Pressure solution inhibition in a limestone–chert composite multilayer: Implications for the seismic cycle and fluid flow

Lorenzo Petracchini a,⁎, Marco Antonellini a, Andrea Billi b,⁎, Davide Scrocca b, Fabio Trippetta c, Silvio Mollo d

a Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Bologna University, Italy
b Istituto di Geologia Ambientale e Geoingegneria, CNR, Rome, Italy
c Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
d Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Bologna University, Italy

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A B S T R A C T

Pressure solution seams (PSSs) are frequent features in carbonate rocks undergoing tectonic shortening. In particular, pervasive, anticline-axis-parallel, bed-normal PSSs are known to develop during layer-parallel-shortening of (marly) carbonate rocks in fold-thrust belts. These pressure solution features can impact subsequent fracture development, fluid circulation, and strain localization including the seismic cycle. It is here demonstrated that the occurrence of frequent and continuous chert layers may strengthen a limestone sequence and inhibit pressure solution under layer-parallel-shortening. Field observations and laboratory determinations are reported from marly limestone with continuous chert layers of the Scaglia Fm. (Cingoli anticline, northern Apennines, Italy) exhumed from a depth of c. 1 km. In these outcrops, bed-normal solution seams do not occur or they occur only where infrequent chert layers have been shortened by small thrusts. In analogy with laminae-reinforced composite materials, a model is developed explaining the field observations with the strengthening effect of chert in the chert–limestone composite multilayer. During layer-parallel-shortening, the composite multilayer deforms under equal strain boundary conditions. In this situation, the tectonic load is mostly supported by the stiff and frequent chert layers and the strain of the whole chert–limestone composite remains in the elastic field, so that pressure solution seam development is prevented in the limestone beds. Our model may be applied down to a depth of a few kilometers in the upper crust that is relevant for the seismic cycle and fluid flow.

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1. Introduction

The Cretaceous–Eocene marly limestone of the Scaglia Fm. in the northern Apennines (Italy) has been the topic of a number of studies concerned with the understanding of pressure solution mechanisms operating during syn-orogenic contraction (Alvarez et al., 1976, 1978; Engelder and Marshall, 1985; Marshall et al., 1982; Meike and Wenk, 1988; Tavani et al., 2008). In several documented instances, the Neogene Apennine orogenesis caused the formation of pervasive pressure solution seams (PSSs) in carbonate rocks as for the case of anticline-axis-parallel, bed-normal seams developed during the initial layer-parallel-shortening. These early structures may have influenced the subsequent formation of syn-folding brittle deformation (Graham Wall et al., 2003; Storti and Salvini, 2001; Tavani et al., 2008, 2015), the subsurface flow of several geo-fluids (Heap et al., 2014), and ultimately the seismic cycle (Gratier and Gamond, 1990; Gratier et al., 1999, 2013b, 2014; Tesei et al., 2013) by controlling seismic or aseismic fault slip (Fagereng et al., 2010; Petracchini et al., 2012; Viti et al., 2014).

Understanding the development of PSSs is therefore relevant for many theoretical and practical geological applications (e.g., Aharonov and Katsman, 2009; Billi, 2003; Billi and Salvini, 2000; Gratier et al., 2013a; Koehn et al., 2012; Viti et al., 2014; Yasuhara et al., 2005).

One particular exception to the documented rule of pervasive bed-normal PSSs formed within the Scaglia Fm. of northern Apennines (e.g., Alvarez et al., 1976, 1978) is represented by some exposures from the Miocene–Pliocene Cingoli anticline located in the frontal part of the fold-thrust belt (Mazzoli et al., 2002; Fig. 1). In this anticline, the Scaglia Fm. and the entire Meso-Cenozoic pelagic carbonate sequence are heavily affected by anticline-axis-parallel, bed-normal PSSs (Fig. 2; Petracchini et al., 2012) except where chert occurs as continuous and frequent layers interposed between the carbonate beds. This evidence has never been documented and explained in the Apennines or elsewhere, although instances of pressure solution inhibition are known, as an example, in sandstones (Sathar et al., 2012).

The main aim of this paper is to address the following key questions concerning pressure solution mechanisms: why are anticline-axis-parallel, bed-normal PSSs absent where continuous and frequent layers of chert alternate with carbonate beds? May this absence be the effect of...
the carbonate sequence being strengthened under layer-parallel-compression by the chert layers?

We use field observations from the Cingoli anticline, laboratory analyses, and mechanical modeling to answer these questions. We then briefly and qualitatively discuss the related relevance for the process of fracturing, fluid flow, and earthquake nucleation across sedimentary carbonate strata.

2. Field observations

We analyzed the deformation of the Scaglia Fm. on a set of outcrops distributed in different structural domains of the Cingoli anticline (Fig. 1 and Table 1). This anticline is part of the external (eastern) front of the northern Apennines fold-thrust belt, which developed an eastward piggy-back thrusting sequence during Miocene–Pliocene time (Bally et al., 1986; Calamita and Deiana, 1986; Mazzoli et al., 2002). The first phase of growth of the Cingoli anticline occurred during late Messinian time and was followed by a later thrusting phase during early Pliocene time. The anticline shows gently dipping limbs and a NW–SE-trending flat hinge region curving to N–S toward the south (Fig. 1).

The studied outcrops are usually characterized by multiple sets of structures including PSSs and faults, which are variably oriented. In a previous work on the Scaglia Fm. from the Cingoli anticline, seven main sets of PSSs partly evolving into later small-displacement faults were observed (Petracchini et al., 2012). These PSSs nucleated in part during the layer-parallel-shortening phase and in part during the later folding phases, which also led to fault development. This deformation progression is schematically shown in Fig. 2 together with an example of Scaglia Fm. outcrop affected by multiple sets of PSSs and late faults. All these syn-tectonic sets of PSSs and faults were anticipated by the widespread formation of bed-parallel compaction stylolitic seams developed during syn-sedimentary burial of the Scaglia Fm.
(pre-orogenic times). These seams are present in all the limestone beds of the Scaglia Fm. including settings A to C, which are described below (Figs. 3 to 5).

The main focus of this paper is on bed-normal PSSs parallel to the Cingoli anticline axis and conceivably related to the layer-parallel-shortening process during the very early stage of folding (e.g., Marshak...
In particular, we integrated the observations of Petracchini et al. (2012) on bed-normal PSSs by studying in detail also some outcrops where these latter structures are absent or poorly developed. For more information on other structures (Fig. 2) not described here, we refer the reader to Petracchini et al. (2012). As the Cingoli anticline has not been overthrust by tectonic sheets, the following main structural settings (A, B, and C; Table 1) are also indicated.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Northing</th>
<th>Easting</th>
<th>Structural position</th>
<th>Mechanical stratigraphy</th>
<th>Setting type</th>
<th>PSSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcrop 1</td>
<td>43° 22’ 51”</td>
<td>13° 09’ 17”</td>
<td>Anticline backlimb</td>
<td>Limestone (no chert)</td>
<td>A</td>
<td>Present</td>
</tr>
<tr>
<td>Outcrop 2</td>
<td>43° 22’ 54”</td>
<td>13° 09’ 23”</td>
<td>Anticline backlimb</td>
<td>Limestone and faulted chert</td>
<td>C</td>
<td>Present</td>
</tr>
<tr>
<td>Outcrop 3</td>
<td>43° 23’ 06”</td>
<td>13° 09’ 40”</td>
<td>Anticline hinge</td>
<td>Limestone and faulted chert</td>
<td>C</td>
<td>Present</td>
</tr>
<tr>
<td>Outcrop 4</td>
<td>43° 23’ 46”</td>
<td>13° 10’ 39”</td>
<td>Anticline forelimb</td>
<td>Limestone (no chert)</td>
<td>A</td>
<td>Present</td>
</tr>
<tr>
<td>Outcrop 5</td>
<td>43° 21’ 51”</td>
<td>13° 10’ 14”</td>
<td>Anticline backlimb</td>
<td>Limestone (no chert)</td>
<td>A</td>
<td>Present</td>
</tr>
<tr>
<td>Outcrop 6</td>
<td>43° 21’ 55”</td>
<td>13° 10’ 30”</td>
<td>Anticline backlimb</td>
<td>Limestone and chert</td>
<td>B</td>
<td>Absent</td>
</tr>
<tr>
<td>Outcrop 7</td>
<td>43° 22′ 28”</td>
<td>13° 11′ 39”</td>
<td>Anticline hinge</td>
<td>Limestone (no chert)</td>
<td>A</td>
<td>Present</td>
</tr>
<tr>
<td>Outcrop 8</td>
<td>43° 22′ 32”</td>
<td>13° 12′ 11”</td>
<td>Anticline forelimb</td>
<td>Limestone (no chert)</td>
<td>A and B</td>
<td>Present where limestone and chert</td>
</tr>
<tr>
<td>Outcrop 9</td>
<td>43° 19′ 20”</td>
<td>13° 12′ 46”</td>
<td>Anticline backlimb</td>
<td>Limestone and chert</td>
<td>B</td>
<td>Absent</td>
</tr>
<tr>
<td>Outcrop 10</td>
<td>43° 19′ 59”</td>
<td>13° 14′ 07”</td>
<td>Anticline forelimb</td>
<td>Limestone and chert</td>
<td>B</td>
<td>Absent</td>
</tr>
</tbody>
</table>

Fig. 3. Setting-A: limestone without chert. (left) Photograph of a pelagic limestone with marly layers and no chert (Scaglia Fm., outcrop 5 in Table 1). The enlargement shows bed-normal PSSs about parallel to the anticline axis (see the Schmidt net). (right) Microphotograph of a bed-normal PSS with dissolution features.
(Fig. 4), the chert of setting-C is highly fractured. The limestone is characterized by some bed-normal strata-bound PSSs striking parallel to the Cingoli anticline axis (NW–SE) and characterized by stylolite peaks oriented perpendicularly to the PSSs. Similarly to setting-A, also in this setting there is evidence of slip (striae) along bedding surfaces with slip orientation perpendicular (NE–SW) to the anticline axis.

3. Mechanical model

3.1. Workflow

With the following mechanical model, we aim at testing whether the lack of bed-normal PSSs in the outcrops where the limestone beds are alternated with frequent chert layers (see setting-B in Fig. 4) is due to the strengthening effect of chert. The model is based on an analogy with the mechanics of composite materials (or composites or composite multilayers). Our workflow is as follows: (i) we address the mechanical theory of composites under equal strain conditions (layer-parallel-shortening); (ii) we address the issue concerning the determination of Young's moduli for the studied materials (chert and limestone of the Scaglia Fm.), as we then use these moduli in the model development; (iii) we address the issue concerning the strain threshold for PSS development in limestone starting from the known differential stress threshold for bed-parallel stylolite development; (iv) using the measured Young's moduli, we develop the model by applying the theory of composites under equal strain conditions to the case of the chert–limestone multilayer under layer-parallel-shortening in a way to test our hypothesis; (v) we explore the case of burial loading (equal stress boundary conditions) to understand why the occurrence of chert layers do not inhibit the formation of bed-parallel compaction stylolites, which are frequent in the studied limestone beds also where they alternate with frequent chert layers; and (vi) eventually, we conceptually synthesize our model and observations.

Fig. 4. Setting-B: limestone with unfaulted chert. (left) Photograph of a pelagic limestone with continuous and frequent chert layers (Scaglia Fm., outcrop 7 in Table 1). The close-up photograph shows an enlargement of unfaulted chert layers whereas the Schmidt net shows the bedding attitude. (right) The microphotograph shows a sedimentary microtexture very similar to that shown in Fig. 3 (setting-A), but with no PSSs and other dissolution evidence. No PSSs normal to bedding occur in this outcrop.

Fig. 5. Setting-C: limestone with infrequent chert layers shortened by small thrusts. (left) Photograph of a pelagic limestone with small thrusts across chert layers (Scaglia Fm., outcrop 2 in Table 1). The close-up photograph shows the stylolitic surface of a bed-normal PSS. The Schmidt net shows poles to PSSs normal to bedding observed in the outcrop. (right) This enlarged photograph shows a small thrust across a highly deformed and fragmented chert layer.
3.2. Mechanical theory of composites under equal strain conditions

Composites consist of stiff components (e.g., particles, fibers, or laminae) embedded into a weaker matrix. Applying a laminae-parallel compression, the stress is unequally partitioned between the two components, with the stiff material strengthening the entire composite (Cox, 1952; Hosford, 2005; Roylance, 1996; for geological composite materials see Fagereng, 2013; Ji and Zhao, 1994). Under layer-parallel-compression, the strain of both components (matrix and laminae) is equal (i.e., equal strain boundary condition) and, assuming elastic deformation parallel to layering, the mechanical behavior of the composite is expressed as:

$$E_c = E_\alpha V_\alpha + E_\beta V_\beta,$$

where $E_c$ is the Young’s modulus of the composite, $E_\alpha$ and $E_\beta$ are the Young’s moduli of the laminae and matrix, respectively, and $V_\alpha$ and $V_\beta$ are the laminae and matrix volume percentages, respectively. Eq. (1) is also known as the “rule of mixtures” and shows that stiff laminae in a composite under equal strain condition can strengthen the composite material (Fig. 7). In other words, the larger the volumetric percentage of stiff laminae in the composite, the higher the composite Young’s modulus (strengthening effect; Eq. (1); Hosford, 2005).

3.3. Young’s moduli determination

To develop a stress–strain model (Fig. 8) for our case study (Figs. 3–5), we sampled limestone and chert (Scaglia Fm.) from the Cingoli anticline and measured their static Young’s moduli using the BRAVA rock deformation apparatus (Collettini et al., 2014). We performed uniaxial deformation tests under room thermo-baric and humidity conditions at the HP-HT Laboratory of Experimental Volcanology and Geophysics of Istituto Nazionale di Geofisica e Vulcanologia (Rome, Italy) obtaining Young’s moduli of 17 GPa for the Scaglia limestone and 32 GPa for the chert (Fig. S1 and Tables S1 and S2. The chert Young’s modulus measured in this work (i.e., 32 GPa) is significantly lower than previous measurements on similar rocks and materials reported in the literature (Tables S1 and S2). As the tested samples come from a strongly-deformed area (Apennines fold-thrust belt; Fig. 1), they may contain flaws and micro-fractures (e.g., Figs. 4 and 5; Trippetta et al., 2013) influencing the Young’s modulus laboratory measurements. For this
the assumption of a Poisson’s ratio of 0.25, this difference is equal to 2/3 stresses (e.g., Gratier et al., 2013a).

Following Jaeger et al. (2007) and on (i.e., the non-hydrostatic tectonic stress) at the onset of PSS formation considering uniaxial strain in syn-sedimentary burial conditions and try; Gratier et al., 2013a), based on the aforementioned studies, we

Fig. 8. Stress–strain diagram showing the effect of stiff layers (i.e. chert) on the mechanical behavior of the limestone–chert composite (green lines) compared to the behavior of a limestone with no chert layers (blue line) under equal strain boundary conditions (i.e., layer-parallel-shortening). Different green lines are for different Young’s moduli of chert–limestone composite ($E_{\text{composite min.}}$, $E_{\text{composite mean}}$, and $E_{\text{composite max.}}$), derived from the minimum, mean, and maximum Young’s moduli of chert in Table S1(a). The Young’s modulus used for the limestone (blue line) is 22.5 GPa (Table S2). In the limestone–chert composite, PSSs would develop at a differential stress larger than the one required to develop PSSs in limestones with no chert. The stylolite nucleation threshold of limestone is derived from the literature (see text; Ebner et al., 2009; Tada and Siever, 1989).

reason and to account for the variability in Young’s modulus reported in the literature for chert, we used the minimum, mean, and maximum values (32, 70, and 100 GPa, respectively) obtained from our test and from previous literature data (Fig. 8 and Table S1a). In a similar way, for the limestone, we used a Young’s modulus of 22.5 GPa, which is the mean value obtained from our test and from previous literature data (Table S2).

3.4. Strain threshold for PSS initiation

To develop our model, it is necessary to know or assume the stress–strain threshold for PSS nucleation (i.e., elastic–ductile transition in Fig. 8). From previous literature, it is known that bed-parallel compaction stylolites in limestones under syn-sedimentary burial conditions start forming at about 90 m depth (Ebner et al., 2009; Tada and Siever, 1989; see also experiments by Croizé et al., 2010, 2013; Zhang and Spiers, 2005). Although this depth can vary depending upon several conditions (e.g., grain size, temperature, clay content, and fluid chemistry; Gratier et al., 2013a), based on the aforementioned studies, we consider 90 m as a reliable depth for stylolite initiation in limestone. Considering uniaxial strain in syn-sedimentary burial conditions and homogeneous isotropic rocks, we can derive the differential stress (i.e., the non-hydrostatic tectonic stress) at the onset of PSS formation from the difference between the vertical (lithostatic) and the horizontal stresses (e.g., Gratier et al., 2013a). Following Jaeger et al. (2007) and on the assumption of a Poisson’s ratio of 0.25, this difference is equal to 2/3 $\rho g h$, where $\rho$ is the rock density (2700 kg/m$^3$ for carbonate rocks), $g$ is the gravitational acceleration (9.8 m/s$^2$), and $h$ is the depth (90 m in this case). The so calculated differential stress is c. 1.5 MPa. A 1.5 MPa differential stress corresponds, in the case of the studied limestone (i.e., average limestone Young’s modulus 22.5 GPa; Table S2), to a strain of $6.7 \times 10^{-5}$ (Fig. 8). We assume, therefore, this latter strain as being the required value for PSS initiation in the limestone (shaded field in Fig. 8). It is worth noting that this is the minimum estimate of strain threshold that is the worst case scenario for our model. A stylolite nucleation depth greater than 90 m would be, in fact, more favorable to support our model (Fig. 8), as the stress difference at the PSS nucleation between the blue and green lines (pure limestone and chert–limestone composite, respectively) would increase (see below for further explanations).

3.5. Application of composite theory to this case study

We developed a mechanical model where a laminae-reinforced composite experiences an external load parallel to the laminae direction (Fig. 7a). This case is analogous to the limestone–chert sedimentary sequence undergoing layer-parallel-shortening (setting-B, Fig. 4), where the continuous and frequent chert layers are the laminae where-as the carbonate strata form the embedding matrix (Fig. 7). Our model is summarized in a stress–strain diagram (Fig. 8) derived by calculating the composite elastic strain for increasing values of laminae-parallel differential stress (green lines in Fig. 8) and by considering a composite with 15% chert and 85% limestone. This volumetric composition is the observed average one for the studied outcrops (Fig. 4).

The composite stress–strain relationships (green lines in Fig. 8) are compared with the one for a pure limestone (blue line in Fig. 8), showing that, at the strain threshold for stylolite initiation (red vertical line in Fig. 8), the differential stress required to generate PSSs is larger in the composite (green dots in Fig. 8) than in the pure limestone (blue dot in Fig. 8). We propose that the analogy with the mechanics of laminae-reinforced composite materials (Figs. 7 and 8) can explain the observed absence of normal to bedding PSSs (Fig. 4) during layer-parallel-shortening (equal strain boundary conditions; Figs. 8 and 9). The tectonic load is mostly taken by the stiff chert, so that the total strain of the composite remains in the elastic field and no PSSs form in the limestone beds (Figs. 7–9). Where the chert is scarce (<3%), the strength of the composite decreases and fails, accommodating the deformation by localization of small thrusts across the chert layers and by development of some PSSs normal to the limestone beds (Fig. 9). Our results are consistent with previous similar studies on two-phase rocks under external load (Fagereng, 2013; Ji and Zhao, 1994). Moreover, the model we propose in Figs. 8 and 9 is fully consistent, from a different perspective, with the multimillenarian human use of chert for arrowheads despite a much larger availability of limestones (Sieveking and Newcomer, 1987).

3.6. Formation of bed-parallel compaction stylolites during burial

We observe that the strengthening effect of chert layers should not be very effective when the composite multilayer is perpendicular to the maximum compression (i.e., syn-sedimentary burial conditions), as demonstrated by the abundant occurrence of bed-parallel compaction stylolites in limestone beds also where these beds are alternated with chert layers. We mechanically explore this case as follows.

We consider the case where a laminae-reinforced composite experiences an external load normal to the laminae direction (Fig. 7a). As previously mentioned, this case is mechanically similar to our studied rock during burial. The stresses applied to the two components (matrix and laminae) are equal (i.e. equal stress boundary condition) and, assuming elastic deformation, the mechanical behavior of the composite is expressed as (Hosford, 2005; Roylance, 1996):

$$E_c = \left( E_a + E_b \right) / \left( V_a E_{b0} + V_b E_{a0} \right)$$  

(2)

Through Eq. (2), we obtain that the strengthening effect of chert on the composite is minimum for chert contents lower than 20% (see the
orange curve in Fig. 7c). This evidence suggests that, in the case of the composite multilayer perpendicular to the maximum compression, the mechanical behavior may be modified by the presence of the rigid layers (Hosford, 2005; Roylance, 1996) without nevertheless preventing carbonate dissolution on surfaces that are perpendicular to the maximum compression (Robin, 1979). This result reinforces our idea that the lack of bed-normal PSSs in setting-B is due to the strengthening effect of chert layers under layer-parallel-shortening and not to other factors such as the limestone chemical, mineralogical, and textural composition.

3.7. Conceptual synthesis

The latter point and the previous ones are conceptually synthesized in Fig. 9. In pre-orogenic times, during burial, bed-parallel stylolites form in the limestone beds of the Scaglia Fm. regardless of the presence vs. absence of chert layers. In equal stress boundary conditions, in fact, the strain through the composite multilayer is unequally distributed with the soft limestone beds absorbing large part of the deformation through development of bed-parallel compaction stylolites (Fig. 9a). In later times, during syn-orogenic layer-parallel-shortening, the chert layers can significantly strengthen the composite multilayer, thus inhibiting development of bed-normal PSSs where this strengthening effect is larger (Fig. 9b). This model implies a heterogeneous horizontal shortening at different levels within the carbonate succession as a function of chert layer occurrence. Such a heterogeneous shortening could be partly accommodated by layer-parallel slip between adjacent sections of the sequence where PSSs occur and where PSSs are inhibited, respectively (i.e., between Setting-B and Settings-A and -C, Fig. 9b).

4. Relevance and uncertainty

Our results are relevant for theoretical and practical issues and have the following important implications.

(1) Where chert layers occur in carbonate sequences, subsurface models of secondary porosity may overestimate the medium porosity if the strengthening effect of chert layers is not accounted for (Fig. 8). PSSs are known, in fact, as early structures that can act as nuclei for fracture and fault initiation further developing into potential fracture corridors for geofluids (Antonellini et al., 2014; Graham Wall et al., 2003; Petracchini et al., 2012). The presence of continuous chert layers may inhibit the formation of such fracture corridors in carbonate sequences. The absence of PSSs, on the other hand, will prevent concentrations of oriented smectite nanostructure along seams (Viti et al., 2014) that are potentially barriers to fluids, although this latter issue is currently debated (Heap et al., 2014).

(2) In the seismic cycle, pressure solution is known as a ductile aseismic process that dissipates continuously strain energy. The presence of continuous chert layers increasing the strength but also the brittleness of a marly limestone sequence may thus inhibit the continuous strain energy dissipation and favor its elastic behavior. As pressure solution and mobility of quartz (chert) increases, the multilayer from brittle to ductile (potentially aseismic to seismic behavior). As pressure solution and mobility of quartz become significant over 150–200 °C (Dewers and Hajash, 1995), also in this case our model should be valid at least over the 0–8 km depth range in settings where the geothermal gradient is c. 25 °C/km. This depth range is relevant for earthquake nucleation and/or propagation. It is also true, however, that quartz (chert) pressure solution would correspond to contemporaneous pressure solution in the limestone beds, thus invalidating our idea of multilayer strengthening induced by the chert layers and switching the behavior of the multilayer from brittle to ductile (potentially seismic to aseismic behavior). As pressure solution and mobility of quartz become significant over 150–200 °C (Dewers and Hajash, 1995), also in this case our model should be valid at least over the 0–8 km depth range in settings where the geothermal gradient is c. 25 °C/km.

4. Relevance and uncertainty

Our results are relevant for theoretical and practical issues and have the following important implications.

(1) The main uncertainty concerns the Young’s modulus of chert. Due to the strong deformation of our study area typical of fold-thrust belts, it was impossible to collect a homogeneous and intact sample for a reliable measurement. There is, however, an extensive literature of Young’s moduli measured in chert and in SiO2-rich natural and industrial materials suggesting that a reasonable modulus for the intact chert should be well above 40–50 GPa (Table S1) that is an interval for which our mechanical model well explains the observed field geological structures (Fig. 4).

(2) We did not consider the effect of temperature and confining pressure on Young’s moduli, because layer-parallel-shortening...
in the Scaglia Fm. exposed in the Cingoli area occurred at a relatively shallow depth (i.e., less than 1000 m; Fig. 1c), that is less than about 50 °C and 25 MPa. We assume that, under these conditions, the differential between the Young's moduli of limestone and chert does not vary so much to invalidate our model. As previously mentioned, we assume also that the same differential should not vary so much with increasing temperature and confining pressure over the 0–8 km depth range, so to invalidate our model.

(3) An alternative explanation to our field observations (Fig. 4) could be found by invoking a different amount of clay content in setting-A vs. setting-B limestones (i.e., the non-CaCO₃ component in Fig. 6a). The lesser amount of clay in setting-B (Fig. 6a) could, in fact, inhibit pressure solution (Aharonov and Katsman, 2009; Renard et al., 2001). The observation, however, that PSSs develop also in the limestone–chert multilayer, where the chert layers are affected by small thrusts (setting-C, Fig. 5), suggests that this explanation is not applicable. In addition to being compositionally similar (Fig. 6a), we demonstrated that the Scaglia Fm. limestones of setting-A and setting-B are texturally (sedimentologically) and mineralogically similar (Figs. 3, 4, and 6b).

We infer that the textural, chemical, and mineralogical properties are not the driving factors for pressure solution inhibition in setting-B.

5. Conclusions

We conclude that the mechanical stratigraphy of sedimentary sequences under bed-parallel-loading can determine different deformation patterns thus bearing potential consequences on the hydraulic properties and seismic behavior of the sequences themselves. In the specific case studied here, the presence of continuous and frequent chert layers strengthened the carbonate sequence in a way analogous to the behavior of laminae–reinforced industrial composite materials. This stratigraphic setting inhibited the formation of PSSs perpendicular to the bedding in the limestone beds under layer-parallel-shortening. The presence of such a section in carbonate sequences may constitute a rheological, hydraulic, and seismic anomaly different from deformational patterns thus bearing potential consequences on the hydraulic properties and seismic behavior of the sequences themselves. In the specific case studied here, the presence of continuous and frequent chert layers strengthened the carbonate sequence in a way analogous to the behavior of laminae–reinforced industrial composite materials. This stratigraphic setting inhibited the formation of PSSs perpendicular to the bedding in the limestone beds under layer-parallel-shortening. The presence of such a section in carbonate sequences may constitute a rheological, hydraulic, and seismic anomaly different from deformational patterns thus bearing potential consequences on the hydraulic properties and seismic behavior of the sequences themselves.