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SPECIAL

The weak and superfast Cretan detachment, Greece: exhumation at subduction rates in extruding wedges

U. RING & T. REISCHMANN*
Institut für Geowissenschaften, Johannes Gutenberg-Universität, 55099 Mainz, Germany
(e-mail: ring@mail.uni-mainz.de)
**Also at: Max-Planck-Institut für Chemie, Abteilung Geochemie, 55020 Mainz, Germany*

Low-angle normal faults (detachments) are only efficient agents for bringing rocks from 40–>100 km depth back to the Earth's surface if they operate with extreme slip rates exceeding 20 km Ma^{-1}. Here we propose a slip rate of ≧20–30 km Ma^{-1} for the Cretan detachment in the Aegean, Greece. The Cretan detachment and the subjacent subduction thrust bounded an extruding wedge above the Miocene Hellenic subduction zone. During exhumation the high-pressure rocks in the wedge were not significantly deformed. Very low shear coupling at the bounding faults (which are therefore weak) is needed to prevent significant deformation in the extruding wedge. The proposed slip rate of ≧20–30 km Ma^{-1} is similar to the subduction rate of 35–45 km Ma^{-1} at the Hellenic subduction zone. We argue that extruding wedges can only slip at rates similar to subduction rates if there is very low shear coupling at the bounding faults, which may also explain the paradox of almost non-deformed but very rapidly exhumed rocks.

Keywords: Greece, exhumation, high-pressure, metamorphism, tectonic wedges, extension.

Normal faulting is a widely envisioned process for exhuming high- and ultrahigh-pressure rocks (Platt 1986). Some normal faults are weak and formed with a low-angle (>30–45°) geometry for the basal cut-off (Davis & Lister 1988; Wernicke 1995). Low-angle normal faults form the upper boundary of so-called extrusion wedges above subduction zones. The low-angle normal faults are subparallel to the subjacent subduction thrusts (Fig. 1). Extrusion wedges are thought to play an important role in the exhumation of high- and even ultrahigh-pressure rocks (Chemenda *et al.* 1995; Thomson *et al.* 1999; Hacker *et al.* 2000). For some high- and ultrahigh-pressure rocks exhumation rates of up to 30–35 km Ma^{-1} have been proposed (Duchêne *et al.* 1997; Wallis *et al.* 1998; Rubatto & Herrmann 2001). Such extreme exhumation rates demand very great slip rates and large displacements at both low-angle faults that bound an extrusion wedge (Fig. 1).

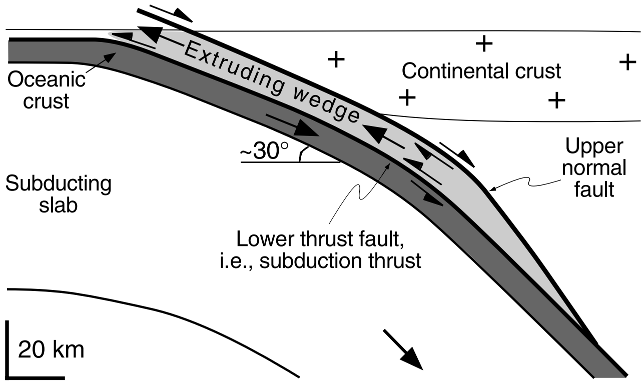

Fig. 1. Schematic sketch of an extrusion wedge in a subduction setting. The wedge is defined by the subduction thrust at the base and a normal fault at the top. Recent work suggests that 30–45° dipping extrusion wedges may cause extremely fast (up to 30–35 km Ma^{-1}) exhumation of high- and ultrahigh-pressure rocks. For such cases, envisioned slip rates at the bounding thrust and normal faults must be up to 40–70 km Ma^{-1}.

Large displacements on low-angle normal faults were reported for instance from the Buckskin–Rawhide detachment (*c.* 90 km; Spencer & Reynolds 1991) and the Whipple detachment (>40 km; Lister & Davis 1989) in the Basin-and-Range province of the western United States. Some of these large-displacement detachments operated at slip rates of 7–9 km Ma^{-1}, but most have significantly smaller rates (Foster & John 1999). In Greece, a displacement of *c.* 50 km and a slip rate of 15 km Ma^{-1} was reported from the Khelmos detachment in the Corinth–Patras rift (Sorel 2000). Recently, a displacement of ≧100 km was proposed for the Cretan detachment in the Aegean (Ring *et al.* 2001) (Fig. 2). Herein, we further explore the tectonic implications of the large displacement and estimate slip rates for the Cretan detachment.

The Cretan detachment. Recent studies proposed that the Cretan detachment is a shallowly north-dipping normal fault, which formed subparallel to the subjacent subduction thrust in the Early Miocene (Fassoulas *et al.* 1994; Jolivet *et al.* 1996; Thomson *et al.* 1998) (Fig. 2). The work by Jolivet *et al.* (1996) and Thomson *et al.* (1998, 1999) implies very large displacement at the Cretan detachment. Accounting for the post-Early Miocene stretching in the Aegean, the implied large-scale displacement demands that the Cretan detachment must be underlying the Cyclades as proposed by Ring *et al.* (2001) (Fig. 2).

The Cretan detachment and the subjacent subduction thrust defined an extruding wedge above the southward retreating Hellenic subduction zone (Thomson *et al.* 1999). The Cretan detachment separates the external high-pressure belt in its lower plate from non-metamorphosed rocks in the upper plate. The high-pressure rocks of the external belt on Crete equilibrated at pressures of *c.* 1 GPa and temperatures of 350–400 °C at 20–24 Ma (Seidel *et al.* 1982; Thomson *et al.* 1998). Early Miocene movement on the Cretan detachment started during high-pressure metamorphism, lasted for *c.* 3–5 Ma and achieved *c.* 90% of the exhumation of the external high-pressure belt from *c.* 40 km depth (Jolivet *et al.* 1996; Thomson *et al.* 1998, 1999). The rocks in both plates of the Cretan detachment were exceptionally weakly deformed during extensional faulting and exhumation (Stöckhert *et al.* 1999). This

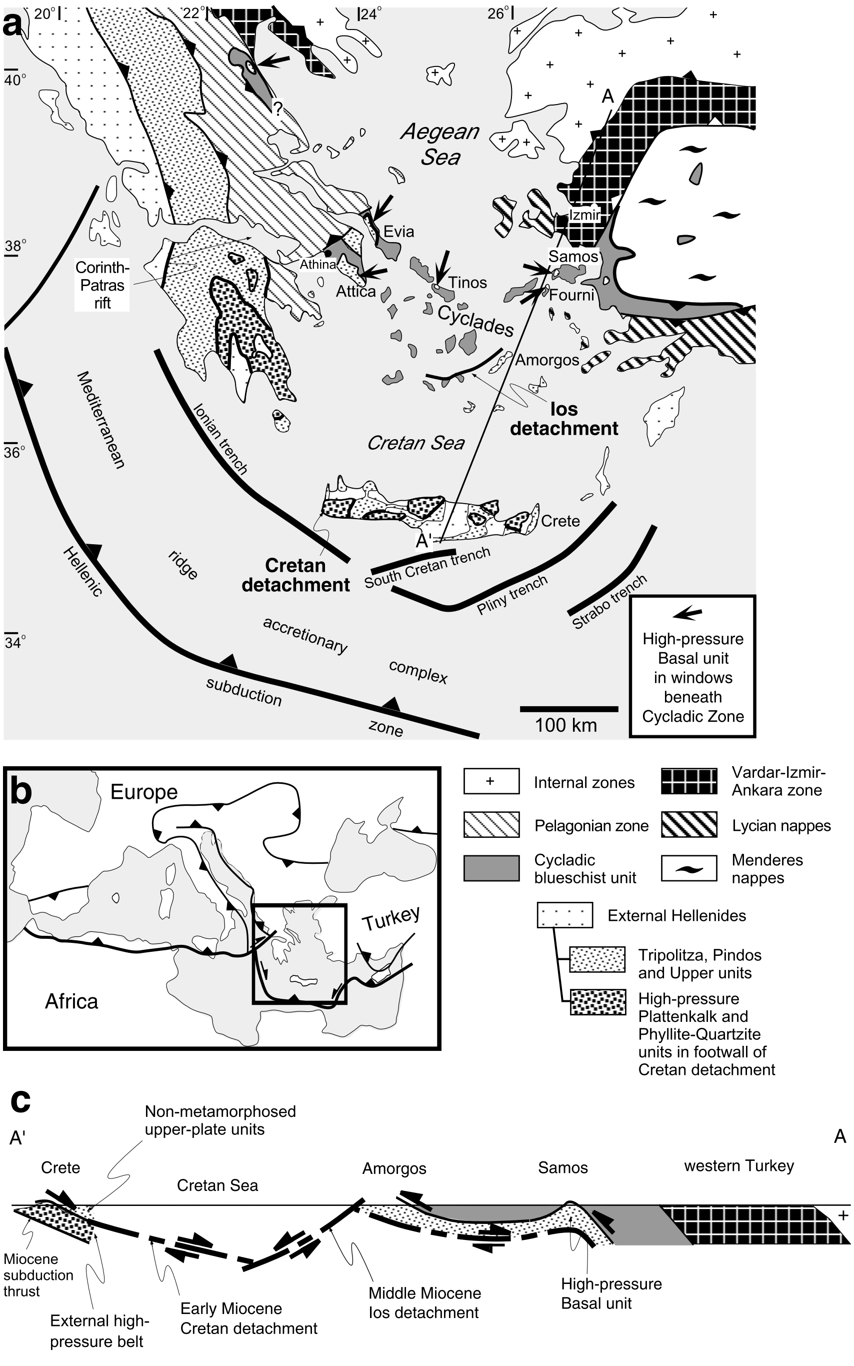

Fig. 2. (**a**) Generalized tectonic map of the Aegean (modified from Ring *et al.* 1999*a*). The Cycladic blueschist unit, which has a Late Cretacous to Eocene high-pressure overprint, is fringed to the north by the oceanic Vardar–Izmir–Ankara suture zone and the continental Pelagonian zone/Lycian nappes. The Basal unit of the Cyclades is part of the External Hellenides and crops out below the Cycladic blueschist unit in some windows (arrows show Olympos and Attica windows on Greek mainland, Almyropotamus and Panormos windows on Evia and Tinos islands and Kerketas nappe on Samos and Fourni islands). On Crete, the External Hellenides are made up of unmetamorphosed units in the upper plate of the Cretan detachment and the external high-pressure belt below the Cretan detachment. High-pressure metamorphism in the external high-pressure belt is dated at *c.* 20–24 Ma (Seidel *et al.* 1982). The present distance from the Cretan high-pressure rocks to the exposures of the Basal Unit in the northern Cyclades is on the order of 200–250 km. (**b**) Miocene to Recent thrust fronts in Mediterranean region and location of main map. (**c**) NE–SW cross section showing nappe pile and position of Cretan detachment with high-pressure metamorphic Basal unit in the Cyclades and non-metamorphosed units on Crete in the upper plate. The Cretan detachment is crosscut by younger Ios detachment (Forster & Lister 1999), which brings the Cretan detachment into a relatively high position in the Cyclades.

indicates that exhumation-related deformation was concentrated in the *c.* 0.5–10 m thick detachment, which therefore must have been weak and flowed at low shear stress.

In the Cyclades some 200–250 km to the north of Crete, the Basal unit forms the upper plate of the Cretan detachment (Ring *et al.* 2001) (Fig. 2). In the northern Cyclades (Evia, Tinos, Samos and Fourni islands), Oligocene/Early Miocene thrusting of the Cycladic blueschist unit onto the Basal unit caused high-pressure metamorphism (*c.* 1 GPa, 350–400 °C) (Ring *et al.* 1999*b*; Shaked *et al.* 2000) in the latter. In the southern Cyclades (Amorgos Island), a weaker high-pressure overprint than in the north indicates that metamorphism of the Basal unit increases northwards in the direction of movement on the Cretan detachment (Ring *et al.* 2001).

The exposure of the Basal unit in the northern Cyclades suggests that the *c.* 1 GPa-high-pressure rocks extend over a cross-strike distance of about 50 km. The lack of a significant increase of metamorphic grade across these 50 km suggests that these *c.* 1 GPa-high-pressure rocks are underlain by a subhorizontal fault. Given the evidence provided by Jolivet *et al.* (1996) andThomson *et al.* (1998, 1999), it appears likely that the Cretan detachment is this subhorizontal fault (see above).

Age of high-pressure metamorphism in the Basal Unit. The best-preserved high-pressure assemblages in the Basal Unit occur on Evia Island (Shaked *et al.* 2000) and provide an excellent opportunity to date the age of high-pressure

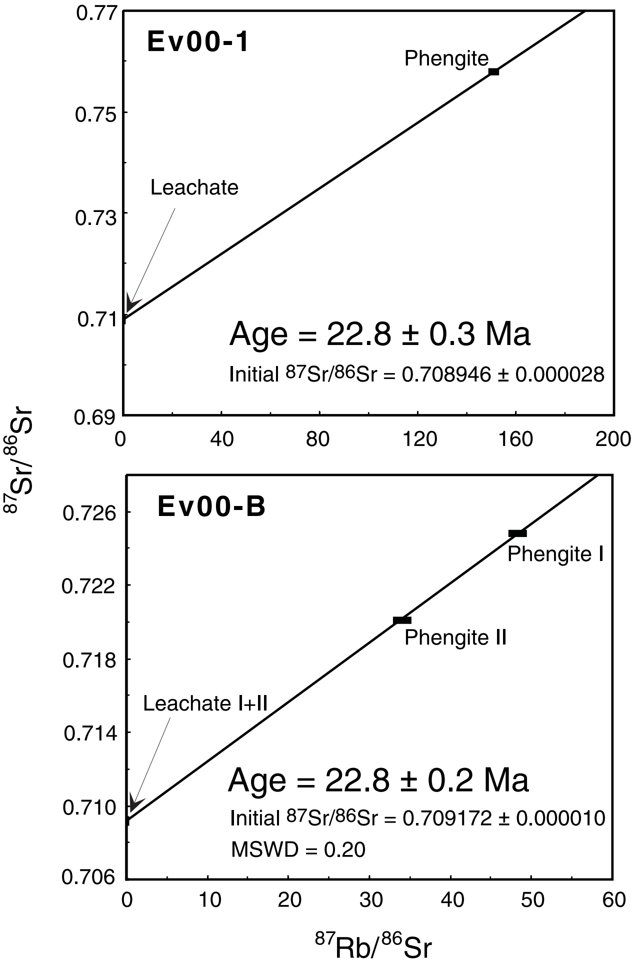

Fig. 3. Rb/Sr isochron diagrams for phengite and diluted HCl leachates of phengites from non-retrogressed high-pressure assemblages from Evia Island. For sample Ev00-B two phengite fractions were analysed (see Table 1). Due to high Rb/Sr ratios of phengite the ages of 22.8 ± 0.3 Ma and 22.8 ± 0.2 Ma are well constrained. Ages were calculated using the in-run error of the $^{87}Sr/^{86}Sr$ ratio and an error of 1.5% for the $^{87}Rb/^{86}Sr$ ratio. Uncertainties are given at the 2σ level.

metamorphism in the Basal unit in the Cyclades. This age is needed to estimate slip rates for the Cretan detachment. High-Si phengite has been used by Shaked *et al.* (2000) to derive peak-metamorphic pressure in the Basal unit of Evia Island and it was our goal to date the growth of this high-Si phengite. Rb/Sr analysis on such high-Si phengite from mica-rich phyllites was carried out at the 'Max-Planck-Institut für Geochemie' in Mainz, Germany (for analytical procedures see Ring *et al.* 2001). The silica content of the dated phengite varies from 3.41–3.58 per formula unit. Previous research indicates that the silica content in phengite increases with increasing pressure and that phengite with a silica content of >3.4 per formula unit does not form during greenschist-facies metamorphism (Velde 1967; Massone & Schreyer 1987). Detailed microscopic work and microprobe mapping revealed no compositional zoning indicating that the phengites we dated were not affected by post-high-pressure recrystallization. Rb/Sr phengite/phengite–leachate isochrones for samples Ev00-1 and Ev00-B yielded identical ages of 22.8 Ma (Fig. 3, Table 1).

The closure temperature for Rb/Sr in phengite is on the order of 500 ± 50 °C (Jäger 1973) and thus well above the maximum temperatures in the Basal unit of Evia. Hence, and because the dated phengite did not undergo post-growth deformation and/or recrystallization, we interpret the ages of *c.* 23 Ma as phengite growth ages during high-pressure metamorphism. Rb/Sr and $^{40}Ar/^{39}Ar$ phengite ages from the Basal unit on Tinos and Samos islands are similar (21–24 Ma) (Bröcker & Franz 1998; Ring *et al.* 2001). These ages and the metamorphic data indicate that high-pressure metamorphism affected the entire Basal unit in the upper plate of the Cretan detachment in the Cyclades at the same time and under the same pressure-temperature conditions as the rocks of the external high-pressure belt on Crete in the lower plate of the Cretan detachment. Therefore, both units were metamorphosed in close proximity with each other in the Early Miocene Hellenic subduction zone and provide a critical piercing point for determining a slip rate for the Cretan detachment.

Discussion. The geometric reconstruction for the Early Miocene Cretan detachment of Ring *et al.* (2001) yielded a displacement of ≧100 km and a dip of 10–15° for the detachment. This dip angle is similar to the present subduction angle of the Hellenic slab (Giunchi *et al.* 1996). Based on the duration of ∽3–5 Ma for movement on the Cretan detachment, an exhumation rate of >4 km Ma^{-1} has been estimated for the external high-pressure belt on Crete (Thomson *et al.* 1998, 1999). These data yield an extreme slip rate of ≧20 km Ma^{-1} (up to >30 km Ma^{-1}) for the Cretan detachment. This slip rate is greater than the slip rate of the Khelmos detachment (Sorel 2000) and more than two to four times larger than the greatest slip rates reported from the Basin-and-Range province (Foster & John 1999). Nonetheless, such extreme rates are needed for shallowly dipping normal faults to make a significant contribution to the exhumation of high- and ultrahigh-pressure rocks (Ring *et al.* 1999*c*). The implications of our great slip rate are far-reaching because this rate shows

Table 1. *Rb/Sr phengite data of samples from Evia Island*

Sample Analysed material	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	2σ error
Ev00-1					
Phengite	218.6	4.2	151.11	0.757929	0.000022
Phengite leachate	5.3	72.7	0.20	0.709013	0.000029
Ev00-B					
Phengite I	120.6	7.3	47.93	0.724717	0.000015
Phengite II	133.7	11.3	34.17	0.720185	0.000015
Phengite I leachate	30.9	311.6	0.28	0.709271	0.000019
Phengite II leachate	33.3	320.1	0.30	0.709264	0.000012

that superfast detachments do exist in nature and may thus contribute significantly to the exhumation of deep-seated rocks.

When do superfast detachments form? The Cretan detachment probably reactivated a former subduction thrust, the latter of which became inactive as the subduction zone retreated southward (Ring *et al.* 2001). The extensionally reactivated subduction thrust (i.e. the Cretan detachment) and the newly formed subduction thrust bounded the extruding wedge in which the external high-pressure belt was exhumed. Analysis of strain and rotation in accreted rocks of the external high-pressure belt shows that there was very little interplate coupling on the Miocene subduction thrust (Brandon & Ring 1998). The remarkable lack of deformation during exhumation of the external high-pressure belt (Stöckhert *et al.* 1999) also implies that the extruding wedge was almost fully decoupled from the down-going plate and from its upper plate. This indicates that the bounding faults of the extrusion wedge were very weak. The proposed slip rate of $\geqq$20–30 km Ma^{-1} for the Cretan detachment is similar to the subduction rate of 35–45 km Ma^{-1} at the Hellenic subduction zone. Faults in subduction-related extrusion wedges can only slip at rates similar to subduction rates if there is very low friction, i.e. very low shear coupling, at the bounding faults. Very rapid exhumation at subduction rates (Rubatto & Herrmann 2001) was also proposed for the weakly to non-deformed ultrahigh-pressure rocks of the Dora Maira Massif in the western Alps (Compagnoni *et al.* 1995). We propose that fast exhumation at subduction rates only occurs when the bounding faults are very weak; therefore, the exhuming rocks do not deform significantly.

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