Late Miocene high-angle faulting in the Cyclades: offshore-onshore tectonic studies and U-Pb calcite dating.

Déformation fragile à la fin du Miocène avec failles normales à fort pendage dans les Cyclades: étude tectonique offshore-onshore et datation U-Pb sur calcite.

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Abstract

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Aegean extension began during Eocene-Oligocene times and led to the thinning of the upper plate into a retreating slab system. The style of extension during the Miocene remains controversial, with a majority of studies arguing for extension accommodated by low-angle extensional brittle-ductile faults, called detachments. In other hands, the present-day active seismic faults in the Aegean Sea are only high-angle normal faults and dextral strike-slips. We aim to constrain and date the style of faulting in central Greece by combining analysis of 19 offshore seismic lines with onshore structural observations on Syros Island and LA-ICP-MS U-Pb dating of calcite sampled in two major fault zones of Syros (Palos and Fabrika faults). Three main sets of faults have been identified in the Central Cyclades: NW-SE trending normal faults, NNW-SSE oblique (sinistral)-normal faults, and NNE-SSW trending dextral strike-slip faults. High-angle normal faults define regularly spaced horsts and grabens, suggesting a wide rifting-type of extension. Dextral strike-slip faults occur at Syros, mainly offshore, and are kinematically compatible with normal faults. U-Pb dating of calcite crystallizing in normal fault planes at Syros yields ages at c.a. 10 Ma for high-angle normal faults activity. On these bases, we propose that wide rifting with high-angle normal faults accommodated Aegean extension when trench retreat accelerated in the middle to late Miocene. At this time, dextral strike-slip faults formed as a response of the onset of Anatolia lateral extrusion.

Keywords: LA-ICP-MS U-Pb calcite dating, offshore seismic lines, onshore tectonics, normal faults, strike-slip faults

Résumé

L'extension de la Mer Egée a commencé à l'Eocène-Oligocène et a entraîné l’amincissement de la plaque supérieure par le recul de la fosse de subduction contrôlé par le roll-back du panneau plongeant. Le style d'extension reste controversé, avec une majorité des études qui plaide en faveur d’une extension au Miocène accommodée par des failles fragiles-ductiles à faible angle, appelées détachements. D'autre part, les failles sismiques actives actuelles dans la mer Égée ne sont que des failles normales à fort angle et des décrochements dextres. L’objectif de cette étude est de contraindre et dater le style de faille en Grèce centrale en combinant l'analyse de 19 lignes sismiques offshore avec des observations structurales faites sur l'île de Syros et la datation LA-ICP-MS U-Pb de la calcite échantillonnée~~s~~ dans deux zones de faille majeures de Syros (failles de Palos et de Fabrika). Trois ensembles principaux de failles ont été identifiés : des failles normales orientées NO-SE, des failles normales obliques NNW-SSE (senestres) et des failles décrochantes dextres orientées NNE-SSW. Les failles normales à fort pendages définissent des horsts et des grabens régulièrement espacés, suggérant une extension de type rift distribué. Des failles décrochantes dextres ont été identifiées à Syros, principalement au large, et sont cinématiquement compatibles avec les failles normales. L’activité des failles normales à fort pendage a été estimée à environ 10 Ma grâce à la datation LA-ICP-MS U-Pb de la calcite cristallisée dans les plans de failles normales de Palos et Fabrika sur l’île de Syros. Nous proposons qu'un rifting distribué avec des failles normales à fort pendage a permis l'extension de la mer Égée lorsque le retrait de la fosse s'est accéléré au milieu et à la fin du Miocène. À cette époque, des failles de décrochement dextre ont été formées au début de l'extrusion latérale de l'Anatolie.

Mots-clés : Datation LA-ICP-MS U-Pb de la calcite, lignes sismiques en mer, tectonique à terre, failles normales, failles décrochantes

1. Introduction

The Aegean subduction zone is one of the most active regions in the Mediterranean, characterized by the interplay between extension and strike-slip faulting. The present day tectonics of the Aegean domain is controlled by the south-westwards Hellenic trench retreat at a current rate of approximately 3 cm/yr and Anatolia westward extrusion at 2 cm/yr (McClusky et al., 2000; Reilinger et al., 2006; Hollenstein et al., 2008; Fig. 1). Active tectonics is marked by the coeval activity of strike-slip faults (e.g. North Anatolia and others imaged offshore, Sakellariou and Tsampouraki-Kraounaki, 2018) and normal faults (e.g. Corinth, Evvia rifts; Fig. 1; see discussion in Pérouse et al., 2012). It is classically assumed that the present-day tectonic patterns, with both strike-slip and high-angle normal faults, only developed during the Pliocene or Pleistocene with the westward propagation of the Anatolian fault and the opening of the Corinth rift (Armijo et al., 1999). In this study, we aim to determine the age of the development of this tectonic pattern by combining offshore seismic lines analysis with onshore identifications of major faults and LA-ICP-MS dating of calcite precipitating in faults.

The Hellenic trench retreat has created extension of the upper Aegean plate since around 45 Ma (Brun and Sokoutis, 2007). Since then, the extension of the Aegean Sea has been accommodated by a progressive change in deformation style. This started with the exhumation of high-pressure/low-temperature metamorphic rocks, followed by the formation of high-temperature metamorphic core complexes (e.g. review in Jolivet and Brun, 2010). High-pressure/low-temperature exhumation brought the Cycladic Blueschist Unit (CBU) to the upper crustal level, which today constitutes the Cyclades (Fig. 1). It is proposed that ductile exhumation of the CBU is partly accommodated by low-angle extensional faults/shear zones, also known as detachment faults (see for examples, Lister et al., 1984; Gautier and Brun, 1994; Jolivet et al., 2010; Graseman et al., 2012). The ages of these low-angle extensional structures have been estimated as Miocene (Ring et al., 2003; Brichau et al., 2010).

There is also ample evidence that strike-slip faulting in the Aegean started during the middle-late-Miocene and not only during the Pliocene or Pleistocene. Anatolian extrusion started in the middle Miocene, as evidenced by the initiation of large-scale dextral shear zones around 11-13 Ma in Turkey (Şengör et al., 2005) and recent calcite LA-ICP-MS U-Pb ages (c.a. 11 Ma) obtained on the eastern portion of the North Anatolian Fault in Turkey and interpreted as reactivation ages due probably to the collision between the Arabian plate and Anatolian block (Nuriel et al., 2019). There is also evidence of NE-trending strike-slip faults in the central Aegean, which partly controlling magma emplacement since the middle Miocene (Kokkalas and Aydin, 2013). Therefore, rollback-related extension may have interacted with extrusion-related strike-slip faulting since the middle Miocene (Philippon et al., 2014). Furthermore, low-temperature thermochronology ages associated with tectonic observations support a middle Miocene strike-slip activity of the Pelagonian fault in Evvia and Attica (Fig. 1; Faucher et al., 2021). Strike-slip faulting was therefore potentially active coevally with high-angle normal faulting in Miocene times, when both N-S extension and E-W shortening occurred (Fig. 1). Brun et al. (2016) further suggest that ductile extension into the Aegean Sea ended around the middle Miocene (c.a. 15 Ma), when the style of deformation shifted to high-angle normal faulting and strike-slip faults, creating dispersed sedimentary basins (e.g. Mascle and Martin, 1990; Beniest et al., 2016). The low-temperature age distribution observed in the Cyclades (see age synthesis in Fig. 1) suggests that this switch from ductile to high-angle brittle faulting occurs around 12 Ma (see discussion in Philippon et al., 2012 and Brun et al., 2016).

This study focuses on the Cyclades block in the central Aegean Sea (Fig. 1). The novelty of this study is to correlate offshore seismic data with onshore field data for the first time, in order to propose an accurate estimate of fault kinematics, strain tensors, and to date these faults activity. We conducted our field study on the island of Syros whose geology is well understood and which has documented late high-angle faults (e.g. Keiter et al., 2011). Offshore data enable us to identify recently active faults and their basin-scale pattern, while onshore data allows us to characterise their kinematics with accuracy.

The timing of slip on brittle faults is still difficult to constrain, and direct radiometric dating of minerals from fault zones is the most explicit approach. Calcite is one of the most common syn-tectonic mineral precipitates, typically found along shear fractures or faults as cutting fibers and fault-related open-mode fractures as veins. Recent improvements in the sensitivity of inductively coupled plasma mass spectrometry (ICP-MS) instruments coupled to a laser ablation (LA) system have allowed to date minerals with very low U and radiogenic Pb concentrations, such as carbonates (e.g. Li et al., 2014; Coogan et al., 2016). Direct dating of faults in the brittle regime requires the presence of calcite that would have formed during or shortly after fault slip or associated fracture opening, either in gouge, veins or along fault surfaces. Roberts and Walker (2016) and Ring and Gerdes (2016) were the first to use the LA-ICP-MS U-Pb technique on calcite for dating brittle faulting. Since then, this method has been increasingly used to establish the absolute timing of brittle deformation in the upper crust (e.g. Roberts et al., 2020). Here, calcite sampled along two high-angle normal faults of Syros was dated by LA-ICP-MS U-Pb technique to test the hypothesis that the activity of these on-shore faults is indeed middle Miocene, as suggested by the compilation of low-temperature thermochronology ages (Fig. 1).

2. Offshore faulting in the northern Cyclades

2.1 Seismic reflection data

In this study, we combined recent bathymetry data (from EMODnet Bathymetry 2021 emodnet-bathymetry.eu and the Hellenic Centre for Marine Research-H.C.M.R.) with 2-D shallow seismic reflection images acquired in the 1980s, by the H.C.M.R. These lines were used to propose a recent tectonic interpretation of the Aegean domain (Sakellariou and Tsampouraki-Kraounaki, 2016; 2018, Fig. 1). Since the original analog data were not available, we used static images of the profiles without depth/time axes. We are therefore unable to indicate the depth of the interpretation, and the profiles only image the shallow subsurface. We used 10 NE-SW and 3 NW-SE profiles (location on Figure 2A), and only two characteristics are shown in Fig. 2 (profile 3 and 14, in Figure 2B and 2D respectively). The profiles set is provided in the supplementary materials.

For each profile, we performed a structural interpretation mainly based on syn-kinematic sediment packages in faulted blocks. Faults are identified as steep features abutting other reflectors. Sediment sets can be recognized by their close reflectors (bedding), and their abrupt interruption against steep faults. Syn-kinematic packages further exhibit bedding reflectors, which do not have a continuous thickness, i.e. these packages thicken where accommodation space is created during fault activity. The position of this thickening within a graben indicates which bounding fault is dominant, as the largest accommodation space is created closest to the dominant fault. Unlike sediment packages, the basement (Cycladic Blueschist Unit) does not show many internal reflectors, and poor data quality limits interpretation inside the basement. So we only interpret the top of the basement as much as possible.

The strike of active faults is interpreted from bathymetry, on a map view. Where possible, interpreted faults were correlated from one seismic profile to another using a combination of bathymetry and imaged fault character. As the original seismic data are not available and the lines are not closely spaced, horizon correlation was not possible.

Two main fault families have been interpreted: (high-angle) normal faults and strike-slip faults. Hereafter, we show two representative interpreted profiles, which illustrate the reasoning behind our interpretation. For interpreted profiles set and their locations, refer to the supplementary material (Figures S1-S17).

2.2 Fault interpretation on seismic profiles

Normal faults

Analysis of the 17 seismic profiles allows identifying several major faults that are all plotted on the map (Fig. 2A; white lines). Normal faults are dominant and are indicated by a red colour, both on the map and on cross sections. Red boxes with fault numbers correspond to the faults identified in seismic lines (Fig 2A and supplementary materials). The interpreted faults are based on the correlation between seismic lines.

From south to north, an east-dipping normal fault has been identified in seismic lines 1 to 7, referred to as the fault F1. Figure 2D shows the seismic line #3 (location Fig. 2A) where the F1 fault to the west is responsible of the formation of a half-graben with eroded basement in the footwall. The F1 fault has a relatively large offset (impossible to quantify on our seismic lines) and also a clear bathymetric signature (Fig. 2A). Following the same procedure, we identified seven major normal faults: F2 (dipping to the westward, south of Syros and present in seismic lines #1 and #2), F4 (dipping to the west-southwestward, present in seismic lines #4-7), F5 (dipping to the north-eastward, present in seismic lines #5-7), F6 (dipping to the south-westward, south of Tinos and present in seismic profiles #4-7), and F9 and F10 (dipping to the southward, south of Andros, present in seismic lines #8-10 and # 13).

At map-scale, normal fault F1, F2 and F4 define a graben between Kithnos/Serifos and Syros/Giaros. Between Giaros and North-Syros, normal faults F4 and F5, form a horst. Finally, between normal faults F5 and F6, another major graben can be defined between Tinos/Andros and Giaros/Syros. Normal faults seem to have varying strikes, i.e E-W for faults F9 and F10 and NW-SE for faults F1, F2 and F6. We will discuss this feature using the Syros example.

Strike-slip faults

In addition to these normal faults (red lines), we observe evidence of minor and major strike-slip faults (blue lines) (Fig. 2A). An example of minor strike-slip fault can be observed on the eastern rim of seismic line #3 (Fig. 2D), where two small negative flower structures can be seen on the eastern edge of the half-graben (Fault F3, Figs. 2A and 2D). The western subsurface part of the flower seems to have ceased activity, as newer sediments cover it. The easternmost flower is currently active, as it creates a small trough in the seafloor. Other minor flower structures can be observed in seismic profiles #7 (western edge) and #8 (middle of the profile) presented in the supplementary material (Figures S7 and S8) and plotted by blue squares in Fig. 2A as F8 fault. A major strike-slip fault is visible both on the seismic lines and in the bathymetry (Cava Doro straight). This strike-slip (denoted F7 fault) is seen in profiles #13, 14 and # 7,8, 9, 10 (location in Fig. 2A and seismic profiles in supplementary materials). The interpretation of profile #14 is presented in Fig. 2B. This profile, trending NW-SE, thus shares the strike of the grabens described previously, which explains why the sediment horizons appear relatively flat. However, to the north of the profile, there is a complex deformation zone with a distinct trough in the seafloor.

We interpret this as a major negative flower structure (Fig. 2C), which creates a bathymetric depression with an overall depth of 300-350 m, relative to the surrounding footwall which has a depth of ~140 m NW of the fault zone. The major strike-slip zone trends NNE-SSW across the northern Cyclades.

At map-scale and based on our analysis of the seismic lines and on the bathymetric signal, we can identify a major strike-slip fault trending SSW-NNE (F7 fault) from Kithnos to the Kafireas strait between Attica and Andros. A minor strike-slip fault, of NE-SW direction, can be identified between Kithnos and Giaros (F8 fault) and a second one located west of Syros (F3 Fault) (Fig. 2A).

Offshore fault pattern

The offshore fault pattern shows both high-angle normal faults and strike-slip faults. Normal faults are widespread and form regularly spaced horsts and grabens. Strike-slip faults are less abundant than the normal faults. No cross-cutting relationships between normal and strike-slip faults are observed, suggesting a potential coeval activity. Analysis of these seismic lines allowed characterization of the offshore fault patterns but did not enable accurate definition of the tectonic regime (directions of stretching and shortening), since fault kinematics are not observable from seismic data. We address this by analysing fault exposures onshore. To do so, field data from the Syros Island, in the central Cyclades, where both normal and strike-slip faults are observed, will be discussed. We will also use the Syros example to explain why normal faults have variable strikes, from E-W (F9 and F10 faults) to NNW-SSE (F1, F2 and F6 faults).

3. Late brittle faulting in Syros

3.1 Tectonic framework of Syros

Syros consists mainly of the Cycladic Blueschist Unit (CBU), a sequence that underwent high-pressure metamorphism during subduction in the Eocene. The sequence experienced retrogression and ductile exhumation in the Oligocene - early Miocene followed by exhumation by brittle faulting that took place in the middle-late Miocene (see Philippon et al., 2011, 2012 for a synthesis). The Syros CBU is structured in NE dipping layers. From the structural base to the top, the sequence is composed of albitic micaschists and gneisses (e.g. Komito unit, Fig. 3), alternating marbles and micaschists (e.g. Pyrgos and Kastri units, Fig. 3), and metabasites (mainly present in Kastri unit, Fig. 3) (Keiter et al., 2011; Philippon et al., 2011).

Since exhumation and ductile extension, Syros has suffered brittle faulting (e.g. Philippon et al., 2015, 2011; Keiter et al., 2011) which has received much less attention than its ductile history. In this section, we present the results of the structural mapping of the late stage of brittle structures, which are summarized in Figure 3. For simplicity, we use a simplified tectonic map (main lithologies and foliation after Hecht (1985), Keiter et al. (2011) and Philippon et al. (2011)), overlain with the late stage of the major high-angle faults observed in this study. Three fault sets can be described: NW-SE striking high-angle normal faults, NNW-SSE striking high-angle oblique (sinistral) normal faults and NE-SW striking dextral strike-slip faults.

3.2 NW-SE-trending pure normal faulting (e.g. Fabrika fault).

The NW-SE striking normal faults at Syros are interpreted as a major fault set, which offsets the lithology (e.g. in south-central Syros, between Galissas and Vari; and north Syros between Palos and Ermoupouli, Fig. 3). Several structures associated with NW-SE normal faulting have been observed on the Syros Island. The most characteristic ones were found at Fabrika (southeast Syros, Fig. 3).

The NW-SE trending fault at Fabrika separates the marbles from the eclogites and blueschists, as shown in Figure 4A. The main fault shows vertical slickenlines (Fig. 4B), indicating that this fault set is purely extensional. This observation is similar at other places on the island. Numerous NW-SE trending tensile joints in marbles also constrain the extensional direction to be subhorizontal and trending NE-SW. Locally, normal faults develop in pull-apart associated with apparently sinistral NNW-SSE strike-slip faults (with well-developed gouges) (Fig. 4C). The stereonet plot (Fig 4D) shows normal faults (with slickenlines), strike-slips and joints that are used to infer the direction of maximum stretching and maximum shortening (in red and blue, respectively). The direction of stretching is horizontal and at N50 (Fig. 4E). This suggests that high-angle normal and strike-slip faults (at least here sinistral along almost NNW-SSE striking fault) are compatible and developing coevally.

At map-scale, the Fabrika outcrop marks the local expression of a much larger NW-SE trending fault zone (from Fabrika to Galissas), explaining the unroofing of the deepest units (Pyrgos) in the center of the island and the general foliation trend, as shown in the N-S cross-section (Fig. 3C).

3.3 NNW-SSE oblique faulting (e.g. Palos fault)

NNW-SSE striking normal faults have already been documented by Philippon et al. (2015) in the Pyrgos marbles located north of Ermopouli (Fig. 3). On map, this fault set is visible in the southwest from Syros to Galissas (Fig. 3A). This fault set is also observed at Palos (Fig. 5A) and is correlated with minor faults observed offshore (Fig. 2 and seismic lines #4 in Fig. S4 in supplementary material). This portion of the coastline is defined by a major fault, visible in the Google Earth image along with tensile joints shown in Figure 5B. This fault plane creates a major cliff (Fig. 5A), which shows tensile mineralized veins, and oblique slickenlines (Fig. 5 B, C and D). It also creates a fault breccia and gouge section of the order of ~20 m. At kilometer scale, this NNW-SSE striking faults (black line, Fig. 5A) are associated with NW-SE joints or normal faults (red line, Fig. 5A and in the stereoplot). The stereonet plot (Fig. 5E) shows that the fault plane has a dominant NNW-SSE trend (brown) and shows sinistral oblique slickenlines. The tensile mineralized veins, plotted in red, also indicate sinistral normal slip. Therefore, this NNW-trending fault shows sinistral normal (oblique) slip, similar to the NNW trending sinistral fault observed at Fabrika (Fig. 3). The stereoplot of Palos and Galissas data (with normal faults with slickenlines and joints) (Fig. 5E) constrains the stretching directions to be horizontal, trending NE-SW, very similar to those inferred for Fabrika.

At map-scale, this fault is connected to F4 fault and defines the eastern border of the Syros/Giaros graben (see discussion in previous section and Fig. 2A).

3.4 NE-SW dextral strike-slip faulting

Central Syros lies along the minor strike-slip fault observed on seismic line #3 (F3 fault, Fig. 2A and 2D). In addition, we found field evidence of a minor NE-SW-trending strike-slip fault zone across central Syros. We interpret this as a minor fault set at Syros, consisting of small-scale segmented structures. Fault planes are poorly exposed here, and only a few exposures could be documented (Fig. 6). Available satellite imagery shows that this fault zone offsets the marble layers with a dextral sense of shear (Fig. 6A). A fault plane was identified, revealing oblique lateral slip (Fig. 6B). Figure 6C shows an exposure of this fault set in the eastern part of Syros, North of

Ermoupouli, where en-echelon shear fractures also indicate a dextral motion. No single major fault plane is found, but instead small segments of faults and associated fractures, which we plot collectively as associated structures on Figure 6B. The orientations vary, but are on average NE-SW. We also found a 10 m thick breccia layer NE-SW trending within the fault zone in central Syros, NE of Galissas Bay, which allows us to extend the fault zone drawn on the tectonic map to Galissas (Fig. 3).

The presence of this fault zone in central Syros is also supported by the surrounding foliation, as the foliation to the north turns into the fault zone (Fig. 3) creating a broad fold in the Pyrgos marbles (Philippon et al., 2011; 2015). This fault zone also separates the gently dipping southern half of the island from the steeper northern half, which could be explained by the occurrence of a strike-slip fault. The stereoplot, although with limited data, shows clear directions of shortening and stretching, trending E-W and N-S, respectively.

At map scale, this ENE-WSW dextral strike-slip is connected to the strike-slip fault F3 identified through seismic lines (Fig. 2). In addition, like for the offshore analysis, at Syros no cross-cutting relationship between dextral strike-slip and normal faults was found, suggesting potential coeval activity. Their kinematical compatibility will be discussed in section 5 in order to support the hypothesis of the coexistence of a normal and a strike-slip faulting.

4. LA-ICP-MS U-Pb dating on calcite.

4.1 Sampling

For this study, of the 7 calcite samples tested, only calcite from two samples collected from the pure-normal Fabrika and oblique Palos fault cores (see locations in Figs 3, 4A-B-C and 5A-B-C-D) were dated by the LA-ICP-MS U-Pb method, the others being U-free.

On the Palos site, at the northern extremity of the island, numerous calcite-filled veins are present inside the fault core (Fig. 5A). The thickness of these veins varies between the decimeter and the centimeter (Fig. 5B). These veins show a continuous transition from a stretching vein with delocalized sealing crack to a syntaxial vein where euhedral calcite crystals grow from the wall rock into the vein (Bons et al., 2012; see Fig 5C and close-up in Fig. 5D). Sample SY19-02, which is calcite precipitated as a consequence of fracture opening associated with the NNW-SSE Palos oblique fault, was collected in the partial to perfect sealing zone of one of these veins (Fig. 5C).

In contrast, at the Fabrika site in the southern part of Syros, the dated sample (SY19-10) occurs as a calcite slickenfibers that precipitated along the fault plane of NW-SE Fabrika normal fault (Fig. 4A and B). It is a typical crack-seal-slip calcite mineralization (Petit et al., 1999; Roberts et al., 2022).

Dextral strike-slip faults have not been dated because we did not find any fault core or calcite precipitation associated with these faults. In the present study we will therefore only date the activity of high-angle normal faults. We will then discuss the relationship between high-angle normal faults and dextral strike-slip faults, and hence by extrapolation discuss the age of the overall fault pattern in the northern Cyclades.

4.2 Instrumentation and analytical method

Carbonate U-Pb dating was carried out using Laser Ablation-Inductively Coupled Plasma Spectrometry (LA-ICP-MS) at the Laboratoire Magmas et Volcans (Clermont-Ferrand, France). Small centimeter-size fragments of two samples were mounted in a 25 mm diameter epoxy resin disc and were polished to a 1 µm finish.

Carbonate samples were ablated under pure He using a Resonetics Resolution M-50 system equipped with a 193 nm Excimer laser coupled to a Thermo Element XR sector field ICP-MS using a jet interface high-capacity pumping device in combination with X cones. N2 was supplemented to Ar and He carrier gas for sensitivity enhancement (Paquette et al., 2014). The laser operated with a spot diameter of 120 µm, a repetition rate of 10 Hz, and a fluence of 3.5 J/cm2 for both samples and reference materials. The mass spectrometer was tuned to maximize the 238U intensity and minimize ThO+/Th+ (<1%) using the NIST SRM 612 glass. Background levels were measured on-peak with the laser off for ~30 s, followed by ~60 s of measurement with the laser firing and then ~10 s of washout time (Hurai et al. 2010). The ^{235}U signal is calculated from ^{238}U based on the ratio ^{238}U/^{235}U = 137.818 (Hiess et al. 2012). Each analytical session consists of a repetition of blocks comprising two NIST 614 reference material, four WC-1 reference material and four unknowns.

Given that there is no available carbonate reference material yielding a concordant U-Pb age, dating of carbonates requires a two-steps data normalization procedure approach consisting of (i) ^{207}Pb/^{206}Pb mass bias correction based on a NIST 614 standard glass and (ii) a U/Pb inter-element fractionation correction based on the lower intercept age in the Tera Wasserburg isotopic space using the WC-1 calcite matrix-matched reference material. The data reduction method strictly follows the one described in Roberts et al. (2017). Gas-blank-corrected intensities, raw ratios and uncertainties are injected into an in-house spreadsheet based on Microsoft Excel following the protocols of Roberts et al. (2017). The ratio uncertainties of reference standards ($^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ values of NIST 614 and WC-1) and the excess scatter of the reference standard (NIST 614) are propagated into the uncertainties of WC-1 and unknown analyses (samples). After correction by NIST 614 of each $^{238}U/^{206}Pb$ and 207Pb/206Pb ratio of WC-1 and unknown samples, a correction factor is applied to the $^{238}U/^{206}Pb$ ratios of each analysis point. This correction factor is determined from the WC-1 analyses for each analysis session, so that WC-1 gives an age of 254.4 Ma on a Tera Wasserburg diagram, with a initial $^{207}Pb/^{206}Pb$ value anchored at 0.85 (Roberts et al., 2017).

Concentrations of U, Th, and Pb were calculated by normalization to the certified composition of NIST-614 reference material. Tera Wasserburg diagrams and isochron calculation were generated using Isoplot/Ex v. 2.49 software package by Ludwig (2001). Error ellipses for each point are quoted at the 2σ level. Owing to the large analytical uncertainty on the ages, no additional correction for U-Th disequilibria was carried out. Common Pb-corrected $^{206}Pb/^{238}U$ dates for each analytical point were calculated by IsoplotR software package (Vermeesch, 2018) using the initial lead composition ($^{207}Pb/^{206}Pb)_0$ obtained by isochron regression (Table SM 1). ~~The binned frequency histograms coupled with a Kernel-Density Estimators (KDE) plots were generated with the same software package.~~

4.3 LA-ICP-MS U-Pb dating results

All data obtained for the two carbonate samples are presented in supplementary material (Table SM 1). Uranium contents of the sample SY19-02, ranging from 0.5 and 3.5 ppm, are relatively homogenous and low (average value = 1.8 ppm), whereas U contents of the sample SY19-10 have a wider range, with a large majority of slightly higher values (between 0.06 and 6.3 ppm; average value = 3.0 ppm) and few very high values (46-50 ppm) (Table SM1). Pb concentrations are also variable from sample to sample. They are on averaging very low about 0.1 ppm (between 0.01 and 0.66 ppm) for sample SY19-02 whereas those of sample SY19-10 are between 0.06 and 14.22 ppm (average value = 4.30 ppm). For the common Pb-corrected ^{206}Pb/^{238}U dates of these two samples, the dates are ranging between 9.17 and 11.31 Ma (SY19-02) and between 9.88 and 10.42 Ma (SY19-10). All the data not corrected for common Pb are plotted in Tera Wasserburg concordia diagrams (^{207}Pb/^{206}Pb ratios vs. ^{238}U/^{206}Pb ratios) (Fig. 7A and B). Of the 40 measured analyses for sample SY19-02, 16 have large uncertainties (arbitrarily chosen for ≥50% for ^{207}Pb/^{235}U) and are discarded (dashed ellipses) for the linear regression calculation. Similarly, only one of the 17 data was not taken account for the age calculation of sample SY19-10. Note that the elimination of these data has little influence on the final date. Unconstrained linear regression on these data yields a lower intercept date of 9.3 ± 1.7 Ma with an upper intercept ^{207}Pb/^{206}Pb composition of 0.82 ± 0.01 (MSWD = 0.11; N = 24) for sample SY19-02 and a lower intercept of 9.7 ± 1.8 Ma with a ^{207}Pb/^{206}Pb ratio at the upper ordinate of 0.76 ± 0.01. (MWSD = 0.34; N = 16), for sample SY19-10 (Fig. 7A and B). Both lower intercept dates are similar in their error bars, at c.a. 10 Ma (Fig. 7A and B).

5. Discussion

5.1 Offshore and onshore faulting pattern and kinematics of the North Cyclades

Figure 8 presents a synthesis of the fault pattern inferred from seismic lines and onshore study in Syros.

5.1.1/ High-angle normal faults

High-angle normal faults interpreted from Syros and offshore seismic profiles in the Cyclades (red faults, Fig. 8) show consistent direction with a dominant direction, mainly trending NW-SE with an evolution towards NNW-SSE. Normal faults appear to be presently active offshore, with marked bathymetric signatures. Slickenlines observed on Syros show a pure or near pure vertical slip on the NW-SE fault set (e.g. Fig. 4), and a sinistral oblique slip on the NNW-SSE fault set (e.g. Fig. 5). Additionally, the pull-apart structure in Fabrika (Fig. 4) shows an older sinistral fault trending NNW-SSE with a later extensional structure trending NW-SE. This faulting pattern is consistent with previous studies (Mascle and Martin, 1990; Gautier and Brun, 1994; Graseman et al., 2012). The novelty of our study is to provide a higher resolution offshore and to provide accurate direction of stretching (slickelines in Syros, see discussion in 5.1.3). For example, the northern part of Syros is a horst while the southern part has several tilted blocks (Figs. 3 and 8). The geometry of the northern part of Syros is consistent with the presence of a horst: northeast-trending foliation, numerous normal faults dipping southwards (Fig. 3). The north-dipping border fault is not present onshore and is only inferred offshore. The occurrence of the Kini anticline and the overall foliation trend can be a good indicator of this horst-type geometry (see Philippon et al., 2015). The interplay between normal faults and NNE-SSW dextral strike-slip faults may further explain the non-symmetrical aspect of the Kini anticline (Fig. 3 and discussion in Philippon et al. 2015). In the southern part of Syros, tilted blocks can be identified with only southward high-angle dipping normal faults. This is consistent with the inferred offshore graben between Syros and Serifos/Kithnos (Fig. 8).

5.1.2/ Dextral strike-slip faults

The major novelty of this study is also to show that strike-slip faulting is widespread in the Northern Cyclades and is always associated with high-angle normal faulting, both onshore and offshore (blue faults, Fig. 8). For example, in Syros, minor NE-SW strike-slip faults have been identified, with a dextral shear sense. A major strike-slip zone limits the Cyclades, from Attica to the West, with a segment apparently trending NNE-SSW (e.g. CDL (Cava Doro-Lesvos) fault identified in Sakellariou and Tsampouraki-Kraounaki, 2018; see Figs 1 and 8). Previous studies on active tectonics of the Aegean have shown strike-slip faulting mainly in the North Aegean, north of the Cyclades (e.g. earthquakes located north of Skyros with dextral strike-slip focal mechanisms, Taymaz et al., 1991).

We propose here that strike-slip faults are not only present in the northern Aegean but also in the Cyclades, as well as in Attica (Pelagonian fault, Faucher et al., 2021). These strike-slip faults in the central Aegean are mainly trending NNE-SSW to NE-SW and have a dextral offset. We propose that, in the Cyclades, this strike-slip faulting pattern is controlled by a main strike-slip displacement along a NNE-SSW trending plane (thick blue lines, parallel to the CDL, Pealognian fault, Fig. 8) and minor strike-slip displacement along NE-SW trending plane (thin blue line, Fig. 8). Here the strike-slip faults inferred in and west of Syros are Riedel shears type R (see tectonic sketch in inset at the scale of the Cyclades, Fig. 8).

5.1.3/ Strain tensor and kinematics

This study on Syros allows quantifying strain tensors and associated kinematics for the faulting pattern. The strain tensors showed a NE-SW stretching for both normal faults (Palos and Fabrika, stereoplots in Figs. 4 and 5) and a more N-S stretching associated with E-W shortening for strike-slip at Syros (stereoplot in Fig. 6). The strain tensor calculated with the three sets of faults observed in Syros show that they are compatible and associated with a NNE stretching λ_1, a main subvertical shortening λ_3 (since the majority of data are normal faults) and minor E-W shortening associated with λ_2 (Syros tectonics inset, Fig. 3). In this tectonic setting, NNW-SSE faults exhibit both normal and oblique (sinistral) slips.

The strain kinematics on the scale of the Northern Cyclades cannot be quantitatively inferred from fault data but it can be outlined by the three sets of faults identified. The major dextral strike-slip faults are trending NNE-SSW with Riedel shears type R oriented NE-SW (like the one observed in Syros). This suggests an almost N-S extension and an E-W shortening. These principal stress directions are different from those obtained at Syros. This difference can be explained by the presence of the Riedel shears type R at Syros that produces a local stress rotation (Northern Cyclades tectonics inset, Fig. 8).

5.1.4/ Northern Cyclades tectonics

On this basis, we propose that the normal faults together with the dextral strike-slip are compatible and reflect N-S extension and E-W shortening. Due to local stress rotation, pure normal faults are oriented NW-SE at Syros and almost E-W in the Northern Cyclades, as shown by the horst at Giaros/Syros, and the deep Myrtoon basin (Fig. 8). Normal faults define regularly spaced horst and graben (e.g. wide rift, Buck, 1991). Based on their compatibilities and on the absence of crosscutting relationship, we propose moreover that normal and strike-slip faults were active at the same time. During finite strain, clockwise rotation occurs and likely explains the variety of strikes of normal faults from E-W/NW-SE (pure normal in red, Fig. 8) to NNW-SSE (oblique-sinistral, in black, Fig. 8).

We will now discuss the chronology of the development of this faulting pattern, including the first results obtained by LA-ICP-MS U-Pb dating of calcite that precipitated in two fault zones in Syros.

5.2 Interpretation of U-Pb dates: ages of high-angle normal faulting in Syros

Only calcite sampled along the fault zones belonging to the Fabrika high-angle pure normal fault and the Palos high-angle oblique (sinistral) normal fault could be dated by the LA-ICP-MS U-Pb method. The Fabrika calcite (SY19-10) occurs as slickenfibers, whereas the Palos calcite (SY 19-02) is located in fault-related opening-mode fractures as veins.

For both samples, the binned frequency histograms coupled with KDE plots of Pb-corrected common ages suggest the presence of a single analysis population with a peak date of c.a. 10 Ma (Fig. 7A). LA-ICP-MS U-Pb dating of calcite from these two samples yielded similar lower intercept dates (within analytical uncertainties) at 9.3 ± 1.7 Ma (sample SY19-02) and 9.7 ± 1.8 Ma (sample SY19-10) for the Palos and Fabrika faults, respectively (Fig. 7B and C).

Dating of the calcite precipitates type crack-fill, like those associated with the Palos fault (SY19-02 sample), is the least reliable techniques for obtaining robust constraints on fault slip. However it can provide minimum dates of fault slip (Roberts et al, 2020, 2022). Indeed, the time gap between fault slip and precipitation in an open fracture void can be prolonged and could be much greater than the uncertainty of the dating method. The vugs may remain open to the present day, or be obstructed by calcite or other minerals.

On the other hand, Robert et al (2022) suggest that crack-seal-slip veins are most advisable for direct dating methods because, they are the most easily identifiable as syn-kinematic. The calcite slickenfibers (SY19-10 sample) grown along the Fabrika fault plane belong to this category. Both lower intercepts at c.a. 10 Ma obtained by U-Pb dating on calcite are interpreted as a minimum estimation for the age of (re)crystalization of calcite, which may have been associated either to fault motion or fluid-flow post-slip with U and Pb mobilisation. It is therefore reasonable to assume that the Fabrika high-angle pure normal fault and the Palos high-angle oblique (sinistral) normal fault have been active for at least 9-10 Ma and have recorded the same Miocene event (c.a. 10 Ma).

Moreover, Fabrika sample SY19-10 shows a significantly lower initial (i.e. common) Pb ratio ((^{207}Pb/^{206}Pb)$_0$ = 0.76 ± 0.01) than that estimated using the traditional two-stages terrestrial Pb evolution model (~ 0.836 for Miocene samples; Stacey and Kramers, 1975). Such isotopic ratios for young calcite are already described in the literature, but the underlying process is not yet well understood. In our case, this low ratio could perhaps suggest that fluids from which the calcite precipitated contained abundant radiogenic lead. A ~~It is likely that a~~ significant amount of deep-seated fluid-rock interaction could have occurred prior to the formation of the calcite vein ~~precipitation~~. Indeed, the hypothesis of a Pb loss that could have been thermally activated after calcite precipitation is considered unlikely to explain this low initial Pb ratio, as the diffusive mobility of Pb is very slow in brittle conditions at temperatures below ~ 400°C (Cherniak, 1997). However, this hypothesis needs to be confirmed.

5.3 Age of faulting in the Cyclades.

Our two U-Pb ages obtained on calcite precipitates sampled in both pure normal and oblique (sinistral) normal faults constrained their activity during at least the late Miocene times (c.a. 10 Ma, Figs. 7 and 8). The faulting pattern drawn in Figure 8, with coeval activity of high-angle normal faults and dextral strike-slip faults, therefore develops during the Late Miocene.

Previous studies have consistently proposed dextral strike-slip faulting during the late Miocene in the Cyclades. Kokkalas and Aydin (2013) have analyzed syn-tectonic plutons in the Central Aegean, at Ikaria, Tinos, Naxos and Serifos (reported on Figure 8 as red stars). These plutons are dated with varying methods (Kokkalas and Aydin, 2013) between 14 and 9 Ma (ages reported on Fig. 8). Naxos pluton is affected by NE-SW dextral strike-slip (plotted on Figure 8). Ikaria plutons are marked by a major NNE-SSW dextral strike-slip, most probably linked to a major dextral transfer zone in Turkey. Tinos and Mykonos plutons are more affected by NNW-SSE sinistral strike-slip and normal faults, which are well related to what we observed at Syros (Palos normal and oblique sinistral fault) and Fabrika (NNW-SSE sinistral strike-slip associated with NW-SE normal fault in pull-apart basin). Our structural features are therefore highly consistent and independently confirmed by this previous study. In addition, the deformation of plutons during emplacement argues a late Miocene age, independently validating the 10 Ma calcite U-Pb age we propose as the age of faults motion.

In Continental Greece, Faucher et al. (2021) proposed also in Evia and Attica that the Pelagonian fault acted as a major dextral strike-slip during late Miocene and the deposition of the late Miocene Kimi basin (Fig. 8). Structural data and low-temperature thermochronology ages further show that these strike-slip faults developed coevally with NW-SE trending normal faults. In Turkey, calcite U-Pb ages in the North Anatolian Fault in Turkey at around 10-11Ma show moreover that strike-slip faulting occurs much older than plio-quaternary (Nuriel et al., 2019).

Kokkalas and Aydin (2013) have shown that this strike-slip activity in the Cyclades continues to the present-day, based on structural analysis of quaternary volcanism and on seismo-tectonic analysis in southern Cyclades. We can therefore propose that our tectonic framework developed at least 10 Ma and is representative of the central Cyclades to the present day. This is also consistent with the faulting pattern proposed Sakellariou and Tsampouraki-Kraounaki (2018) for Plio-Quaternary (e.g; Fig 1).

5.3 Detachment faulting or high-angle normal faulting

The faulting pattern identified in this study, both onshore and offshore, shows only high-angle faults and no low-angle normal faults (e.g. detachment fault). Ductile exhumation of the Cycladic Blueschist Unit (CBU) is however proposed to be partly accommodated by detachment faults (see Jolivet et al., 2013 and Graseman et al., 2012 for a synthesis): the North Cycladic detachment, the Vari detachment (in Syros), the South Cycladic detachment, and the Cretan detachment (in Crete). These detachment faults accommodated the ductile exhumation of the CBU since Oligocene times and are assumed to be still active until early Miocene to late Miocene (e.g. zircon and apatite fission-track: 9-12 Ma in Syros for the Vari detachment, Ring et al., 2003). High-angle normal faults and detachment faults mechanically interact and define the Miocene tectonics of the Aegean (Graseman et al., 2012; Menant et al., 2013).

The offshore seismic lines used here were most probably too shallow to allow identification of structures inside the Cycladic Blueschist Unit that is the basement of the sediments. We have therefore focused our study here on high-angle normal and strike-slip faults at Syros to correlate them with the offshore data. This brittle faulting pattern, identified and marked by the coeval activity of strike-slip and high-angle normal faults, is dated at 10 Ma by our new U-Pb ages on calcite. These normal faults will allow unroofing of Cycladic units to the last km, providing a possible explanation for the cluster of low-temperature ages at 10 Ma (Fig. 1). We propose that our U-Pb ages on calcite as well as the low-temperature ages group therefore mark the onset of distributed high-angle faulting in the Cyclades, as previously suggested by Philippon et al. (2012) and Brun et al. (2016). Consistently, the transition from low-angle detachment to high-angle normal faulting was also documented by fission track thermochronology on Naxos at about 10 Ma (Seward et al., 2009). This high angle normal faulting can occur coevally with detachment faulting, as suggested by Menant et al. (2013) in Mykonos.

5.4 Roll-back, extrusion: high-angle normal faulting and strike-slip faulting during Miocene in the Aegean

Aegean extension started around Eocene times and controlled by trench retreat driven by slab roll-back (Brun et al., 2016). It occurs at a relatively low rate from Eocene-Oligocene to mid-Miocene (0.6 cm/yr) and is accommodated by ductile detachment faulting (Brun et al., 2016). At c.a. 15 Ma, the style of Aegean extension was modified by two main events. Firstly, trench retreat increased (from 1.7 cm/yr in late Miocene to 3.2 cm/yr today), most probably due to a change in slab roll back (slab tear, Royden and Papanikolaou, 2011). This increase in extension rate may trigger a switch from a Metamorphic Core Complex style (with detachment faulting) to a wide rifting style with high-angle normal faulting (Buck, 1991; Gueydan et al., 2008). Secondly, the onset of Anatolia extrusion (Sengör et al., 2005) leads to the formation of numerous strike-slip zones inside the hotly deforming Aegean plate (Kokkalas and Aydin, 2013; Philippon et al., 2014). On these bases, we can propose that the fault patterns constrained and dated in central Greece entirely reflect the modification in the geodynamical setting occurring in middle-late Miocene. Dextral strike-slip faults accommodated Anatolia extrusion, while the wide rifting with high-angle normal faults and regularly spaced horsts and grabens accommodated the trench retreat at a high rate.

Note that alternatively, orogenic gravitational collapse without Anatolia extrusion, with North-South extension (and locally East-West extension) accommodated by strike slip faulting can also explain the Miocene tectonic patterns, as discussed in Gautier et al., 1999; Vanderhaeghe et al., 2007; Vanderhaeghe and Teyssier, 2001.

Finally, a more recent kinematic reorganisation (in Pleistocene, Armijo et al., 1999), most probably related to slab tear below Kephalonia (Royden and Papanikolaou), 2011, would explain the progressive localization of strain in the North Anatolia fault, in the Corinth rift and in Kephalonia (Perouse et al., 2012).

6 Conclusion

We have combined offshore seismic interpretation, structural data from Syros and LA-ICP-MS U-Pb dating on calcite precipitates from two Syros fault zones to characterise and date fault pattern and kinematics in the central Cyclades. We draw the following conclusions:

- The Cyclades shows three coexisting fault sets: pure normal faults trending E-W to NW-SE; oblique (sinistral-normal) faults trending NNW-SSE and dextral strike-slip faults trending NNE-SWW to NE-SW.
- For the first time, direct dating of high-angle normal faults in the Cyclades has been carried out using the LA-ICP-MS U-Pb method on calcite yielding a minimum age of c.a. 10 Ma.
- Normal faults are accommodating by slab rollback at a high rate since 15 Ma, forming wide rifting style of extension.

- Dextral strike-slip faults accommodated Anatolia extrusion that also started 15 Ma ago.

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Figure captions

Figure 1 : Tectonic map of the Aegean domain and of Continental Greece with reported active plio-Quaternary faults (strike-slip faults in dark gray, normal faults in red; from Sakellariou and Tsampouraki-Kraounaki, 2018). The main strike-slip faults: North Anatolian fault, SB: Skyros-Biga, Pelagonian fault, CDL: Cava Doro-Lesvos, MI: Myrtoon-Ikaria. The main rift systems: Corinth and Evvia rifts. References for low-temperature data (shown as triangles, stars, diamonds and squares, respectively for Apatite fission tracks, Zircon fission tracks, (U-Th)/He on Zircon and (U-Th)/He on Apatite) can be found in Faucher et al., (2021). Blue arrow: average directions of Anatolia westward extrusion and read arrow: southward Hellenic trench retreat related to slab rollback (Reilinger et al., 2006).

Figure 1 : Carte tectonique du domaine égéen et de la Grèce continentale avec les principales failles actives plio-quaternaires (failles décrochantes en gris foncé, failles normales en rouge ; d'après Sakellariou et Tsampouraki-Kraounaki, 2018). Les principales failles de décrochement : Faille nord-anatolienne, SB : Skyros-Biga, Faille pélagonienne, CDL :

Cava Doro-Lesvos, MI : Myrtoon-Ikaria. Les principaux systèmes de rift : Rifts de Corinthe et d'Evvia. Les références pour les données à basse température (représentées par des triangles, des étoiles, des diamants et des carrés, respectivement pour les traces de fission de l'apatite, les traces de fission du zircon, le (U-Th)/He sur le zircon et le (U-Th)/He sur l'apatite) peuvent être trouvées dans Faucher et al. (2021). Flèche bleue : directions moyennes de l'extrusion de l'Anatolie vers l'ouest et flèche rouge : retrait du fossé hellénique vers le sud lié au retournement de la plaque (Reilinger et al., 2006)..

Figure 2 : Offshore seismic data analysis. A/ Tectonic map of the Central Cyclades (EMODnet Bathymetry 2021 emodnet-bathymetry.eu). Seismic lines used in this study from the Hellenic Centre for Marine Research-H.C.M.R, shown in white with corresponding numbering (see all lines in Supplementary Materials, Figs S1 to S17). Inferred faults from the analysis in seismic lines: boxes for fault observed on seismic lines (red for normal fault, blue for strike-slip fault). Red/blue lines for inferred normal/strike-slip faults by correlation between seismic lines and bathymetry signature. B/ Seismic line number 14 (location in A/) with interpretation. C/ Interpretation of a negative flower structure observed in B/. D/ Seismic line number 3 (location in A/) with interpretation.

Figure 2 : Analyse des données sismiques offshore. A/ Carte tectonique des Cyclades centrales (EMODnet Bathymetry 2021 emodnet-bathymetry.eu). Les lignes sismiques utilisées dans cette étude proviennent du Centre hellénique de recherche marine (Hellenic Centre for Marine Research-H.C.M.R) et sont représentées en blanc avec la numérotation correspondante (voir toutes les lignes dans les matériaux supplémentaires, Figs S1 à S17).

Failles déduites de l'analyse des lignes sismiques : carrés pour les failles observées sur les lignes sismiques (rouge pour les failles normales, bleu pour les failles décrochantes). Les lignes rouges/bleues pour les failles normales/décrochantes par corrélation entre les lignes sismiques et la signature bathymétrique. B/ Ligne sismique numéro 14 (emplacement dans A/) avec interprétation. C/ Interprétation d'une structure en fleur négative observée en B/. D/ Ligne sismique numéro 3 (localisation en A/) avec interprétation.

Figure 3 : Simplified tectonics of Syros. A/ Simplified geological map (from Keiter et al., 2011 and Phillippon et al., 2011) with major fault zones observed. Red lines: pure normal faults. Black lines: oblique (normal) faults. Blue lines: dextral strike-slip faults. Boxes: locations of Figures 4, 5 and 6. Stars for locations of the two samples used for LA-ICP-MS U-Pb dating (Figs. 7). B/ Stereoplot (from the entire set of fault data in this study, presented in Figs. 4D, 5E, 6E) for the entire Syros island computed with FaultKin (Marrett and Allmendinger, 1990; Allmendinger, et al. , 2012), suggesting a coeval activity of normal faults and strike-slip faults as shown in the tectonic sketch. C/ Simplified cross-section B-B’ (location in A/) showing tilted blocks associated with high-angle normal faults and the Kini-anticline in the hanging-wall.

Figure 3 : Tectonique simplifiée de Syros. A/ Carte géologique simplifiée (d'après Keiter et al., 2011 et Phillippon et al., 2011) avec les principales zones de faille observées. Lignes rouges : failles normales pures. Lignes noires : failles obliques (normales-décrochantes). Lignes bleues : failles décrochantes dextres. Encadrés : emplacements des figures 4, 5 et 6. Les étoiles indiquent les emplacements des deux échantillons utilisés pour la datation U-Pb par LA-ICP-MS (Fig. 7). B/ Projection stéréo (à partir de l'ensemble des données sur les failles

de cette étude, présentées dans les figures 4D, 5E, 6E) pour l'ensemble de l'île de Syros calculé avec FaultKin (Marrett et Allmendinger, 1990 ; Allmendinger, et al. , 2012), suggérant une activité simultanée de failles normales et de failles décrochantes, comme le montre l'esquisse tectonique. C/ Coupe transversale simplifiée B-B' (emplacement dans A/) montrant des blocs basculés associés à des failles normales à fort pendage et montrant l'anticlinal de Kini dans le mur des failles normales.

Figure 4: Fabrika outcrop description (location in Fig. 3A) for NW-SE trending high-angle pure normal faults. A/ Drone view of the outcrop with main normal faults and joints in red and oblique (sinistral) normal faults in black. White star: location of sample Sy19-10. B/ Photo of a typical NW-SE trending high-angle normal faults with recrystallized fault plane (sample Sy19-10) and slickenlines. C/ Close view of the interplay between oblique and pure normal faults. D/ Stereoplot of the faults data (in red pure normal faults, in black oblique sinistral normal faults, with slickenlines in blue when present) and pole to joints as red dots. E/ Strain tensor calculated from the fault data (in D/) with FaultKin (Marrett and Allmendinger, 1990; Allmendinger, et al. , 2012) suggesting a pure extensional setting, with horizontal NE-SW stretching and vertical shortening.

Figure 4: Description de l'affleurement de Fabrika (localisation dans la Fig. 3A) pour des failles normales pures à fort pendage orientées NW-SE. A/ Vue aérienne de l'affleurement avec les failles normales principales et les fentes de tension en rouge et les failles normales obliques (senestres) en noir. L'étoile blanche indique l'emplacement de l'échantillon Sy19-10. B/ Photo d'une faille normale à fort pendage typique orientée NO-SE avec plan de faille recristallisé (échantillon Sy19-10) et lignes de glissement. C/ Vue rapprochée de

l'interaction entre les failles obliques et les failles normales pures. D/ Projection stéréographique des données sur les failles (en rouge les failles normales pures, en noir les failles normales obliques senestres, avec les stries en bleu lorsqu'elles sont présentes) et les pôles des fentes de tension sous forme de points rouges. E/ Tenseur de déformation calculé à partir des données de failles (en D/) avec FaultKin (Marrett et Allmendinger, 1990 ; Allmendinger, et al. , 2012) suggérant un contexte d'extension pure, avec un étirement horizontal NE-SW et un raccourcissement vertical.

Figure 5: Palos outcrop description (location in Fig. 3A) for NNW-SSE trending high-angle oblique (normal) faults. A/ Satellite image (Google Earth) of the Palos peninsula area with inferred oblique (sinistral) normal faults (in black) and pure normal faults (in red). B/ Close view of one major fault plane with gouge, breccia and open joints with calcite precipitation (sample Sy19-02). C/ Details from B/ of an oblique slickenlines on the fault plane. D/ Details from B/ of open joints with calcite (location of sample Sy19-02). E/ Stereoplot of the faults data (in red pure normal faults, in black oblique sinistral normal faults, with slickenlines in blue when present) and pole to joints as red dots. F/ Stain tensor calculated from the fault data (in E/) using FaultKin with FaultKin (Marrett and Allmendinger, 1990; Allmendinger, et al. , 2012), suggesting oblique extensional setting, with horizontal NE-SW stretching and sub vertical shortening.

Figure 5: Description de l'affleurement de Palos (localisation dans la Fig. 3A) pour les failles obliques (normales) à fort pendage orientées NNW-SSE. A/ Image satellite (Google Earth) de la région de la péninsule de Palos avec des failles normales obliques (senestres) présumées (en noir) et des failles normales pures (en rouge). B/ Vue rapprochée d'un plan

de faille majeur avec gouge, brèche et fentes de tension ouvertes avec précipitation de calcite (échantillon Sy19-02). C/ Détails de B/ d'une strie oblique sur le plan de faille. D/ Détails de B/ de fentes de tension ouvertes avec précipitation de calcite (emplacement de l'échantillon Sy19-02). E/ Projection stéréographique des données sur les failles (en rouge les failles normales pures, en noir les failles normales senestres obliques, avec les stries en bleu lorsqu'elles sont présentes) et le pôle des fentes de tension sous forme de points rouges. F/ Tenseurs de Tenseur de déformation calculé à partir des données de failles (en E/) en utilisant FaultKin avec FaultKin (Marrett et Allmendinger, 1990 ; Allmendinger, et al. , 2012), suggérant un contexte d'extension oblique, avec un étirement horizontal NE-SW et un raccourcissement subvertical.

Figure 6: Central Syros outcrop description (location in Fig. 3A) for NE-SW trending dextral strike-slip faults. A/ Satellite image (near Episkopeio and Kini) with observed and inferred dextral strike-slip faults (in blue) offsetting marble layers (drawn in white dashed line) and high-angle normal faults in red. B/ Satellite image (north of Ermopouli, near Papouri Episkopeio and Kini) with observed and inferred dextral strike-slip faults (in blue) offsetting marble layers (drawn in white dashed line) and oblique (sinistral) normal faults in black. C/ Fault plane (location in A/) with observed oblique slickenlines. D/ Example of dextral strain corridor (location in B/) with en-échelon joints showing dextral motion. E/ Stereoplot of the faults data (in red pure normal faults, in black oblique sinistral normal faults, and in blue dextral strike-slip faults with slickenlines when present) and pole to joints as red dots. F/ Strain tensors calculated from the fault data (in E/) using FaultKin

(Marrett and Allmendinger, 1990; Allmendinger, et al. , 2012), suggesting dextral strike-slip setting, with horizontal N-S stretching and E-W horizontal shortening.

Figure 6: Description des affleurements du centre de Syros (localisation dans la Fig. 3A) pour les failles de décrochantes dextres orientées NE-SW. A/ Image satellite (près d'Episkopeio et de Kini) avec des failles décrochantes dextre observées et déduites (en bleu) décalant des couches de marbre (dessinées en pointillés blancs) et des failles normales à fort pendage en rouge. B/ Image satellite (au nord d'Ermopouli, près de Papouri Episkopeio et Kini) avec des failles décrochantes dextre observées et déduites (en bleu) décalant des couches de marbre (dessinées en pointillés blancs) et des failles normales obliques (sinistrées) en noir. C/ Plan de faille (emplacement en A/) avec stries obliques observées. D/ Exemple de couloir de déformation décrochant dextre (emplacement en B/) avec des fentes en-échelon montrant un mouvement dextre. E/ Projection stéréographique des données sur les failles (en rouge les failles normales pures, en noir les failles normales obliques senestres, et en bleu les failles décrochantes dextre avec les stries lorsqu'elles sont présentes) et le pôle des fentes de tension sous forme de points rouges. F/ Tenseur de déformation calculé à partir des données des failles (en E/) à l'aide de FaultKin (Marrett et Allmendinger, 1990 ; Allmendinger, et al. , 2012), suggérant un décrochement dextre, avec un étirement horizontal N-S et un raccourcissement horizontal E-W.

Figure 7: LA-ICP-MS U-Pb results obtained on calcite sampled along the Palos (SY19-02) and Fabrika (SY19-10) faults. **A** ~~binned frequency histograms coupled with a Kernel-Density Estimators (KDE) plots with all common Pb-corrected dates for both samples. B~~ and **B**: Tera Wasserburg pots for samples SY19-02 and SY19-10, respectively. Error ellipses and

uncertainties on dates are ± 2σ. Dotted ellipses are not taken into account for the date calculation (see text).

Figure 7 : Les résultats LA-ICP-MS U-Pb obtenus sur les calcites prélevées le long des failles de Palos (SY19-02) et de Fabrika (SY19-10). **A** ~~: les histogrammes de fréquences couplés avec les estimations par noyau (Kernel-Density Estimators: KDE) obtenus avec toutes les données corrigées du Pb commun pour chaque échantillon.~~ **B et B :** Les diagrammes Tera Wasserburg pour les échantillons SY19-02 et SY19-10, respectivement. Les ellipses d'erreur et les incertitudes sur les âges sont à ± 2σ. Les ellipses en pointillées ne sont pas prises en compte pour le calcul des âges (voir texte).

Figure 8 : Synthetic tectonic map of the Central Cyclades and Attica showing major faults inferred from our onshore and offshore study: dextral strike-slip in blue, pure normal faults in red and oblique (sinistral) normal faults in black. Major dextral strike-slip faults: Pelagonian fault, SB, CDL and MI (see Fig. 1). Blue octogones for dated syntectonic plutons suggesting Miocene activity of the Myrthes Ikaria (Kokkalas and Aydin, 2013). Stars for the fault plane dated in this study (high-angle normal fault and oblique (sinitral) normal faults). Inset: tectonic sketch showing the coeval activity of dextral, normal and oblique faults with N-S extension and E-W shortening.

Figure 8 : Carte tectonique synthétique des Cyclades centrales et de l'Attique montrant les failles majeures déduites de notre étude onshore et offshore : décrochement dextre en bleu, failles normales pures en rouge et failles normales obliques (senestres) en noir. Décrochements dextres majeurs : faille pélagonienne, SB, CDL et MI (voir Fig. 1). Octogones bleus pour

les plutons syntectoniques datés suggérant une activité miocène du décrochement MI (Kokkalas et Aydin, 2013). Étoiles : plans de faille datées dans cette étude (failles normales pures à fort pendage et failles normales obliques (senestres)). En médaillon : croquis tectonique montrant l'activité contemporaine des failles dextres, normales et obliques avec extension N-S et raccourcissement E-W.

Supplemantary materials

Table S1: Operating conditions and instrument setting for U-Pb analyses

Table S1 : Conditions opératoires et réglages des instruments pour les analyses U-Pb

Table S2: U-Pb data obtained by LA-ICP-MS on calcite analyses for samples SY19-02 and SY19-10 and for standard WC-1.

Table S2 : Données U-Pb obtenues par LA-ICP-MS sur la calcite pour les échantillons SY19-02 et SY19-10 et pour le standard WC-1.

Figure S1 : Seismic line #1, location on Figure 2A

Figure S1: Ligne sismique #1, localisation sur la Figure 2A

Figure S2 : Seismic line #2, location on Figure 2A

Figure S2: Ligne sismique #2, localisation sur la Figure 2A

Figure S3 : Seismic line #3, location on Figure 2A

Figure S3: Ligne sismique #3, localisation sur la Figure 2A

Figure S4 : Seismic line #4, location on Figure 2A

Figure S4: Ligne sismique #4, localisation sur la Figure 2A

Figure S5 : Seismic line #5, location on Figure 2A

Figure S5: Ligne sismique #5, localisation sur la Figure 2A

Figure S6 : Seismic line #6, location on Figure 2A

Figure S6: Ligne sismique #6, localisation sur la Figure 2A

Figure S7 : Seismic line #7, location on Figure 2A

Figure S7: Ligne sismique #7, localisation sur la Figure 2A

Figure S8 : Seismic line #8, location on Figure 2A

Figure S8: Ligne sismique #8, localisation sur la Figure 2A

Figure S9 : Seismic line #9, location on Figure 2A

Figure S9 : Ligne sismique #9, localisation sur la Figure 2A

Figure S10 : Seismic line #10, location on Figure 2A

Figure S10: Ligne sismique #10, localisation sur la Figure 2A

Figure S11 : Seismic line #11, location on Figure 2A

Figure S11: Ligne sismique #11, localisation sur la Figure 2A

Figure S12 : Seismic line #12, location on Figure 2A

Figure S12: Ligne sismique #12, localisation sur la Figure 2A

Figure S13 : Seismic line #13, location on Figure 2A

Figure S13: Ligne sismique #13, localisation sur la Figure 2A

Figure S14 : Seismic line #14, location on Figure 2A

Figure S14: Ligne sismique #14, localisation sur la Figure 2A

Figure S15 : Seismic line #15, location on Figure 2A

Figure S15: Ligne sismique #15, localisation sur la Figure 2A

Figure S16 : Seismic line #16, location on Figure 2A

Figure S16: Ligne sismique #16, localisation sur la Figure 2A

Figure S17 : Seismic line #17, location on Figure 2A

Figure S17: Ligne sismique #17, localisation sur la Figure 2A

Figure S18 : Mg X-ray map and backscattered electron (BSE) images of a calcite grain from sample SY19-10, collected at the Fabrika site. This sample occurs as a calcite slickenfibers that precipitated along the fault plane of NW-SE Fabrika normal fault. It is a typical crack-seal-slip calcite mineralization.

Optical photograph, and cathodoluminescence (CL) and backscattered electron (BSE) images of an euhedral calcite crystal from one of the many calcite-filled veins present inside the Palos fault core. Sample SY19-02 is relatively impurity-free calcite which precipitated following the opening of a fracture associated with the NNW-SSE Palos oblique fault, and was collected in the partial to perfect sealing zone of one of these veins. These two dated samples clearly show the presence of a single homogeneous calcite population in both cases.

Figure S18 : Cartographie X de la répartition du Mg et imagerie en électrons rétrodiffusés (BSE) d'un grain de calcite de l'échantillon SY19-10, prélevé sur le site de Fabrika. Cet échantillon provient d’une calcite qui a précipitée sur une strie du plan de faille normale NW-SE de Fabrika. Il s'agit d'une minéralisation typique de calcite de type fracture-colmatage-glissement.

Photographie optique, imagerie en cathodoluminescence (CL) et d'électrons rétrodiffusés (BSE) d'un cristal de calcite euédrique provenant d'une des nombreuses veines remplies de calcite présentes à l'intérieur du cœur de la faille de Palos. L'échantillon SY19-02 est une calcite relativement exempte d'impuretés qui a précipitée suite à l'ouverture d'une fracture associée à la faille oblique NNW-SSE de Palos, et qui a été prélevée dans la zone de colmatage partiel à total d'une de ces veines. Ces deux échantillons datés montrent clairement la présence d’une seule et unique population de calcite homogène dans les deux cas.