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TERTIARY STRUCTURAL EVOLUTION OF THE SOUTHERN RHODOPE METAMORPHIC PROVINCE: A FUNDAMENTAL REVISION

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ABSTRACT

The Rhodope province is conventionally interpreted as a continental fragment that was caught between Apulia and Europe and deformed and metamorphosed in the hinterland of the Hellenic collisional orogen. Geologic mapping in the Strymon Valley region of northeastern Greece augmented by new U-Pb and $^{40}Ar/^{39}Ar$ geochronologic data support an alternative view that the southwestern Rhodope province represents the core of an Alpine collisional orogen that was extended and tectonically unroofed by a succession of three late Cenozoic low-angle normal fault systems that alternated in polarity.

INTRODUCTION

In two locations along the eastern margin of the Strymon Valley in northeastern Greece, amphibolite-facies gneiss and schist belonging to the Serbo-Macedonian metamorphic complex overlie greenschist-facies marble and schist belonging to the Rhodope metamorphic province on strongly sheared contacts that regionally dip gently to the southwest (Kockel and Walther, 1965; Koukou-zas, 1972). These contacts have long been considered outcrops of a northeast-vergent Alpine thrust, the "Strimon_berschiebung" (Kockel and Walther, 1965; Schenk, 1970), but were recently reinterpreted as segments of a top-to-the-southwest low-angle normal fault, the "Strymon Valley detachment" (Dinter and Royden, 1993, 1994). The tectonic and paleogeographic implications of this reinterpretation are profound: The Serbo-Macedonian metamorphic complex was not thrust northeastward over the western margin of the Rhodope province du-ring a mid-Tertiary (late Alpine) convergent event as previously supposed, but rather slid southwestward to its present location on a Neogene extensional detachment from a former position overlying the southwestern Rhodope province (Fig. 1).

Rhodopian marble and gneiss and Tertiary intrusives that crop out between the Strymon and Nestos Rivers thus compose a metamorphic core complex that lay at mid-crustal depths within the Alpine collisional orogen until it was tectonically unroofed in the footwall of the Strymon Valley detachment system beginning in middle Miocene time (Dinter, 1991, 1994; Dinter and Royden, 1993). This extensional unroofing event exposed a low-grade metamorphic and igneous province characterized by pervasive stretching lineations and large- to small-scale isoclinal and sheath folds that have remarkably uniform orientations, typically plunging 0°-25° northeast or southwest throughout much of the core complex. Gentle northeast plunges are most common, varying in trend from about N35°-55°E, but clustering strongly in the range N40°-50°E (Meyer and Pilger,

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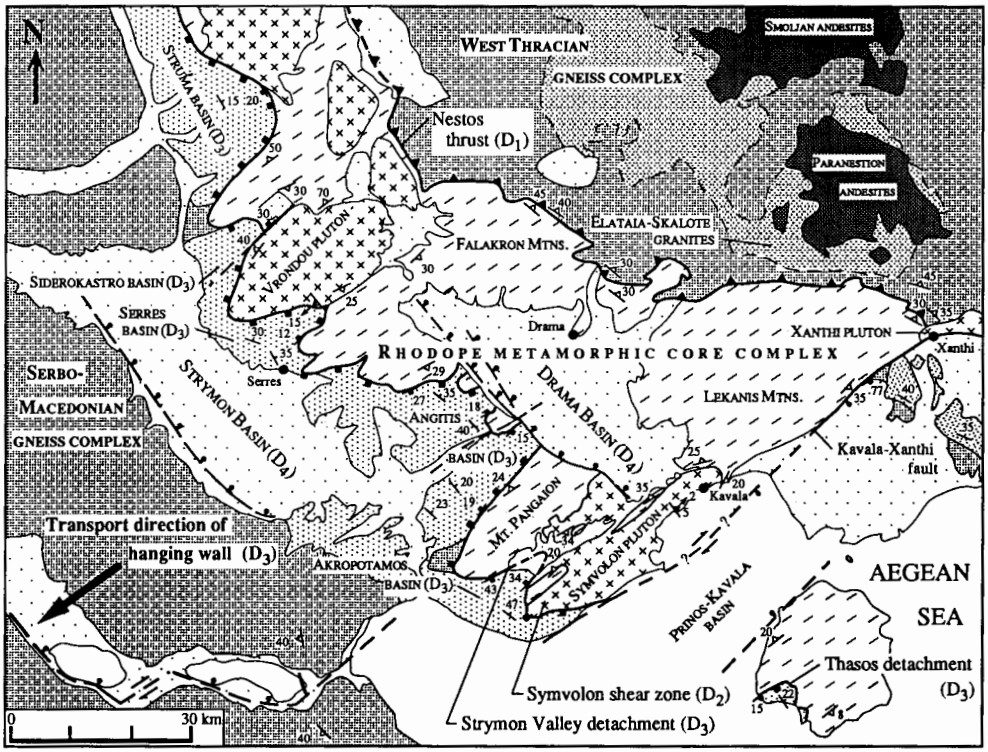

Fig. 1: Generalized geology of the Strymon Valley region. Heavy lines - faults: with barbs - thrust fault (barbs on hanging wall), with boxes - low - angle normal fault (boxes on hanging wall), with balls - high - angle normal fault (balls on hanging wall), with arrows parallel to fault trace - strike - slip fault with inferred sense of displacement as shown by arrows. Attitude symbols: open triangles - metamorphic foliations, solid boxes - fault planes, short lines - bedding. Light solid lines - depositional or intrusive contacts. Light dashed line in West Thracian gneiss complex - contact between migmatitic granite and host rock. See Fig. 2 for explanation of tectonostratigraphic units.

1963; Jordan, 1969; Kronberg, 1969; Meyer, 1969; Birk et al., 1970; Kokkinakis, 1980a; Dinter, 1991, 1994; Kolocotroni and Dixon, 1991; Dinter and Royden, 1993).

Northeast-trending folds and stretching lineations in the southwestern Rhodope province have conventionally been interpreted as products of a single, early Tertiary, Alpine convergent event (e.g., Kronberg, 1969). More recently, however, it has been shown that some of these ductile structural elements must have formed in an extensional environment (Dinter, 1991; Kolocotroni and Dixon, 1991; Dinter and Royden, 1993, 1994). Additional structural and geochronologic constraints described below establish unequivocally that northeast-trending folds and stretching lineations in the Rhodope metamorphic core complex represent at least three Tertiary deformational events entirely distinct in time and tectonic setting (Dinter, 1994). The recognition of these discrete, successive, ductile-fabric-forming events constitutes a fundamental revision of the structural development of the southwestern Rhodope province

and necessitates a reassessment of the role it played in the Alpine tectonic evolution of the Balkan Peninsula

GEOLOGIC FRAMEWORK OF THE SOUTHERN RHODOPE PROVINCE

The gross structural geometry of tectonostratigraphic units involved in Alpine tectonism in the southwestern Rhodope province is quite simple: The strongly deformed Falakron marble series[1], exposed in thicknesses as great as 7000 m between the Strymon and Nestos Rivers, is overlain at its northeastern margin on a northeast-dipping shear zone by the West Thracian gneiss complex[2] and at its southwestern margin, on a brittle, gently southwest-dipping shear zone, by the Serbo-Macedonian gneiss complex (Figs. 1 and 2). The Falakron series bears upper greenschist-facies mineral assemblages (e.g., Schenk, 1970; Kronberg et al., 1970), whereas the overlying Serbo-Macedonian and West Thracian gneiss complexes were both regionally metamorphosed to upper amphibolite facies, with conditions locally reaching anatexis (Kockel et al., 1977; Kronberg and Raith, 1977, respectively).

The moderately northeast-dipping contact between the West Thracian gneiss complex and the underlying Falakron marble, exposed in the Nestos River vicinity, is referred to here as the Nestos thrust[3] (Fig. 1). Metamorphic foliations in the units juxtaposed at this contact typically dip northeast within several kilometers of the contact zone (Kronberg and Eltgen, 1973), and northeast-plunging minor fold axes and stretching lineations are also common to the marble (Meyer, 1969) and the gneiss complex (e.g., Koukouvelas and Doutsos, 1990). A uniform southwesterly vergence has been established for the Nestos thrust, principally on the basis of mylonitic fabric asymmetries (Kilias and Mountrakis, 1990).

As noted above, cataclasized, southwest-dipping contacts between the Serbo-Macedonian gneiss complex and the underlying Falakron marble exposed intermittently at the northeast margin of the Strymon Valley are outcrops of a Neogene low-angle normal fault, the Strymon Valley detachment. Rocks exposed in this vicinity may be divided into three sequences based on their structural positions with respect to the Strymon Valley detachment: They either lie in its footwall and so belong to the Rhodope metamorphic core complex, in its

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1 The "Falakron marble series" of this study corresponds exactly to the "lower tectonic unit" of the Greek Rhodope province as defined by Papanikolaou and Panagopoulos (1981). Earlier workers divided this unit into an upper sequence dominated by massive marbles, the "Marmorserie F" (Osswald, 1938) or "Marmor-Folge" (e.g., Meyer and Pilger,1963; Kronberg, 1969), and a lower sequence of gneiss and schist with sparse marble intercalations, the "Gneis-Serie E" (Osswald, 1938) or "Untere Schiefergneis-Folge" (e.g., Meyer and Pilger, 1963; Kronberg, 1969).

2 The "West Thracian gneiss complex" has been referred to by previous authors as the "Glimmerschiefer-Serie G" (Osswald, 1938), the "Obere Schiefergneis-Folge" (e.g., Meyer and Pilger, 1963), the "upper tectonic unit" (Papanikolaou and Panagopoulos, 1981), the "Sideronero unit" (Kilias and Mountrakis, 1990), and the "Xanthe-Echinos gneiss complex" (Kotopouli et al., 1991).

3 While acknowledging that this contact is strongly sheared, early workers presumed that it preserved essentially primary stratigraphy (e.g., Kronberg, 1969; Kronberg and Raith, 1977). Based on the contrast in metamorphic grade between the two units, however, Papanikolaou and Panogopoulos (1981) suggested that the contact might be a thrust fault, and Zachos and Dimadis (1983) openly favored a thrust origin.

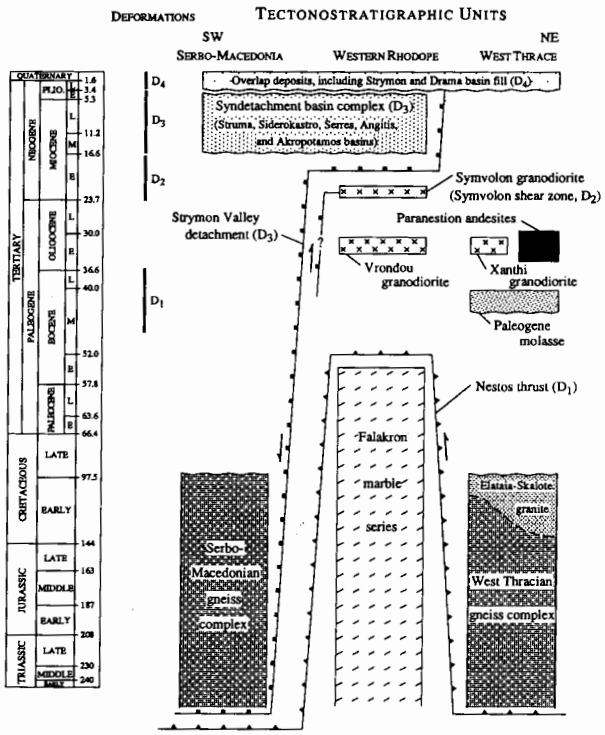

Fig.2: Tertiary deformational - intrusive sequence, generalized tectonostratigraphy, and schematic structural ralationships in the Strymon - Nestos region, northeastern Greece.

hanging wall, or are part of the "overlap sequence", composed of late Pliocene and Qua-ternary sediments deposited after detachment motion ceased. Hanging-wall rocks are further subdivided into a crystalline sequence that existed prior to the origin of the Strymon Valley detachment system, that is, the SerboMacedonian gneiss complex, and a syndetachment basin complex that accumulated near the up-dip limit of the detachment system and was penecontemporaneously incorpora-ted into its hanging wall (Dinter and Royden, 1993).

The syndetachment basin complex associated with the Strymon Valley detachment system is represented in northeastern Greece by the Siderokastro, Serres, Angitis, and Akropotamos "basins", which are not actually discrete depocenters, but compose a series of strongly deformed, lobate, sedimentary wedges that widen and merge southwestward beneath the modern Strymon Basin. These deformed wedges do not lie in depositional contact upon the underlying Rhodope bedrock, they do not occupy in situ grabens, they are not in any way genetically related to the modern Strymon or Drama Basins, nor is the clastic material within them locally derived from surrounding highlands (cf. von Freyberg, 1951; Gramann and Kockel, 1969; Armour-Brown et al., 1979; Psilovikos et al., 1981; Psilovikos and Syrides, 1983; Dermitzakis et al., 1985; Karistineos and Georgiades-Dikeoulia, 1985; Karistineos and Ioakim, 1985). The Siderokastro, Serres, Angitis, and Akropotamos sedimentary lobes occupy large, primary, southwest-plunging structural troughs in the Strymon Valley detachment surface, which is strongly

corrugated parallel to the direction of hanging-wall transport, 3°, S53°W (Dinter and Royden, 1993). They were deposited some tens of kilometers northeast of their present positions in a syndetachment basin complex and deformed during their southwestward transport in the hanging wall of the detachment system. Relatively undeformed sediments of the modern Strymon and Drama Basins represent the "overlap sequence" that was superposed on the highly tectonized syndetachment deposits after the Strymon Valley detachment system became extinct, probably beginning in late Pliocene time (see below). Late Cenozoic strata in the Strymon Valley region therefore represent two successive basin systems that are distinct in age, provenance, and tectonic origin (Dinter, 1994).

TERTIARY TECTONISM IN THE SOUTHWESTERN RHODOPE PROVINCE

The Tertiary tectonic evolution of the southwestern Rhodope region may be rationalized as a succession of four deformational events: D_1 is identified with the final pulse of Alpine convergence in northeastern Greece and comprises the pre-mid-Oligocene ductile folding, penetrative deformation, and dynamic metamorphism of the Falakron marble series as it descended to mid-crustal depths beneath the West Thracian gneiss complex in the footwall of the Nestos thrust. The northeast-southwest extensional collapse of the Alpine nappe pile began with the early Miocene (~21-22 Ma) emplacement and mylonitization of the Symvolon or "Kavala" granodiorite within a northeast-dipping coaxial shear zone that may represent an extensional rupture of the Falakron carbonate slab (D_2). The Symvolon shear zone was succeeded in middle Miocene time by the southwest-dipping Strymon Valley detachment system (D_3), which facilitated the southwestward-progressive tectonic unroofing of the Rhodope metamorphic core complex and a consequent transition from ductile to brittle deformation ~16-3.5 Ma. Continuing extension from late Pliocene time to the present (D_4) is principally expressed by the subsidence of the Strymon and Drama basins, whose northwest-striking bounding faults may sole into an active northeast-dipping detachment that terminates to the southeast at the North Aegean trough (Dinter and Royden, 1993).

D_1: Early Tertiary(?) Alpine convergence

D_1 is the early Tertiary(?) Alpine convergent event recognized by previous workers (e.g., Kronberg, 1969; Meyer, 1969), and was the first of three Tertiary deformational periods during which gently plunging, northeast-trending stretching lineations and folds formed within the Falakron marble series. By contrast with the later D_2 and D_3 ductile-fabric-forming events, which strongly affected only areas south and west of the Drama Basin, D_1 deformation and metamorphism pervasively and penetratively disrupted the entire exposure area of the Falakron series between the Strymon and Nestos Rivers, destroying all but crude compositional expressions of original stratigraphic layering. Late in the D_1 event, a generation of centimeter- to meter-scale folds developed nearly perpendicular to the earlier northeast-trending set, with axes trending 110° to 130°. Such folds typically show weak southwest vergence and, northwest of the Drama Basin, axial planes of this late population have commonly ruptured to form southwest-vergent thrusts with offsets up to 100 meters (Meyer, 1966; Kilias and Mountrakis, 1990).

The principal D_1 structure preserved in northeastern Greece is the Nestos thrust, which accommodated the southwesterly emplacement of the West Thracian gneiss complex over the Falakron marble series (Kilias and Mountrakis, 1990; Koukouvelas and Doutsos, 1990). The cumulative displacement

on the Nestos thrust is unknown, but must exceed ~70 km, the displacement-parallel width of the Falakron marble series (Fig. 1). Ductile D_1 fabrics and structures in both the footwall and hanging wall of the Nestos thrust are crosscut by the unde-formed Xanthi pluton, and must, therefore, be older than mid-Oligocene, because that intrusive has yielded K-Ar biotite and hornblende dates ranging from 27.1 ± 0.4 Ma to 30.4 ± 0.6 Ma (Meyer, 1968; Liati, 1986). D_1 structures are also crosscut by the eastern Vrondou pluton, which has yielded K-Ar hornblende dates as great as 33.0 ± 2.0 Ma (Marakis, 1969).

D_2: Early Miocene extension, intrusion, and coaxial shearing (Symvolon pluton)

The Symvolon or "Kavala" pluton intrudes the Falakron series at the southwest margin of the Rhodope metamorphic core complex and has conventionally been considered to share the regional D_1 shear fabric because it bears pervasive northeast-plunging folds and stretching lineations (Meyer, 1968, 1969; Kokkinakis, 1980a). However, recently obtained U-Pb and $^{40}Ar/^{39}Ar$ dates and thin-section determinations of mylonitic fabric asymmetries in the Symvolon intrusive necessitate a fundamental reevaluation of its emplacement age and tectonic significance (Dinter, 1994). $^{206}Pb/^{238}U$ titanite ages ranging from 19.7 ± 0.3 Ma to 21.1 ± 0.8 Ma and $^{40}Ar/^{39}Ar$ mylonitic hornblende dates in the range 20.1 ± 0.3 Ma to 21.7 ± 0.4 Ma provide conclusive evidence that the Symvolon pluton was emplaced and mylonitized within a shear zone in the southwestern Rhodope province ~21-22 Ma (Dinter, 1994). Mylonitic shear-sense indicators in the central part of the pluton are roughly equally divided between top-to-the-NE and top-to-the-SW asymmetries and suggest emplacement within a zone of coaxial or "pure" shear (Dinter, 1994), contrasting markedly with the consistent, simple, top-to-the-SW sense of shear associated with the Nestos thrust zone (Kilias and Mountrakis, 1990). The areal extent of the Symvolon pluton coincides with an order-of-magnitude thinning of the Falakron marble series (Kronberg, 1969; Kronberg et al., 1970; Schenk, 1970). I tentatively infer on this basis that the pluton was intruded within a northeast-southwest extensional rupture of the Falakron carbonate slab. The occurrence of northwest-trending aplitic dike boudins within the intrusive mass is consistent with this interpretation. Based on the extension-parallel width of the pluton, the Symvolon rupture may have attained a width of 35-40 km (Fig. 1).

From the results of a single U-Pb zircon analysis that gave discordant $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ model ages of 95 ± 5 Ma and 101 ± 8 Ma, respectively, and a $^{207}Pb/^{206}Pb$ age of 335 ± 40 Ma, Kokkinakis (1980b) interpreted a minimum Carboniferous emplacement age for the Symvolon pluton. New U-Pb analyses and SEM images of zircons from the Symvolon body show unequivocally that discordant Mesozoic to Paleozoic U-Pb ages are unrelated to the emplacement of the pluton, but derive instead from an inherited Pb composition in zircon cores surviving from the magmatic source rocks (Dinter, 1994).

D_3: Middle Miocene - early Pliocene extension (Strymon Valley detachment system)

The northeast-dipping Symvolon extensional rupture (D_2) was succeeded by the Strymon Valley detachment system (D_3), which comprises a regionally southwest-dipping low-angle normal fault and related structures in its footwall and hanging wall (Dinter and Royden, 1993). The main detachment forms the southwestern boundary of the Rhodope metamorphic core complex, cutting across D_1 and D_2 structural elements for >200 km along strike in the region northeast of

the Strymon River and, possibly, on the island of Thasos (Fig. 1). Hanging-wall rocks, which were displaced relatively 3°, S53°W in the detachment system, include the Serbo-Macedonian gneiss complex and a strongly deformed syndetachment basin complex.

The Rhodope metamorphic core complex emerged from mid-crustal depths in the footwall of the Strymon Valley detachment and in doing so, passed upward through the ductile-brittle transition in the crust, resulting in the overprinting of gently southwest-plunging early-D_3 mylonitic fabrics by increasingly brittle late-D_3 structures, including slickenside grooves, fault-plane duplexes, and fault mullions developed on shear surfaces streaked with chloritic microbreccia (Dinter and Royden, 1993). The unroofing of the core complex progressed from northeast to southwest such that brittle deformation within upper levels of the detachment system proceeded contemporaneously with ductile shear down dip to the southwest (Dinter, 1991, 1994). Based on the displacement-parallel width of the exposed core complex, which approximately coincides with the Falakron marble series exposure between the Strymon and Nestos Rivers, total displacement on the Symvolon detachment system may have exceeded 80 km near the Aegean coast (Fig. 1).

The timing of displacement on the Strymon Valley detachment system is constrained by two independent data sets: fossil ages of syntectonic basinal deposits in the hanging-wall suite and radiometric ages of igneous rocks in the footwall. Fossils contained within the syndetachment basin complex range in age from ~16 Ma to 3.5 Ma (Kojumdjeva et al., 1982; Armour-Brown et al., 1979, respectively). K-Ar biotite dates of 15.5 ± 0.5 Ma and 17.8 ± 0.8 Ma from the Symvolon pluton (Kokkinakis, 1980b) and 13.8 ± 0.2 Ma and 15.0 ± 0.3 Ma from the Mesolakkia pluton, which intrudes the Falakron series beneath Mt. Pangaion (Harre et al., 1968), have conventionally been interpreted as "rejuvenation" or "reset" metamorphic ages, but are now recognized as cooling ages related to the emergence of the Rhodope metamorphic core complex in the footwall of the Strymon Valley detachment (Dinter and Royden, 1993, 1994). This reinterpretation is corroborated by more reliable $^{40}Ar/^{39}Ar$ biotite and K-feldspar ages ranging from 11.1 ± 0.2 Ma to 15.5 ± 0.3 Ma, recently obtained from the central part of the Symvolon pluton (Dinter, 1994).

D_4: Late Pliocene - Quaternary extension (Strymon and Drama Basins)

Northwest-striking, high-angle normal faults bounding the southwest margins of the Strymon and Drama Basins are the defining elements of a D_4 extensional system that superseded the Strymon Valley detachment system ~3.5 Ma (Dinter and Royden, 1993). Such faults displace the Strymon Valley detachment by as much as 3.5 km vertically based on the depth to the base of unconsolidated deposits in the Strymon 1 borehole (Erki et al., 1984). The northeast margins of the Strymon and Drama Basins slope more gently toward the basin axes. This asymmetry is suggestive of a half-graben morphology and is shared by the Vardar-Thermaikos basin west of Thessaloniki (Bornovas and Rondogianni-Tsiambaou, 1983) and by several offshore basins in the north Aegean Sea (e.g., Lyb_ris, 1984). Dinter and Royden (1993) suggest that these basins may be subsiding above an active, northeast-dipping "North Aegean detachment" that succeeded the Strymon Valley detachment as the major structure accommodating extension in the north Aegean region. The D_4 detachment system probably terminates southward at the northeast-trending North Aegean Trough, which represents the offshore continuation of the dextral North Anatolian fault. The sole chronological datum presently constraining the transition from D_3 to D_4 extensional deformation is the youngest known age of deposits within the D_3 supradetachment

basin, ~3.5 Ma (see above).

DISCUSSION AND CONCLUSIONS

The reinterpretation of a supposed Tertiary Alpine thrust, the "Strimon_berschiebung", as a Neogene low-angle normal fault necessitates fundamental revisions to presently accepted ideas concerning the Tertiary structural evolution of the southwestern Rhodope province:

(1) The concept that an Oligocene or Neogene compressional event affected the Strymon-Nestos region must be abandoned. Tilting, folding, and deformation of Oligocene and younger strata attributed by previous authors to compressional tectonics actually occurred exclusively within an extensional en-vironment, primarily in the hanging wall of the Strymon Valley detachment sy-stem.

(2) Northeast-trending folds and stretching lineations in the Rhodope metamorphic core complex represent not one, but three successive ductile-fabric-forming deformations: a pre-mid-Oligocene Alpine convergent event (the Nestos thrust), early Miocene coaxial extension (intrusion of the Symvolon pluton within a widening rupture of the Falakron marble series), and middle Miocene-early Pliocene extensional simple shear accommodated by the Strymon Valley detachment system.

(3) A simple palinspastic restoration of pre-Strymon Valley paleogeography implies that prior to middle Miocene time, the Serbo-Macedonian gneiss complex lay atop the Falakron marble series in the region between the present Strymon and Nestos Rivers. Thus, the Serbo-Macedonian and West Thracian gneiss complexes are strictly correlative and formed a single, continuous, high-grade gneiss complex prior to their middle Miocene separation. In other words, the Strymon Valley detachment reactivated the Nestos thrust as a Neogene low-angle normal fault, opening a tectonic window, the "Falakron window", into the footwall of an Alpine thrust zone.

(4) Late Cenozoic sedimentary strata exposed in the Strymon Valley region represent two successive basin systems. The Siderokastro, Serres, Angitis, and Akropotamos "basins" are actually lobes of a middle Miocene-early Pliocene supradetachment basin complex that was translated some tens of kilometers southwestward from its original position in the hanging wall of the Strymon Valley detachment system. The modern Strymon and Drama depocenters represent a younger system of extensional faults that succeeded the Strymon Valley detachment, probably beginning in late Pliocene time.

The Rhodope metamorphic province has conventionally been regarded as the interior of a Tethyan continental fragment that was deformed in the hinterland of a Mesozoic to early Tertiary subduction zone, remnants of which are preserved in the ophiolitic Vardar suture in northern Greece and rump Yugoslavia (e.g., Burchfiel, 1980). Structural and geochronologic constraints described above imply a fundamentally different origin for the Rhodope province, in Greece at least, as the core of an Alpine collisional orogen that accommodated at least 80 km of NE-SW shortening prior to mid-Oligocene time, and was subsequently greatly extended on a series of NE- and SW-vergent Neogene-Quaternary detachments in the back-arc of the Hellenic subduction system.

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