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# Reply on RC1

Amir Kalifi et al.

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Author comment on "Chronology of thrust propagation from an updated tectono-sedimentary framework of the Miocene molasse (western Alps)" by Amir Kalifi et al., Solid Earth Discuss., https://doi.org/10.5194/se-2021-46-AC1, 2021

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Dear editor.

Here follow our responses to the review by Thierry Dumont (RC1) of our manuscript submitted to Solid Earth.
Reviews are listed in black - italic while our answers are in black - bold text.

• Review of the manuscript "Chronology of thrust propagation from an updated tectono-sedimentary framework of the Miocene molasse (Western Alps)", Kalifi et al., submitted to Solid Earth, july 2021 Thierry Dumont, CNRS, ISTerre, Université Grenoble Alpes
Overview

*The topics of this manuscript is of major interest, since the Tertiary sedimentation allows to constrain the orogenic propagation in the Alpine foreland. The core of the manuscript consists of integration of new geochronological data (biostratigraphy, chemostratigraphy, magnetostratigraphy) with the existing database in a sequence statigraphic framework, along with a synthesis of available well-log and seismic profiles. Besides this, the authors provide a reappraised structural framework based on existing maps, subsurface information from key seismic profiles, and field overview of some key areas. This reappraisal also benefits from some previously published field sections or even unpublished elements from the geol- alp.com website. These sedimentary and structural synthesis are correlated to propose a dynamic tectono-sedimentary and paleogeographic framework of the forward propagation of Alpine orogeny since Oligocene times.*
*This work is clearly worth of publication, provided it takes into consideration the comments listed below. The most reliable and solid input is the chronostratigraphical synthesis, and the important information brought by field sections and wells/profiles analysis. I have more reservations about the structural synthesis, which lacks kinematic data about brittle deformation (thrusts, faults), folds analysis, ductile deformation (Bornes) and transport directions, which also lacks 3D maps analysis, and which attempts anyway to conclude about stress evolution and chronology of thrusting. Thus, some conclusions appear overinterpreted, such as the complete allochtony of the northern Subalpine massifs, or the attribution of an Oligocene age to the earliest identified thrust (the paper is furthermore devoted to Miocene). From geodynamic point of view, the demonstration and time-space quantification of the forward propagation of the Alpine front since early-middle Miocene is convincing, although the geodynamic and structural*

*inheritance and specificity of the Oligocene phase, along with older inherited structures (Hercynian trends), could have been better considered.*

**We are happy to see that reviewer #1 considers that our work clearly worth publication. It is clear that our main contribution are the chronologic constraints that we bring and we understand the concern about some of our structural conclusions, most of them not being the main focus of the paper. We answer in more details below to that concern.**

*General comments*
*Organisation of the manuscript is correct but the "Geological setting" and the "overall structure.." § partly overlap concerning the description of main thrusts, their description in §2 could be simplified as both are describing fig. 1B; lines 115 and following partly duplicate § 4.3 (i.e. "the southern prolongation of this fault is contentious" found line 120 and line 348).*

**The Geological setting (§2) is a brief summary of what is known on the structure of the area, while the § 4.3 goes deeper into the details. We slightly changed the text to keep the general picture for §2 and the details for § 4.3.**

*The structural descriptions of §4.3 are long and tedious, even the 4.3.6 "summary" trying to justify the options choosen in the cross-sections. Could be better organised and shortened.*

**§ 4.3 brings a lot of descriptions of local structures and comparisons with previous work in order to discuss the fault zones geometry. This may appear long and tedious. We have significantly rewritten that section, and hope that it is easier to follow.**

*Stratigraphy, sedimentology*
*This is of course the main input of the paper, thanks to field sections and synthesis of borehole data and seismic profiles. Synthetic sections provided in appendix are original and essential. The chronostatigraphic integration of different methods seems solid, and provides an essential framework to analyse the tectonosedimentary features.*
*Structures and deformation*
*Despite the structural study refers to "new field data", synthetic presentation of these new data is lacking (i.e. line 389 "210 stations.." without location map nor data synthesis). Kinematics and structural chronology are tentatively deduced from maps analysis (fold and thrust trends), which is not suitable for proper identification of stress directions and discrimination of deformation phases. There is confusion between finite deformation (folds, thrusts) and "shortening phase", suggesting that paleostress can be inferred from the present structural trends, which is abusive. Thrusts and folds are oblique (eastern thrust in Chartreuse is western in Bauges) and sometimes curved. Such variations could be explained by structural inheritance beneath the foreland, with the possible influence of basement inherited structures oblique to Alpine stress, however this would require a specific microtectonic analysis is to determine paleostress, which obviously is not the main aim of this paper. Nevertheless, such analysis will now be facilitated by the improved chronostratigraphic framework provided by it.*

**We have indeed conducted new field work and collected new structural data during the course of this study at more than 730 locations (Most of these data are bedding measurements used to constrain the 3D geometry and the cross-sections. This is clearly stated in chapter 3 "Material and methods" and the location of these stations are given in figure S1, and we have now added a table in the supplementary data (table S6). Such measurements have been used to calculate the fold axis of the Proveyzieux and Sassenage anticlines (Fig. 7). We**

**have not conducted precise paleostress analysis that would require another PhD, and are aware that our approach is approximate and thus give only broad estimates of the directions of compression.**

*Some more specific comments about FZ1:*
*The connection of thrust 1 both to the western Bauges and to the eastern Bauges implies that the Bauges and Bornes are regarded as an allochtonous nappe. This extreme opinion should be documented by structural observations in the Eastern Bauges massif, which are lacking. Although deformed, the Jurassic cover near Ugine is not detached but only affected by distributed shear. The autors use the data of Gidon's website (i.e. fig. B1C = "unpublished" http://www.geol-alp.com/h_mt_blanc/_schemas/coupe_Aravis_mtBlanc_4.gif) but Gidon himself does not consider that the sedimentary cover of the Bornes massif is detached, although it looks sheared and deformed. The authors should provide additionnal structural data from their own to support the detachment interpretation, or give a better consideration to ductile deformation.*

**We indeed present no new observations for the geometry of that fault zone on the NW flank of Belledonne. We rely on previously proposed observations and interpretation (i.e. Deville et al., 1994; Barfety and Gidon, 1996; Barféty and Barbier, 1983; Doudoux et al., 1982, 1999). We use this to suggest that the situation more precisely described in the South (Moucherotte) probably extends further north as already proposed by others (i.e.; Lacassin et al., 1990; Menard and Thouvenot, 1987). Such geodynamic evolution makes sense with respect to our sedimentological data, but we do not pretend that the debate is definitively closed.**

*Thrust 1 shows a strong lateral increase in amplitude from S to N. It seems that accomodation is increasing northwards during the deposition of sequences S2 and S3, maybe the correlation between both should be underlined.*

**We have not underlined this correlation because thrust 1 is probably not active during deposition of sequence S2 and S3.**

*The onset of activity of FZ1 ("phase 1) is proposed as early Oligocene (5.1.1, fig. 16). I do not understand the argument for this? 1) eastward thickening of the Oligocene sequence in profiles 10B may be a flexural response related to more internal structures than FZ1, 2) Oligocene series are transported in the hangingwall of FZ1 (Bauges), 3) in the southern termination of FZ1 around Grenoble, there is absolutely no evidence for Oligocene activity, the thrust is overlying Aquitanian/Burdigalian, 4) early Oligocene corresponds to the activation of the Penninic thrust, further deformed by FZ1. This opinion must be better discussed and justified, and the "P1" bar in dashed line for Oligocene.*

**We do agree that it remains some questions about the FZ1 activity and the duration of the first deformation phase (P1), and especially its timing of initiation. On fig.16 we therefore have dashed the FZ1 line for the pre 21 Ma history.**
**1) Yes, we do agree that it is another possibility, which is clearly mentioned in the paper (end of the paragraph 5.1.1).**
**2) and 4) In the Bauges area, it depends on which Oligocene we are speaking about. In the Rumilly syncline, the Oligocene is mostly represented by Upper Oligocene and also Lower Aquitanian deposits. To the east, in the Bauges massif, east of the Entreverne thrust (E, Fig. 1), these deposits are absent or very thin, while Lower Oligocene and Eocene deposits are dominant (these deposits occurred during the Penninic thrust activity). Between these two domains, there is the "Les deserts", "Leschaux" and "Les Aillons" syncline showing both**

**Eocene/Lower Oligocene deposits and Upper Oligocene/Aquitanian deposits (phD Kazo, 1975). We think that the FZ1 history was complex and most probably propagating during Upper Oligocene, from the Entreverne thrust to the frontal thrust called FZ1 in this paper but we agree that more detailed work is needed to constrain that history as now clearly expressed at the end of paragraph 5.1.1. Moreover, the first marine transgression never reached the domains east to the FZ1 suggesting that the FZ1 constituted a morpho-structural barrier at least since 21.0 Ma. In this scenario, the presence of Oligocene deposits in the hangingwall of the FZ1 is possible and not contradictory with the scenario proposed in this paper.**
**3) Around Grenoble, in the footwall of the FZ1, only few meters or tens of meters of Oligocene outcrops (Col de la Charmette). Above, these the Miocene is atributed to the sequence S1 (21-18 Ma) while upper Burdigalian sequences (S2, S3, 18-15 Ma) were not dated but probably present according the sequence stratigraphy interpretations (Fig. A2). The deformation of Lower Miocene units (21-18Ma) in the footwall of the FZ1 is compatible with an activity of FZ1 between 21Ma and 18Ma.**

*Other ZF:*
*The connexion from the Subalpine front to the Jura debatable:*
*The S-N continuity of thrust zones 2-3 remain a matter fo debate even with the help of seismic profiles (i.e. FZ2 discussion p. 22)*

**Indeed, the continuity of FZ2 is not so clear north of St Laurent Du Pont. We discuss that point in details and then use 2a in the south and 2b in the north. The continuity of FZ3 was in fact not discussed at all. We have added that sentence: "According to the published geological maps the Chailles anticline appears to connect in the north with the Tournier anticline (TO) (Fig. 1B), suggesting that the FZ3 could connect with the Jura internal thrust (fIJu) (Fig. 1B)." and a question mark on Fig. 1B and Fig. 16.**

*The offset of FZ4 is much greater to the S (Royans) and tends to lower in front of N Vercors and Chartreuse (fig.9), this makes its northern cotinuity towards Jura questionnable.*
*The extent of FZ5 to the N is not well constrained (line 522)*

**We do agree that the northern continuity of FZ5 is not well constrained and we have added question mark on the maps (Fig. 1 and Fig.16). The FZ4 continuity is better constrained, at least until the 91CHA1-91CHA2 profile to the North. However, we do agree that without outcrops and seismic profile, its continuity with the southern Jura transfer fault is difficult and questionable. We have added a question mark on the maps (Fig. 1 and Fig.16) north to the 91 CHA1-91CHA2 profile**

*Moreover, the connexion of FZ2-FZ3 towards Jura + the interpretative roots of FZ2-FZ3 beneath Belledonne would imply that the Jura thrusts are rooted beneath N Belledonne, that is 150km further SE.*

**We assume this hypothesis and the S-N continuity of thrust zones 2-3 because North to the Chartreuse massif, the triassic decollement level is much more efficient. Triassic evaporites thickness increase to the North (from north to south; ~500m in the HU2 well log; ~200m in the LTA1 well log; ~50m of sandstones and clays in the PA-1 well log)**

*More generally, the boundaries of the structural domains appear to be defined and chosen "à priori" by map synthesis (fig. 1B, §2), so that the final identification of thrust activity is* *partly a circular argument.*

**We are not sure to understand how the fact that the structural domains were defined from map synthesis would render the identification of the thrust activity a circular argument. As a matter of fact the sedimentologic domains have been defined independently from the fault zones which we think is a strong argument in favour of a structural control of the sedimentology.**

*Geodynamics*

*Oligocene is a very specific period from geodynamic point of view (west European rift system, Ligurian sea rifting) and the study area is located at the hinge between the Alpine orogen and the rift system. The inheritance of Oligocene structures and paleogeography could be better introduced. More specifically, I think that the "forebulge" interpretation put forward in section 5 and fig. 17 is, to me, somehow model- driven. The study area is large, and it would be worth to distinguish the flexural foreland situation in front of the Swiss molasse basin to the NE, from the Rhone valley rift to the SW. While a forbulge uplift seems reasonable in the former case (section A), the Royans Oligocene paleorelief is more probably related with the large-scale half-graben structure nicely illustrated in fig. 9D, whose Miocene reactivation of the eastern part localized FZ4-FZ5. I would not identify this structure as a forebulge.*

**We do agree that Oligocene has been a time of creation of normal faults from Alsace to the Rhône valley, with some of them within the alpine system. These may have created paleo-reliefs latter affected by the alpine compression. We do not think however that these normal faults have been systematically reactivated during the compression. Concerning the Bas-Dauphiné basin, a Seravalian depocenter (sequence 5 14-12 Ma) exist in the footwall of the FZ5 (Fig. 15C), and we suggest it is related to the activation of that fault zone. It is true however that such depocenter could have been created by another mechanism, for example a normal fault. However, this is unlikely as we have no other evidence of normal faulting at that time. We have changed the text as follow: "In the FZ5 footwall the presence of a sequences S5a-S5b depocenter (~14.0 to ~12.0 Ma) (Fig. 15C) suggests a continuous westward migration of the depocenters (Fig. 17), that could be controlled by the FZ5 activity at that time. This hypothesis is consistent with the general trend …", and we have removed the term "forebulge" from Figure 17.**

**Please also note the supplement to this reply for our answers about the more specific comments and corrections suggested : "se-2021-46-RC1-detailed-response"**

Please also note the supplement to this comment:
https://se.copernicus.org/preprints/se-2021-46/se-2021-46-AC1-supplement.pdf