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Geodynamics

How reliable are growth strata in interpreting short-term (10 s to 100 s ka) growth structures kinematics?

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Abstract

High-frequency stratigraphic cycles (10 s to 100 s ka) often show, at a specific location, an alternation of 'dynamic' (proximal-energetic), and 'non-dynamic' (distal-pelagic) processes with time. When sedimentation is syn-deformation, these processes tend respectively to fill-up tectonically-induced topography or to drape it. As a consequence, growth strata are alternatively thickened and isopach across the growth structure. High-resolution kinematic studies of growth structures (folds and faults), which assume that sedimentation always fills up topographies ('fill-to-the-top' model), may therefore mistake sedimentary cyclicity for tectonic cyclicity. We address this problem with one example of growth anticline in the Spanish Pyrenees, and we discuss the fill-to-the-top model. ***To cite this article: S. Castelltort et al., C. R. Geoscience 336 (2004).***

Résumé

Strates de croissance et cinématique à court-terme de la déformation (dizaines à centaines de milliers d'années). Les cycles stratigraphiques haute-fréquence (dizaines à centaines de milliers d'années) montrent souvent une alternance de processus dynamiques (proximaux–énergétiques) et nondynamiques (distaux–pélagiques). Lorsque la sédimentation est syndéformation, ces processus comblent ou drapent respectivement les topographies d'origine tectonique, les dépôts étant ainsi alternativement épaissis et isopaques au passage des structures de croissances. Les études à haute-résolution de la cinématique des plis et failles synsédimentaires faisant l'hypothèse d'une sédimentation comblant toujours les topographies (modèle *fill-to-the-top*) risquent de confondre cyclicité sédimentaire et cyclicité tectonique. Nous analysons ce problème sur l'exemple d'un pli synsédimentaire dans les Pyrénées espagnoles et discutons l'hypothèse du modèle *fill-to-the-top*. ***Pour citer cet article : S. Castelltort et al., C. R. Geoscience 336 (2004).***

Keywords: growth strata; growth structures; slip rates; episodic deformation

Mots-clés : strates de croissance ; tectonique synsédimentaire ; taux de déplacement ; déformation épisodique

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1. Introduction

Nous savons d’après l’observation des séismes que les failles ont des mouvements discontinus sur de courtes périodes (<10 ka). Cependant, leur comportement sur des périodes plus grandes (>10 ka) reste problématique. La déformation peut-elle être considérée comme continue ou discontinue sur des échelles de temps de l’ordre de la dizaine à plusieurs centaines de milliers d’années ? Des études néotectoniques récentes vont dans le sens de l’hypothèse continue (par exemple, [26,28]). Au contraire, à partir de l’analyse des strates de croissance sur des failles ou des plis synsédimentaires, de nombreux travaux invoquent une tectonique épisodique sur ces mêmes échelles de temps (par exemple, [1,3,15,16]). Cette cyclicité tectonique est basée sur l’alternance existant entre des dépôts épaissis et isopaques.

Dans ce travail, à partir de l’analyse des relations entre déformation et sédimentation sur un exemple de pli synsédimentaire (Pico del Aguila, Pyrénées espagnoles), nous discutons ces conclusions qui, selon nous, ne prennent pas en compte la nature variable de la sédimentation, en particulier à haute fréquence (dizaines à centaines de milliers d’années).

2. L’exemple de l’anticlinal du Pico del Aguila

L’anticlinal du Pico del Aguila, d’axe nord–sud, est situé à la limite entre les bassins de l’Ebre et de Jaca dans le Nord de l’Espagne (Fig. 1). Il affecte des séries d’âge Crétacé/Éocène inférieur sur un décollement situé dans les évaporites du Trias, et se développe de la fin du Lutétien au début du Priabonien, contemporain de la progradation d’est en ouest d’un appareil deltaïque [17]. Les dépôts synsédimentaires sont fortement épaissis dans le synclinal (1200 m) par rapport au sommet de l’anticlinal (300 m). L’architecture séquentielle est constituée de six cycles régressifs–transgressifs (cycles 1 à 6, Fig. 2), de durées comprises entre 90 et 850 ka [5], qui sont eux-mêmes composés de séquences à plus haute fréquence, de durée de l’ordre de 100 ka (paraséquences). Ces séquences correspondent à des phases d’avancée/recul du delta [5, 13] et sont parfois corrélées à l’échelle du bassin [13], ce qui leur confère une origine de longueur d’onde supérieure au pli (par exemple, eustatisme, tectonique, climat).

Les phases de progradation sont marquées par une sédimentation terrigène sableuse et sont toujours plus épaisses que les phases de rétrogradation, qui sont caractérisées par des dépôts plus marneux et carbonatés (Fig. 3). Dans l’ensemble, les paraséquences sont plus épaisses vers le synclinal que sur son sommet. Cependant, les phases de fin de progradation/agradation, plus sableuses (dépôts proximaux), sont plus épaissies, alors que les phases de début de progradation/rétrogradation, qui sont plus marneuses et carbonatées (dépôts distaux), ne montrent pas, ou que peu, d’épaississement.

Deux interprétations sont proposées : soit (1) la croissance du pli est épisodique et donne lieu à des épaississements, pendant les phases d’activité, et à des strates isopaques, pendant les phases de quiescence, soit (2) le pli étant contrôlé à la base par un décollement, il se comporte globalement de manière ductile, sa croissance est continue, et la configuration des strates de croissance est le résultat de la superposition d’une sédimentation variable sur un taux de croissance constant [4,5].

Pendant la progradation, la sédimentation est « dynamique », c’est-à-dire sableuse, et est préférentiellement piégée dans les creux topographiques (synclinaux) créés par la déformation. Pendant la rétrogradation, la sédimentation est « non dynamique », c’est-à-dire plus pélagique et carbonatée, et nappe la topographie sans épaississement vers les synclinaux.

3. Discussion–conclusion

Des travaux récents (par exemple, [1,3,15,16]) ont interprété le même type d’observations comme résultant d’une tectonique discontinue (Fig. 4A), en prenant pour hypothèse que la sédimentation remplit toujours la topographie créée par la tectonique, ou modèle *fill-to-the-top* [10].

Nous contestons ce modèle, car l’enregistrement stratigraphique est, par nature, constitué de cycles à toutes les échelles de temps et d’espace, liés à des facteurs tels que l’eustatisme, la tectonique ou le climat (par exemple, [11,22]). En particulier, les variations climatiques induisent des cycles stratigraphiques à haute fréquence (dizaines à centaines de milliers d'années), ou paraséquences. Ces cycles s'expriment fréquemment, au cours du temps, par une alternance entre des processus dynamiques (courants, vagues, marées), et non dynamiques (décantation).

Les études visant à déterminer la cinématique des structures de croissance doivent tenir compte du fait que les strates de croissance enregistrent la superposition d'au moins deux signaux : (1) la cyclicité sédimentaire inhérente à l'enregistrement stratigraphique, et (2) la subsidence différentielle locale due à la déformation.

En particulier, l'occurrence périodique de processus non dynamiques (pélagiques) peut conduire à la préservation d'escarpements topographiques d'origine tectonique [18,20,27,29].

De ce fait, les travaux utilisant les variations d'épaisseurs selon le modèle *fill-to-the-top* et concluant à un fonctionnement épisodique des failles, avec la même périodicité que les cycles stratigraphiques, peuvent aussi bien être considérés comme mettant en évidence un déplacement continu (Fig. 4B) sur ces échelles de temps (dizaines à centaines de milliers d'années). Cette interprétation est plus en accord avec les études néotectoniques récentes, qui mettent en évidence un taux de fonctionnement constant des failles crustales sur des périodes supérieures à 100 ka [26,28].

1. Introduction

It is a currently observable and historically documented fact through earthquakes that movements on faults are episodic on short time scales (<10 ka). However, less is known for time scales of more than 10 ka, i.e. beyond historical documentation. The key problem is: can deformation be considered as a continuous or a discontinuous process over time scales ranging from 10 s to 100 s of thousands years? Neotectonics studies, by surface dating of crustal strike-slip faults offsets, have recently evidenced constant slip rates over such periods (e.g., [26,28]), which would better support the continuous hypothesis. By contrast, in sedimentary basins, numerous works have argued for episodic development of intra-basin growth structures (faults and folds) with periods of 10 s to 100 s of thousands years (e.g., [1,3,15,16]). These are based on the observation of growth strata that are alternatively thickened and of equal thickness across structures.

In this paper, we propose that such a pattern can instead be interpreted as the result of a continuous growth (of fault or fold) superimposed on variable sedimentation. To do this, we first examine the relation between growth strata thickness variations and the nature of sedimentation in the case of a growth detachment-fold. Then, we discuss the 'fill-to-the-top' model, which consists in assuming that sedimentation always fills the topographies created by growth structures, and its application to fault and fold kinematics reconstruction.

2. The Pico del Aguila anticline example

The Pico del Aguila anticline is situated on the South-Pyrenean Frontal Thrust (SPFT), at the separation between the Jaca and the Ebro Basins in northern Spain (Fig. 1). It is a ∼5-km-wide anticline, which is one of a series of north–south trending folds called the *Sierras marginales*, which developed during Middle to Late Eocene times in response to the southward advance of the South-Central Pyrenean Unit (SCPU). The deformation affects a pretectonic sedimentary layer composed mainly of ∼800 m of Lutetian limestones that are detached over a 600- to 800-m ductile unit dominated by Triassic evaporites.

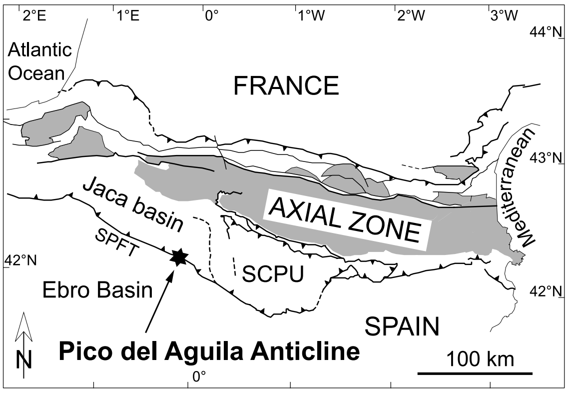

Fig. 1. Simplified structural map of the Pyrenees (modified from [8]) with location of the Pico del Aguila anticline (black star). SPFT: South-Pyrenean Frontal Thrust. SCPU: South-Central Pyrenean Unit. The grey colour delineates the Hercynian basement.

Fig. 1. Carte structurale simplifiée des Pyrénées (modifiée d'après [8]) montrant la localisation de l'anticlinal du Pico del Aguila (étoile noire). SPFT : chevauchement frontal sud-pyrénéen. SCPU : unité centrale sud-pyrénéenne. Le grisé délimite le socle hercynien.

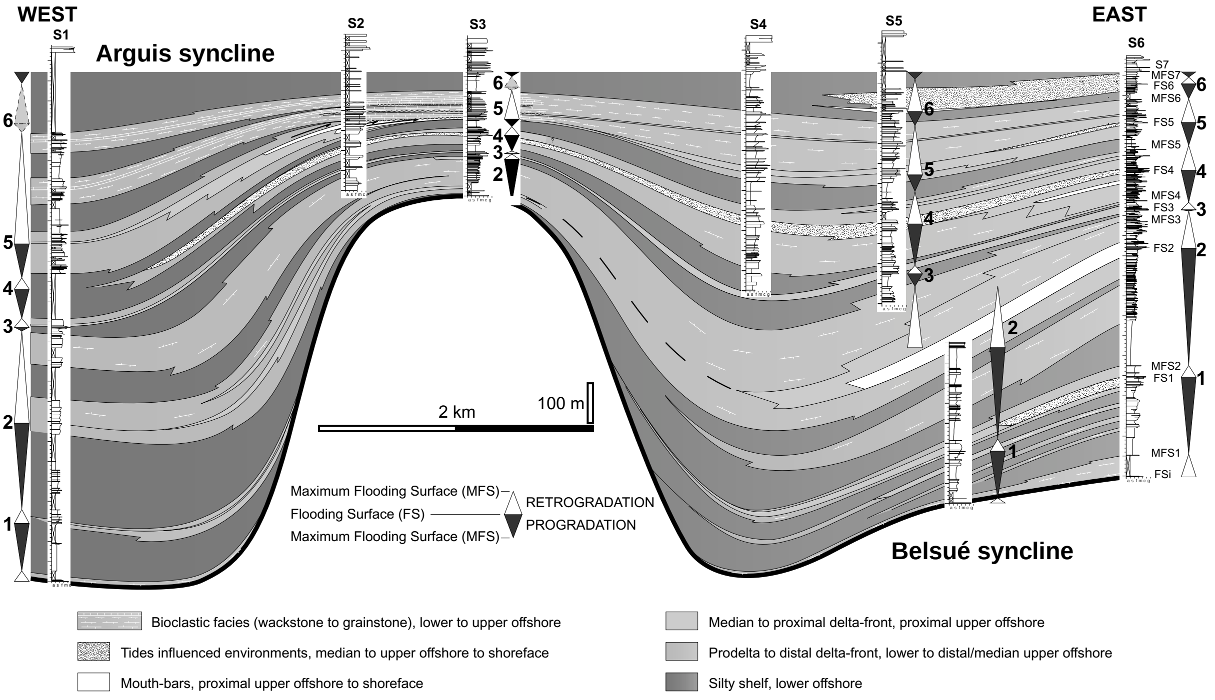

Fig. 2. East–west cross-section of the Pico del Aguila anticline showing large-scale sequence-stratigraphic framework (cycles 1 to 6) and facies (modified from [5]). The parasequences grossly represent the small-scale lithology variations on the sedimentologic vertical cross-sections.

Fig. 2. Coupe est–ouest de l'anticlinal du Pico del Aguila montrant l'architecture séquentielle générale (cycles 1 à 6) et les faciès (modifiée d'après [5]). Les paraséquences représentent grossièrement les variations de lithologie à petite échelle sur les coupes sédimentologiques verticales.

From Late Lutetian to Early Priabonian, the anticline developed in a subsiding basin that was coevally filled by a delta prograding from east to west. As a consequence, during its development the fold was progressively buried by sediments that now exhibit progressive unconformities on both sides of the anticline and thickness variations from ∼1200 m in the synclines to ∼300 m on the hinge (Fig. 2). The current attitude of the anticline that plunges ∼30° to the north and its intersection with the topography result today in a good exposure of the growth strata. This allows us to follow them physically across the fold from Arguis syncline to Belsue syncline (Fig. 2). Sedimentary facies are mainly terrigenous and reflect the westward progradation of the delta [17]. They range from prodelta marls to mouth-bar coarse sandstones, some of these showing evidences of tides and storms influences. In addition, carbonates are also present, probably because of the destruction and redistribution by storms of a carbonate platform situated southward and of nummulites patch reefs developing in protected (from siliciclastic input) areas, as also evidenced in the eastern part of the South-Pyrenean foreland during Bartonian times [14].

The sequence stratigraphic framework of these deposits is made of six fourth-order regressive–transgressive cycles (named minor cycles 1 to 6, Fig. 2) of duration ranging between 90 and 850 ka [4,5]. They are themselves composed of stacked high-frequency regressive–transgressive cycles (named parasequences hereafter), of durations on the order of 100 ka or less.

These cycles (minor cycles and parasequences) are defined between two Maximum Flooding Surfaces (MFS), and the boundary between progradation and retrogradation (flooding surface, FS) is marked by the shallowest facies in each cycle. The sedimentation is on the whole continuous, unless locally on the hinge of the anticline, where erosion sometimes takes place at both minor cycles (e.g., end-progradation of cycle 5) and parasequences scales.

2.1. Parasequences

As a whole, the expression of parasequences can be summarized as follows: progradation phases are markedly terrigenous and always thicker than retrogradation phases, which are more carbonated and marly. This results from the volumetric partitioning [7] of sediments in a marine deltaic setting: the detritic supply is mainly stocked in the marine realm (delta) during progradation, whereas it is trapped landward during retrogradation, which allows the expression of carbonates seaward. These parasequences therefore record high-frequency cycles of advance and retreat of the delta. As shown in [13] and [4,5], even if they cannot all be correlated across the fold, they can often be well followed across it and sometimes correlated at the basin scale.

The parasequences are therefore controlled by a phenomenon of broader extent than the structure, i.e. eustatic, basin-scale tectonics or sediment input variations.

In this paper, we focus on the general expression of the parasequences (Fig. 3) of cycle 5 (Fig. 2), situated between the hinge of the anticline and the western syncline, because they can be particularly well followed there, on the field as well as on aerial photographs.

As a whole, parasequences are thicker toward the syncline and condensed on the hinge of the anticline, because accommodation space increases toward synclines. More in detail, we observe that most of the thickness expansion takes place during end-progradation and aggradation periods, when deposits are proximal and more sandy in proportion. This is expressed by the time equivalence of proximal delta-front facies on the west flank with a by-pass/erosive surface on the hinge. By contrast, retrogradation and early progradation are far less affected by the growth of the fold, and are nearly of equal thickness on the hinge and in the syncline.

2.2. Interpretation

Two main interpretations are possible: (1) the fold growth could have been episodic (discontinuous) with periods of activity during end-progradation/aggradation periods explaining the thickening at this moment, and periods of quiescence during retrogradation/early-progradation periods, explaining the isopach layer at this moment; (2) alternatively, the fold growth could also have taken place as a continuous process, with this pattern of thickened and isopachs sedimentary layers being only the result of variable sedimentation superimposed on a constant rate of fold growth [4,5].

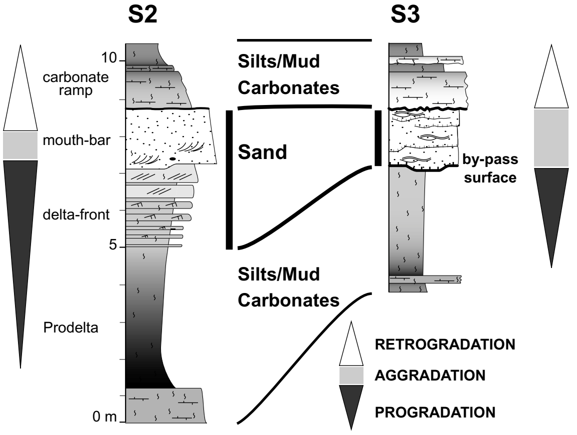

Fig. 3. Illustration showing the variable expression of a parasequence between the hinge of the anticline (S3) and the western flank (S2) during cycle 5. Sandy facies of end-progradation/aggradation phase are thickened toward the syncline, whereas marls and carbonates of early-progradation/retrogradation phase are nearly of equal thickness across the fold.

Fig. 3. Illustration mettant en évidence l'expression variable d'un exemple de paraséquence entre le sommet de l'anticlinal (S3) et son flanc ouest (S2), pendant le cycle 5. Les faciès les plus sableux de fin de progradation/aggradation s'épaississent vers le synclinal, alors que les faciès marneux et les carbonates gardent une épaisseur égale sur toute la structure.

The second interpretation is favoured here because the Pico del Aguila anticline is a detachment fold [17,23], i.e. developed over a ductile basal 'décollement'. This strongly suggests that the fold has grown continuously as long as no strain accumulation is possible in the ductile layer. The fold growth may therefore be entirely controlled by the 'décollement', and behave as a whole in a ductile manner. However, this only means that fold growth should be continuous rather than episodic. Indeed, Castelltort et al. [5] have shown that fold growth has taken place with a variable rate over timescales of several hundreds of thousands years.

With this hypothesis of a continuous growth, why are end-progradation/aggradation periods thickened toward the syncline, and retrogradation/early-progradation of more equal thickness across the fold?

During retrogradation and early progradation periods, the sedimentation is distal (marls) and dominated by particle settling (decantation), carbonates production and redistribution by storms. This induces almost equal sedimentary thicknesses on highs and lows. By contrast during end-progradation, sedimentation processes are more 'dynamic' (i.e. energetic), and are preferentially trapped in topographic lows [25]. Moreover, the lowering of base level imposes sedimentation to take place only in structural lows, i.e. toward synclines. Indeed, the hinge of the anticline, where by-pass or erosion surfaces are recorded, may be aerial or subaerial during progradation.

The important point that is put forward through this example is the first-order dichotomy between 'dynamic' (energetic) and 'non-dynamic' (decantation) sedimentary processes with regard to the syntectonic thicknesses. Non-dynamic sedimentary processes drape topography with a homogeneous thickness of sediments, while dynamic processes preferentially fill-up topographic lows before highs.

3. The 'fill-to-the-top' model: discussion

Recent works [1,3,15,16,19] have used similar observations to argue for the episodic development of growth faults and folds, with periods in the range of 10 s to 100 s ka. In those studies, it is assumed that thickened strata reflect tectonic activity, whereas strata with equal thickness across structures reflect tectonic quiescence. Actually, those studies make the strong assumption that sedimentation always fill-up the topography created by tectonic movement, or 'fill-to-the-top' assumption [9]. Moreover, certain authors, such as [1,3,15] note that the periodicity of fault activity is correlated with the cyclic stratigraphy. In particular, quiescence is in phase with retrogradation (fine-grained) periods and activity corresponds to progradation (more coarse-grained) periods. This leads them to invoke a coupling between fault activity and sediment loading in a gravity driven context, and even, for periods such as the Cainozoic, an astronomic control on fault activity [15]. However, we should point out that, because the fill-to-the-top model implies a constant filling of the topography created by the fault, the load should never diminishes and should therefore maintain fault activity, unless fault scarps are developed which is in contradiction with the model statement. By this way, using the fill-to-the-top model requires to consider implicitly that deformation is controlled by sedimentation. Also, we note that the loading/unloading mechanism, that is supposed to be responsible for the cyclic activity of growth faults, remains to be quantified.

As explained above, in the case studied herein, the same observations lead us to rather different conclusions, because the Pico del Aguila anticline is linked to a basal 'décollement' and due to compression [2,23,24]. This means that the fold is not associated to a gravity instability and is therefore not sensitive to small-scale cycles of sediment loading/unloading. Also, as long as parasequences are of broader origin than the fold, there is no reason that fold activity should occur during progradation periods, and fold quiescence during retrogradation. Moreover, similar growth strata patterns have been documented in other compressive [10] and extensive [12,21] settings, without being interpreted as alternative phases of tectonic activity and quiescence. As a consequence, for growth folds as for growth faults, the alternation between thickness expansion and continuity across structures does not need being related to a cyclic tectonic activity. It should rather simply be related to cyclically varying sedimentary processes superimposed on a continuous structure growth. Indeed, the fill-to-the-top model implies that sedimentary processes are uniform throughout the deformation (Fig. 4A), i.e. on-time scales of more than 10 s ka. However, it has been known for a long time that, due to numerous factors, such as eustasy, tectonics, or climate, the stratigraphic record is, by nature, made of cycles at all time and space scales (e.g., [11,22]). In particular, climate acts on eustasy and sediment supply to produce stratigraphic cycles with periods on the order of 10 s to 100 s ka (parasequences). At a given location in a basin, this is expressed by a variation with time of the type of sedimentation and sedimentary processes. In marine deltaic parasequences, for example, the volumetric partitioning of sediments induces, schematically, an alternation of large input of coarse materials supplied dynamically (currents, waves, tides) during progradation, and smaller input of finer particles mainly deposited at low energy (settling) during retrogradation [7]. Generally speaking, in all depositional settings, the sedimentation is characterized by such alternations between energetic/dynamic and calm/non-

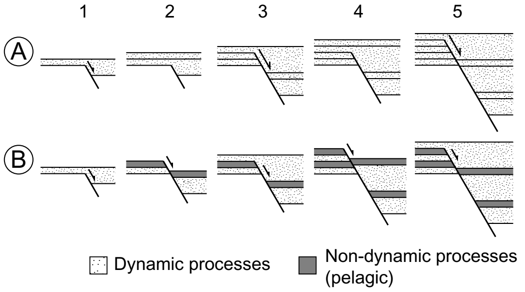

Fig. 4. Sketch illustrating the two opposed end-members hypotheses discussed in this work: both lead to the same final growth strata pattern. (**A**) Discontinuous deformation and ‘fill-to-the-top’ sedimentation. Fault growth occurs only during intervals 0–1, 2–3, and 4–5. Sedimentation always fill-up topography. (**B**) Continuous deformation and variable sedimentation. The fault is always active, but topography is alternatively filled-up and draped by dynamic and non-dynamic processes respectively.

Fig. 4. Schéma illustrant l’opposition entre les deux hypothèses discutées dans cette étude : elles aboutissent toutes les deux à la même configuration finale. (**A**) déformation discontinue et sédimentation *fill-to-the-top*. La croissance de la faille n’a lieu que pendant les intervalles 0–1, 2–3, et 4–5. La sédimentation comble toujours la topographie. (**B**) Déformation continue et sédimentation variable. La faille est toujours active, mais la topographie est alternativement comblée et drapée par des processus respectivement dynamiques et non dynamiques.

dynamic periods. These different processes react differently to differential subsidence due to growth faulting or folding. Non-dynamic (pelagic) sedimentation can be distributed homogeneously across structures [3,15], without being diffused to topographic lows on time scales of 10 s to 100 s ka [18,29]. This leads to the creation of fault- or fold-induced topography (e.g., [20,27]) when structures are active during non-dynamic sedimentation (Fig. 4B). Along with deformation, sedimentation is likely to be made of processes that alternatively fill-up and drape topography with periods of 10 s to 100 s ka. This is why the ‘fill-to-the-top’ assumption may not be valid for most natural cases, and in particular during periods of strong climatic variations.

Kinematic analyses based on this assumption are therefore likely to mistake sedimentation cycles for tectonic activity cycles.

The same conclusions are also applicable for studies based on seismic profiles, because boundaries between sedimentary units depicted from seismics are likely to represent changes in lithologies and sedimentary processes. This also induces a potential bias in relating syntectonic strata thickness variations to growth-structure kinematics from seismic data.

Eventually, it can be pointed out that using sedimentary cycles to infer tectonic cyclicity and conclude about a causal relationship between sedimentation and tectonics should be made with caution to avoid any circular reasoning.

4. Conclusion

In studies attempting to infer the kinematics of intra-basin faults and folds, one should be aware that growth strata always record the superimposition of at least two signals: (1) the sedimentary cyclicity inherent to the stratigraphic record and (2) the local differential subsidence due to growth faulting or folding.

In particular, the periodic occurrence of non-dynamic (pelagic) processes can lead to fault- or fold-induced topographies. This underscores the need for quantification of synsedimentary topographies and the search for accurate paleobathymetric indicators, and potential sedimentary processes disturbances.

At the moment, works that have used growth strata with simple ‘fill-to-the-top’ assumptions and concluded about the episodic development of faults and folds with the same periodicities as for stratigraphic cycles could as well be taken as evidences of constant slip rates on time scales of 10 s to 100 s ka. This would be more in line with recent neotectonics studies using cosmogenic radionuclides, which have evidenced constant slip rates on crustal faults over periods of up to 110 ka [26,28].

Our reasoning also raises questions regarding growth-strata thickness variations and ‘episodicity’ of tectonics at greater times scales of 10^6-10^7 a (e.g., [6]), as long as stratigraphic cycles also naturally exist at those time scales.

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