Supplemental data: Outcrop descriptions and examples of deformation mechanisms

lementary Data 1.

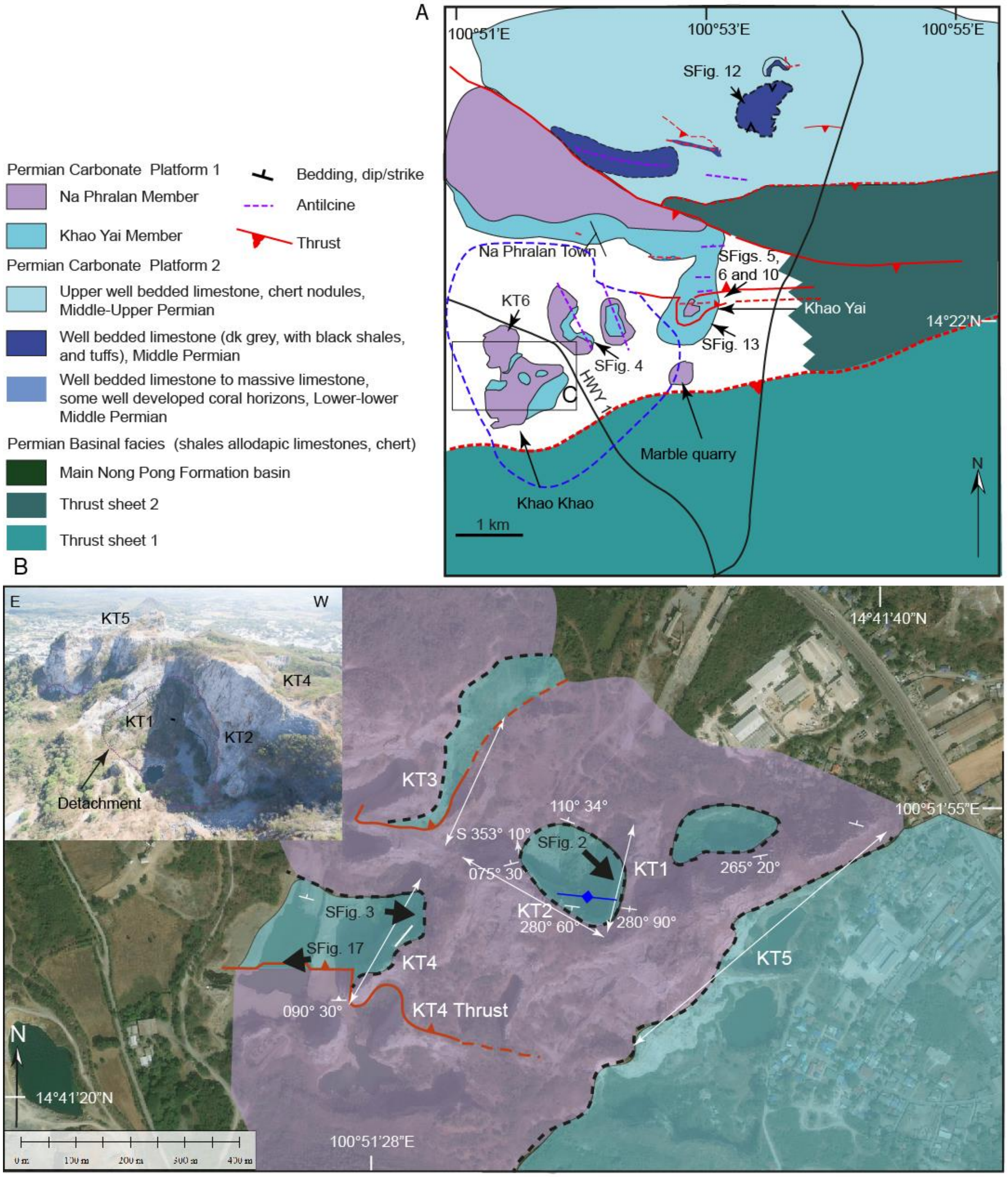
Quarries KT1-KT3 form a continuous section on the NE side of the hill (SFig. 1). While KT4 lies on the opposite (southwestern) side of the hill to KT1-KT3. These quarries are described below.

Quarry KT1 (220 m long, trend N004°)

The largest fold in KT1 lies within the Khao Yai Formation, and verges towards the south. The vertical forelimb is sharply separated from the upper few meters of Khao Yai Formation below the formation boundary, by a thrust fault (SFig. 2). Minor folds above the largest fold verge northwards on its backlimb, and verge towards the south on the forelimb. These folds die out at the detachment at the formation boundary, or cause low-relief folding of the detachment. The different fold vergence directions suggest that displacement is not consistent in one direction on the detachment, but varies locally.

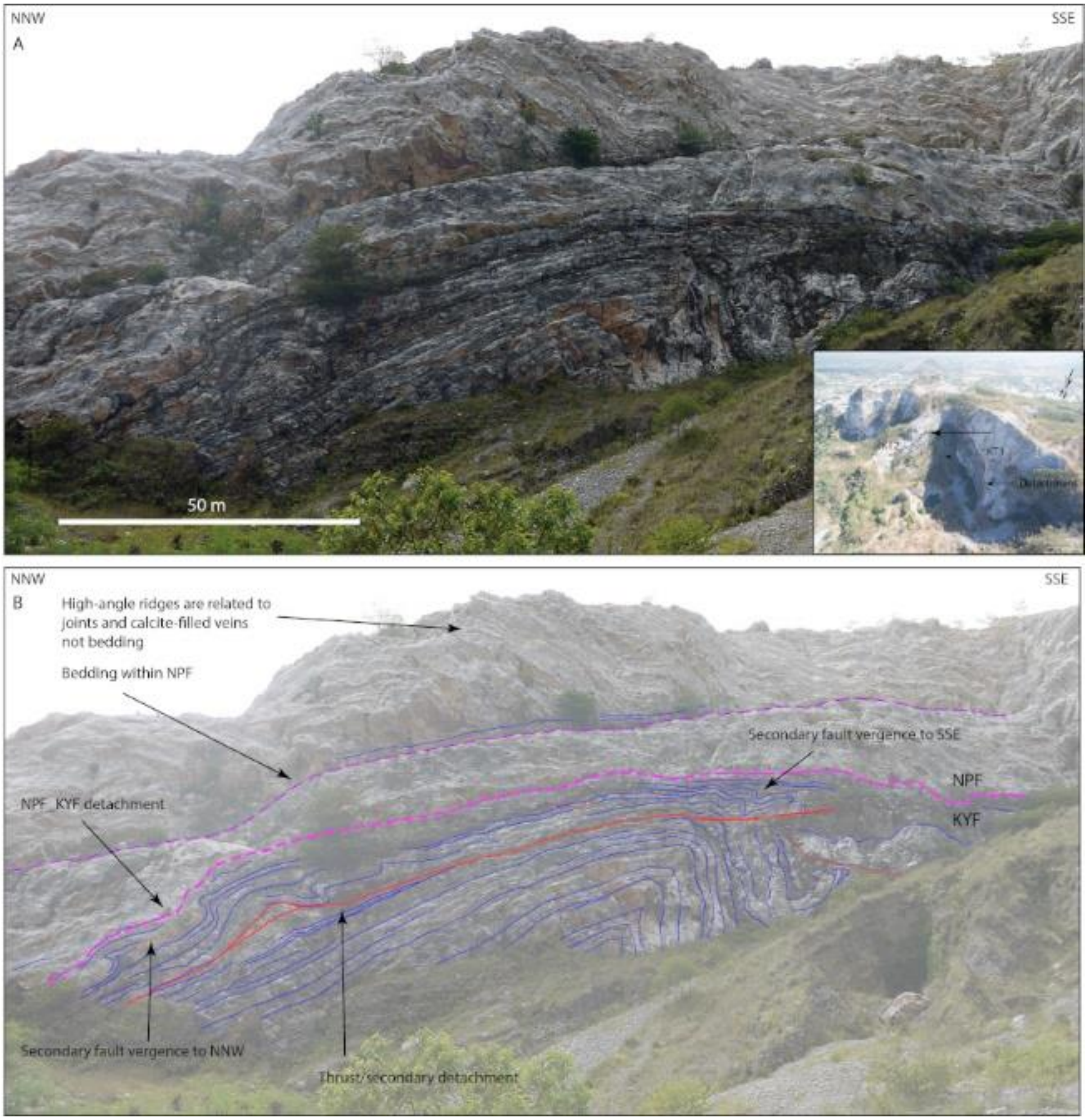
Quarry KT2 (320m long, trend N306°)

KT2 lies only a few hundred meters along strike from KT1, but shows some significant differences. The main fold appears more symmetric than in KT1, however the steeply dipping forelimb (~60°) appears to have a lower dip due the apparent dip effect of the cliff face relative to bedding (Fig. 5). The thrust is absent, or is a very difficult to identify bedding parallel feature.



SFigure 1. Location map of the Na Phra Lan area.

The lowest part of the Na Phra Lan Member shows a lateral transition from a massive section in the SE part of the quarry, to a well-bedded section passing northwards into the main part of KT2. In the uppermost part of the Khao Yai Member, particularly in the forelimb of the main fold, recumbent tight to isoclinal folds with gently dipping axial surfaces are present. Some of these folds show vergence to the south, while others verge to the north. This illustrates that the detachment morphology is likely to be complex since the mechanical stratigraphy varies laterally as well as vertically. The Na Phra Lan Member exhibits a consistent dip towards the north, and shows none of the effects of folding seen in the Khao Yai Member. This dip brings the detachment down to ground level in the NW part of the quarry. Details of the detachment are described in the section: Transition from bedding to massive limestone.



SFigure 2 View to the ESE of quarry KT1 (see SFig. 1B), Khao Khao. A) Uninterpreted, B) interpreted photo. The photo shows sparse gently dipping, largely unfolded, or gently warped bedding surfaces within and at the base of the Na Phra Lan Member (the detachment level), and strongly folded and thrusted closely spaced bedding surfaces within the Khao Yai Member. The sense of vergence varies in asymmetric folds close to the contact with the Na Phra Lan Member. A thrust zone helps accommodate the transition from the steeply dipping forelimb of a large anticline in the Khao Yai Member, to bedding that is sub-parallel to the detachment.

Quarry KT3 (300 m long, trend N019°)

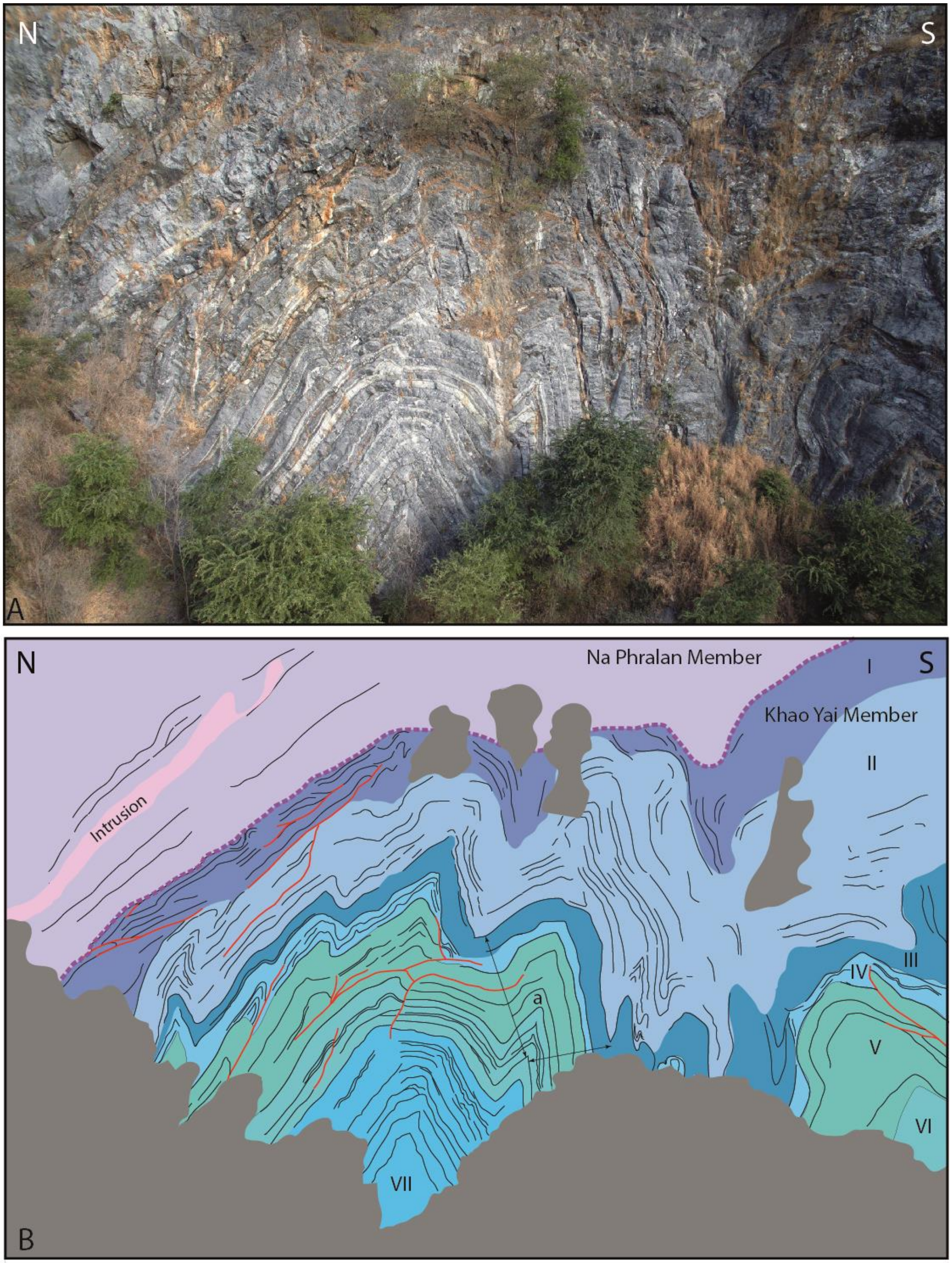
The NPM is exposed in KT3, the quarry is affected by a number of prominent sills and dikes that are up to a few meters thick. Bedding generally dips gently (~15°) to the NNE. Within the quarry there is a bedded interval that shows folding, and offset by a NNE-dipping thrust (Fig. 6). There is some uncertainty whether this bedded interval lies within the NPM, or whether it is actually the KYM, but in the figures it is shown as representing the upper part of the KYM. The uncertainty arises because the bedding is not quite as closely spaced, or regularly occurring as the typical KYM. However, the unit is composed of dark grey to black limestone, with regular bedding, and so may represent subtle lateral change in characteristics that occur locally particularly at the top of the KYM, or at the base of the NPM. In the footwall of the main thrust a sill is offset by a small thrust indicating sill emplacement prior to, or during the Indosinian orogeny.

Quarry KT4 (500 m long, trend 016°)

The best exposed example of the deformation styles in the Kao Yai and Na Phra Lan members is KT4. Old, NNW-facing quarry faces are present in hills, on the SSE side of a new quarry that has been sunk >30 m below ground level. The new quarry is predominantly located in the tightly folded KYM. However, in the WSW part of the quarry a south-directed thrust with at least 100 m offset, is well exposed (Figs. 7 and 8). This thrust emplaces the KYM over the NPM, and is the only thrust in the study area that shows this relationship. In the new quarry, bedding within the KYM is prominent. Whereas the NPM shows little bedding, and instead is massive and strongly fractured, with numerous calcite veins, and little organized macroscopic structure is visible in the footwall of the thrust. In thin section fossils, including fusulinids are still visible, and display little strain, and in places early marine cements are still present (e.g. Fig. 3D), which all support the macroscopic perspective that the NPM is less deformed than the KYM.

In the old quarries the boundary between the KYM and the NPM is spectacularly exposed (Figs. 7 and 8), and demonstrates the overall change from tightly folded, relatively short-wavelength structures in the KYM, to relatively long-wavelength, open folds, or unfolded section in the NPM (SFig. 3). The details of this change are described in subsequent sections. Igneous intrusions are extensively present in KT4.

Quarry KT4 reveals the most complex folding of the KYM in the study area. The KYM is exposed in the core of a culmination that is uplifted between a north dipping thrust on its southern margin (Figs. 8), and south-dipping faults that are interpreted as inverted normal faults (Fig. 8). It has been suspected that the broad facies distributions of Permian limestone platforms separated by deepwater deposits (cherts, shales, allodapic limestones) is controlled by syn-depositional normal faults (e.g. Morley et al., 2013; Dew et al., 2018; Vattanasak et al., 2020). However, KT4 is the first location where a structural case can be made for the presence of normal faults. In this quarry the base of the Na Phra Lan Formation (the detachment) is a typical, distinctive, sharp transition from underlying well bedded, dark grey to black limestone units (Figs. 7 and 8), to a more massive, medium-grey, limestone, with early marine cements (e.g. Figs. 3E) present in places. This transition lies at a higher level in the north side of the quarry, than in the centre of the quarry, where the base of the formation is deformed in a broad, northverging anticline, with a strongly attenuated, thinned northern fold limb (Fig. 7). Consequently, despite the contractional nature of the deformation, the sense of offset of the base Na Phra Lan Formation on the two main south-dipping faults, is extensional, indicating these faults are inverted normal faults.



SFigure 3. ~~B~~A) Outcrop photo and B) sketched cross-section of detailed part of KT4 quarry (see SFig. 1B for location), illustrating the change in deformation style passing upwards from the

Khao Yai Member to the Na Phra Lan Member. I-VII are arbitrarily defined lines that illustrate the change from steeply inclined folded layers lower in the section to more gently inclined layers higher in the section. Note the secondary folds particularly around layer III have the characteristics of Z-M-S type folds. The line length of the layer boundaries (III, base of I, and top of I) decreases upwards from 47% (III) to 10% at the detachment boundary between the Na Phra Lan Member and the Khao Yai Member. At location 'a' the lines with arrows indicate the change in thickness of the same interval from the relatively thin backlimb to the thick forelimb. This change in thickness is largely a result of preferential pressure solution shortening in the steeply dipping backlimb area.

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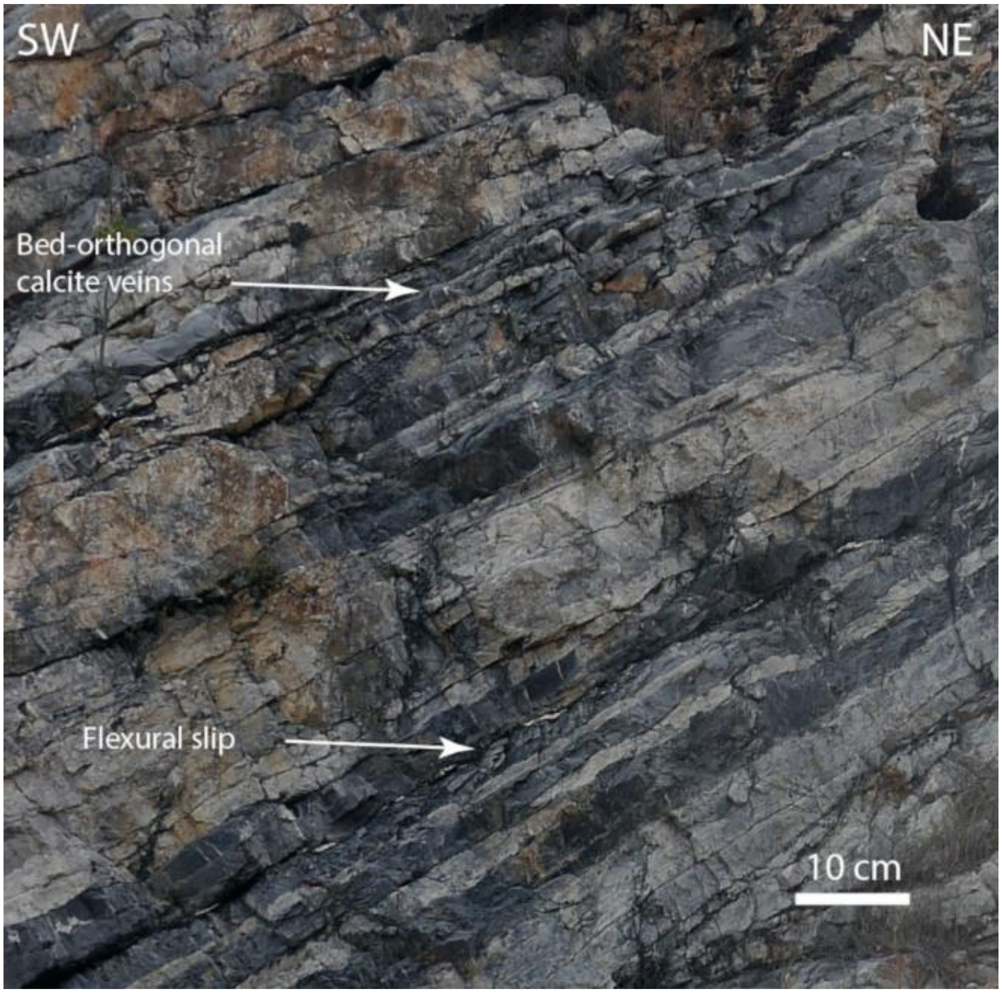
Quarry KT5 (600 m long, trend 040°)

Quarry KT5 shows the clearest development of structures along the NE half of the 600 m long face (Fig. 6). The quarry shows a near strike-section, with the NPM overlying the KYM. Strike-sections through folds can be seen in the upper part of the KYM, the bases of many of the folds are marked by thrusts. The folds show very rapid along-strike changes in geometry, and are highly non-cylindrical. The sharp flat base of the NPM contrasts with the folding and thrusting in the underlying KYM.

Quarry KT6 (Na Phra Lan Member

Deformation mechanisms during folding of the Khao Yai Member

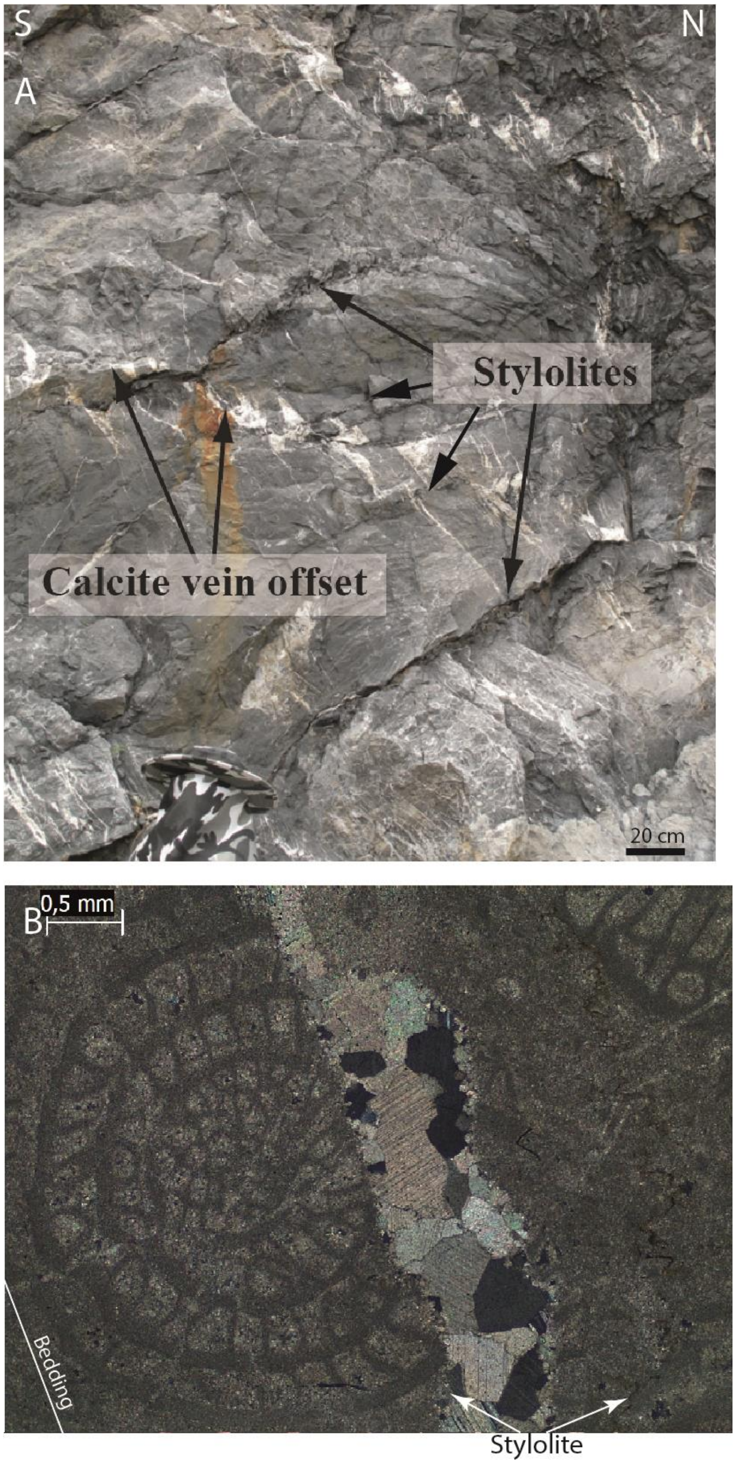
This section provides additional information and images particularly focused on the role played by pressure solution and vein generation during folding of the Khao Yai Member, and particularly how tight to isoclinal folding is achieved. A very weakly deformed section of the Khao Yai Formation is shown in SFigure 4 to demonstrate the low intensity of veining, and absence of pronounced thickness changes in bedding in such a section.



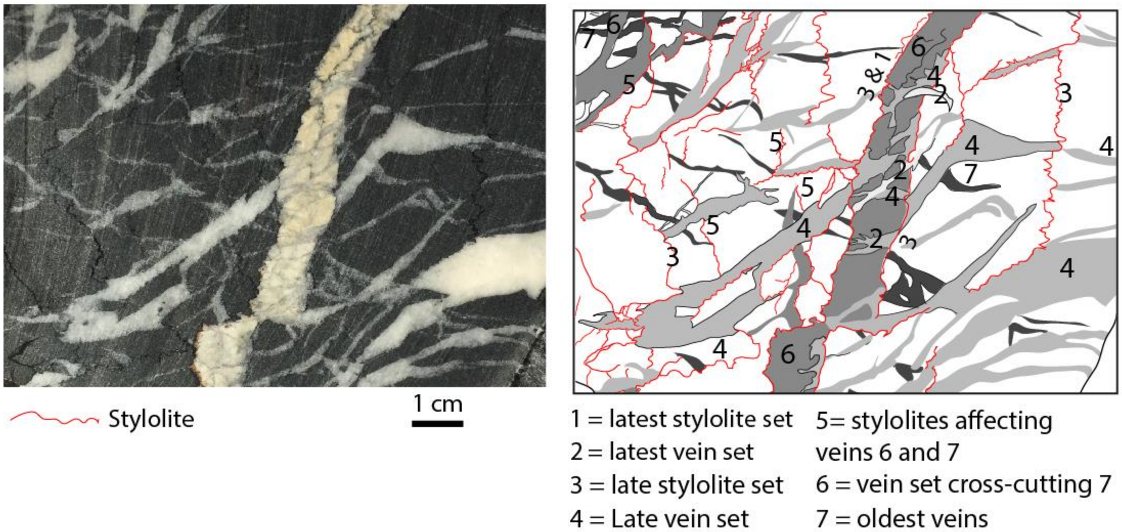
SFigure 4. Photo illustrating the appearance of bedding within the Khao Yai member in an area whether deformation intensity is low. Characteristics of the key features of the section in Fig S1 are: 1) alternating stratigraphic layers that in general show only minor modification of bedding by pressure solution. 2) Very minor presence of calcite veins, which also supports minor pressure solution affecting this section. 3) One layer shows bedding parallel veins, which are striated, suggesting flexural slip of this surface. See SFig. 1A for location.

In areas where folding is strong bed-parallel veins, veins at a high angle to bedding, sets of tension gashes, flexural-slip related veins are common. SFigure 5A shows examples of tension gashes crossing bedding which is defined by stylolites. The stylolites are more than just burial-related features because in places there is dissolution of some of the calcite veins. But in other places calcite veins cross-cut the pressure solution seams, indicating multiple phases of deformation. Such complexity can be seen in SFigure 5B, where a stylolite has developed at the interface between a calcareous mudstone and a packstone, and is more clearly demonstrated in slabbed sample where multiple stages of vein and stylolite growth are identified (SFig. 6). As folds become tighter fossils can become sheared and deformed (SFig. 7A,C), clay-rich zones of pressure solution can become regions of slip for flexural slip and wedge thrusts (SFig. 7B), and pressure solution (SFig. 7A,D) results in large volumes of calcium carbonate being available for deposition as calcite in veins in high strain regions (typically tight to isoclinal fold cores; SFig. 7E,F). The original bedding fabric in the cores of isoclinal folds can be largely lost, and replaced by multiple generations of veins, and sheared veins, compositional differences (e.g. areas of higher clay content related to pressure solution selvages, original host rock, and calcite veins) can have blurred boundaries due to recrystallization of older boundaries, and sharp boundaries of relatively young events as illustrated in SFigures 8 and 9. Wedge Thrusts (SFigure 10) are another feature of fold development, and tend to locally form particularly around fold crests and in areas where bedding is not well developed, or flexural slip is unable to operate.

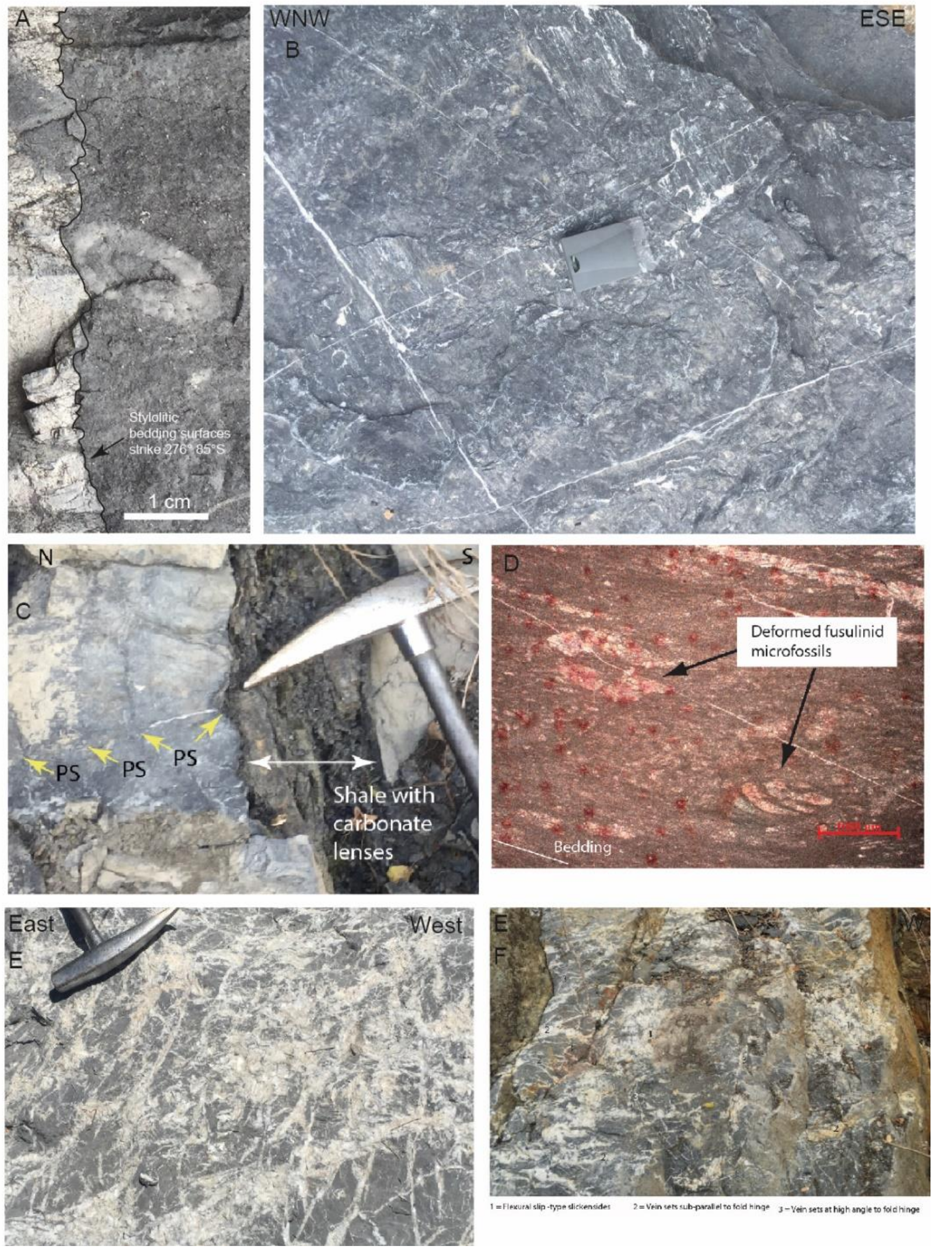
In SFigure 11 most of the vein samples plot on a burial trend of gradually decreasing C^{12} values and increasingly negative O^{18} that represent a burial trend. The other grouping on the graph highlighted as the teleogentic zone is related to Neogene karstification. Oxygen and carbon stable isotopes measured from calcite veins in the limestone, show a many veins in the burial



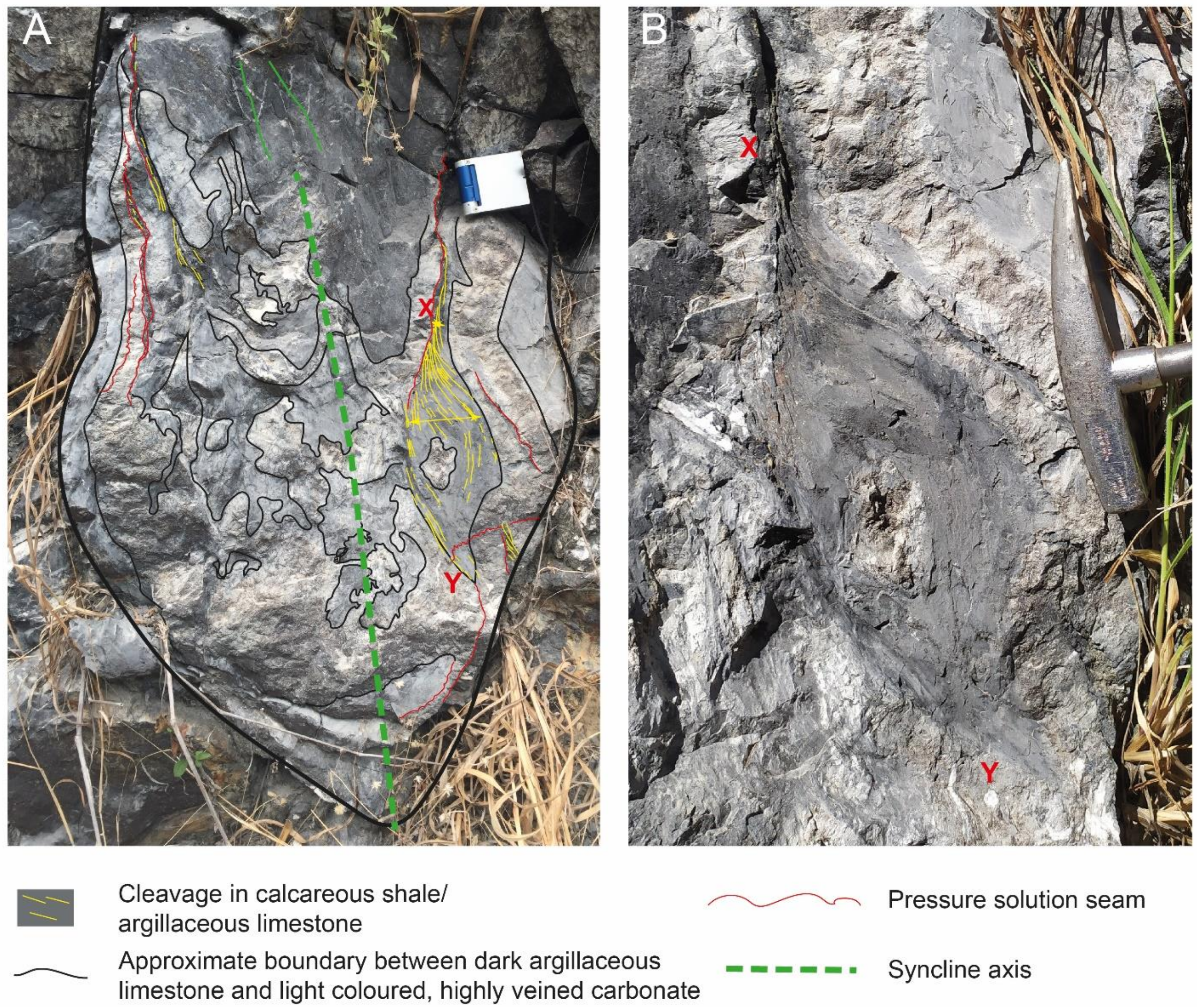
SFigure 5. Outcrop (A), and thin section (B) examples of pressure solution interacting with vein development in the Khao Yai Member. East side of Khao Yai hill (see SFig. 1A).



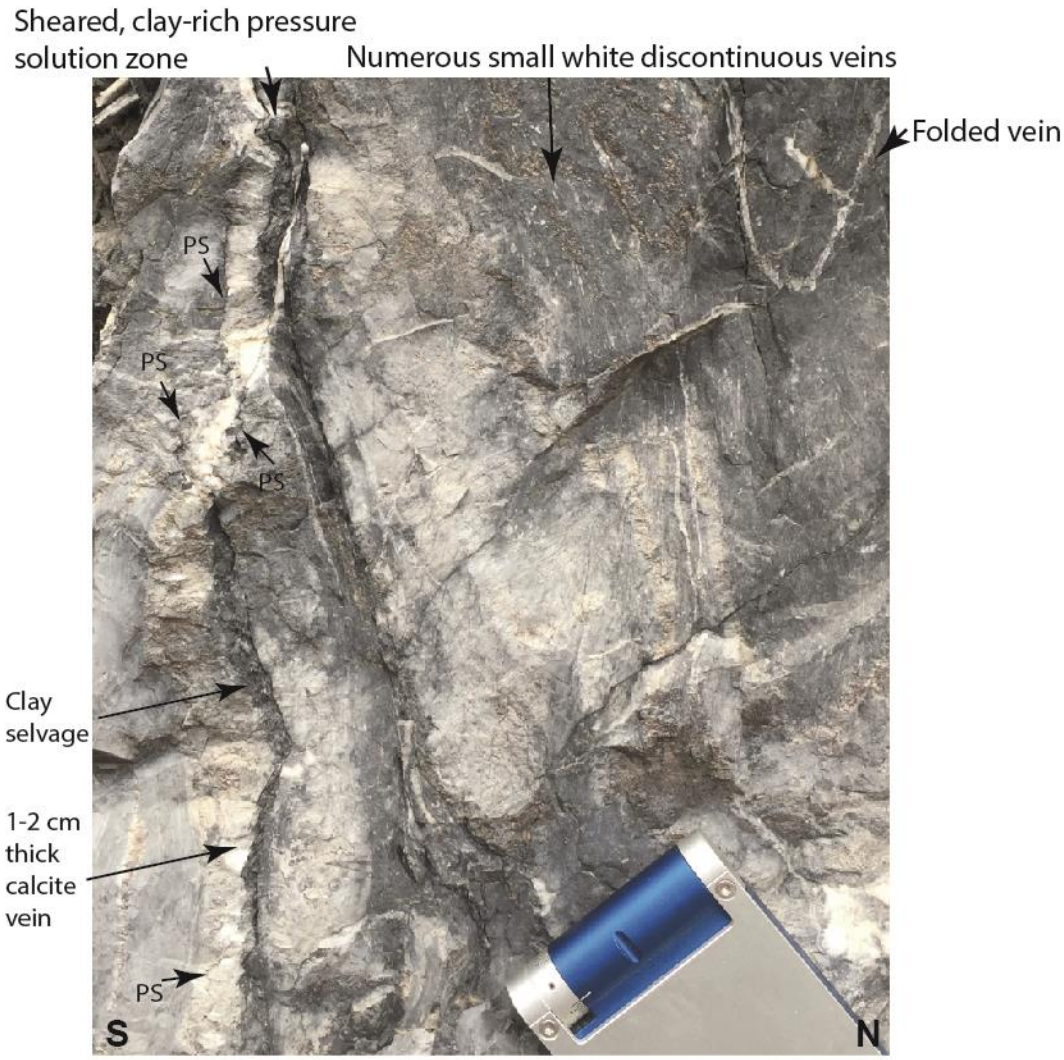
SFigure 6. Slabbed sample of carbonate from a strongly folded part of the Khao Yai member illustrating how much of the local internal deformation of the rock is accommodated by multiple episodes of tensile failure and the growth of veins and pressure solution with a network of stylolites of multiple orientations, some of which are influenced by vein-host rock boundaries. Location Khao Yai (see SFig. 1A).



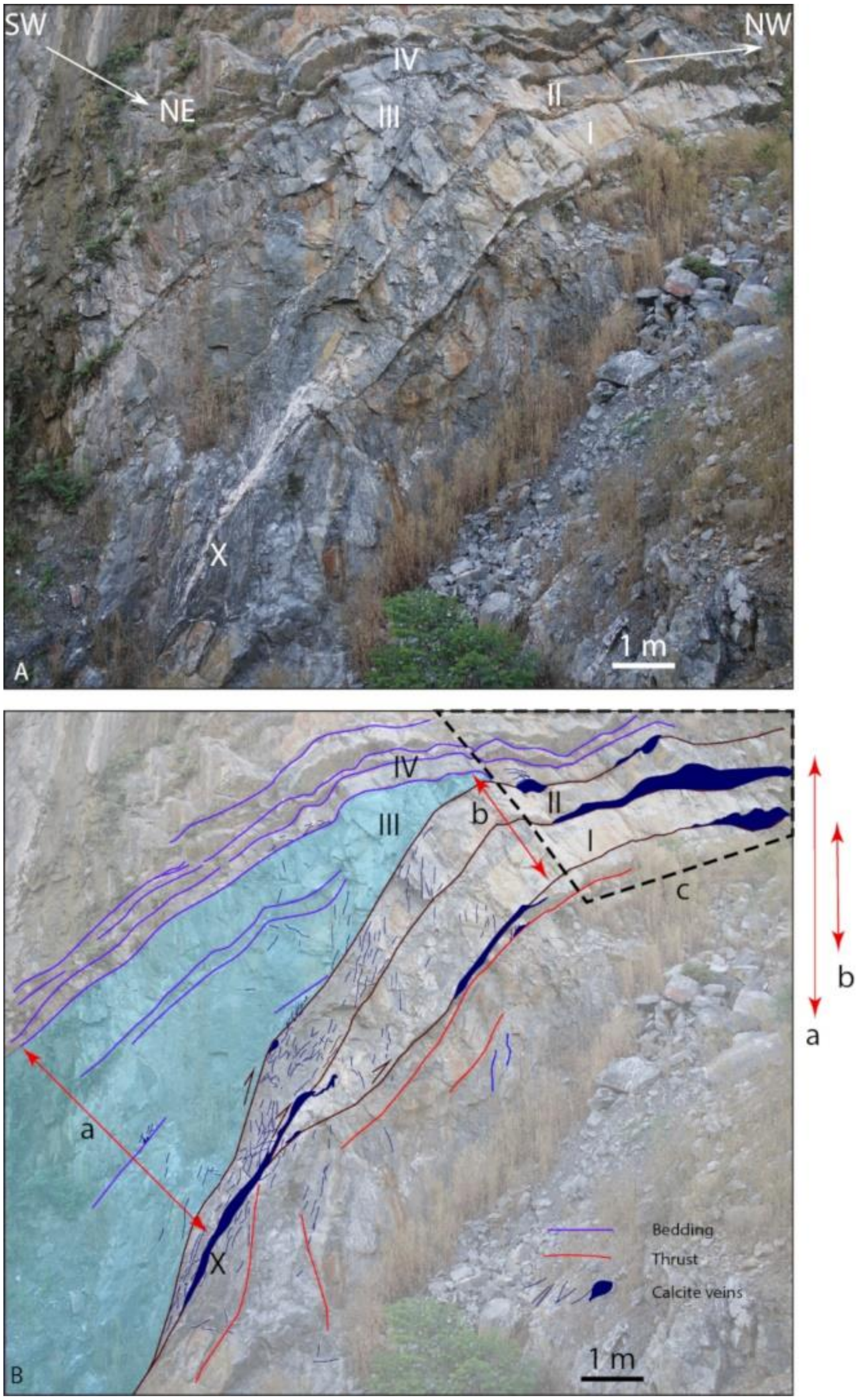
SFigure 7. Outcrop examples of deformation within the Khao Yai Member. A) Strained crinoid ossicle with dissolution at stylolite seam (parallel to bedding, in vertical bed). B). View onto the top surface of a well-developed pressure solution surface, with a clay layer several centimeters thick, the surface has been modified by flexural slip and growth of calcite slickensides. C) Limestone bed affected by muliple pressure solution seams (PS). D) Thin section showing deformed fusulinid microfossils. E) and D) example of locally highly veined limestones, this type of rock where >40% of the rock volume is vein material typically occurs in the cores of tight to isoclinal folds. Location for all A-C and F, quarry KT4, D and E, Khao Yai (see SFig. 1).



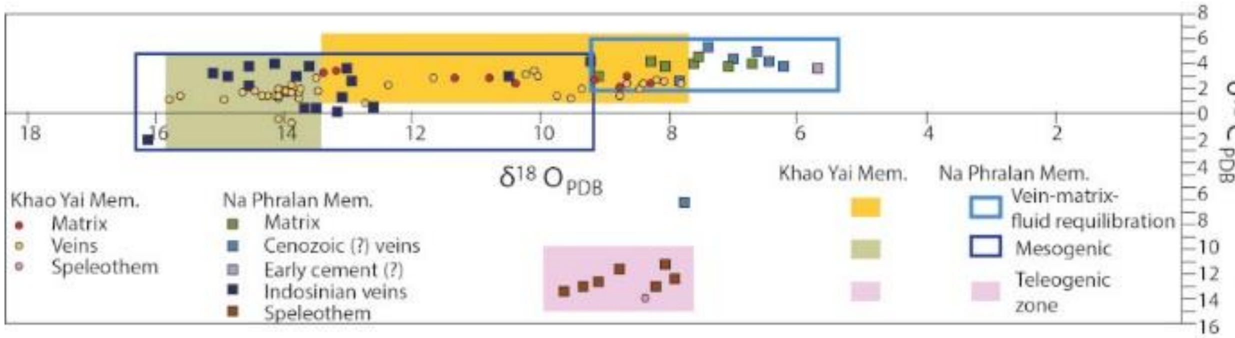
S.Figure 8. A). Highly deformed core of upright isoclinal fold in the Khao Yai Member. B) Detail (see locations X and Y for position in A) of A) showing the sheared cleavage fabric locally developed in the dark grey limestone. And the considerable thinning of thee dark grey limestone around location X. Quarry KT4 (see SFig. 1 for location).



SFigure 9. Highly deformed, limestone in the core of a tight fold. Quarry KT4.



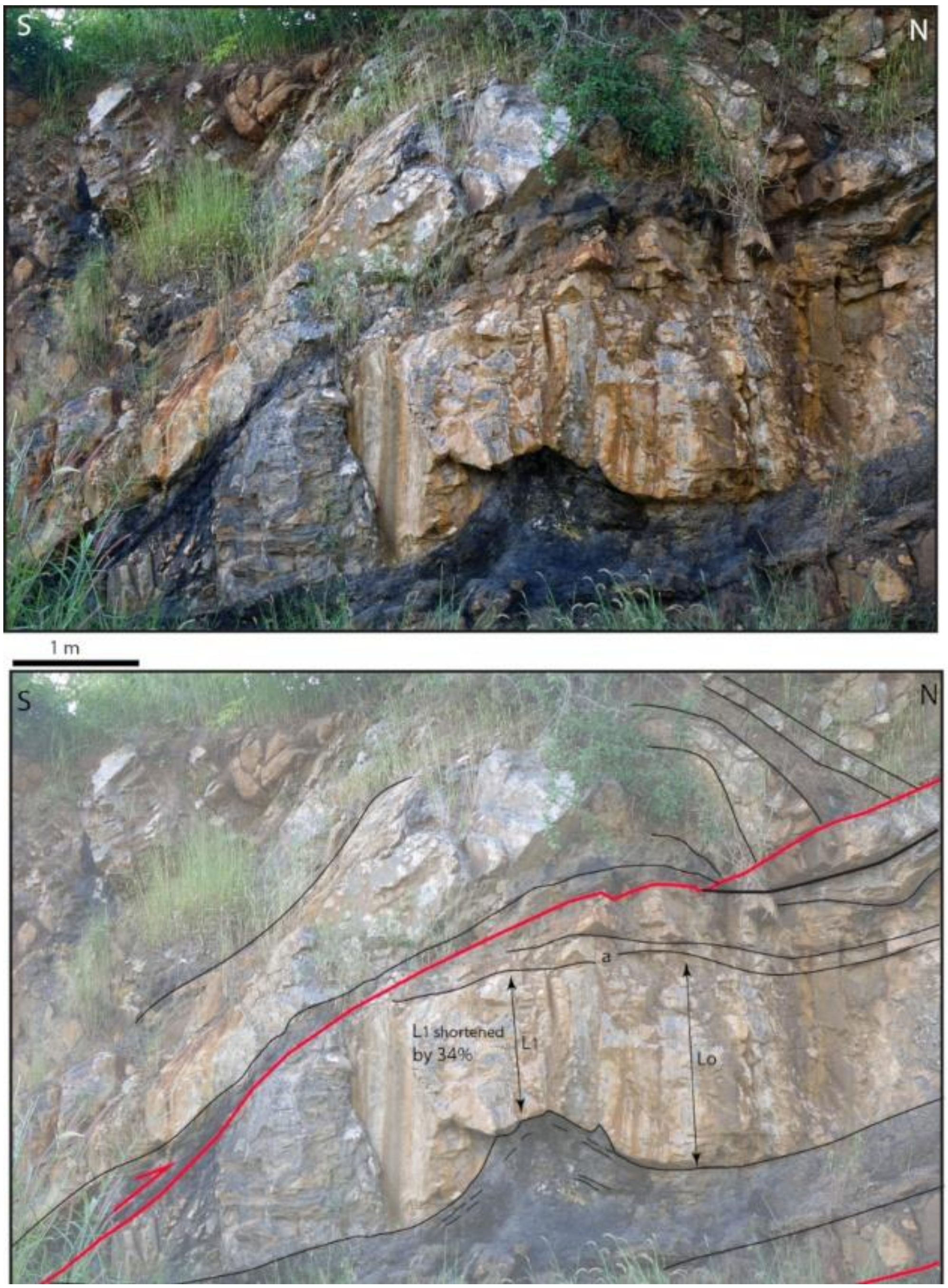
S Figure 10. Example of wedge thrusts affecting bedding. The SW-NE face is close to a dip section, while the NW-SE face is close to a strike-section. The NW-SE faces shows how difficult it can be to discriminate between small thrusts and bedding surfaces on some sections. I, II and III are thrust slices, IV is probably a bed. 'a' shows the maximum thickness of III in the photo, while 'b' shows the maximum width of slices I and II. See SFig. 1A for location.



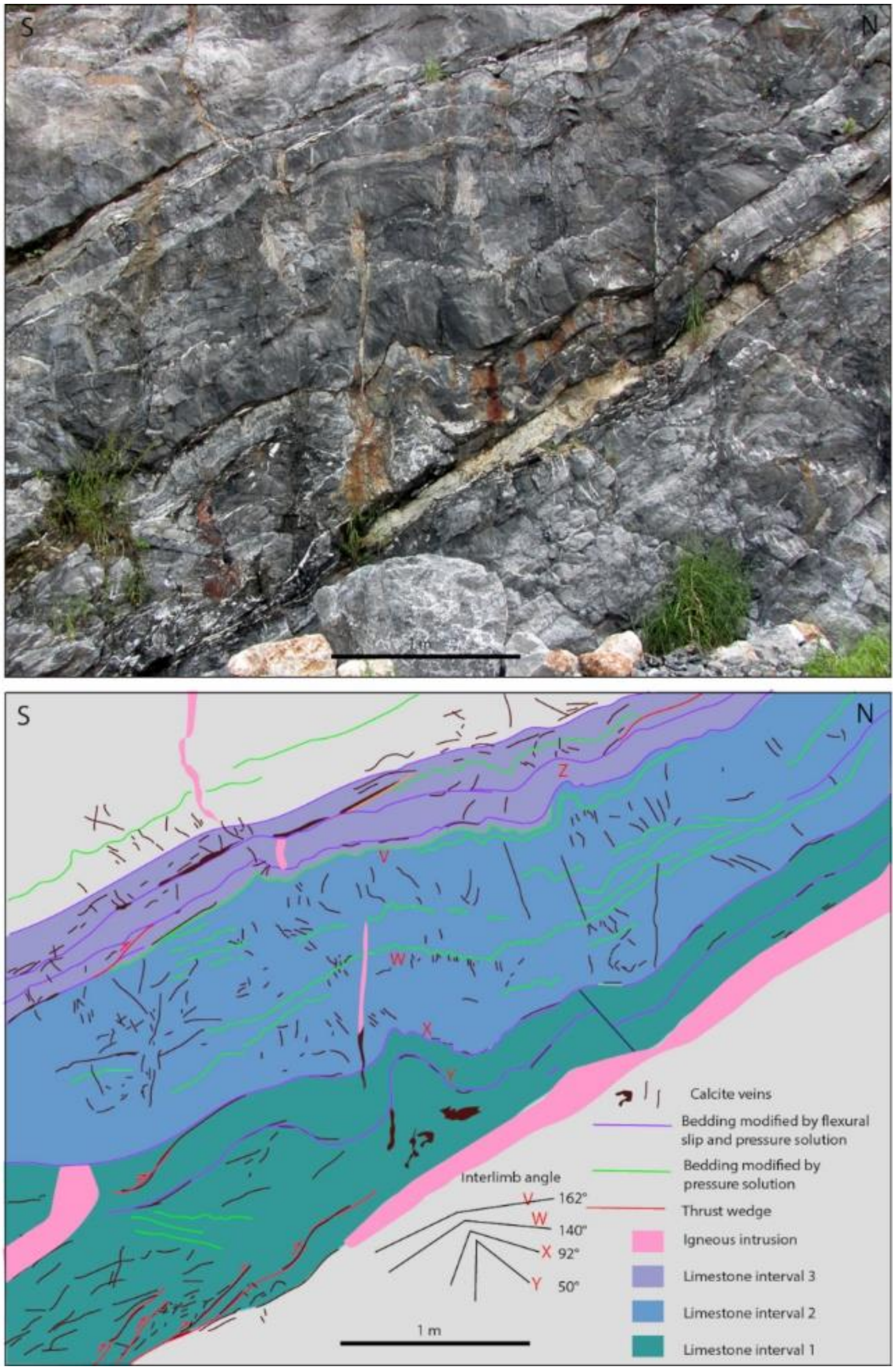
SFigure 11. Plots of stable oxygen and carbon isotopes from calcite veins in the Na Phra Lan area, comparing the results from the Khao Ya and Na Phra Lan members. The results are similar, despite the measurements for the Na Phrlan Member coming exclusively from the marble quarry.

trend are close in isotopic composition to the host rocks. Some veins exhibit higher negative O^{18} values than the host rocks. These are interpreted to be hot fluids tapping a deeper source than the host rock, and they typically coincide with veins related to thrusts. The smaller vein complexes such as those shown in SFigures 6-9, tend to exhibit similar values to the host rock. This coincidence supports the inference that the veins are a largely a product of dissolution of the host rock along stylolites and other pressure solution seams.

The vertical growth of some anticlines also appears to be inhibited in some areas by pressure solution seams. SFigures 12 and 13 provide examples where anticline amplitude decreases upwards, and pressure solution is thought to be responsible.



SFigure 12. A) Uninterpreted, and B) interpreted_photograph of a detachment anticline in limestone overlying a thin black shale bed. Overlying the anticline is a thrust. The anticline does not fold the thrust, and only gently warps the upper bedding in the carbonate. Pressure solution along bedding around location ‘a’ appears to be responsible for the for the upwards reduction in fold amplitude. See SFig. 1A for location.



SFigure 13. A) Photograph and B) interpreted sketch of outcrop showing different types of modified bedding. At localities V, W, X and Y an anticline which has a tight interlimb angle and high amplitude in the deepest part of the section (Y), dies out by becoming low amplitude and more open upwards (V). Pressure solution along bedding surfaces enables this change in morphology. A smaller example is seen at location Z. See SFig. 1 A for location.

Na Phra Lan Member

The Na Phra Lan Member exhibits a variety of lithologies, including medium-grey fossiliferous limestone, white marble, recrystallized fine-grained and sparry limestone (SFig. 14) and a black fossiliferous micritic limestone (quarried as black marble), that is described in the main paper. The deformation in the Na Phra Lan Member is much less intense than in the Khao Yai Member. Hence many of the features described above cannot be shown in this section. The lowest part of the Na Phra Lan Member is the most deformed. Illustrative of the strongly deformed section a few meters above the boundary (and detachment) with the Khao Yai Member, is SFigure 15C, where sets of superimposed conjugate tension gashes, amongst other vein types, are present. Locally, strained fossils, host rock surrounded by veins are present (SFig. 16A,B).   This lowest unit grades into a medium grey recrystallized limestone, that exhibits few fossil, veins or pressure solution seams, that is about 20 m thick (SFig. 15A). There are narrow zones a few meters wide within this limestone that are affected by ENE-WSW to WNW-ESE trending veins, and NNW-SSE to NNE-SSW trending pressure solution seams (SFig. 15B). Perhaps these represent localised zones of fluid escape from the underlying Khao Yai Member.

Overlying the recrystallized limestone is a fossiliferous partially recrystallized medium grey limestone. Zones of stylolites are present in the limestone, but they tend to be quite short, discontinuous features (SFig. 16C, D), and are not associated with the high quantity of vein material seen in the Khao Yai Formation.

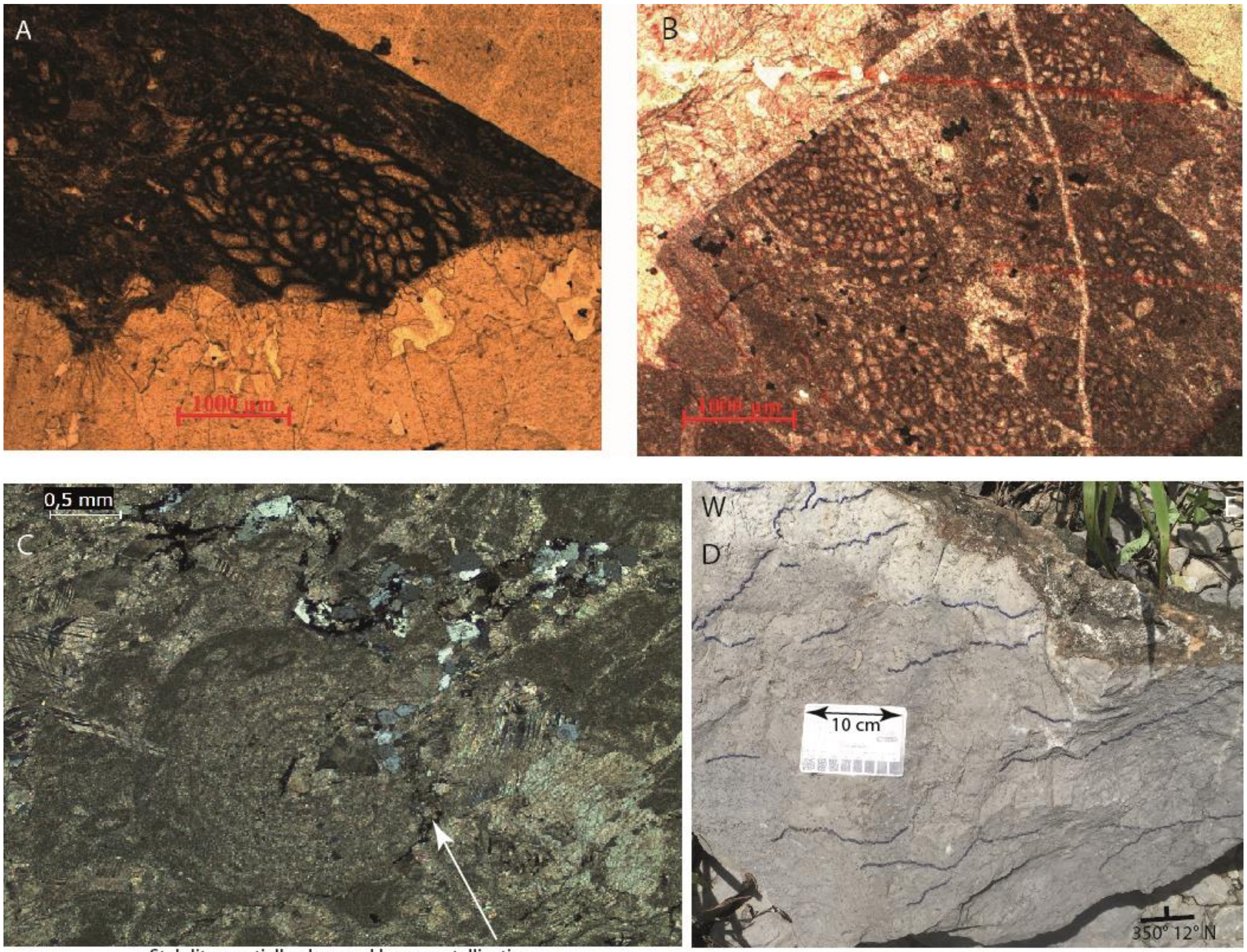
The decrease in shortening passing from the Khao Yai Member to the Na Phra Lan Member at the local and microscopic scale, indicates that larger-scale structures must pick up the shortening in the Na Prha Lan Member. Erosion has removed too much of the Na Phra Lan

Member to be able to identify these structures and measure their shortening. However, the KT4 Thrust (SFig. 1B, SFig. 17) provides an example of the type of large-scale structure that is required to accommodate extra shortening within the Na Phra Lan Member.

SFigure 14. Examples of lithologies in the Na Phra Lan Member. A) Recrystallized medium-grey limestone with corals (white tubular features) still preserved KT2 quarry. B) Cut face, and C) block in marble quarry showing white to pink marble with thin grey anastomosing seams. In some cases the grey seams retain traces of features indicating they are clay selvages produced during pressure solution. D) Pure recrystallized, sparry limestone, KT4 quarry. E) Darker grey

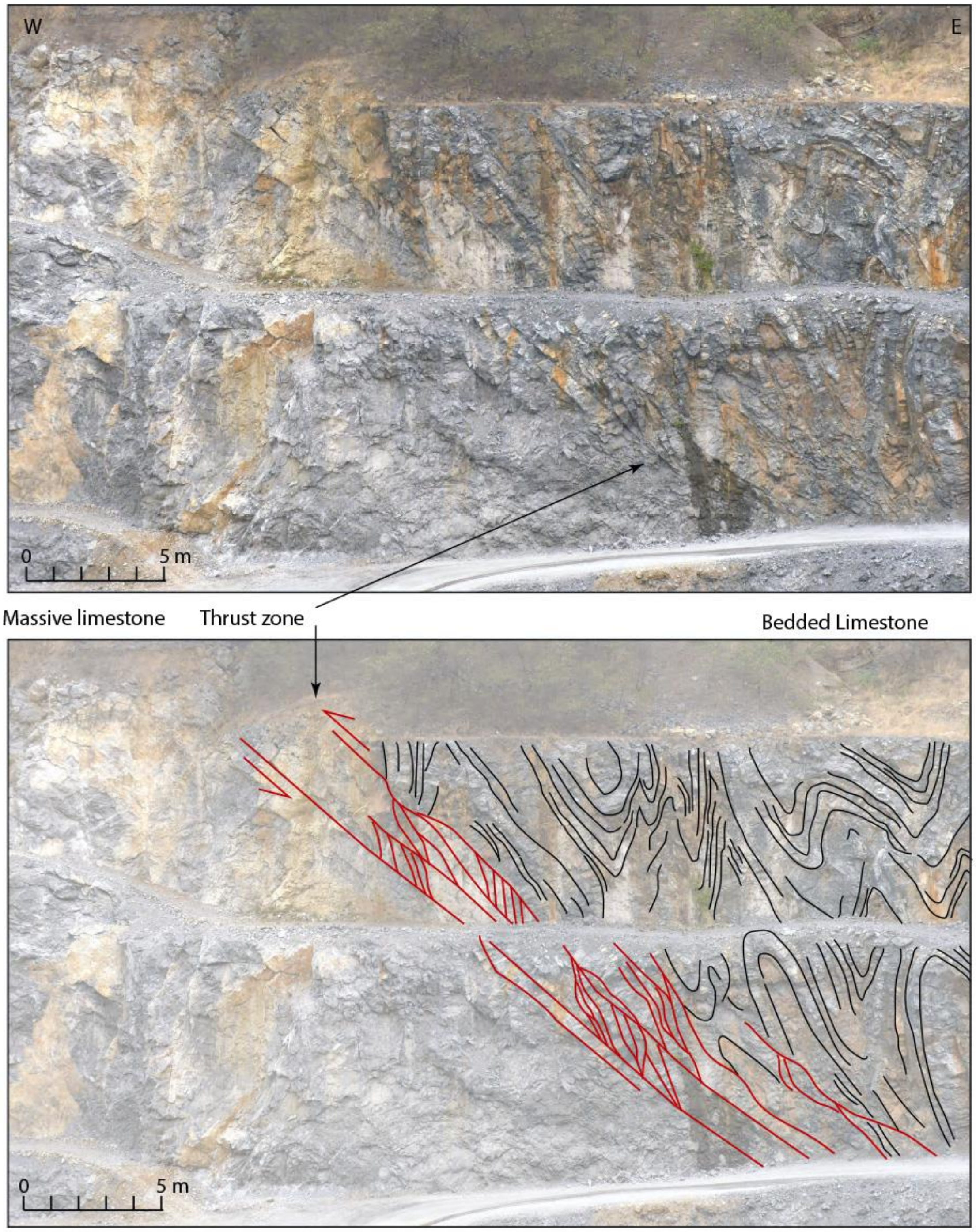
limestone, with possibly recrystallized early marine cement, KT4 quarry. See SFig. 1 for locations.

SFigure 15. Outcrop examples of the Na Phra Lan Member just about the detachment in quarry KT2 (see SFig. 2 for location). A) Recrystallised, unfossiliferous limestone. B) The limestone in A locally, along strike passes into zones of intense calcite filled fractures and pressure solution (PS). C) The lowest 5 m of the Na Phra Lan Member is a black to dark grey limestone, strongly affected by tension gash vein arrays, and planar vein sets.



Stylolite -partially obscured by recrystallization

SFigure 16. Thin sections of the Na Phra Lan Member. A) and B) strained fusulinids in heavily host rock surrounded by veins. C) Unstrained fusulinid partially truncated by stylolite, with later recrystallization partially obscuring the stylolite. D). Illustration of pressure solution seam spacing and length in fossiliferous limestone. The seams have been highlighted by blue marker pen. A,B = KT2 quarry, C = KT4 quarry, D = KT5 quarry, (Fig. 1).



SFigure 17. KT4 Thrust exposed in quarry face showing the bedded liemstone of the Khao Yai Member thrust over massive limestone of the Na Phra Lan Member. See Fig. 1B for location.

Supplemental data: XRF analysis of mineral composition in the KYM and NPM

Chemical analysis using semi-quantitative X-ray fluorescence (XRF) spectrometry has been conducted to estimate the mineral composition in the KYM and the NPM. The results demonstrate that calcium oxide (CaO) is dominant in all sampling locations (Table S1). Other elemental compositions are mostly similar in the KYM and the NPM. Silica (SiO_2) and magnesium oxide (MgO) constitute the main common impurity. Only two samples from the sheared, thick pressure solution seams of the KYM contain higher percentage of Aluminium oxide (Al_2O_3).

Based on the X-ray diffraction (XRD) analysis, all samples contain calcium carbonate in the crystal form of calcite (76-99.91wt% in the limestone samples), and dolomite (0.09-73.74 wt%). Some samples contain small amount of quartz (0.40-2.59 wt%). Pyrophyllite ($Al_2Si_4O_{10}(OH)_2$) is only found in the sheared samples of the KYM (6.41 wt% and 0.88 wt%, Figure S1). It may have formed by the reaction of kaolinite and quartz in aluminous, Fe-poor clay-rich zone at the late diagenetic or very low-grade metamorphism under low pressure (~2 kbar) and low temperature (~240-260ºC) (Frey 1987). The presence of pyrophyllite in the pressure solution seams of the KYM suggests early-stage burial of limestones to depths of about 8 km with concentration of clay (kaolinite) parallel to bedding. This clay zone then became a slip surface for the later stage of deformation.

Table S1. Chemical composition of the KYM and the NPM samples.

Element (wt %)	Sample ID							
	NPM 31-10-19-1	NPM 31-10-19-11	NPM 31-10-19-24	KYM 31-10-19-2 blue	KYM 31-10-19-2 red	KYM 31-10-19-20	KYM 31-10-19-21	KYM 31-10-19-25
CaO	61.14	59.84	45.45	52.32	54.49	41.79	50.57	52.33
SiO2	0.09		0.63	0.45	2.18	12.47	5.66	0.56
Al2O3	0.06	0.01	0.02	0.12	1.12	7.22	3.46	0.24
MgO	0.63	0.33	10.97	4.04	0.58	0.48	0.87	3.61
K2O					0.05	0.20	0.12	0.02
Fe2O3			0.18	0.04	0.04	0.17	0.22	0.08
MnO			0.05	0.01				
Na2O	0.04				0.04	0.08		
SO3	0.01			0.09	0.04	0.06	0.11	0.10
SrO	0.04	0.03	0.03	0.08	0.25	0.04	0.06	0.09
P2O5			0.03					0.02
TiO2							0.08	
LOI	38.00	39.80	42.65	42.80	41.20	37.50	38.85	42.95

31/10/19/1 Quarry KT2, Na Phralan Member, recrystallized lighter and darker grey limestone folded contact.

31/10/19/2 blue writing - Quarry KT4, Khao Yai Member

31/10/19/2 red writing Quarry KT4 Kha Yai Member

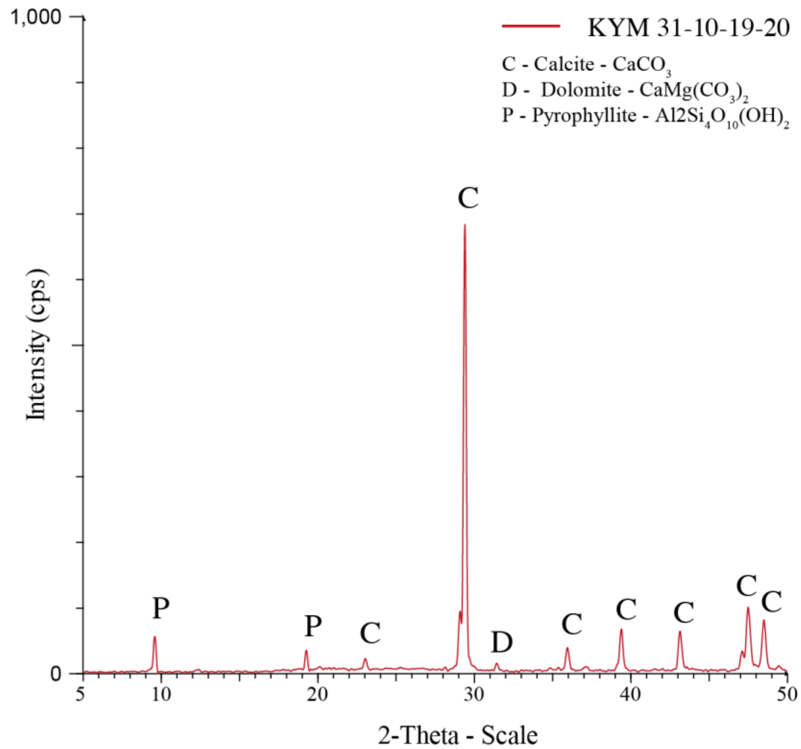
31/10/19/11 Quarry KT4, Na Phralan Member, white recrystallized limestone with disseminated pyrite

31/10/19/20 Quarry KT4, Khao Yai member sheared, thick pressure solution seam

31/10/19/21 Quarry KT4, Khao Yai member second thick pressure solution seam

31/10/19/24 Marble - Na Phralan Marble quarry

31/10/19/25 Quarry KT4, Khao Yai member from isoclinal syncline


KYM 31-10-19-20
C - Calcite - CaCO3
D - Dolomite - CaMg(CO3)2
P - Pyrophyllite - Al2Si4O10(OH)2
Intensity (cps)
2-Theta - Scale
1,000
0
5
10
20
30
40
50
P
P
C
C
D
C
C
C
C
C

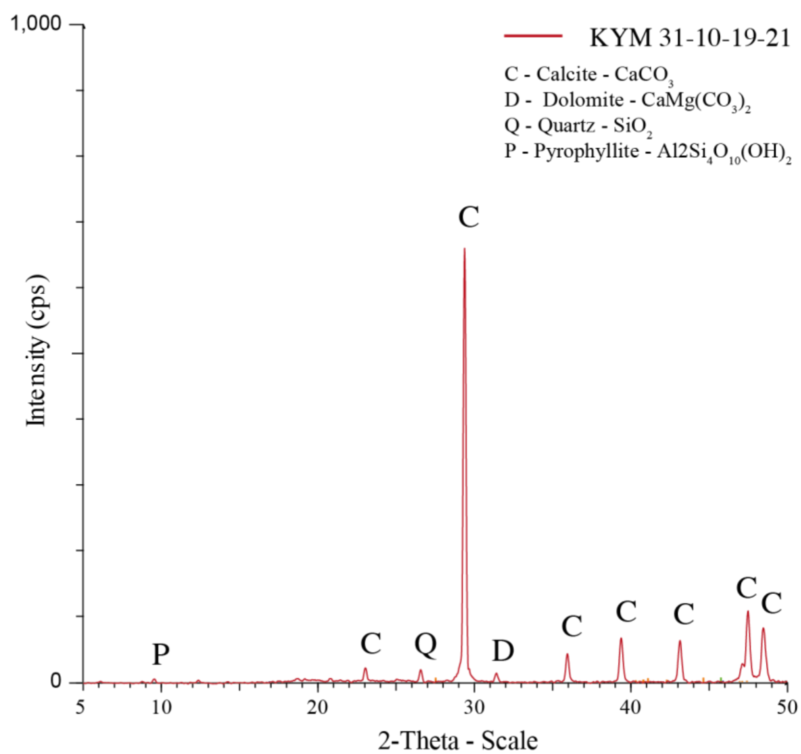

KYM 31-10-19-21
C - Calcite - CaCO3
D - Dolomite - CaMg(CO3)2
Q - Quartz - SiO2
P - Pyrophyllite - Al2Si4O10(OH)2
Intensity (cps)
2-Theta - Scale
1,000
0
5
10
20
30
40
50
P
C
Q
C
D
C
C
C
C
C

Figure S1. XRD results of the sheared, thick pressure solution seams of the KYM. (Above) KYM 31-10-19-20 sample consists of 92.45% calcite, 1.14% dolomite and 6.41% pyrophyllite. (Below) KYM 31-10-19-21 consists of 94.56% calcite, 2.59 quartz, 1.97% dolomite and 0.88 pyrophyllite.