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Geodynamics

Geometry and kinematics of early Alpine nappes in a Briançonnais basement (Ambin Massif, Western Alps)

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Abstract

Petrological and structural observations from the Ambin pre-alpine basement dome and from its Briançonnais and Piedmont covers show an early D1 nappe-forming event overprinted by a major D2 (+D3) ductile shearing deformation. The D1 event is characterised by garnet-blueschist facies metamorphic assemblages retrogressed to greenschist facies conditions during D2 then D3 stages near the top of the dome. North-verging D1 structures preserved in the core of the dome are consistent with alpine evolutionary models, in which exhumation of HP–LT metamorphic alpine rocks occurs initially in a north–south direction. ***To cite this article: J. Ganne et al., C. R. Geoscience 336 (2004).***

Résumé

Géométrie et cinématique de nappes alpines précoces dans un socle briançonnais (massif d'Ambin, Alpes occidentales). Une étude pétro-structurale du dôme de socle préalpin d'Ambin et de ses enveloppes briançonnaises et piémontaises révèle l'existence de structures alpines précoces liées à un événement D1 de HP–BT. Les structures D1 correspondent à des foliations de faible pendage et à des paragenèses métamorphiques du faciès des schistes bleus à grenat, rétromorphosées au sommet du dôme en faciès de schistes verts par un cisaillement majeur D2 (+D3). La préservation de nappes de socle D1 au cœur du dôme d'Ambin suggère une dynamique d'exhumation précoce à vergence nord pour les unités HP–BT du domaine pennique. ***Pour citer cet article : J. Ganne et al., C. R. Geoscience 336 (2004).***

Keywords: HP metamorphism; exhumation; Penninic domain; Alps

Mots-clés : métamorphisme de HP ; exhumation ; domaine pennique ; Alpes

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Selon de nombreux auteurs [19,20,22], la genèse des éclogites et des schistes bleus est associée à des contextes géodynamiques de subduction et/ou d'obduction. Les contraintes correspondantes de pression et de température sont bien calibrées dans le cas de la chaîne alpine (pour une revue, voir [8,24]). Cependant, dans les Alpes occidentales internes, peu d'études tiennent compte des microstructures liées à la (aux) déformation(s) précoce(s) affectant les éclogites et les schistes bleus lors de leur exhumation au cours d'un événement globalement dénommé D_1 [1,5,15,21,23,26]. La cartographie structurale du massif d'Ambin a permis de proposer une reconstitution de la géométrie originelle de ces structures D_1. La caractérisation du régime de déformation et des assemblages métamorphiques associés à D1 permet une comparaison avec les prédictions des modèles géodynamiques alpins (pour une revue, voir, par exemple, [28]).

Le massif cristallin d'Ambin forme un dôme composé d'un socle poly-métamorphique anté-Permien [4,9]. Il appartient à la zone briançonnaise, interprétée par la plupart des auteurs comme issue de l'ancienne marge passive européenne [16], ou d'une microplaque allochtone [27]. Le socle est au centre d'une fenêtre (Fig. 1a) surmontée par des enveloppes métasédimentaires parautochtones à allochtones, d'origines variées : couvertures mésozoïques et cénozoïques briançonnaises, piémontaises sensu stricto et liguro-piémontaises. Le socle est constitué par deux groupes lithostratigraphiques superposés [13,18]. Le plus profond (groupe de la Claréa) est constitué par des micaschistes sombres, avec quelques lentilles de roches d'origine magmatique (roches vertes). Il est surmonté par le groupe d'Ambin, composé principalement de métasédiments très siliceux et de métaconglomérats. Le groupe d'Etache, attribué au Permo-Trias, puis les quartzites blancs du Scythien, les lambeaux de couvertures carbonatées briançonnaises ainsi que des unités océaniques de Schistes lustrés viennent surmonter les deux groupes du socle.

La cartographie des fabriques de cisaillement (Fig. 1b) nous a permis de mettre en évidence l'existence de deux phases principales de déformations ductiles alpines (D_1 et D_2), caractérisées, à toutes les échelles, par des foliations et des vergences bien spécifiques. La fin (?) de la deuxième phase alpine, que nous nommerons D_3, est caractérisée par des structures beaucoup plus froides (failles normales conjuguées), qui accompagnent la voussure tardive du massif. D_1 et D_2 caractérisent plus particulièrement certains groupes : (1) le cœur du massif, constitué exclusivement par le groupe de la Claréa, préserve une déformation alpine précoce D1, de vergence nord, associée au pic de métamorphisme et au début du chemin rétrograde [12]. D_1 s'exprime par une foliation métamorphique sub-horizontale (S1) pénétrative. Cette fabrique planaire transpose une foliation préalpine S_{-1} [12], soulignée par des bandes de quartz sub-verticales et intensément microplissées (Fig. 1c). S_1 correspond aux plans axiaux de plis P_1 isoclinaux de type B [25], d'axe moyen est–ouest, déformant la S_{-1}. La foliation S_1 est marquée par l'organisation planaire des minéraux de HP (grenats, phengites fortement substituées, chloritoïde, glaucophane, pyroxène jadéitique). Les plans S_1 portent une linéation minérale bien marquée à glaucophane–phengite ± chloritoïde, d'orientation moyenne NNW–SSE dans la partie nord du massif, et NNE–SSW dans la partie sud du massif (Fig. 1d). La déformation D_1 est non coaxiale dans les roches de la Claréa, ainsi que le montrent sur le terrain et en lame mince les critères qui suivent : (1) cristallisation de minéraux fibreux, comme le glaucophane et la phengite dans les bandes S_1/C_1, indiquant un cisaillement simple à vergence nord ; (2) boudinage dissymétrique de la foliation S_1 associée à ces cisaillements ; (3) cristallisation hélicitique de grenat alpin ; (4) croissance dissymétrique en ombres de pression autour de grenats ou de rouleaux de quartz contournés par S_1 ; (5) micas phengitiques d'aspect sigmoïde. La linéation minérale L_1 peut donc être considérée comme la projection, sur le plan S_1, de la direction de mouvement lors des cisaillements ductiles D_1.

À l'approche du contact entre groupe de la Claréa et groupe d'Ambin, la fabrique planaire S_1 est affectée par de larges ondulations, dues aux interférences avec la phase de cisaillement D_2. Cette déformation augmente progressivement, jusqu'à développer localement des plis isoclinaux P_2, d'échelle pluridécamétrique : les minéraux de HP–BT sont alors recoupés et/où transposés dans une foliation S_2 subhorizontale, surface composite où se développent les minéraux du faciès des Schistes bleus de bas degré et du faciès des Schistes verts (phengites moyennement substituées, albite, glaucophane, chloritoïde). Les dif-

férentes enveloppes constituant la partie supérieure du massif (groupe d'Ambin, couvertures briançonnaises) et son enveloppe de Schistes lustrés sont intensément affectées par la déformation cisaillante D_2, à vergence est, synmétamorphe depuis les conditions de cristallisation du glaucophane jusqu'au faciès des Schistes verts. Seule la partie supérieure du groupe de la Claréa est impliquée dans cette déformation cisaillante, les parties profondes du massif préservant leurs structures alpines précoces D_1. Elles représentent les parties résiduelles d'une nappe précoce D1, que nous proposons d'appeler *nappe de la Claréa*.

Au cœur du domaine pennique des Alpes nord-occidentales, la préservation d'une unité tectonique pouvant représenter une nappe précoce D_1, métamorphisée en faciès de HP–BT, fait figure d'exception. De telles traces de structuration précoces sont rares [1,7,14,17,21,26], et leur interprétation en termes de paléocontraintes alpines sont sujettes à controverse à l'échelle régionale (par exemple, [7,23]). L'étude structurale du cœur de la nappe de la Claréa a fourni deux conclusions importantes : (1) la direction de mouvement vers le nord enregistrée par les linéations minérales à glaucophane est compatible avec une direction de raccourcissement précoce nord–sud, conforme aux reconstitutions géodynamiques alpines [28] et aux observations dans les nappes précoces plus faiblement métamorphisées du domaine pennique [3, 6] ; (2) le caractère non coaxial de la déformation cisaillante D_1, associé à une fabrique subhorizontale S_1, nous incite à privilégier une dynamique d'extrusion plus horizontale [10] que verticale [2] comme moteur de l'exhumation précoce des unités HP–BT du massif d'Ambin. Cette conclusion a une valeur locale et ne peut être généralisée à l'ensemble des unités penniques qu'avec prudence.

1. Introduction

Blueschist and eclogite facies metamorphic assemblages are usually attributed to subduction and/or obduction processes [19,20,22]. The proposed models are consistent with thermobarometric constraints that are well calibrated in the alpine belt (e.g., [8,24] for a review). However, the structural and microstructural characteristics of the exhumation of the high-pressure rocks from the Internal Alps during a complex deformation event globally called D1, are still in discussion [1,5,15,21,23]. Early kinematics of the Penninic domain is poorly known, due to the intense post-D_1 transposition features [1,14,17,21,26].

The Ambin Massif occupies a key position among the metamorphic units of the Internal Western Alps (Briançonnais and Piedmont domains) and was chosen for tracking the early alpine kinematics. It corresponds to an almost perfect pre-Permian basement dome [4, 9] that preserves alpine HP–LT metamorphic assemblages. The initial geometry of the D_1 event, corresponding strain regime and associated metamorphic assemblages are reconstructed in the basement units. Such a reconstruction is used for comparison with the available alpine evolutionary models [28] and to discuss consequences on the knowledge of exhumation processes in the western Alps (e.g., [2,10] for a different interpretation). A recent paper [12] presents petrological evidence favouring an alpine age for the main fabric occurring in the core of the basement dome – D1 event of this study – and argues that garnets are not pre-alpine, as previously inferred [4].

2. Geological setting of the Ambin Massif

The Ambin Massif belongs to the Briançonnais Zone, which is interpreted by most authors as issued from the European passive margin [16] or from an allochthonous terrane [27]. It forms a dome-shaped basement window (Fig. 1a) cropping out beneath allochthonous metamorphic envelopes of various origins (Briançonnais Mesozoic units, ocean-derived Ligurian–Piedmont units). Structural discontinuities separate lithological groups previously defined by Michel [18] and Gay [13]. They are, from bottom to top:

(1) the Claréa and Ambin Groups forming the pre-Permian basement;
(2) the Permo-Triassic Etache Group, considered as Permo-Triassic in age and followed upward by metasediments of Triassic to Eocene age;
(3) the 'Schistes lustrés complex', consisting of Jurassic to Cretaceous allochtonous metasediments of the Liguria–Piedmont zone.

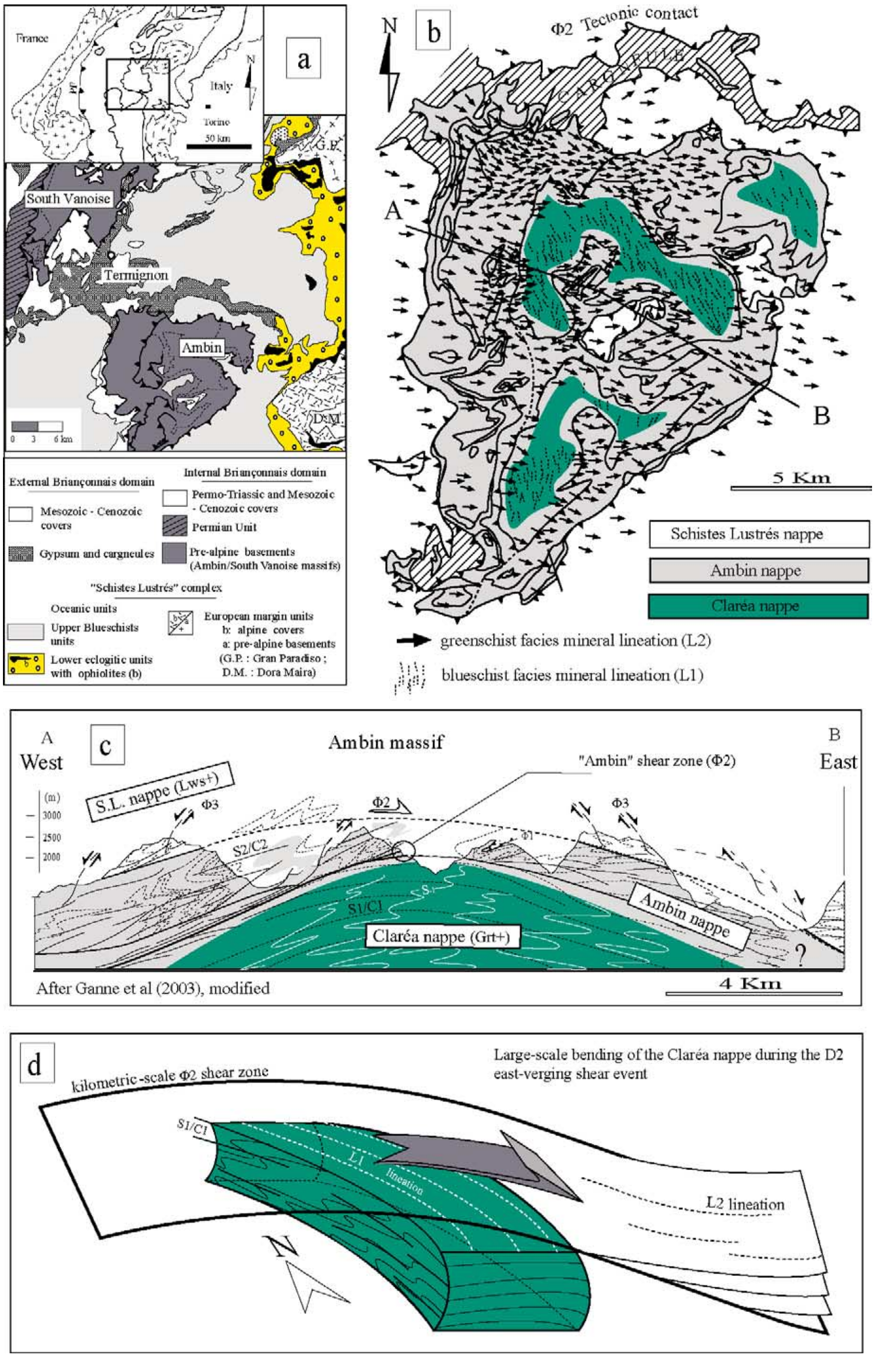

Fig. 1. (**a**) Geological and (**b**) structural map of the Ambin Massif. (**c**) East–west structural cross-section through the Ambin Massif (see Fig. 1b for location). (**d**) The difference in L_1 orientation between the north and south of the massif may indicate a large-scale bending of the Claréa nappe during the D_2 east-verging shear event.

Fig. 1. (**a**) Carte géologique et (**b**) structurale du massif d'Ambin. (**c**) Coupe structurale est–ouest à travers le massif d'Ambin (voir Fig. 1b pour la localisation). (**d**) Une torsion à grande longueur d'onde de la nappe de la Claréa au cours du cisaillement D_2 pourrait expliquer le changement d'orientation de la linéation L_1 entre le nord et le sud du massif.

3. Tectono-metamorphic evolution of the Ambin Massif

The metamorphic evolution of the Ambin Massif has already been addressed in previous articles [11, 12] and will be used as a reference to discuss the tectonic pattern of the massif. To simplify nomenclature and description in Fig. 1b, we have distinguished three main litho-tectonic units within the different envelopes of the Ambin Massif, which have been called ‘nappes’, as they are separated by major tectono-metamorphic discontinuities [12]. The three nappes are, from bottom to top (Fig. 1c):

(1) the Claréa nappe, consisting only of pre-Permian micaschists (Claréa Group);
(2) the Ambin nappe, consisting of slices of pre-Permian basement (Claréa + Ambin Groups), Permo-Triassic and Triassic to Eocene metasediments;
(3) the ‘Schistes Lustrés’ nappe, consisting only of oceanic metasediments from Liguria–Piedmont.

Finite strain analysis revealed the existence of three ductile to brittle–ductile deformation stages, characterised by specific types and/or vergence of structures. Structural and metamorphic data are presented in terms of ductile D_1, D_2 and brittle–ductile D_3 events. The most obvious structures recognisable in the Ambin and ‘Schistes lustrés’ nappes are those related to the D_2 ($+D_3$) retrogressive deformations. These ductile to brittle–ductile shear events overprint pre-existing fabrics such as S_1 (D_1 event, see below), which is the earliest alpine foliation linked to the HP metamorphic peak (M_1) and is clearly distinguishable from a locally preserved S_{-1} pre-Alpine fabrics. The D_1 event is the best preserved in the Claréa nappe, i.e. in the deeper part of the Ambin Massif. Conversely, the Claréa nappe shows little evidence for a D_2 deformation, except close to its upper contact.

3.1. D_1 deformation stage in the Claréa nappe

Most of the folds observed in the Claréa nappe (e.g., folds of mafic layers; Fig. 1c), predate the D_2 stage. They correspond to a strong ductile deformation, responsible for the main foliation. Usually, the main foliation is gently dipping and follows the overall dome pattern. That fabric overprints an earlier fabric now occurring in microlithons. According to previous authors [4,8, and references therein], both fabrics were attributed to pre-alpine events. Indeed, in the albite–biotite-bearing micaschists (about 70% of the Claréa nappe), muscovite and presumably pre-alpine large biotite grains are similarly present in both fabrics and the superimposed growth of blue amphibole (very scarce in the albite–biotite-bearing micaschists) was interpreted as static [4]. New observations [12] show that, in the Claréa micaschists, garnet grains [12] display a pre-alpine core and an alpine rim systematically wrapped by the main fabric of the micaschists, precluding a pre-alpine age for this fabric. At the microscope scale, the clear-cut boundary between the two garnet components is outlined by an inclusion-rim that consists mostly in a very dense concentration of tiny inclusions of quartz, biotite and pre-alpine muscovite. However, newly crystallised alpine minerals such as blue amphibole and phengite also occur in small quantity, associated with the older inherited minerals, suggesting that a strong shearing event of alpine age may have occurred under HP–LT conditions when the rims crystallised. This observation suggests that the gently dipping fabric recognised in most of the Claréa nappe is linked to an early alpine deformation now defined as D_1. The corresponding S_1 fabric is parallel to the axial plane of F_1 folds that deform presumably pre-alpine structures (S_{-1}).

S_1 is defined in the glaucophane-bearing micaschists (about 30% of the Claréa nappe) by HP minerals (Fe, Ca garnets, Si-rich phengite, chloritoid, glaucophane, jadeite, paragonite, clinozoisite). Late chloritoid and lower-Si substituted phengite are also associated with the S_1 fabric, indicating that decompression was initiated during the final stage of D_1 (exhumation process [11]). Glaucophane–phengite ± chloritoid define a mineral lineation on the S_1 foliation. The L_1 mineral orientation strikes at NNW–SSE in the north of the massif and NNE–SSW in the south (Fig. 1d). Field observations show that small-scale F_1 folds correspond to B-type folds (e.g., [25]) with near-east–west trending axes, but it was not possible to relate such micro- to mesoscopic D_1 structures to larger-scale ones. Many micro- to mesoscale structures observed in the glaucophane-bearing micaschists suggest a non-coaxial deformation during D_1. However, the coexistence of east–west-trending B-type folds and north–south mineral lineations indicates that the stretching was not very strong during D_1. Several microstructural evidences confirm the non-coaxial regime and suggest that the L_1 lineation corresponds to the projection, on the S_1 plane, of the movement direction during the D_1 shearing event. They are: asymmetric boudinage of S_1; asymmetric fabrics of phengite, chloritoid and glaucophane wrapped as pressure shadow or strain fringes around garnets; rotation of quartz and inherited plagioclase; sigmoid features developed in syn-kinematic garnet; trails of opaque minerals underlining S_1 and refolded during a continuous shearing event; folded inclusions within syn-kinematic glaucophane.

3.2. *Ductile D_2 stage in the Ambin and the 'Schistes lustrés' nappes*

The most obvious ductile structures – foliation and small-scale shear zones sealed by micas – are those related to D_2. The D_2 stage is characterised by well-developed shear planes and by the gently dipping S_2 foliation observed in most of the Ambin and 'Schistes lustrés' nappes. S_2 corresponds either to a foliation parallel to axial planes of F_2 folds and deforming an earlier S_1 or to a composite surface resulting from a tectonic transposition of S_1 and the lithological layering. In the latter case, S_1 is preserved as micro-folds within microlithons defined by S_2. In the upper part of the Ambin nappe, S_2 corresponds to the main tectonic surface and results from a large-scale reworking of older HP–LT structures. At all scales, ductile shear zones are sub-parallel to S_2 and dip similarly to the west in the western part of the Ambin Massif and to the east in the eastern part of it (Fig. 1c). At the outcrop scale, shear bands and S_2/C_2 fish-like structures indicate always a top-to-the-east movement direction (Fig. 1b). When they are concentrated across several tens of metres, they define major tectonic contacts (e.g., the 'Ambin' shear-zone, Fig. 1c) named Φ_2 to distinguish them from the older, refolded and sheared Φ_1. The overall parallelism between the shear zones and S_2, together with the development of fish structures – which may also exist at the kilometre scale – and with the similarity of associated mineral assemblages suggest that they both belong to a same retrograde metamorphic D_2 event [11]. The corresponding L_2 lineation is commonly characterised in the basement by a greenschist facies metamorphic assemblage involving phengite, actinolite and chlorite and is displayed on both S_2 and on the shear surfaces. L_2 lineation direction is very homogeneous at regional scale (N100–N120) (Fig. 1b) as it was previously quoted in neighbouring areas [1,7]. However, in some places, as in the footwall of the Ambin shear zone, blue-amphibole and chloritoid, associated with phengite and chlorite, have been evidenced in the S_2/C_2 fabric as elongated syn-kinematic mineral, indicating that D_2 shear zones were initiated in blueschist facies conditions.

3.3. *Ductile-to-brittle D_3 stage in the Ambin and 'Schistes lustrés' nappes*

Brittle-ductile shear planes (Φ_3) crosscut the D_2 fabrics at high-angle. An east–west-trending stretching lineation is observed on most Φ_3 planes, marked by stretched quartz and calcite grains, low-Si phengite and chlorite. Observed microstructures – conjugated extensional Φ_3 shear planes, symmetric micro-boudinage of pre-D_3 crystals of poeciloblastic albite, deformed vertical vein networks – point out to an overall coaxial behaviour. Along the western edge of the Ambin dome, extensional Φ_3 shear planes preferentially indicate a top-to-the-west movement direction, whilst east of the dome, the Φ_3 shear planes are preferentially top-to-the-east (Fig. 1c). This pattern indicates that the dome structure was probably formed during the D_3 stage. The dominant simple shear regime (D_2) characterised by top-to-the-east movement and responsible for the development of large-scale gently dipping shear zones may have changed progressively with time toward a pure shear regime (D_3), characterised by high-angle conjugated extensional shear planes [11].

4. Discussion and conclusion

The Ambin Massif shows a coherent tectonic pattern resulting both from D_2 deformation partitioning and differences in preservation of D_1 structure. From top to bottom of the tectonic pile, a clear structural layering was observed (Fig. 1c): (*i*) S_2 and D_2- to D_3-related shear bands are dominant in the 'Schistes lustrés' nappe surrounding the Claréa and Ambin nappes;

(*ii*) S_2 is superimposed on a well-preserved S_1 in the Ambin nappe and is dominant in the upper part of the Ambin nappe, leading to an almost complete transposition, together with Φ_2 shear zones; S_2 is less pervasive at the bottom of the Ambin nappe leading to an incomplete transposition of the D_1 fabric in-between the Φ_2 shear zones; (*iii*) the gently dipping foliation that occurs in the very core of the Ambin dome formed by the Claréa nappe is interpreted here as a penetrative alpine S_1 fabric with characteristic HP mineral assemblages. This early fabric, related to a D_1 horizontal nappe, grades upward to D_1–D_2 interference features [12]. The D_1 nappe-forming event corresponds in the Claréa nappe to a non-coaxial deformation regime with a dominant near-horizontal north–south shortening component, as suggested by the L_1 lineation. This direction is similar to that observed in the less metamorphosed external units of the north Penninic domain [3,6] and consistent with slip vectors deduced from geodynamic reconstruction [23].

There are still too few constraints, in the western Penninic domain, on the initial geometry and kinematic of the slices of continental and oceanic crust formed during the early alpine steps of exhumation, and that might be compared with our D_1 HP-nappes. In the more internal units of the western Penninic domain (e.g., Gran Paradiso), the corresponding D_1 kinematics (or equivalent according to authors) are highly hypothetical and previous interpretations are often contradictory [7,23], due to the post-D_1 intense transposition features [1,14,15,17,21,26]. Field observations of early HP–LT horizontal structures and related D1 nappe-forming event, at the scale of the Ambin Massif, suggest that they could represent a preserved large piece of the original structural pattern directly related to exhumation. Despite the lack of other critical examples to corroborate our assumption, we propose that the geometric and kinematic characteristics of the Claréa nappe, in the Ambin Massif, are actually representative of the early alpine steps of exhumation in the western transect of the Alpine belt. Our assumption strongly relies on the now well-constrained geometry and kinematics of other Penninic early nappes [3,6]. The non-coaxial and flat-lying HP-structures observed in the core of the Ambin Massif suggest that they were probably acquired during the ascent path, along a gently dipping slope. If correct, we may therefore speculate that the early steps of HP-rocks exhumation induced some kind of flat-lying nappes with an overall north- to northwest-directed movement, as classically advocated in previous models (e.g., [10]), rather than protracted extrusion of vertical (or fan-shaped) slices [2].

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