, orogenic collapse and related extension can occur, being-favored by high gravitational potential energy (GPE), isostatic disequilibration and the presence of an orogenic root. This process does not occur in less mature orogens (see post-convergence situation in Fig. 1).

As in the divergent case, answering, in a consecutive way, questions Q_{C1} and Q_{C2}, formulated below, can define the ORO-Genic ID (see Fig. 1 and Tab. 2) of the system.

Q_{C1}: Did an oceanic subduction/slab form and if yes, did it reach steady state?

Q_{C2}: Does the front of the thick-skinned deformation go beyond the necking line?

If the answer to Q_{C1} is "yes" convergent stage 2 was reached, but if the answer is "no" only convergent stage 1 was reached. If the answer to Q_{C2} is "no" the convergent stage 3 was reached, and if the answer is "yes", stage 4 was attained. However, in most cases convergent stages can be modified by the so- called post-convergence stages that can include a dead subduction, long-lasting arc activity, back-arc extension or orogenic collapse. These post-convergence stages are not included in the ORO-Genic ID but are indicated with the symbol * and shown in the WC 2.0 in Figure 1.

4 The oro-genic id approach applied to the Biscay/Pyrenean system

The along strike variation of the orogenic architecture in the Biscay/Pyrenean system, with a well- preserved divergent stage in the Bay of Biscay and a dominant convergent overprint in the Pyrenees, makes this system an ideal example to illustrate the ORO-Genic ID approach and to exemplify different tracks within the WC 2.0. In the past, the highly variable orogenic architecture along strike, reflected by different structures, nature and compositions of basements rocks, tectono-stratigraphic and metamorphic records resulted

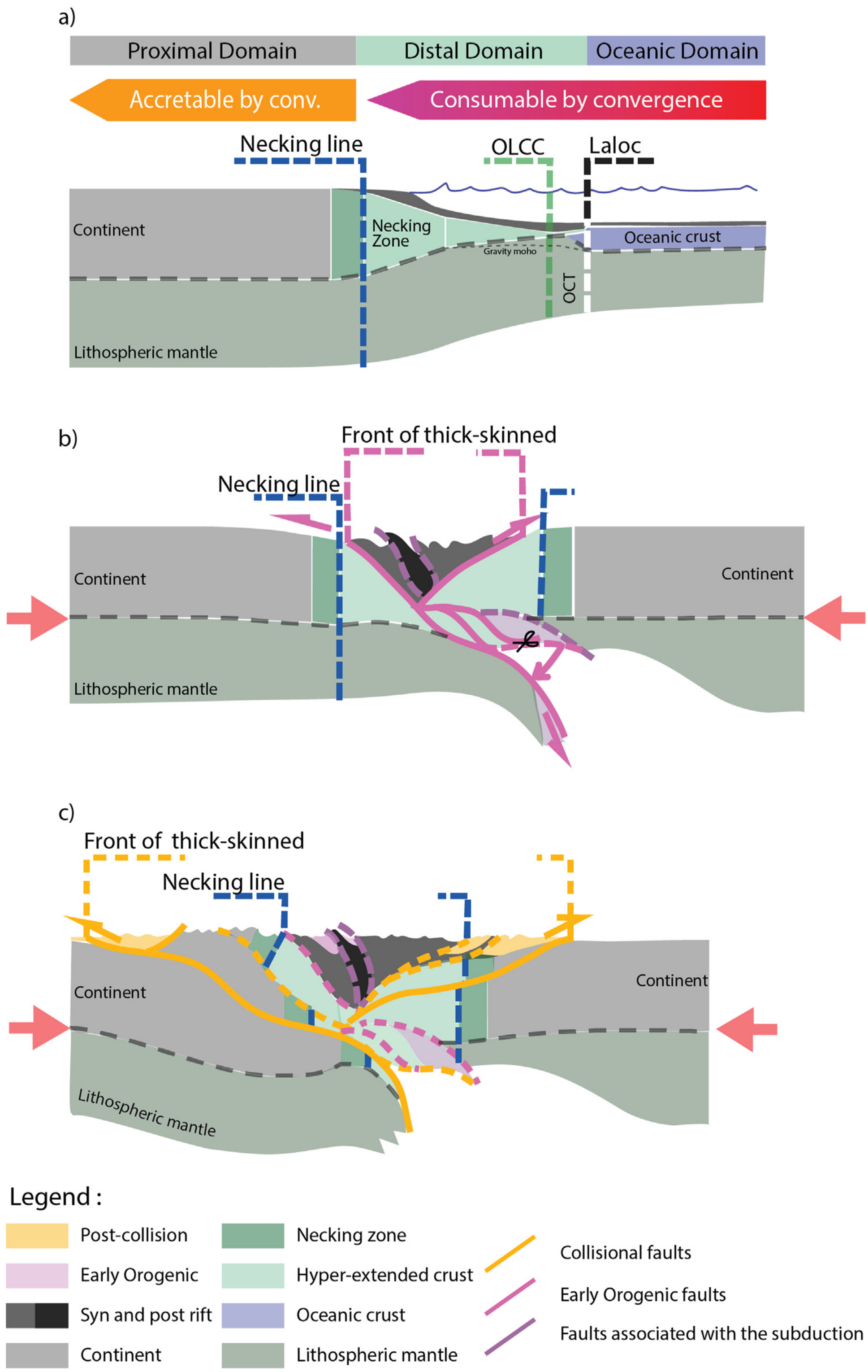

Fig. 2. Schematic representation of a rifted margin and two stages of convergent maturity highlighting the position of the front of the thick-skinned deformation with respect to the former necking line. a) The proximal, distal and oceanic domains are illustrated as well as the main structural limits between them (necking line, Outer limit of Continental crust (OLCC) and landward limit of Oceanic Crust (Laloc). b) In an early Orogenesis convergent stage the front of the thick-skinned deformation doesn't no traverse the former necking line. c) In a mature collision stage, the front of the thick-skinned deformation traverses the former necking line thus involving formerly un-thinned continental crust.

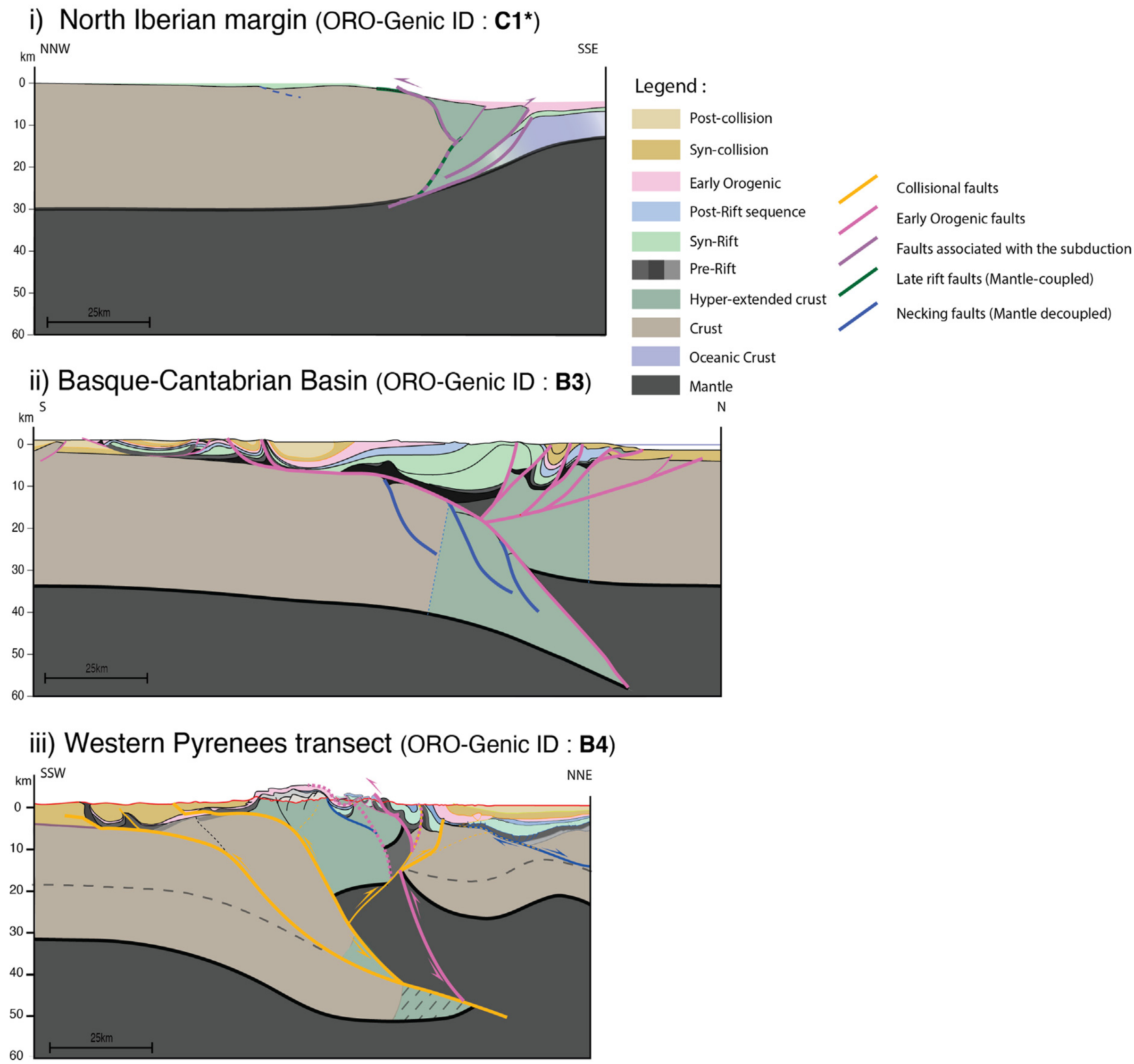

Fig. 3. Example of ORO-Genic ID assigned along three cross sections located in the Bay of Biscay/Pyrenean system. i) C1* : The Northern Iberian margin (modified from Tugend *et al.* (2014)), ii) B3 : The Basque Cantabrian Basin (modified from Miró *et al.* (2021)) iii) B4 : The Western Pyrenees (modified from Teixell *et al.* (2016); Gómez-Romeu *et al.* (2019)). See Figure 4 for location.

in many different, and partly conflicting interpretations of the Biscay/Pyrenean system. One of the major outcomes of the OROGEN project was to demonstrate that the complexity is not only the result of convergence, but also results from the interplay between inherited divergent maturity and the subsequent convergent overprint (Fig. 3). Based on new data and observations acquired during the OROGEN project, it was possible to answer the ORO-Genic questions (Q_{D1}, Q_{D2}, Q_{D3}, Q_{C1} and Q_{C2}) using the diagnostic criteria listed in Tables 1 and 2 and to map the maturity levels of the divergent and convergent stages reached in the Biscay/Pyrenean domain (Fig. 4). Key information on which the study is based can be found in the Orogen Headpapers (Chevrot *et al.* (2022); Jolivet *et al.* (2021); Ford *et al.* (2022); Mouthereau *et al.* (2021); Manatschal *et al.* (2021) and references therein compiling results of the OROGEN project). They are: 1) the new tomographic images that provide information on the existence or non-existence of a slab along strike (see Q_{C1a} andQ_{C1b} in Tab. 2), 2) the mapping of necking zones, the front of the thick-skinned deformation and the syn-rift depocenters across the Biscay-Pyrenean system (see Q_{D1} in Tab. 1 and Q_{C2} in Tab. 2), 3) the study of the syn- and post-tectonic depositional environments and the nature of the exhumed mantle and magmatic rocks (see Q_{D1} in Tab. 1), and 4) new plate kinematic models to test the width of the paleo-Biscay/Pyrenean domain prior to convergence (Q_{D3} in Tab. 1). Based on these new results it was possible to propose new crustal scale sections (Fig. 3) and maps (Fig. 4) that show the life-cycle track (from A to C) and ORO-Genic ID of different domains in the Biscay-Pyrenean system. It is interesting to note that all track types can be found regionally as a non-reactivated mature ocean can be identified in the Iberian Atlantic margin outside the Biscay-Pyrenees area. This shows that the maturity of divergence can change laterally (more mature and wider in the west *vs.* less

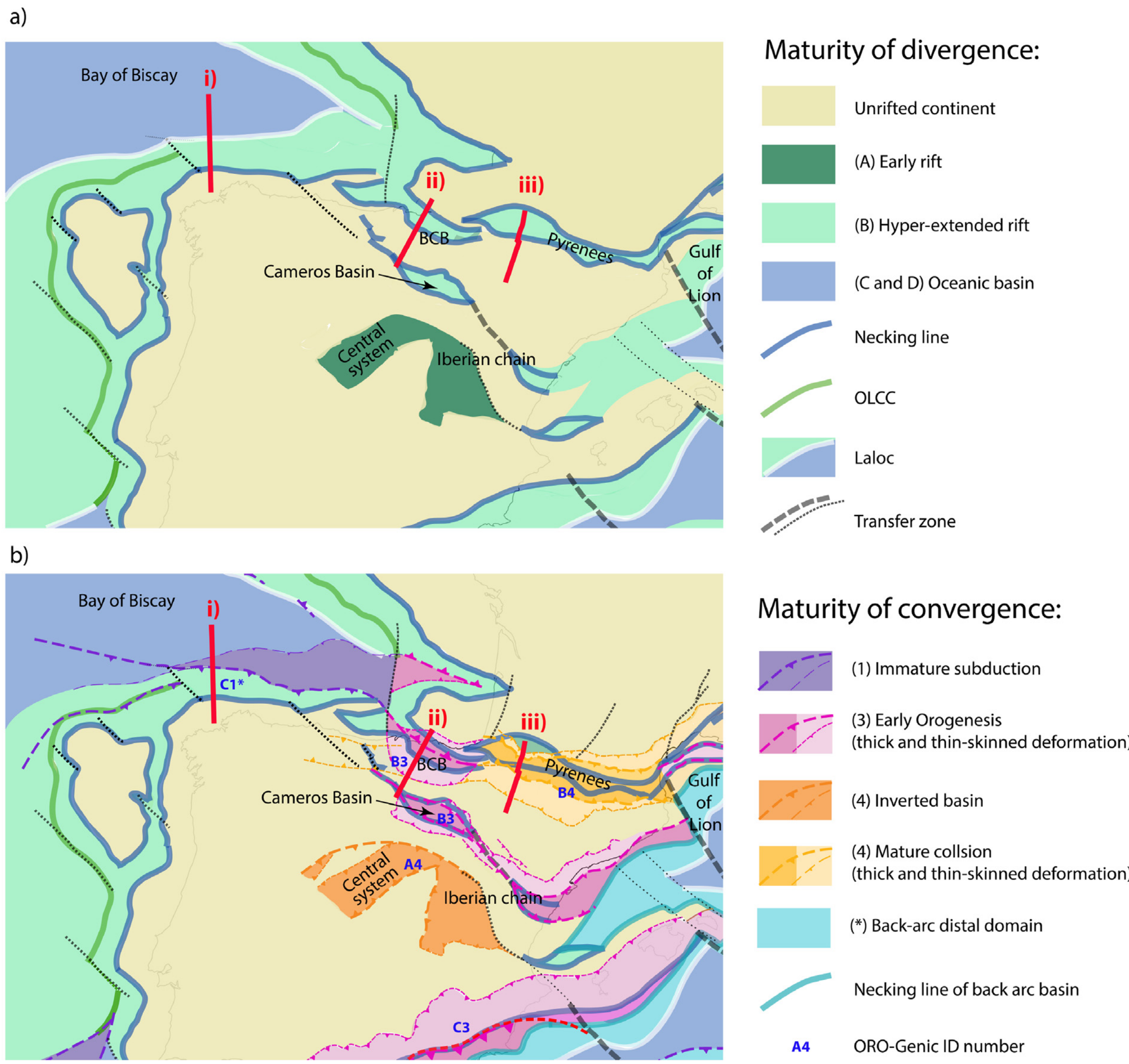

Fig. 4. Map of the Bay of Biscay and Pyrenean area representing: (a) the maturity of the divergence reached in the rift domains preserved in the Bay of Biscay and in onshore fossil analogues. (b) The maturity of the convergence of the orogens present in the area. The location of the sections presented in figure 3 is depicted in red and ORO-Genic IDs are indicated in blue.

mature and narrower in the east). In the following we present some examples, by going from West to East through the Biscay/Pyrenean system.

– The North Iberian margin (Fig. 3a): The North Iberian margin was interpreted as an accretionary prism related to the formation of an oceanic subduction (Boillot *et al.*, 1984; Alvarez-Marron *et al.*, 1997). However, seismic refraction results refuted this hypothesis (Fernández-Viejo *et al.*, 1998; Ruiz Fernàndez, 2007). New studies in the OROGEN project (Cadenas *et al.*, 2020; Miró *et al.*, 2021) interpreted this domain as a former hyperextended domain that has been reactivated during convergence leading to the underthrusting of the domain by exhumed serpentinized mantle. When convergence stopped, the gravity-driven forces (slab-pull) were too low to counteract the buoyancy of the slab. Therefore, subduction stopped naturally resulting in a dead subduction system. In terms of maturity, the divergence reached the level of maturity C (Narrow Ocean, see Fig. 4a and Fig. A3) and the level 1 during convergence (Fig. 1). The ORO-Genic ID of the northern Iberian margin is therefore C1* (Figs. 3a and 4). The asterisk (*) indicates that the system now forms a dead subduction. It is important to note that thick-skinned deformation is recorded within the Cantabrian mountains located in the south- east of the section but this is not related to the subduction but corresponds to a lateral border effect of the Basque Cantabrian belt (BCB) discussed below (see also Miró *et al.*, 2022). The 3D implications will be further explored below.

- The Basque Cantabrian belt (Fig. 3b): The Basque Cantabrian Belt is a good example of the Track B (Fig. A2) as it results from the shortening of an aborted hyperextended rift where mantle rocks have been exhumed (see Fig. 4a) (Miró *et al.*, 2021; Ducoux *et al.*, 2019). During convergence, the deformation remained restricted to the former rift basin, as a thin-skinned belt with no evidence of thick-skinned structural shortcuts (see Fig. 2b) in the pro-wedge and a limited amount of crustal thickening in the pro and the retro-wedge. These characteristics explain why this belt is often referred to as the "Basque Cantabrian Basin" as it still preserves its rift evolution. In map view (Fig. 4b), we can observe that only the front of the thin-skinned deformation goes over the necking line (see Fig. 2 for explanation). For these reasons, we can establish that within the Basque Cantabrian belt the convergence was fossilized at the early orogenesis maturity stage and is characteristic of a B3 ORO-Genic ID (Figs. 3b and 4).
- The Western Pyrenees (Fig. 3c): The Western Pyrenees is another example of the Track B (Fig. A2) as it results from the shortening of an aborted hyperextended rift where mantle rocks have been exhumed (see Fig. 4a) (Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010; Lagabrielle and Bodinier, 2008; Lescoutre *et al.*, 2019; Masini *et al.*, 2014; Saspiturry *et al.*, 2019). But in contrast to the BCB, in the western Pyrenees the thick-skinned deformation clearly propagated beyond the former necking line (see Fig. 2c and Fig. 4b). We can therefore determine that in the Pyrenees the convergence reached the mature collision stage (ORO-Genic ID B4, Fig. 3c). From B3 to B4, the Pyrenean-Cantabrian transition is a good example where the "ORO-Genic ID" changes laterally due to a change of convergent maturity.
- The Cameros basin (Fig. 4): Geological observations from the Cameros basin located in the Central Iberian range demonstrate that this basin is a former hyperextended basin (life-cycle track B, Fig. A2) filled with 8 km of syn-rift sediments (Casas-Sainz and Gil-Imaz, 1998; García-Lasanta *et al.*, 2017) affected by Late Cretaceous to Miocene shortening (Del Rio *et al.*, 2009; Rat *et al.*, 2019) mostly taken up by the Cameros northern thrust front (Salas *et al.*, 2001). Therefore, in a map view (Fig. 4b), we can observe that the front of the thick-skinned deformation corresponds to the former necking line and can conclude that the system didn't reach the mature collision stage. For this reason, this system is identified as another example of the B3 ORO-Genic ID.
- The Central system and the southern part of Iberian chain (Fig. 4): The Central system and southern part of Iberian chain correspond to inverted intra-continental rift systems (Casas-Sainz and Gil-Imaz, 1998; Omodeo Salè *et al.*, 2014; Platt, 1990; Rat *et al.*, 2019) corresponding to the ORO-Genic ID A4. The geological observations (narrowness, apparent absence of deep-water sediments, hyperextension and exhumed mantle or oceanic material) are indeed characteristic of an immature rifted domain (divergent maturity A, Fig. A1) affected by an intra-crustal decollement responsible for the crustal thickening characteristic of collisional deformation and formation of an inverted basin (convergent maturity 4).

5 Discussion

5.1 Is the ORO-Genic ID concept applicable to other orogens?

Orogens are complex systems resulting from a long and polyphase evolution involving a number of processes and displaying a large variability of structures. The OROGEN project illustrates that the observed complexity not only results from orogenic processes but can also be related to the variability of the precursor record of divergence and its implications for the subsequent convergent phases. The ORO-Genic ID concept presented here is an attempt to integrate, in a simple way, the importance of inheritance by introducing the concept of tectonic maturity. The main pillar of this new concept is the observation driven, holistic approach based on diagnostic criteria to identify the main tectonic stages recorded within an orogenic system during its tectonic lifecycle. This adapted Wilson Cycle W2.0 reflects decades of geological research both at sea and onland (see Tabs. 1 and 2). In the Wilson Cycle 2.0 shown in Figure 1, the full range of evolution tracks, can be characterized by answering specific questions (see ORO-Genic questions in Tabs. 1 and 2).

It is beyond the scope of this paper to solve each existing debate on orogenic "singularities" such as those related to exhumation of (ultra)high pressure rocks, the driving processes of subduction dynamics and all inheritances that can impact the pre-orogenic template (occurrence of micro-continents, composition, post-rift thermal relaxation time and age, magma/sediment budget of both rifted margins and oceanic lithospheres, transform margins/fault zones, hot spots...). We can however propose a new level of understanding of the evolution of orogenic systems by relating orogenic variabilities to tectonic maturity that can be understood genetically. In Section 4, we illustrate how the ORO-Genic ID concept can be applied to the Biscay-Pyrenean system, where new seismic imaging methods, focused field studies, and innovative analytical and simulation methods provided unique data coverage. The question remains however, if this concept can be applied to other orogenic systems.

The West European system along the diffuse Africa-Europe plate boundary in Western Europe and northern Africa is another complex orogenic system with along strike variations in orogenic architecture. This system accommodated plate convergence from the late Cretaceous onwards leading to the formation of strikingly different orogenic branches (Macchiavelli *et al.*, 2017; Angrand *et al.*, 2018, 2020; Frasca *et al.*, 2021; Jolivet *et al.*, 2021; Angrand and Mouthereau, 2021; Mouthereau *et al.*, 2021) including the Biscay/Pyrenean system, the Central system and the Iberian chain discussed before, and the Betic/Rif, Tell and Atlas systems, the Apennines and the Alpine system sensu stricto. On the southern edge of the system, for example, the High Atlas belt is an intra-continental belt that presents similarities with the Central system of Iberia and the southern part of the Iberian chain, *i.e.*, half grabens with limited accommodation space and intra-continental decollements (Beauchamp *et al.*1999; Frizon de Lamotte *et al.*, 2008; Giese and Jacobshagen, 1992; Leprêtre *et al.*, 2018; Teixell *et al.*, 2003). It can therefore be described with the ORO-Genic ID A4, corresponding to an inverted rift basin system.

In the eastern edge of the West European system, most of the Alpine system reached the mature collision stage as observed in the Pyrenean belt. However, to understand differences between the Alps and the Pyrenees, it is important to acknowledge that both systems belong to different life-cycle tracks. In the Pyrenees only mantle rocks were exhumed during extension (Track B, hyperextended basin, Fig. A2) and true break up to form oceanic crust did not occur, while both narrow and wide oceanic basins developed in the Alpine system (Lemoine *et al.*, 1987; Handy *et al.*, 2010; Picazo *et al.*, 2016). The Alpine system belongs therefore to the life-cycle track C or D (Figs. A3 and A4) and its ORO- Genic IDs vary from C4 to D4 which contrasts with the B4 of the Pyrenees. Differences between the two orogenic systems are therefore in part the result of the different maturity level reached during divergence.

Similarly, in the Betic-Rif belt, the presence of exhumed mantle domains and MORB-bearing ophiolitic mélanges (Gimeno-Vives *et al.*, 2019; Pedrera *et al.*, 2020; Puga *et al.*, 2011) strongly sup- ports the existence of a narrow or wide oceanic domain (Track C or D, Figs. A3 and A4). A key indication comes from the occurrence of the Alboran slab imaged by tomographic data (Calvert *et al.*, 2000; Villaseñor *et al.*, 2015; Bezada *et al.*, 2013), created by the Miocene opening of the Alboran sea and followed by subduction and slab break-off implying the consumed ocean was wide enough to generate a mature subduction (track D, Fig. A4). In terms of convergence, most of the deformation is concentrated in the inverted rift basin and the front of the thick-skinned deformation does not affect domains beyond of the necking line (see Fig. 2b) implying that the ORO-Genic ID of the Betic belt is D3.

The formation of the Gulf of Lion/Tyrrhenian/Apennine system results from the retreat of the Mediterranean steady-state subduction (Jolivet *et al.*, 2020; Séranne *et al.*, 2021). The formation of this back-arc system suggests the existence of a wide oceanic domain (*i.e.*, divergent maturity D, Fig. A4). Convergence stopped after the formation of the mature subduction. The corresponding ORO-Genic ID is therefore D2* with the asterisk (*) to indicate that the system was affected by post-convergence deformation. All those examples demonstrate that the ORO-Genic ID is a powerful tool allowing to map orogenic systems with different evolutions in an efficient way. Linking key geological characteristics (*e.g.* preserved rift, occurrence of" obducted crust", the tectono-stratigraphic-magmatic-metamorphic and structural records) to an Orogenic ID may also be meaningful to determine what process (and especially which inherited divergent template) could control which "singularity". Moving to economic impacts, we believe this approach may be a key tool to identify orogenic belts for a given targeted resource.

5.2 Consumable domain versus accretable domain

A key in understanding convergent systems is the buoyancy of the rift domains that become involved in orogenesis. While domains with negative buoyancy (*e.g.*, oceanic lithosphere) can be fully subducted and consumed, those with positive buoyancy (*e.g.*, proximal margin domains) cannot be easily subducted and will be accreted to form thick orogenic crust (Lacombe and Bellahsen, 2016) (Fig. 2). The fate of distal margin domains is more complex and first depends on the occurrence and location of decoupling levels that are mostly a function of crustal composition (Miró *et al.*, 2021; Gómez-Romeu *et al.*, 2023) and temperature (*i.e.* age of lithosphere and sedimentary burial). Magma-rich margins, for instance, are assumed to be consumed, as supported by modelling results (Ganade *et al.* 2023). In this case, the main convergent decollement is within the post-rift sedimentary cover leading to the formation of a thin-skinned accretionary wedge without syn- or pre-rift sediments (Gómez-Romeu *et al.*, 2023). In contrast, hyperextended magma-poor margins overlying exhumed mantle can either be directly accreted when the main decollement is within or below the thinned crust (brittle-ductile transition, base of serpentinized mantle), or first subducted and then exhumed in the early orogen as (ultra)high pressure rocks (Ganade *et al.* 2023). Thus, assessing the pre-orogenic divergent maturity is a key to determining the nature and width of the consumable/accretable domains that are involved in the convergence process (see Fig. 2a). In case of an early rift, the consumable domain is zero, resulting in an intra-continental thick-skinned dominated inverted basin with direct crustal thickening (ORO-Genic ID A4 Fig. 1). In the case of hyperextended rifts, the consumable domain is limited, implying that after being consumed during early Orogenesis (ORO-Genic ID B3 in Fig. 1), shortening during collision will be accommodated by thick-skinned structural shortcuts and nappe-stacking affecting the necking zone and the proximal margin (ORO-Genic ID B4 in Fig. 1). During collision, local rift inheritances plays a limited role (inversion of half-grabens) whereas the role of regional mechanical inheritances (compositional and thermal) and the role of the feedback loop between relief creation, erosion, transfer and sedimentation (for more details, see the Source to Sink project vade-mecum (Castelltort *et al.*, 2023) become predominant. In the case of a narrow or wide ocean, the oceanic domain constitutes the main part of the consumable domain. However, if the oceanic system is narrow, the future slab will not be able to generate a sustainable slab-pull force to control subduction. Early orogenesis initiates when the subduction starts to consume the hyperextended margin of the lower plate and to accrete possible slivers of buoyant crustal material detached from the subducting slab. This is a critical moment during convergence that leads to a progressive increase of the orogenic wedge buoyancy (increasing GPE) with the thickening of the buoyant continental crust and incorporation of sediments in the orogenic wedge through time (Early Orogenesis stage, ORO-Genic IDs C3 or D3 in Fig. 1). This mechanism reaches its maximum when the deformation front reaches the necking line. If convergence continues and deformation migrates beyond this line, >20 km thick crust becomes involved in the growing orogen first on the pro-continent side before affecting the retro-continent side (Jammes and Huismans, 2012; Grool *et al.*, 2019). If convergence continues, deformation migrates across the necking line and reaches a mature collision stage (ORO-Genic IDs C4 or D4 Fig. 1). From these possible orogenic tracks, it is therefore clear that a pre-convergence template with different maturity of divergence along strike, such as the Biscay-Pyrenees system, leads to different maturity of convergence along strike and, in a system that continues to converge, different timing for maturity changes with marked boundary effects on lateral segments. For example, if a mature collisional level is reached leading to plate convergence deceleration (counteracting gravity forces and rupture of a thick lithosphere), it could laterally force slab-roll back if convergent maturity decreases laterally to a mature subduction stage. Therefore, complex orogenic systems may derive from variable maturity of divergence along strike (*e.g.*, Biscay-Pyrenean and Alpine systems) and as such, determining the nature and width of the consumable domain is key to constraining 3D boundary conditions to better understand orogenic records in space and time.

5.3 Limitation of the approach

The ORO-Genic ID concept is based on the recognition of diagnostic criteria that are listed in Tables 1 and 2. As such, it can only be applied if the necessary data sets are available. Another key limitation is that the concept is based on Western European Orogens that were preceded by magma-poor Tethyan divergent systems. In contrast, orogens that were preceded by magma-rich margins are notably rarely reported in the Meso-Cenozoic record, even though magma-rich margins represent up to half of modern rifted margins and might not have been rarer in earlier Earth history. This anomaly may either be because magma-rich margins tend to be completely subducted before mature continental collision, or they are not recognized and/or have been misinterpreted. Recently, Gómez-Romeu *et al.* (2023) and Ganade *et al.* (2023) suggest that such margins are indeed mostly subducted and therefore not accreted in early and collisional orogens. Based on geological/geophysical observations and numerical experiments, Gómez-Romeu *et al.* (2023) propose that the lack of deep-water syn-rift strata or thick piles of syn-rift sediments and the absence of distal margins domains preserved in an orogen may point to the existence of a former magma-rich margin. However, if these results suggest that magma-rich and magma-poor margins behave differently during subduction (Gómez-Romeu *et al.*, 2023; Ganade *et al.* 2023), these questions are still in the first stages of research. Applying the ORO-Genic ID approach to Middle East orogens (*e.g.* Zagros) has already led us to recognize fingerprints of magma-rich margin-derived orogens supported by recent petrological studies (Azizi *et al.*, 2023). While not providing clear proof, noting the absence of diagnostic criteria represents valuable information that can contribute to the definition of an orogenic ID. Future research aims to further develop this "code" by adding orogenic tracks for magma-rich rifted and transform margins.

While the ORO-Genic concept allows us to understand the first order lifecycle of an orogenic system resulting from the reactivation of magma-poor rifted margins, the occurrence of local specificities such as crustal blocks (*e.g.*, extensional allochthons, ribbons, microcontinents; for definitions see Péron-Pinvidic and Manatschal (2010)), strongly segmented margins, 3D boundary conditions, or complex kinematic evolutions are not yet integrated and could also be key in controlling, in particular, early orogenic records. Theses specificities may help to explain complex sequences of compression, extension, transient roll-back and delamination in internal parts of orogens and may help address the question regarding mechanisms of exhumation of ultra-high-pressure rocks as observed in the Alps (Malusà *et al.*, 2011; Froitzheim *et al.*, 2003). Note also, that the post-rift thermal relaxation time that controls the initial thermal conditions of the orogenic system (Salazar-Mora *et al.*, 2018; Sacek *et al.*, 2022) and the thermo-mechanical, kinematics and climate forcing parameters are not considered in the Wilson Cycle 2.0 but are known to affect orogenic processes and syn orogenic basins (Jammes and Huismans, 2012; Angrand *et al.*, 2018; Vasey *et al.*, 2024).

Last but not least, another new perspective unlocked by the ORO-Genic ID concept is to switch the understanding of orogens from a chrono-tectonic to an ORO-Genic viewpoint. In helping us to deter- mine and date in a consistent way the maturity of divergence (*i.e.* the pre-orogenic template), the maturity of convergence and the nature/age of post-orogenic records, the ORO-Genic ID concept opens the possibility of studying spatial lithospheric coupling between different orogenic branches/sub-belts across diffuse plate boundary (see Mouthereau *et al.* (2021)). It also questions the role of subduction in space and time in convergent settings (see Jolivet *et al.* (2021)).

5.4 Implications for industry

The first order concept and methodology proposed in this paper are typically designed for crustal/basin-scale applications. As such, they provide significant value for rapid diagnostic assessments of orogenic provinces and their associated basins. One of the key aspects of the ORO-Genic concept is to understand their geodynamic evolution through the identification of their tectonic track. In the Pyrenean system, it has been clearly demonstrated that most of the play elements of the oil and gas system are inherited from the pre-convergence history (see Biteau *et al.* (2006) for a review). The presence or absence of these elements depends on the preservation of (hyper)extended rift domains within the orogen, which in turn relies on the convergent maturity. In systems that do not reach the mature collision stage, such as the Basque-Cantabrian Basin, preservation is maximized. In more mature collisional settings, like the Pyrenees sensu stricto, preservation is limited to the retro-wedge of the orogen or located at the junction between two former rift segments (Lescoutre and Manatschal, 2020). Whatever the targeted resources, we believe this approach enables explorers to contextualize plays within a coherent tectonic framework, making it applicable to mineral system in mining, petroleum system for oil and gas and hydrogen system for geological (white) hydrogen as already adopted by companies.

6 Conclusion

As presented in this paper, the OROGEN project provided keys to genetically compare the different orogenic systems of the Africa-Iberia-Europe diffuse plate boundary. Motivated by the idea of challenging the "classical Wilson cycle", the OROGEN project investigated the roles of different divergent and convergent maturities and their impact on orogenic and post-orogenic processes. In this respect, in proposing the Wilson cycle 2.0 and developing a new tool to map collisional orogens in a genetic (or process-driven) way, the OROGEN project has successfully challenged the preconceived "Orogen singularity" assumption. It redefines what are the unpredictable geological specificities (regional and not genetic) from what can be genetically predicted, by identifying for a specific orogen its tectonic track across the Wilson cycle 2.0. We propose, based on diagnostic criteria and the ORO-Genic questions listed in Tables 1 and 2, to determine the divergence and convergence maturity of an orogen and to identify its ORO-Genic ID. Each ORO-Genic ID characterizes the evolution and the architectural type of an orogenic system and explains differences in the style of deformation at crustal scale and the type of tectono-stratigraphic and magmatic records. In a complex orogenic system presenting variation along strike of the ORO-Genic ID (and therefore the maturity of the divergence and the nature and width of the consumable domain existing before convergence) is key to constraining 3D boundary conditions and to understanding orogenic non-cylindricity and so-called anomalies. Moreover, at a larger scale, the ORO-Genic ID is a mappable concept that, within limitations, can be easily exported to other orogens and will help us to compare and to classify orogens worldwide.

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Appendix

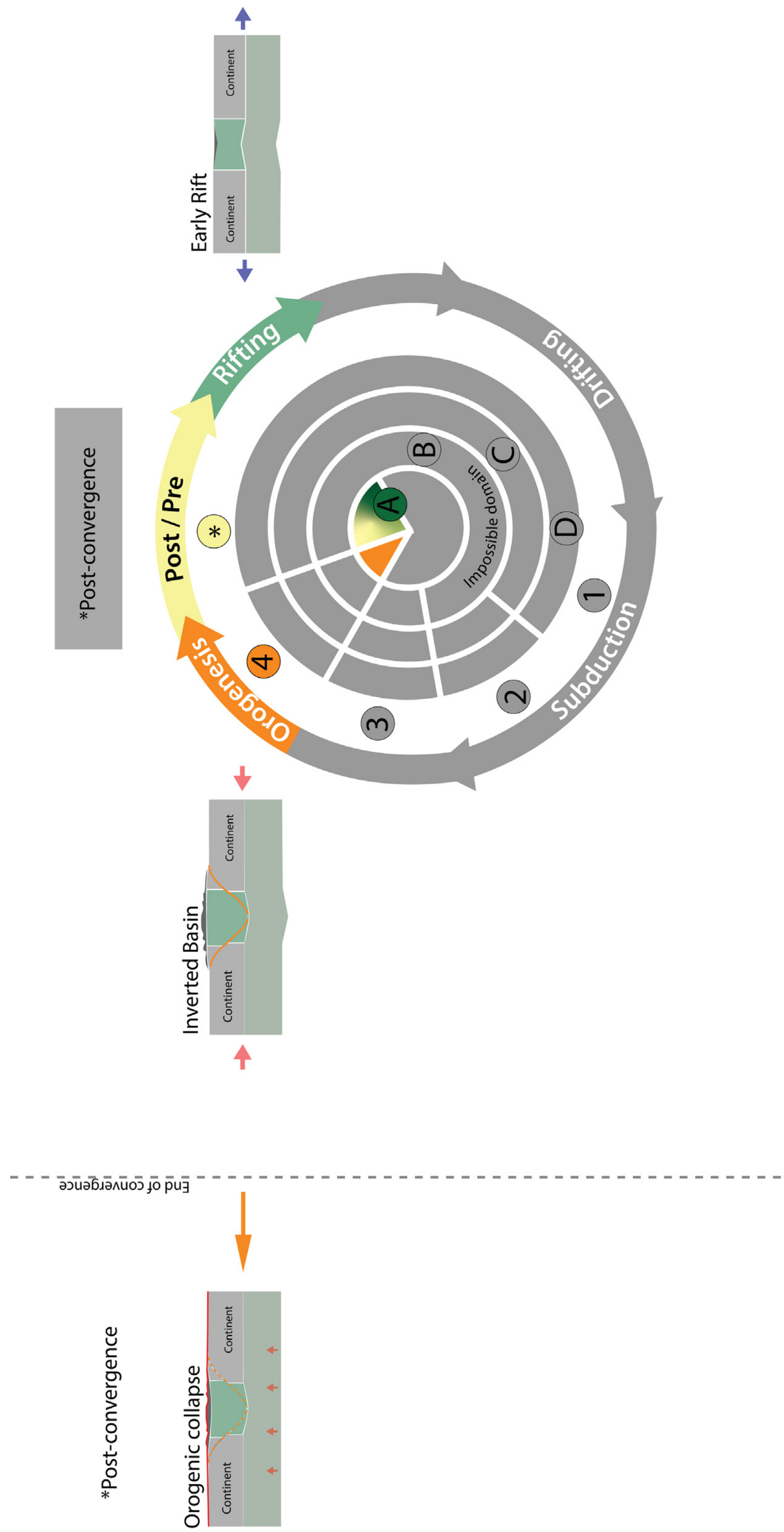

Fig. A1. On the right: Wilson cycle updated for tectonic track A. In the case of the end of convergence, the post-convergent scenario is illustrated on the left side of the figure.

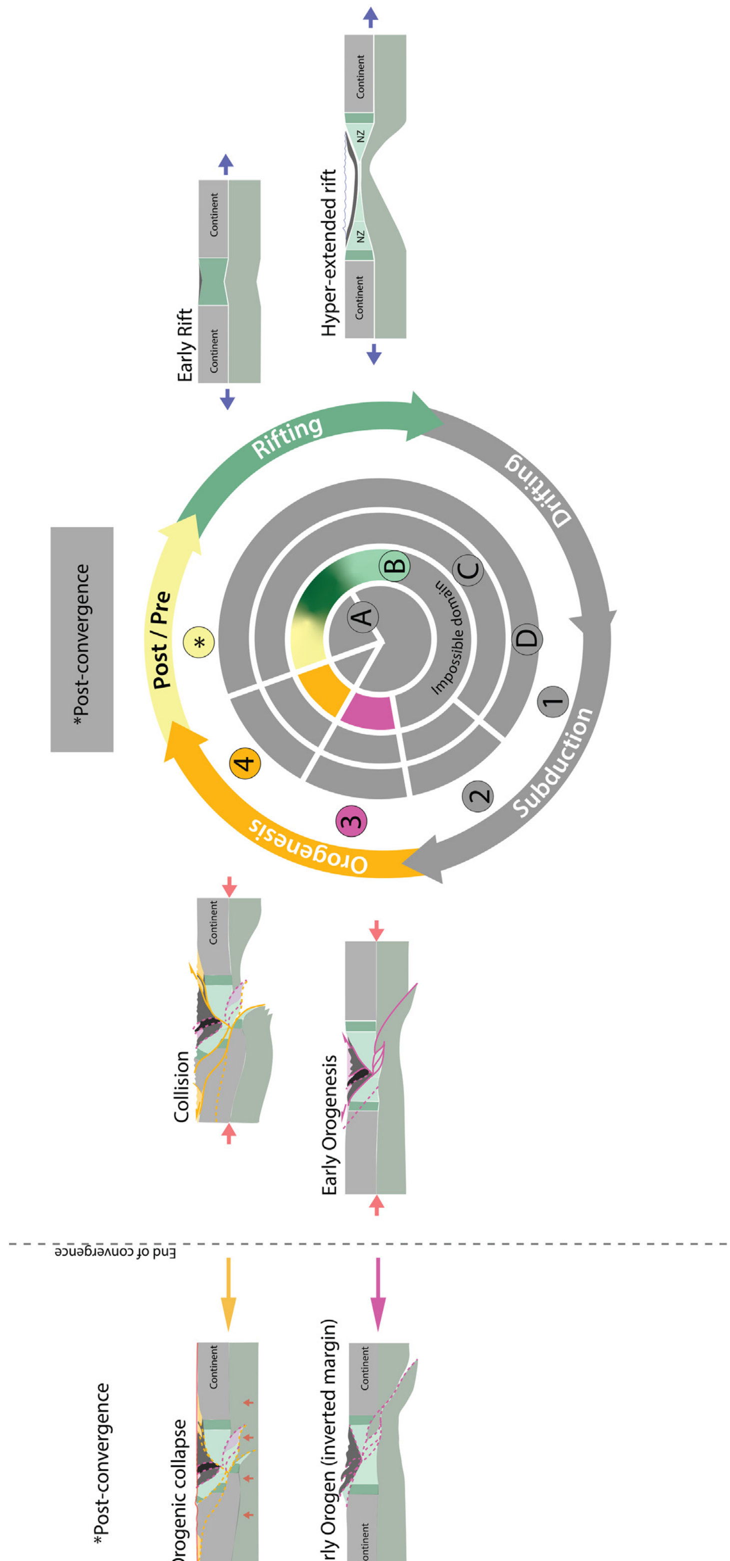

Fig. A2. On the right: Wilson cycle updated for tectonic track B. In the case of the end of convergence, different post-convergent scenarios are possible depending of the maturity stage of the convergence. Those scenarios are illustrated on the left side of the figure.

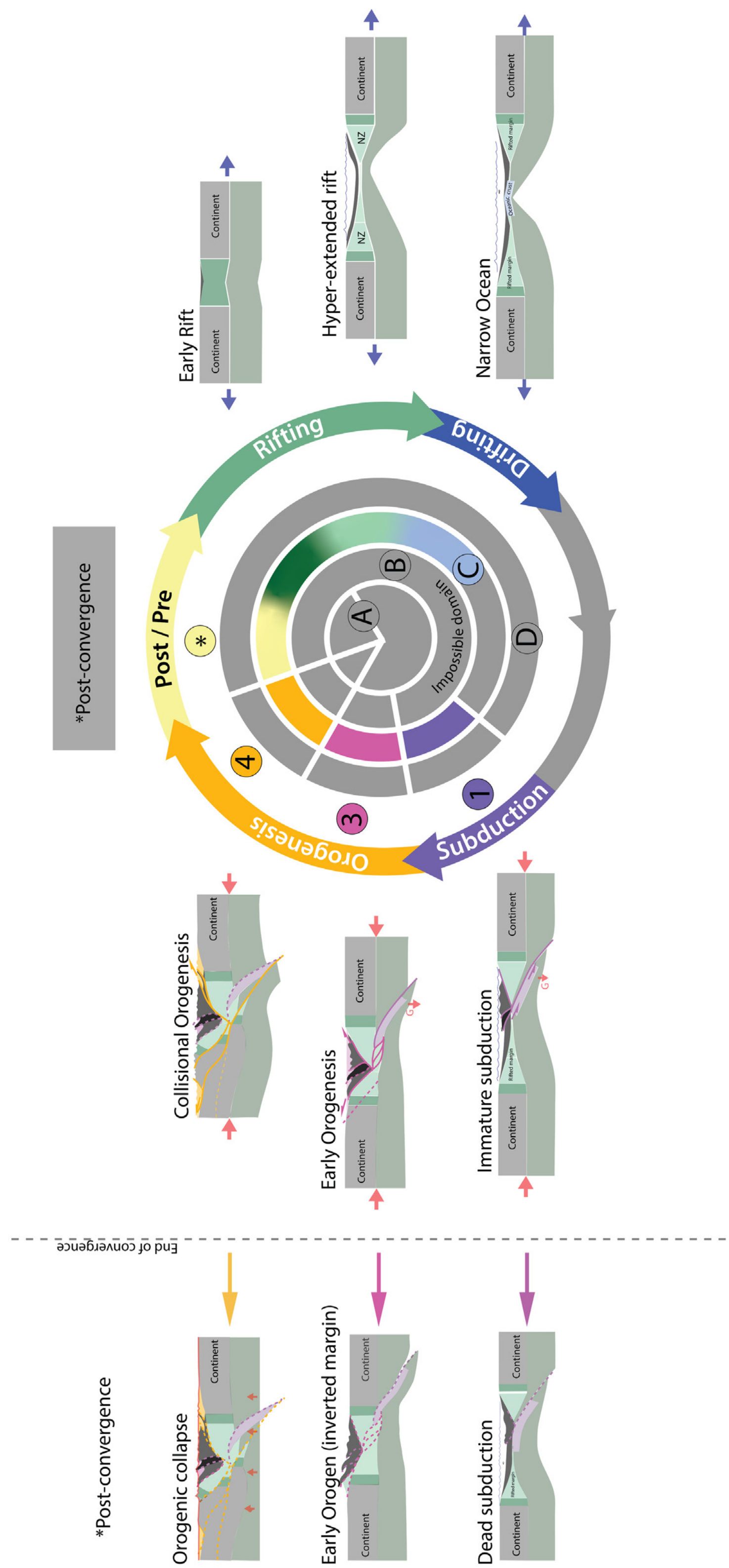

Fig. A3. On the right: Wilson cycle updated for tectonic track C. In the case of the end of convergence, different post-convergent scenarios are possible depending of the maturity stage of the convergence. Those scenarios are illustrated on the left side of the figure.

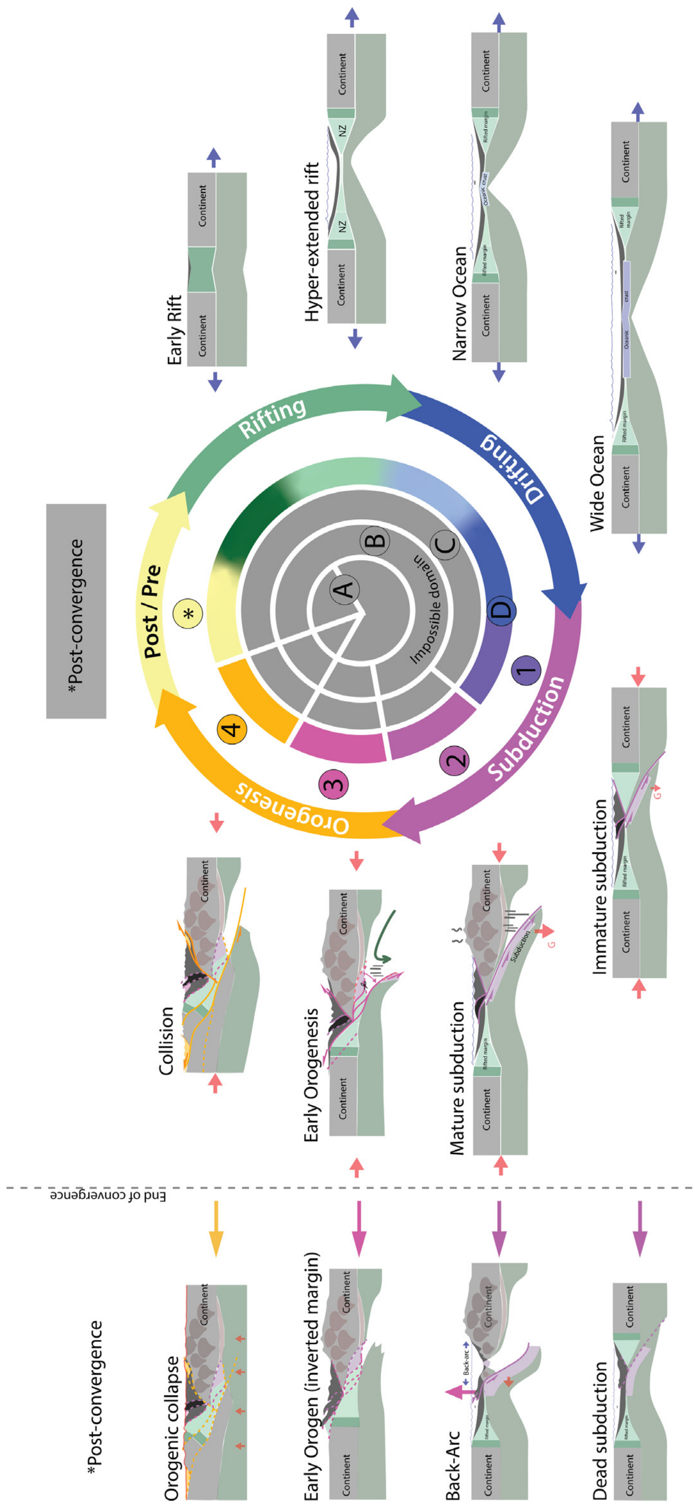

Fig. A4. On the right: Wilson cycle updated for tectonic track D. In the case of the end of convergence, different post-convergent scenarios are possible depending of the maturity stage of the convergence. Those scenarios are illustrated on the left side of the figure.