Cenozoic tectonics of Macedonia and its relation to the South Balkan extensional regime

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ABSTRACT

From Paleogene to Recent time, Macedonia was part of the South Balkan extensional region, the northern part of the Aegean extensional regime. Extension began in the middle to late Eocene in eastern Macedonia with the formation of a NNW-trending east-tilted half graben lying east of a forearc basin in central Macedonia. Following a short-lived period of localized shortening in late Oligocene to early Miocene time, a second period of Neogene extension began that continued to the present. Five cycles of Neogene extension are recognized, and associated sedimentation occurred in extensional basins of complex origins: (1) true graben, (2) tilted half graben, (3) pull-apart basins along strike-slip faults, (4) faulted silled basins filling topographic lows, and (5) complexly faulted basins of mixed fault origin. Neogene faulting and basin formation show a pattern that begins with both NNW- and EW-trending faults in mainly northern and eastern Macedonia progressing to younger times by dominantly NNW- to N-trending faults migrating into western Macedonia and E-W- and NW-trending faults dominant in eastern Macedonia. The origin of the Paleogene basins is interpreted to be related to trench rollback along the northern Hellenic trench and lateral spreading of thick hot crust within an arc. The short period of early Neogene shortening is related to the arrival of the small continental Kruga fragment at the subduction zone in Albania. The younger Neogene extension and westward migration of extensional faulting and basins is related to progressive rollback of the subducted slab in the northern Hellenic trench. The north-south extension in eastern Macedonia is related to the propagation of the North Anatolian fault in the northern Aegean Sea ca. 6 Ma and subsequent movement southward of south Balkan lithosphere north of the fault caused by the rapid SSW movement of the Aegean crust related to trench rollback along the southern Hellenic trench. The amount of southward extension within the Southern Balkan extensional region is much less than that in the Aegean south of the North Anatolian fault.

Keywords: Macedonia, Balkans, tectonics, basins, extension.

INTRODUCTION

The tectonics of Macedonia from the late Eocene to the present is dominated by two periods of regional extension separated by a short interval of shortening deformation in late Oligocene–early Miocene time. Extensional deformation in Macedonia is part of the broader South Balkan extensional regime that in addition to Macedonia affects northern Greece, Bulgaria, Albania, Serbia, Montenegro, and probably parts of southwestern Romania (Fig. 1). Development of the extensional system was diachronous throughout the South Balkans and was related not only to changes at the boundaries of the extensional system but also to changes in lithospheric rheology. This paper develops the late Eocene to Recent tectonic evolution of Macedonia and relates it to our evolving understanding of the regional South Balkan extensional regime.

GEOLOGICAL BACKGROUND

Most of the understanding of the tectonic evolution of Macedonia comes from the study of the numerous Cenozoic sedimentary basins that contain the record of its extensional history (Fig. 2; Dumurdzanov et al., 2004). Unfortunately, the deeper parts of many of the sedimentary basins of Macedonia are poorly exposed and covered by Quaternary deposits. Thus, much of the data from these basins come from drill holes and limited surface exposures, and the three-dimensional framework of these basins is poorly known.

The crust that underlies the Cenozoic basins of Macedonia has had a long and complicated evolution, and structures within the pre-Cenozoic basement rocks have affected the development of some of the basins. Macedonian pre-Cenozoic basement consists of five major tectonic units from west to east (Fig. 3): (1) the Chukali-Krasta zone, (2) the Western Macedonian zone, (3) the Pelagonian massif, (4) the Vardar zone, and (5) the Serbo-Macedonian massif. The Chukali-Krasta zone consists of sheared very low-grade metamorphosed sedimentary rocks of Late Cretaceous and early Tertiary age that are part of the much more extensive N-S-trending belt of rocks in Albania that were thrust eastward below Mesozoic ophiolites and Mesozoic and older metamorphic rocks (Robertson and Shallo, 2000). These low-grade rocks in Macedonia form a narrow half window around the town of Debar where they are tectonically overlain by rocks of the Western Macedonian zone (Fig. 3). The structural evolution and position of these metasedimentary rocks is controversial. Robertson and Shallo (2000) suggested these rocks were part of a narrow
oceanic belt that was closed in early Tertiary time by subduction from both the west and east, whereas others, such as Aubouin and Ndojaj (1964) and Burchfiel (1980), suggested they were subducted only to the east. In either hypotheses, however, rocks of the Western Macedonian zone lie tectonic above the Chukali-Krasta metasediments. The Western Macedonian zone consists of low-grade to locally medium-grade metamorphosed Paleozoic sedimentary and igneous rocks and Mesozoic, mostly Triassic with some Jurassic, sedimentary rocks. These rocks were deformed in Paleozoic, Mesozoic, and Cenozoic time. Paleozoic deformation produced a well-developed regional foliation; Mesozoic deformation produced folds and thrust faults; and older Cenozoic deformation produced strong deformation, but younger Cenozoic deformation was characterized by normal and strike-slip faults. The Pelagonian massif forms the high-grade metamorphic core of a large NW-trending, NW-plunging anticlinorium that also involves the lower-grade rocks of the Western Macedonian zone on the west and north sides. The core of the anticlinorium consists of amphibolite grade gneiss, augen gneiss, and schist formed from protoliths of Precambrian metasedimentary rocks, characterized by a thick section of marble in the upper part that partly...
frames the anticlinorium, and abundant granitic plutons. The east side of the anticlinorium is truncated by the NNW-trending Vardar zone that consists of narrow belts of schist and gneiss, Paleozoic and Mesozoic metasedimentary rocks, and numerous belts of ophiolitic rocks. Some of the Mesozoic rocks in the Vardar zone are of deepwater origin. The Vardar zone represents a Triassic to early Cretaceous ocean that had a long and complicated history of subduction. It began to close in the Late Jurassic and the earliest deformation is of Late Jurassic–Early Cretaceous age. The upper part of the Vardar Mesozoic succession consists of Aptian to Turonian flysch, parts of which are flylfsch, deformed in late Turonian to early Senonian time (Subhercynian phase in the European literature), and unconformably overlain by Senonian and Maastrichtian flysch with rare flylfsch and limestone units in its upper part. The Cretaceous sequences are more than 4000 m thick. Rocks within the Vardar zone were strongly deformed into narrow NNW-trending belts of different rock types bounded by faults that developed in the latest Cretaceous to Paleocene time (Laramide phase of European authors). Latest Cretaceous or earliest Cenozoic strata are absent in the Vardar zone in Macedonia, but are present in Serbia to the north (Arsovski and Dumurdzamov, 1995; Arsovski et al., 1997; Pamics, 2002). The deformed subduction-related complexes in the Vardar zone are unconformably overlain by the oldest Cenozoic basinal sediments of Priabonian age, and perhaps older, that consist of freshwater lacustrine strata which grade upward into marine strata. The Serbo-Macedonian massif consists of Rifean/Cambrian mafic plutonic and volcanic rocks and early Paleozoic schist and phyllite all intruded by large bodies of Paleozoic granite. With the exception of the north-plunging nose of the Pelagonian anticlinorium, the structures in the pre-Cenozoic basement rocks are dominated by NW-trending foliation, folds and faults that form an important crustal anisotropy that controlled many of the basin bounding faults in Cenozoic time.

CENOZOIC BASIN DEVELOPMENT

Within Macedonia, above the basement tectonic units, there are two main groups of sedimentary basins that formed in late Eocene to Recent time and reflect two major periods of extensional deformation separated by a short period of shortening. Most of the basins are
The Neogene basins consist of several different types. Many are true grabens with more or less parallel faults on both sides. These include the Skopje, Polog, Ohrid, Prespa, Lake Ovchepole basins in central Macedonia that contain both marine and nonmarine strata that interdigitate with volcanic rocks to the east. These strata lie in a forearc zone that is characterized by two different basin types whose formation began in the late Eocene and was marked by two different basin types whose formation began in the late Eocene and was locally controlled by NW-striking faults related to extensive volcanic activity. The basin fill consists of mainly volcanic rocks and some clastic and volcanogenic sediments, such as the middle Miocene strata, that filled local grabens. A detailed discussion of the basin sediments for all the Cenozoic basins can be found in Dumurdzanov et al. (2004), which contains the basic data for the Probistip area was locally controlled by NW-striking faults related to extensive volcanic activity. The basin fill consists of mainly volcanic rocks and some clastic and volcanogenic sediments, such as the middle Miocene strata, that filled local grabens. A detailed discussion of the basin sediments for all the Cenozoic basins can be found in Dumurdzanov et al. (2004), which contains the basic data for much of the basin history presented below.

Paleogene Basins

The oldest period of extension and basin formation began in the late Eocene and was marked by two different basin types whose strata range from late Eocene to Oligocene: (1) NW-trending, generally E-tilted half grabens, and (2) a large basin in central Macedonia (Fig. 4). The NW-trending basins lie mainly in eastern Macedonia parallel to similar basins in adjacent Bulgaria (Burchfiel et al., 2000) and include the Kriva-Palanka, Delcevo, and Stojakovo (several basins) basins (Fig. 4). These narrow basins contain red,

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Figure 3. Tectonic basement (pre-Cenozoic) units of Macedonia. I—Chukali-Krasta unit; II—Western Macedonian unit; III—Pelagonian massif; IV—Vardar zone; and V—Serbo-Macedonian massif. Lakes: DL—Dorjan Lake, OL—Ohrid Lake, and PL—Prespa Lake. Major rivers of Macedonia are also shown.

related to extensional faulting and some are clearly grabens, but others are more complex and there is a wide range of basin types.

Cenozoic Basin Types

Most of the basins in Macedonia are fault controlled, others are more irregular areas of subsidence associated with faults, but there are many basins with different relations between faults, subsidence, and deposition. Most of the Paleogene deposits lie in eastern Macedonia and are half grabens with faults on their east sides and basin sediments that dip to the northeast (Fig. 4). The interconnected Tikves and Ovchepole basins in central Macedonia are an exception and contain both marine and nonmarine strata that interfinger with volcanic rocks to the east. These strata lie in a forearc position relative to a coeval volcanic arc to the east and a convergence zone to the west in central Albania where the Apulian plate moved east relative to Macedonia.

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avica, Delcevo-Pechevo, and Pelagonian (with its smaller northwest branching grabens in the southwest) grabens and possibly the Kumanovo graben. Some basins contain faults, with normal and strike-slip components, on only one side and are tilted half grabens, such as Kriva-Palanka, Kocani, Vandalovo, and the southern part of the Strumica graben in eastern Macedonia. Evidence from topography surrounding the basins and the sediments filling the basins suggest that all of these E-W-trending half grabens are bounded by faults on the south side and are tilted to the south. The Kocani and Strumica grabens have faults on the north side, but they have smaller displacements than those on the south side. In western Macedonia, the Debar and Piskupstina grabens are bounded by the same fault zone, but are tilted to the east and west, respectively. Other basins are bounded by faults mainly on one side, but the basin sediments are either horizontal or only slightly tilted. These basins are fault controlled, but the faults formed sills that blocked sediments that filled topographic relief. Deposits in the Mariovo and Raec basins are approximately horizontal and fill negative topographic relief, such as river valleys, but the sediment was trapped by fault-controlled sills on their east sides. The Porecje, Debarca, and Kicevo contain horizontal sediments that fill negative topographic relief, locally river valleys, and are bounded by faults whose upthrown side is on the west side of the basin. Deposits in the Demir Hisar basin filled valleys, which locally may be faulted, but the basin is not controlled by faulting, and the pattern of sediment distribution is clearly dendritic.

Some basins are bounded by faults that form complex patterns. The Tikves basin is bounded by NE-trending faults on the north and south sides and NW-trending faults on the west side, but it has no obvious fault on the northeast side. The Dojran basin has a rhombic outline, internal drainage, and appears to be bounded by faults on all sides. Part of the Veles basin is a NW-trending graben, but sediments of the basin extend beyond the faults, particularly on the west side where sediments fill preexisting valleys that drained into the graben from the west. The Berovo basin is bounded by faults on three sides, but does not have a fault on the west side.

The Mavrovo basin lies along the regional ENE-trending Elbasan-Debar-Skopje-Kustendil fault zone and appears to be a graben of pull-apart origin along this left-lateral fault zone. The Elbasan-Debar-Skopje-Kustendil fault zone figures prominently in the tectonic history of northern Macedonia during the late Cenozoic (see below). Deposition in the Probistip area was locally controlled by NW-striking faults related to extensive volcanic activity. The basin fill consists of mainly volcanic rocks and some clastic and volcanogenic sediments, such as the middle Miocene strata, that filled local grabens. A detailed discussion of the basin sediments for all the Cenozoic basins can be found in Dumurdzanov et al. (2004), which contains the basic data for much of the basin history presented below.

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brown, and yellow sandstone; mudstone; and sometimes very thick sections of conglomerate deposited in nonmarine fluvial and lacustrine environments. Locally these basins contain large masses of brecciated to semicoherent blocks of pre-Cenozoic rocks, mainly Triassic limestone, for example, in the Delcevo basin. The blocks were largely emplaced by gravity induced processes from adjacent tectonically developed relief. They have the same trend and are near the well-studied Padesh graben in western Bulgaria, which shows syndepositional northeast tilted growth strata that dip into a west-dipping listric normal fault (Zagorchev, 1998). The more eastern of these basins, the Kriva-Palanka, Delcevo, and Damian basins, lie within a belt of contemporaneous arc magmatic rocks and their origin is probably related to within-arc extension perhaps due to rollback at the trench or gravitationally induced spreading within the magmatic arc, or both (see below; Harvkovska, 1984; Boev and Yanev, 2001).

The second basin type consists of the large interconnected Tikves-Ovchepole basins in central Macedonia (Fig. 4). The Tikves basin lies to the west and its strata unconformably overlie the deformed rocks of the Vardar zone. It contains up to 3500 m of red, brown, and yellow sandstone; siltstone; mudstone; and conglomerate. Some of these rocks have a phyllitic character, but most of the strata were deposited in complex lacustrine, fluvial, and marine environments. The eastern part of the basin was tectonically active along NW-striking faults that produced local relief, and the sediments grade eastward into the Ovchepole basin that contains abundant volcanic rocks in their upper part. At the time of basin formation a NNW-trending regional magmatic arc of late Eocene and Oligocene age was well developed and extended from northern Serbia through eastern Macedonia and western Bulgaria southward into northern Greece and eastward into Turkey (Fig. 1). The western part of this arc formed above the E-dipping convergent zone that lay to the west within the Chukali-Krasta zone of western Macedonia and Albania (see Robertson and Shallo, 2000) and can be followed into western Greece. The Tikves-Ovchepole basin thus lies in a forearc position relative to the convergent zone and the magmatic arc.

Many of these Paleogene rocks were deformed by two short periods of late Oligocene to early Miocene shortening (Pyrenian and Savian phases of European authors). The Tikves basin is bounded on its east side by an E-dipping thrust fault that brings basement rocks above Paleogene strata. To the west of the thrust fault are numerous NW-trending folds of probably the same age. The amplitude of the folds diminishes toward the west. Unlike the Padesh basin in Bulgaria, many of the narrow basins were affected by a short period of shortening deformation at the end of deposition in early Oligocene time. The Kriva Palanka, Damian, Stojakovo, and probably the Delcevo basins are bounded on their east sides by thrust faults that bring basement rocks over the basin sediments. These short periods of deformation were followed by a period of er-
Neogene Basins

Following the period of erosion and formation of a low relief landscape, the second period of extension began in late early Miocene or middle Miocene time and became the dominant mode of deformation within Macedonia from then to the present. The study of the Neogene basins of Macedonia is hampered by the lack of deep erosion of many of the basins and an extensive cover of Quaternary sediments. We rely on drill-hole information for the presence and character of the sedimentary fill in many of these basins and on geological data for the three dimensional shape of some of these basins. Our analysis of the tectonic history of most of these basins depends on the interpretation of the sedimentary succession in the basins for their time of initiation (Dumurdzanov et al., 2004), and we also infer that most of the present-day bounding faults were initiated at the beginning of sedimentation. This appears to be a reasonable assumption in many basins because sediments present in the basins are not found as remnants outside of the present-day basin limits.

We use the five cycles of basin sedimentation (Fig. 5) discussed by Dumurdzanov et al. (2004) for the temporal division of basin development and present a series of maps that show the temporal and spatial development of the Macedonian basins and associated faults. Sedimentary rocks of the second and third cycles are not separated on the maps because the data do not exist to show accurately the distribution of the deposits in these two cycles, and in many places their deposits are covered by younger Pliocene strata.

**BADENIAN TO LATE SARMATIAN: CYCLE I**

The oldest known strata in the Neogene basins are assigned to the Usje Formation (cycle I) deposited in the Skopje, Kumanovo, Probistip, Kocani, and perhaps the Slaviski grabens (Fig. 6). In general, the sedimentary sequence in the Skopje and Kumanovo basins begins with conglomerate and sandstone and ends with fine-grained marls. The Probistip and Kocani basins contain thick volcanic rocks that interfinger with sedimentary rocks. These basins may have been connected, as the sedimentary deposits in all these basins consist of similar strata. The age of the deposits, dominated by marl and claystone, in the Skopje and

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**Figure 5. Subdivisions of Neogene time and the five cycles of Neogene deposition used in the text.**

Kumanovo has been determined as Badenian by macroflora imprints, ostracods, and rare mollusk and Mammalian fauna (Dumurdzanov and Krstic, 1999) and in the Probistip and Kocani grabens by interfingering with dated volcanic rocks of the middle Miocene Zletovo Formation (Karamata et al., 1992). The sediments in the Skopje and Kumanovo grabens are 1400 m and 400 m thick, respectively. The thickness of volcanic rocks of the Zletovo Formation in the Probistip basin is ~800 m and they locally interfinger with strata correlated with the Usje Formation. These rocks are only known from drill holes in the Kocani basin where Zletovo volcanic rocks interfinger with sediments of the Usje Formation. Ages for the volcanic rocks range from 32 to 29 ± 2 Ma to 16 ± 2 Ma and only the younger parts of the volcanic section interfinger with the Usje Formation.

The basinal deposits conform to the present day boundaries of the Kumanovo and Skopje grabens and we infer that the faults of E-W, NW, and N-S trends controlled the deposition of these strata (Fig. 6). The deposition of the Probistip and Kocani volcanic and sedimentary rocks appear to be controlled by NW-trending faults. In the Kocani basin, rocks in the Usje and Zletovo Formations are known only in its western part and the present day E-W trend of the Kocani basin is probably younger (see below).

The NW-trending faults in these grabens lie along the trends of older faults within the NW-trending Vardar zone basement tectonic unit and appear to be reactivated faults controlled by the basement anastropy. The E-W-trending faults in the Skopje basin are also along older fault lines and are parallel foliation trends in the NW-plunging nose of the Pelagonian anticlinorium and may be controlled by these structures. Thus, the oldest Neogene grabens appear to have had a complex fault pattern in northern Macedonia, but are dominated by faults indicating NE to E-W extension. The E-W-striking faults may have had a strike-slip component and the active displacement on these faults has a left-lateral component.

Grabens in two other areas may have been initiated at this time, but the evidence is inconclusive. Gravity data from the southern part of the E-W-trending Strumica graben in southeast Macedonia indicate the graben fill is more than 1800 m thick. From drill-hole data in other parts of the basin and from surface exposures of the Neogene rocks, upper Miocene strata are only ~600 m thick. Thus, it is likely that rocks at the base of the section may be as old as middle Miocene. The graben continues eastward where it merges with the NW-trending Sandanski graben of southwestern Bulgaria (Zagorchev, 1992). Well-dated Badenian and Sarmatian strata form the basal deposits in Bulgaria (Kojumdgieva et al., 1982; Nedjalkov et al., 1986; Zagorchev, 1992). Thus, the Strumica basin and associated E-W-trending faults could have formed during the Badenian–late Sarmatian interval. However, the Sandanski graben trends at right angles to the E-W–trending Stumica graben, a relation to be discussed below.

Similar sedimentary rocks, more than 1000 m thick, are present in the southern part of the Pelagonian graben, near Bitola, in south central Macedonia (Fig. 6). Only the upper part of the section yields late Miocene fossils and the lower part remains undated. Thus, the possibility exists that the southern part of the graben may have developed in the middle Miocene. Strata of this age are known from the continuation of this graben in northern Greece.

**LATE SARMATIAN–MEOTIAN (TUROLIAN): CYCLE II**

During late Sarmatian–Meotian time (cycle II), the Skopje and Kumanovo grabens widened and abundant volcanic and associated
Figure 6. Distribution of sedimentary and magmatic rocks of cycle I—Badenian to Sarmatian—of Macedonia. Actual outcrops are shown in color and possible extent of sedimentary rocks either eroded or covered is shown by dotted pattern. Faults active during this time are shown in red where established and dashed where inferred. There is not enough detailed mapping to separate actual outcrops of magmatic rocks of this cycle from other Neogene magmatic rocks.

Volcaniclastic rocks were deposited in the Probistip, Kocani, and Slaviski grabens (Fig. 7; cycle II and III sediments are not easily separated and are shown combined on Fig. 7). At the same time, many new fault-controlled basins were formed that include the Pelagonian, Prespa, Strumica, Veles, Tikves, Mariovo, Delcevo-Pehecevo, Berovo, Polog, and Kicevo grabens, and possibly the Piskupstina graben. These grabens indicate that extensional faulting remained active in eastern and central Macedonia and migrated into western Macedonia during this cycle. Many of the strata in these basins are well dated by the Pikermian fauna (Schlosser, 1921) and by the presence of dated coal-bearing units of Meotian age (Dumurdzanov et al., 2004). Cycle II strata began with coarse conglomerate that overlies first cycle marl or volcanic rocks where first cycle sediments are present, but in the newly developed basins, conglomerate overlies underlying pre-Cenozoic rocks.

In the Skopje graben, subsidence continued with deposition of the Nerezi Formation, which has conglomerate at the base that in places overlies the Usje Formation, but also extends beyond the limits of the Usje Formation to rest unconformably on pre-Cenozoic rocks. The formation is a fining upward sequence of sandstone and siltstone with some coal beds. The youngest part of the formation contains the youngest fossils of cycle III (Dumurdzanov et al., 2004). Within the adjacent Kumanovo, Probistip, Slaviski, and Kocani basins, equivalent rocks are mainly volcanic and volcaniclastic sediments. In the Kumanovo basin, the lower part of the Staro Nagoricani Formation of cycle II consists of ~150 m of partly stratiﬁed andesite and latite tuff that directly overlies the Usje Formation of cycle I. The upper part of the formation, ~150 m thick, consists of sandstone, claystone, and siltstone with some coal layers and calc-alkaline basalt ﬂows. The basalt ﬂows yield ages of 8.0–8.5 Ma (Boev and Yanev, 2001) of early Pontian age so that the uppermost part of the Staro Nagoricani Formation belongs to cycle III.

The Probistip, Slaviski, and Kocani grabens during this time period are dominated by volcanic rocks of the Probistip Formation. The youngest volcanic rocks of the Probistip Formation belong to cycle II. The thickness of volcanic tuff and lava ﬂows of this period is...
Figure 7. Distribution of sedimentary and magmatic rocks of cycles II and III—late Miocene—of Macedonia. The actual outcrops (color) and possible extent of sedimentary rocks (dotted pattern) for the two cycles cannot be separated because of lack of detailed mapping. Faults active during this time period are shown in red where established and dashed where inferred. BV—Bukovik volcanic center.

variable; it ranges from \(~150\) m in the Slaviski and Probistip grabens to a little thicker in the Kocani graben.

Deposition in the Veles basin began in Meotian time with the deposition of the basal conglomerate of the Veles Formation that unconformably overlies varied pre-Cenozoic units of the Vardar basement unit. The sedimentary sequence fines upward into claystone and sandy claystone that contains a rich mammalian fauna of Turolian-Pontian age (Dumurdzanov et al., 2004). Thus, the top of this formation is younger cycle II. The thickness of cycle II strata is \(~200\) m. The basin has an irregular shape and older Miocene strata are preserved in the central part of the basin and younger strata extend more widely. The distribution of strata in the southwest part of the basin suggests the filling of preexisting valleys. However, the upper Miocene sediments extend northward and probably connected with the Skopje and Kumanovo basins which are fault controlled. The fault control on the Veles basin at this time is difficult to determine, but connections with the basins to the north suggest a possible general N-S or NW trend parallel to the underlying structural grain of the Vardar zone.

The Tikves and Mariovo basins in south-central Macedonia are partially controlled by N-S and NE-SW-trending faults. The Mariovo basin is deeply eroded and its present-day outcrops are remnants of a much larger basin. The basin remnants appear to fill pre-existing valleys, but the eastern and southwestern boundaries of the basin appear to be fault controlled. The Mariovo basin overlies the NNW-trending boundary between the Pelagonian and Vardar basement units and the NNW-trending fault that controls part of the basin formation appears to be a reactivated basement fault. Deposition began in both basins in Meotian time with \(~120–140\) m of conglomerate and sandstone of the basal Nerezi Formation. Both basins show a fining upward succession of claystone and siltstone with coal beds that reach \(~220\) m thick in the Tikves basin and \(~70\) m thick in the Mariovo basin. The uppermost sediments of the Nerezi Formation in the Mariovo basin extend into basal cycle III. The upper fine-grained units in
both basins contain abundant lacustrine deposits. The Tikves basin lies above the Vardar zone basement and the NNW-trending fault that controls the western part of the basin may be reactivated from basement structures. Northeast-striking faults control its northern and southern boundaries (Fig. 7), and these faults cut across the basement anisotropy.

The Pelagonian, Prespa, Kicevo, and Piskupstina basins are dominantly controlled by NNW- to N-S-trending faults that generally parallel the structural grain in the older Western Macedonian basement unit. The Pelagonian basin is ~25 km wide by ~100 km long and extends into northern Greece. It is a complex graben and contains internal small horsts, one of which divides it into a northern and southern part with thicker basin fill in the south. The upper Miocene sediments are only exposed in the southeastern part of the basin, and information about the rest of the basin strata comes from drill holes. The Pelagonian Formation is the oldest unit and has a variable thickness. Near Prilep it is 150–200 m thick and near Bitola it is 400–500 m thick. The rocks are alluvial gravel and sandstone becoming finer-grained upward. No fossils have been found in these rocks, some of which may be valley fill and not fault controlled, and some of these strata could be part of cycle I as mentioned above. This lower unit grades upward into the finer grained coal-bearing middle unit of the Pelagonian Formation, and correlation of these rocks with similar strata in Tikves, Mariovo, Skopje, and Kicevo gravens suggests a Meotian age. The middle unit is 58 m thick and when combined with some or all the lower unit, ~250 to ~450 m of sediment was deposited in the initial stage graben formation. The Pelagonian basin has a major N- to NNW-trending fault along its western side, N- to NNE-trending faults along its eastern side, and a NW-trending fault along its northeastern side, thus, the basin lies in a graben, but with a distribution of sediments that locally suggests filling of older topography, particularly at its northern end.

Sedimentary rocks are well exposed in the Piskupstina half graben which is bounded on the west side by a NNW-striking normal fault and the section is tilted 10°–20°W. The basal Piskupstina Formation consists of 30–40 m of conglomerate that unconformably overlies Triassic and Paleozoic rocks of the Western Macedonian basement unit. The middle unit is ~100 m thick and consists of gray siltstone and pure marl with some coal layers. These units are assigned a late Miocene age as the overlying upper member of the Piskupstina Formation contains Pontian fauna of cycle III, a relationship also present in the Prespa graben indicating that it too formed during cycle II.

The Kicevo basin is bounded by a N-S-striking fault on its west side and an E-W-striking fault on its south side. The other boundaries of the basin are very irregular and appear that they may have filled river valleys and local topographic lows. The oldest rocks are assigned to the Pelagonian Formation which has a basal conglomerate unit overlain by lacustrine sandstone and claystone followed by coal layers. The upper ~100 m of the basin fill consist of siltstone and claystone with late Miocene flora. Strata in this basin are generally horizontal, thus, displacement on basin-bounding faults appears to have formed depositional sills.

The arcuate Polog graben in northwestern Macedonia had its inception in late Miocene time based on the presence of ~450 m of strata assigned to the Pelagonian Formation that unconformably overlies Paleozoic metasediments of the Western Macedonian tectonic unit. The age of these strata are known only by correlation with fossiliferous strata in the Pelagonian and Kicevo basins. Basin strata, which are covered by Quaternary deposits, are almost entirely known from drill-hole information in this basin. The basin is marked by a continuous, arcuate, convex NW fault that can be traced for ~65 km along its west side. The fault parallels the structural grain of the underlying basement metasedimentary rocks. The surface trace of the fault and the gentle SE slope to the mountains to the west suggest a gently E-dipping possibly listric fault, but there is no information on the nature of the fault with depth. The eastern side of the basin is marked by more irregular faults with steeper mountain fronts. There appear to be several fault breaks in the basement rocks to the east, adjacent to the basin, forming a series of steps, the tops of which appear to be remnants of older erosion surfaces.

The Delcevo-Pechevo graben is a NW-trending basin in eastern Macedonia bounded on both the east and west sides by faults. The oldest sediments belong to the Pancerevo Formation, which consists of a basal unit of fine conglomerate and sandstone overlain by ~100 m of sandstone, siltstone, and claystone without fossils. The middle unit consists of coal-bearing fine-grained strata with Turolian fossils in its upper part.

The Berovo basin is separated from the Delcevo-Pechevo basin by an older Cenozoic, probably pre-Neogene–uppermost Oligocene volcanic complex. The oldest rocks belong to the Pancerevo Formation, similar to the same unit in the Delcevo-Pechevo basin to the north. The upper unit of the Pancerevo Formation contains diatoms of late Miocene age. The basin is bounded by a NNW-striking fault on the east side, a continuation of the fault from the Delcevo-Pechevo basin, and two ENE-striking faults on its north and south sides. Local remnants of similar sediments are found in the mountains to the west suggesting the basin had a larger extent during late Miocene time.

The Strumica graben in southeast Macedo-

nience of rapid subsidence, probably related to rapid movement on the E-W-striking fault along the south side of the basin. The basin is asymmetric with a gentle south slope to the mountains on the north side and a very steep mountain front on the south side. The geometry suggests a southward tilt to the basin, but whether tilting began in late Miocene time is unknown.

LATE MEOTIAN AND EARLY PONTIAN: CYCLE III

During late Meotian and early Pliocene time (cycle III), the Ohrid, Debraca, Debar, and Dojran basins were formed, the Polog, Skopje, Kumanovo, Veles, Tikves, Mariovo, and Pelagonian basins were connected, and the lakes in the Probiست и Kocani gravens (Fig. 7) were drying up. The Pontian age for strata of this cycle is determined by diatoms and fossilized flora and leaf imprints (Dumurdzanov et al., 2004). At the end of this cycle a hiatus is present that extends beyond the limits of the freshwater lakes in the basins. In the Mariovo, Veles, Kumanovo, and Kicevo basins the lakes completely dried up, and were partially dried up in the Skopje, Pelagonian, Strumica, and other gravens. The evidence suggests a period of slower subsidence and perhaps a change in climate from wetter to drier conditions.

Sandstone, siltstone, and claystone units, many deposited in or near lacustrine environ-
ments, are present within the uppermost parts of the Nerezi Formation of the Skopje, Tikves, and Mariovo basins, in the Veles Formation of the Veles graben, and in the Pelagonian Formation of the Polog graben. These strata are correlative from basin to basin and indicate the basins were interconnected during late Meotian and early Pontian time. In some basins, such as the Veles and Tikves basins, there are abundant fossils, in particular a great variety of mammals. Similar beds can be traced into the Kumanovo basin where they intertongue to the east with basalt flows and andesite and latite tuff of the Stari Nagorici Formation. The widespread nature of these deposits suggests that faulting may have been less active during their deposition.

The initial deposits of the Ohrid, Debraca, Debar, and Dojran basins date from this period. The Piskupstina Formation forms the basal unit of the Prespa basin and consists of basal gravel and sandstone resting unconformably on Paleozoic metamorphic and Triassic rocks of the Western Macedonian tectonic unit. Upward finer-grained coal-bearing rocks occur overlain by siltstone, marly claystone, and diatomite. These rocks contain an abundant flora and microflora of Pontian–Early Pliocene age and the lower units are regarded as early Pontian, perhaps late Meotian, in age. The boundary of these deposits are the N-S-striking faults on the east and west sides of the Prespa basin forming a well-defined graben.

The basal units of the Ohrid basin are ~130 m thick and are similar to those in the Prespa basin. Based on lithological correlation with the rocks in Prespa, they are regarded as Pontian and represent the beginning of the Ohrid graben, which, like Prespa, is bounded by major N-S-striking normal faults on both sides. The deposits in the Ohrid basin are also very similar to those of the same age in the Piskupstina half graben, indicating a connection of these two extensional basins at this time. There was probably also a connection with the Debar half graben to the north at this time as well. The eastern part of the Debarca basin has a dendritic pattern caused by the filling of river valleys, and the sediment filling these topographic lows was transported to the west where faults on the west and south sides of the basin formed sills at various times during deposition. At other times sediment deposition was connected with the northern part of the Ohrid basin.

The Kicevo basin is similar to the Debarca basin. It has a dendritic pattern caused by filling valleys along generally west flowing rivers. The oldest sediments are known from drill holes that contain basal alluvial deposits filling upward into lacustrine strata with late Miocene fossils (Dumurdzanov, 1997; Ognjanova-Rumenova, 2000) of cycle III. Deposition occurred by subsidence along faults on the west and south sides of the basin. At times sediment transport spilled eastward into the Porecje half graben (see Fig. 8) along the course of the modern Teska River. It is possible sediment transport may have even extended to the north along the Teska River into the Skopje graben, as there are small remnants of these sediments in the mountains above the northern course of the Teska River.

The Piskupstina Formation forms the basal units of the Debar basin and is known only from drill-hole information. It consists of a basal conglomerate and sandstone, overlain by siltstone, marl, and claystone with some coal. The upper part of the section is very similar with well-dated rocks of Pontian age in the Piskupstina half graben and the two basins and the Ohrid graben were probably connected at this time. The strata in the Debar basin dip gently (~10°–15°) east into the basin bounding fault and form a tilted half graben. This fault strikes NNW and appears to be a major fault that connects with the fault bounding the west side of the Piskupstina and Ohrid basins. However, the Debar basin strata dip east whereas the Piskupstina basin strata dip gently west. This fault trends across the pre-Cenozoic boundary between the Western Macedonian and Chukalı-Krasta basement units.

The Dojran Formation forms the basal unit of the Dojran basin in southeastern Macedonia. The strata rest unconformably on the metamorphic units of the Serbo-Macedonian basin unit, but the strata are only known from drill-hole data. The lower part of the Dojran Formation consists of ~300 m of basal gravel, sandstone, siltstone, and claystone overlain by an upper part with interbedded claystone, marly claystone, and marl. Fossils determined by Garevski (1992) indicate a late Miocene age for the upper part of the sequence. Faults bounding this basin trend N-S and ENE and presently the basin has internal drainage.

PLIOCENE: CYCLE IV

The lower boundary of cycle IV is well marked by a partial or complete hiatus and the Pliocene strata of cycle IV begin with abundant deposits of coarse-grained gravel and sandstone which overlie different stratigraphic levels of cycle III rocks. Widespread thick units or remnants of Pliocene sedimentary rocks of cycle IV demonstrate that new fault-controlled basins were formed, such as the Lakavica and Porecje basins as well as the smaller Mavrovo, Demir Hisar, and Rača basins (Fig. 8). Characteristically during this cycle, the Pliocene strata in many of the basins contain similar polymict gravel and coarse-grained sandstone and abundant lacustrine deposits, and their distribution indicates that many of the basins were interconnected. Most of these strata are assigned to the same formation, the Solnje Formation, first described from the Skopje graben (Dumurdzanov et al., 1997). Unfortunately, this formation is poorly dated and a Pliocene age can be determined in only a few places. Its age is based on its position above dated late Miocene and early Pliocene deposits in the Tikves and Veles basins (see above) and below fossiliferous late Pliocene travertine deposits in the Kumanovo basin (Karajovanovic and Hristov, 1976). Strata in the Mariovo and Tikves basins have yielded diatom and macrofloral imprints of Pliocene age. Radiometric ages (both K/Ar and Ar/Ar) range from 4 ± 0.2 Ma to 1.8 ± 0.1 Ma from pyroclastic rocks that are present throughout the Solnje Formation in the Mariovo basin and from agglomerate and tuff within sandstone and travertine deposits in the Tikves basin date these deposits as Pliocene.

Also within upper Miocene strata of the Kumanovo basin at the Guriski Monastery, Mladno Nagoricani, are calc-alkaline basalt flows dated at 8 Ma (Boev and Yanev, 2001) that are unconformably overlain by sediments of the Solnje Formation which yield a lower age limit for the formation. In other basins the age of the Solnje Formation is based on lithological correlation with the dated rocks from the Mariovo, Tikves, and Veles basins.

Basins initiated in pre-Pliocene before the beginning of cycle IV all show continued subsidence during the Pliocene. Characteristically, cycle IV strata begin with a sequence of conglomerate and gravel and continue with interbedded or poorly stratified gravel, sandstone, and sandy claystone strata assigned to the Solnje Formation. These deposits range in thickness from ~60 to 200 m except in the Tikves basin, where they are 400 m thick. Because cycle IV strata all begin with conglomerate that lies above a widespread unconformity and the stratigraphic section is coarser grained than older strata, dominated by conglomerate and sandstone, it indicates that the rate of faulting probably increased during Pliocene time. In many of the basins, the Pliocene strata are limited by young and active faults, (see discussion below) and we infer...
CENOZOIC TECTONICS OF MACEDONIA

Figure 8. Distribution of sedimentary and volcanic rocks of cycle IV—Pliocene—of Macedonia. The actual outcrops (color) and possible extent of sedimentary rocks (dotted pattern) are shown. Faults active during this time are shown in red where established and dashed where inferred. Outcrops of volcanic rocks are shown in solid color (green) and their possible extent is shown by random v pattern. BV—Bukovik volcanic center.

that these faults were active during deposition of cycle IV strata.

The Kumanovo, Skopje, and Veles basins contain conglomerate and sandstone that locally grades into lacustrine siltstone and claystone, all assigned to the Solnje Formation. Similar rocks occur in the small Slaviski basin where they are assigned to the Ginovci Formation. The lacustrine deposits indicate renewed lake development following the hiatus at the base of the Solnje Formation. In the western part of the Veles basin, the Solnje Formation lies on pre-Cenozoic rocks indicating locally more widespread deposition than older Cenozoic strata.

Pliocene deposits are missing in the Probis-tip basin, but are present in the E-W-trending Slaviski and Kocani basins. Both of these basins are bounded by faults along their south sides, and the Kocani basin has a poorly developed fault on its north side. The morphology in the eastern part of the Slaviski basin suggests it is tilted gently south with a steep mountain front to the south and a very gentle slope to the south on the basement rocks north of the basin. Strata in the southern part of the Kocani basin dip south 10° into the boundary fault indicating the Kocani basin is also tilted to the south. The E-W trend of these basins and their southward-tilted strata indicate these two half grabens are transverse to the underlying basement structure in the Serbo-Macedonian tectonic unit and are also transverse to the older NW-trending late Miocene basins in eastern Macedonia. The sediments and structure of these two basins suggest that the western part of the Slaviski basin formed in cycle III and the eastern part in cycle IV, and that the Kocani basin formed in cycle IV. The fault on the south side of Slaviski basin is part of the regional Elbasan-Debar-Skopje-Kustendil fault zone. If so, it indicates the Cenozoic activity on this fault may have begun in latest Miocene and early Pliocene time in its eastern continuation.

Unlike most of the other basins, the Tikves basin contains ~400 m of sandstone, tuff, and agglomerate. The volcanic rocks yield ages of
shape of the basin bounding faults suggest continued formation of the west-tilted graben.

The Pelagonian basin is largely covered by Pleistocene deposits, but drill holes indicate it contains gravel and sandstone of the Solnje Formation. The very thick (600 m) underlying Miocene deposits and the Pliocene rocks are restricted to a basin bounded by generally N-S-striking normal faults on both the east and west sides, thus, the basin is a true graben. Exposures of Miocene and locally Pliocene rocks along its SE side suggest the graben may have a west tilt.

Pliocene rocks in the Delcevo-Pehcevo basin contain gravel and sandstone of the Solnje Formation. The strike of these strata is NNW along the upper reaches of the Bregalnitz River valley, and their deposition appears to be controlled by NNW-trending faults which mainly bound the older upper Miocene deposits. The Pliocene sediments deposit continue south into the Berovo basin whose upper Miocene deposits are controlled NE-striking faults. These Pliocene basins may be controlled by the older faults inherited from late Miocene cycle II and III faulting.

The Dojran basin contains gravel, sandstone, and sandy claystone of the Solnje Formation. This is only known from drill-hole data, thus, there is little information on the structural character of this basin during Pliocene time.

The Debar basin contains gravel and sandstone assigned to the Solnje Formation that are exposed along incised rivers and are tilted east into a fault that bounds the east side of the basin above which the mountains rise to more than 2000 m. The fault continues to the south and bounds the west side of the Piskupstina west-tilted half graben which also contains gravel and sandstone of the Solnje Formation.

In southwestern Macedonia and extending into northern Greece are the N-S-trending Ohrid and Prespa grabens, two of the largest and best developed grabens in Macedonia. Both grabens have active faults on both east and west sides. Pliocene deposits consist of conglomerate and sandstone of the Solnje Formation that are only exposed at the north ends of these grabens, but are known from limited drill-hole data to be ~100 m thick within the grabens. The distribution of Pliocene deposits indicates that the faulting that formed these grabens in the late Miocene continued through the Pliocene and into the Pleistocene. One of the N-S-striking faults extends northward from the Ohrid graben and forms the sill at the west side of the Debarca basin whose deposits fill older river valleys. The southern arm of this basin is controlled by an E-W-trending fault, a geometry similar to the Kicevo basin to the north.

The Debar-Skopje-Kustendil fault zone (see below) that was particularly active from the southern Prolog to Debar basins during this cycle. Sediments of the basin are only known

5–1.8 Ma (Boev and Yanev, 2001) confirming the Pliocene age of these deposits that are assigned to the Vitacevo Formation. The Marivo basin contains poorly stratified gravel and sandstone assigned to the Solnje Formation indicating continued subsidence during Pliocene time; the age of these strata is based on correlation with similar dated rocks in the Kumanovo basin. Like the Tikves basin the Marivo basin also contains volcanic rocks in the Vitacevo Formation. The Vitacevo Formation conformably overlies the Solnje Formation and contains ~50 m of tuff overlain by sandstone and gravel interbedded with tuff, sandy claystone, and diatomite beds ~5–30 m thick. The diatomite is richly fossiliferous and yields floras of Pliocene age (Dumurdzanov et al., 1976; Ognjanova-Rumenova, 2000). K/Ar ages from volcanic rocks also yield Pliocene ages that range from 4.0 ± 0.2 to 1.8 ± 0.1 Ma. The sediments in the Marivo basin probably were transported east along an ancient course of the Crna River, and the volcanic rocks were sourced in the south and east from the volcanic area in the southern Tikves basin. The basin is formed by filling of river valleys that were dammed by a sill formed by west-side-down movement along a N-S-striking normal fault along its east side.

Like the Marivo basin, the Kicevo basin contains conglomerate and sandstone assigned to the Solnje Formation that rests unconformably on Miocene rocks. The strata fill an irregular three-armed basin formed by river valleys that are controlled by N-S, NE, and E-W faults (Fig. 8). Strata in the basin are generally horizontal. The river valleys that form the basin are fault controlled, but the basin is not a simple structural basin. The faults along its west and south sides probably produced the most significant relief during basin formation.

The Strumica graben has coarse gravel over lain by sandstone, claystone, and gravel assigned to the Vladevici Formation. Unlike the other basins, these strata have a gradational contact with rocks below and their Pliocene age is based on the assumption that the beginning of gravel deposition is Pliocene and indicate the faults along the south and west side of the Strumica basin continued to be active during cycle IV deposition.

The Polog basin contains 130 m of the Solnje Formation, but these rocks are only exposed at the southern and northern ends of the basin (Fig. 8). The Pliocene strata within the basin are known from numerous drill holes. The gentle east slope of the high mountains (2500 m) on the west, the steeper slopes on the mountains to the east, and the convex east
CENOZOIC TECTONICS OF MACEDONIA

Figure 9. Distribution of sedimentary and volcanic rocks of cycle V—Pleistocene—of Macedonia. The actual outcrops (color) are shown. Faults active during this time are shown in red where established and dashed where inferred. Volcanic rocks are shown in solid color (blue-green) and larger deposits of travertine deposited in lakes are shown in purple. BV—Bukovik volcanic center; BM—Belasica Mountains.

from 50-yr-old drill holes that contained coarse gravel, sandstone, and claystone that correlate lithologically with the Pliocene deposits in the adjacent Polog basin. Its position along the major left-lateral strike-slip fault suggests the basin is a pull-apart structure.

The deposits in the Demir Hisar basin have a dendritic pattern and fill older valleys whose rivers probably drained eastward into the northern part of the Pelagonian basin. The strata in this basin begin with gravel and sandstone of probably Pliocene age. Although deposition was caused by subsidence due to faults, the filled river valleys trend N-S parallel to the structural grain of the underlying Paleozoic rocks of the Western Macedonian tectonic unit. The deposition in this basin may have been controlled by older basement structures, but whether faults controlled the basin formation is unclear.

PLEISTOCENE: CYCLE V

Sedimentary rocks of Pleistocene age (cycle V) are the most widespread Cenozoic deposits in Macedonia (Fig. 9). In many places they cover older Cenozoic deposits and make it difficult to accurately reconstruct the distribution of the older strata. Quaternary age (cycle V) tectonic activity is characterized by a general uplift and development of glacial deposits that appear above 1200–1500 m (rarely 1000 m) elevation. The remains of moraine, glaciofluvial strata, and glacially sculptured landscapes are clear evidence for the glacial activity. Garcevski (1969) has determined abundant mammalian fauna of Riss and Wurm ages from these glacial deposits. Subsidence and shaping the present Aegean Sea, and the simultaneous elevation of the central Balkan Peninsula, influenced both the burial of lacustrine deposits by glaciofluvial and proluvial-alluvial material and the draining of the extensive lake system within central Macedonia. Most of the basins of central Macedonia were interconnected and formed an extensive system of lakes with surrounding fluvial and glaciofluvial environments. The Ohrid and Prespa lakes, as well as
the preserved lacustrine strata and travertine deposits in the Tikves, Mariovo, and Skopje grabens are the remnants of the extensive lake system. The dam for this lake system was at the southern end of Tikves basin. Within, central Macedonia lakes were widespread during early Pliocene time, but may have begun to drain as early as early Pleistocene time by the formation of the through-going Vardar River and its important tributaries, such as the Crna, Treska, and Bregalnica Rivers which now flow into the northern Aegean Sea (Fig. 2). The timing of draining of the lake system within Macedonia is somewhat uncertain. It appears that the northern lakes may have begun to drain in the early Pleistocene; however, the dam at the southern end of the lake system was clearly breached by the early (?) or middle Pleistocene. Most of the Pleistocene and Pliocene strata have been deeply incised in the Macedonian basins, and they are preserved in many places as terraces at different elevations due to tectonic uplift and incision by the Vardar River and its tributaries. Even though there was extensive draining of the central Macedonian lake system, local small lakes remained in some of the basins.

The dam for the central Macedonian lake system, formed by Jurassic limestone at the southern end of the Tikves basin, was breached and the lakes were drained by development of the Vardar River and its tributaries. The elevation of the top of the dam is hard to define because some erosion has modified it, but it lies between 400 and 440 m. Headward erosion along the Vardar River and its tributaries removed considerable Pleistocene and older strata from the central Macedonian basins. The knickpoint for incision has passed through the Tikves, Skopje, Kriva Palanka, Kocani, Berovo, and Lakavica basins in the north and east, and lies at the southeastern corner of the Polog basin to the west. The Polog and Pelagonian basins are drained by the Vardar River or its tributaries, but have not been incised by the rivers and remain covered by Pleistocene deposits.

Headward erosion has affected several of the smaller basins where older river valleys have been filled, such as the Kicevo and Porece basins that contain 10–30 m of Pliocene strata, which represent remnants of more widespread deposits. The Lakavica basin was a site of more rapid subsidence during the Pleistocene with deposition of ~100 m of poorly sorted gravel before it was incised by the Lakavica River, a tributary of the Bregalnica River and ultimately the Vardar River.

Pleistocene subsidence along basin-bounding faults continued in the Pelagonian, Prespa, Ohrid, and Polog grabens. Pleistocene deposits occur across the entire Polog basin and are thick near the western side of the basin indicating greater subsidence (westward tilting) related to activity along the western boundary fault. Lake deposits in the basin have yielded Pleistocene ostracods (Petkovski et al., 1985).

The Pelagonian basin has been little affected by Pleistocene river incision and only recently has incision reached the southeastern part of the basin along the Crna River, a major tributary of the Vardar River. Pleistocene deposits cover the entire basin and consist of thin (10–20 m) alluvial sediments near Prilep, and glacial fluvioluvial sediments near Bitola.

The Prespa and Ohrid grabens still contain lakes and are preserved as remnants of the very extensive Quaternary lake system of Macedonia. They lie at 853 m and 700 m elevation, respectively, well above the sill elevation at the south end of the Tikves basin. Both grabens contain 50–60 m of Pleistocene lacustrine and marsh sediments, with local peat deposits. Ohrid Lake is presently being drained by the Crni Drim River with a knickpoint at the north end of the basin. The river flows north through the Piskupstina and Debar basins that contain 10–15 m of Pleistocene deposits which are presently being actively eroded as the river continues northward into Albania emptying into the Adriatic Sea. Little erosion has occurred in the Ohrid basin strata, but incision becomes deeper downstream. The Prespa basin remains completely enclosed. There exist topographic sills to the Ohrid, Prespa, and Pelagonian basins to the south in Greece where steep south-facing faulted mountain fronts may be breached in the near future by headward erosion by rivers from the south.

In the Tikves basin deposition of lacustrine strata continued into the Pleistocene where they interfinger with thick beds of breccia conglomerate and agglomerate, tuff, and volcanic breccia extruded from volcanic centers at the southwestern edge of the basin. These volcanic rocks yield ages of 4–1.8 Ma (Boev and Yanev, 2001) so some of the strata are Pliocene. Most of the Pleistocene deposits of the Tikves basin have been deeply incised by the Vardar River, but the thick volcanic rocks in the southern part of the basin have only been partially incised by the Vardar River tributaries and still preserve original depositional surfaces that lie at more than 1400 m elevation. ~1000 m above the sill at the southern end of the Tikves basin. Tributaries of the Vardar River have deeply incised the western part of the Vala, Raec, and Mariovo basins west of the Tikves basin. The Mariovo basin contains pyroclastic rocks with travertine deposits up to 20 m thick. These deposits are extensively eroded but retain evidence for the existence of the widespread Mariovo Lake. Shelly fossils indicate a Pleistocene age for these deposits (Dumurdzanov et al., 1976).

The Delcevo-Pechevo and Berovo basins contain Pleistocene alluvial, lacustrine, and swamp deposits. An 80-m-thick unit of limnic breccia is well developed around the Bukovik volcanic area in both basins indicating renewed activity along the eastern boundary fault. Pleistocene headward erosion by the headwaters of the Bregalnica River has deeply incised the deposits of these basins and forms a deep valley in the basement rocks along the river where it passes through the mountains between the Kocani and Delcevo-Pechevo basins.

The Dojan, Valandovo, Geyvelja, and Strumica basins lie outside of the central Macedonian interconnected basin system, although there may have been a connection between the Strumica and Lakavica basin at the northwest end of the Strumica basin. The Dojan graben lies to the south beyond the sill of the extensive lake system and has remained an enclosed basin during Pleistocene to Recent time. It contains 50–60 m of sandstone and claystone overlying a thick package of clay and marsh deposits indicating continued subsidence of this basin during Pleistocene time. It has a very low sill and will soon be drained by rivers from the south. The Strumica basin is being incised by tributaries that flow eastward into the Struma River in western Bulgaria where it flows south into the northern Aegean Sea. The central part of the Strumica basin remained a site of Pleistocene deposition and contains aluvial sediments adjacent to the Monosipitovo Lake lacustrine and marsh deposits. Near the Belasica Mountains Pleistocene glacioluvial sediments are 50–60 m thick indicating activemovement along the southern basin boundary fault during Pleistocene time and continued southward tilting of the basin.

**ACTIVE AND YOUNG (QUATERNARY) FAULTS**

The relations between basin formation and faulting can best be established for the Pleistocene (cycle V) basins. The study of active and young (late Quaternary) faults in Macedonia (Fig. 10) is hampered by slow slip rates on faults, <1 to ~2 mm/yr as determined from GPS studies (Robert King, 2004, personal commun.), low seismicity (Fig. 11), and long recurrence intervals. The central and eastern parts of Macedonia have been affected...
by rapid erosion caused by the incision of the Vardar River and its tributaries during the later part of Pleistocene time which has eroded many of the faults and fault-related features. Thus, direct evidence for active and young faults, such as fault scarps, is poorly developed, and we have sometimes had to rely on second-order morphological features to identify or infer active and young faults. On the map (Fig. 10) for active and young (Quaternary) faults we show three groups of faults. The first is where there is direct evidence for active faulting, the second is where there is well-developed morphological evidence for faulting, but active scarps were not recognized, and the third is where morphological evidence is present but not well developed and young or active faulting is inferred. The location of active faults is also marked by seismic activity (Fig. 11), although the location of earthquakes relative to known faults is not always clearly established, and much more detailed studies of the seismicity are warranted. Positive geological evidence for active faulting is present on a number of faults in Macedonia. The Debar half graben in western Macedonia is bounded by a fault along its east side above which there is a steep linear mountain front. There is a prominent break in slope at the mountain front, but abundant vegetation makes it impossible to see fresh scarps. At the northern end of the fault trace, before it enters Albania, there are numerous hot water springs along the fault and the fault shows right-lateral deflections of small streams that flow west across the fault. Together these data suggest the fault is an active normal, down-to-the-west, right-lateral fault.

In the Ohrid graben, the only observed fault scarp is along the southeast side of the graben. The steepest and highest (700 m) slopes are along the east side of the graben, and the greatest displacement, 1800 m from the mountain top to the base of the graben fill, is on a series of closely spaced faults along the mountain front suggesting these have been the most active faults during graben development. Abundant seismic activity along the eastern margin of the Ohrid graben supports the modern activity along these faults (Fig. 11). The fault on the west side of the graben continues northward to the Debar half graben, but passes through a forested area, and evidence for recent activity, while possible, is not evident. Seismic activity along the Ohrid-Debar and Ohrid-Kicevo trends (Fig. 11) sup-

Figure 10. Active and young (late Pleistocene) faults of Macedonia. Faults with evidence for active displacement (scarps or deflected rivers) are shown in red, faults with well-developed morphological evidence for recent activity are shown with solid blue lines, and faults with weak morphological evidence for recent activity are shown with dashed blue lines. Faults with evidence for strike-slip displacement are shown with arrows. Regional Elbasan-Debar-Skopje-Kjustindil fault zone is shown by shaded zone. Krupnik and Kjustindil faults in western Bulgaria are also shown.
port the active nature of the faults along these trends.

The faults bounding the Prespa graben show only morphological evidence of young or active faulting by the sharpness of the break between basin and mountain fronts. The west side fault appears to have the sharpest break in slope, and a small segment of the E-W-striking fault on the jog on the west lakefront shows a small scrap. Seismic activity along the west side of the graben supports geological evidence for active faulting along this side of the graben (Fig. 11).

The Pelagonian graben near Bitola has weak morphological evidence for young or active faulting along its east side, but the west side fault shows clear morphological evidence for young and active faulting in the sharpness, linearity, and continuity of the mountain front as well as seismic activity. The NNW-striking fault bounding the northern part of the graben becomes more well defined morphologically to the north, where it passes into rocks of the Western Macedonian tectonic unit. North of the Treska River, the streams that flow east across the fault and incise into the Porecje half graben sediments show right-lateral deflections indicating this part of the fault is active, although there is no seismic activity to support this interpretation. The two small grabens that branch to the NW from the Pelagonian graben near Bitola show sharp and well-defined contacts between sediment and bed rock, and Corona images show local scars in this heavily tree-covered area suggesting at least parts of these faults are active and all of them are young. Seismic evidence supports the geological evidence for active faulting at least along the northern of the two branches (Fig. 11).

The faults bounding both sides of the Polog graben show well-developed morphological evidence for active or young faulting, but fault scarp have not been observed in this area. The west-side fault marks a long curved sharp break in slope. The east-side faults are more irregular and have steeper mountain fronts and remnants of low-relief landscapes capping numerous topographic steps above the faults. The Vardar River flows north along the eastern mountain front suggesting this side of the graben may be subsiding more rapidly than the western side, the opposite sense suggested by data indicating the Pleistocene sediments are thicker on the west side of the graben (see above). In addition, the Vardar River flows north past a wind gap whose sill lies less than 100 m above the river level to cut through the mountains farther north into the Skopje basin. This supports the interpretation that the east side fault system is young and possibly active.

Seismic activity in the Polog basin, however, lies mainly along the west side indicating that this side of the graben is also active (Fig. 11).

The Skopje basin is well known for its active faults. In many places, Pleistocene deposits are stranded on uplifted fault blocks, and they are locally interbedded with 10–20 m of travertine deposits that were once part of the widespread Pleistocene lake system. The central part of the Skopje basin continued to subside and Pleistocene strata are 60–80 m thick. Differential displacement of the Pleistocene strata occurs along numerous faults that define the complex Skopje graben and adjacent uplifted mountains (Figs. 9 and 10).

Seismic activity is abundant in the Skopje graben and the major 6.1 M earthquake in 1963 was on an intrabasin WNW-trending fault within the city near the Vardar River. Earthquakes are known also from 518 and 1550 in the Skopje area. The evidence for young and active faulting is present on scarps and offset Quaternary deposits on the graben-bounding and intrabasin faults in the northwest part of the graben. One morphologically clear E-W-striking fault marks the north side of the Vondo Mountain southwest of Skopje. Along that part of the mountain are several flat-topped topographic steps that may be faulted erosion surfaces indicating young fault
activity. This fault has a clear trace and follows the structural grain in the basement rocks and its location is probably controlled by basement anisotropy. The fault forms a segment along the regional Elbasan-Debar-Skopje-Kjustendil fault zone, that besides the 1963 earthquake in Skopje, is marked by a 6.1 M earthquake in 1967 near Debar, and a recent earthquake in 2004 near Gostovar at the SW end of the Polog basin. This fault zone is interpreted by Macedonian geologists to be a major regional fault with left-lateral normal displacement. From Kustendil through the Slavinski graben and to the Skopje basin it is a clearly continuous fault in the field (Arsovski and Petkovski, 1975). According to Janevski (1987) this fault zone is an early alpine structure reactivated during recent time. The fault zone cuts across the West Macedonian, Vardar, and Serbian-Macedonian tectonic units. The displacement on this fault zone was important in the development of the Skopje and Kumanovo grabens. Seismic and geological evidence supports the existence of the western part of this fault zone, but only geological evidence supports its eastern part within Macedonia. Morphological evidence suggests the NW-striking fault on the northeast side of the Skopje graben is also young and possibly active, but the evidence is not as clear as on the south side of the graben.

Faults along the west side of the Kumanovo graben form morphologically sharp straight segments suggesting young and possibly active faulting. A study of Corona images suggests scarps on the northern two segments of the graben bounding faults.

The eastern part of the Slaviski half graben is marked by a sharp break in slope along the southern boundary fault. The Kriva River along the western end of the graben, just before it turns south, flows along the fault trace, and there is a possible scarp adjacent to the river; however, it has been modified by human activity so it is uncertain if it is a fault scarp. The morphological evidence in this vegetated area suggests the fault is young and that the western part of the fault is active. This fault forms the eastern segment of the Elbasan-Debar-Skopje-Kjustendil fault zone; however, it is not marked by post-1976 seismicity.

The fault along the south side of the Kocani half graben shows clear morphological evidence for young faulting with a sharp continuous break between basin sediments and basement rocks. The mountain front is marked by triangular facets indicating young faulting, and there is a suggestion of fault scarps, but human activity and heavy vegetation obscure clear evidence the fault is active.

Streams that cross the fault along the west side of the Lakavica graben near the villages of Zagarci and Konce show left-lateral deflections indicating the fault is active. Further north the fault disrupts surface topography, but farther north its activity is not clear; however, its northern projection bounds the northeast side of a small horn of basement rocks surrounded by Paleogene sediments. Southward the fault jogs to the east and enters basement rocks where evidence for its activity becomes less clear.

The Strumica half graben shows clear evidence for active faulting along its southern and western borders. Morphologically its E-W-trending southern boundary is sharply defined by the steep Belasica Mountain front that rises ~1800 m above the basin floor. The fault trace is irregular with branches of the fault striking from the mountain front into the mountains. In only two places is there evidence for fault scarps in this heavily vegetated area (shown by the two red line segments in Fig. 10). The western part of the half graben trends NW, and a fault along its southwestern side forms a sharp linear mountain front. North of Strumica there are discontinuous scarps and streams that flow east across the fault and show left-lateral deflections indicating active faulting. There is minor seismic activity in the SW corner of the graben where the evidence for active faulting is present. Northward the evidence for young or active faulting is mainly morphological. At one locality along the road from Damian into the Lakavica graben are exposures of a NNW-striking fault dipping 55° NE that displaces the youngest alluvial deposits but no scarp can be identified. There are a few earthquakes along the trends of the NW-striking faults in the Lakavica and NW part of the Strumica grabens, but the accuracy of their locations is unknown.

There is a sharp, straight E-W-trending morphological boundary between basin and mountains along the southern boundary of the Vandalovo half graben. An earthquake cluster occurs in the western part of this basin and a major earthquake occurred in 1932 with magnitude 6.5–6.8. The geological and seismic evidence indicates that the E-W-striking fault along the southern side of the basin is active.

A sharp morphological break is present along the small NW-trending basin that branches southeast from the Vandalovo half graben toward the Dorjan basin. The Dorjan basin also is bounded by sharp and straight morphological segments. There is no direct geological evidence for active faulting, but the morphological evidence indicates young faulting. However, seismic evidence suggests at least some of the faults are active (Fig. 11).

The fault along the northern boundary of the Dorjan basin continues eastward into Greece along the south side of the Belasica Mountains. In Greece there are scarps along this fault indicating at least the eastern part of the fault is an active normal fault.

The largest earthquake in Europe in the last century occurred in 1904 along the ENE-striking down-to-the-north Krupnik fault in western Bulgaria near the Macedonian border (shown on Fig. 10), and there is a cluster of post-1976 earthquakes along it (Fig. 11). Meyer et al. (2002) assigned this earthquake a magnitude of 6.9 based on their geological investigation; however, the Macedonian data recorded at Pehcevo assigned a magnitude of 7.5–7.8 to the earthquake, and the Bulgarians also give a similar magnitude (Rangelov et al., 2001). The fault strikes west toward the Berovo graben; however, the continuation of the Krupnik fault in Macedonia is not clear in the Berovo basin. The fault may be discontinuous and may have its continuation either along the northern fault in the Berovo basin or the southern boundary fault of the Kocani half graben. There is minor earthquake activity in the southern Berovo graben, but whether this is connected with the Krupnik fault is unclear (Fig. 11).

Our GPS studies show uniform 1–3 mm/yr southward movement of most of Macedonia with respect to Europe (Robert King, 2004, personal commun.). There is little evidence for differential velocities within Macedonia except possibly an ~1 mm/yr southward increase in velocity with a left-lateral component across the Polog and Skopje grabens and possibly in the area of NE Macedonia in the area of the Slaviski half graben. This change in velocity is across the trend of the Elbasan-Debar-Skopje-Kjustendil fault zone and preliminarily supports the interpretation of the regional nature of the fault zone. The uniform velocity field in most of Macedonia is interesting in light of the abundant evidence for active strike-slip faulting along the Debar, Lakavica, Porecje, and Strumica basins and major sharply defined relief along many grabens, such as the Ohrid and Prespa grabens, and half grabens, such as the Strumica and Kocani half grabens. It suggests that the present magnitude of uncertainty in the GPS velocity field is insufficient to show the slip on active faults. Importantly our geological interpretation shows a lack of young and active faults in the central part of Macedonia, an interpretation supported by the prominent lack of seismicity in this area (Fig. 11).
The temporal and spatial distribution of Cenozoic structural activity in Macedonia is part of a broader tectonic regime that we have referred to as the Southern Balkan Extensional regime (Fig. 1; Burchfiel et al., 2000). The tectonic evolution of this regime is dominated by a geodynamic system related to E-directed subduction that migrated from the Vardar zone in latest Mesozoic–early Cenozoic time westward to its present position in offshore northern Greece, Albania, and southern Yugoslavia (Montenegro). Contemporary with the migration of the subduction zone were changes in the dynamics of the suprasubduction lithosphere that extends from Bulgaria across Macedonia and Albania that may have caused lateral spreading due to the gravitational instability of hot thick crust within the Cenozoic volcanic arc. Thus, it requires a broader view of the geodynamic evolution across the entire Southern Balkan region in order to understand the Cenozoic tectonic evolution of Macedonia which makes up a small, but critical part of this regime.

Final closure of the Vardar zone ocean probably occurred in the latest Cretaceous or earliest Paleogene, but continued deformation was localized in this zone of lithospheric weakness during latest Cretaceous-Paleogene time with thrusting, strike-slip faulting and folding (Pamic’i, 2002). This deformation was related to continued eastward underthrusting of lithosphere from the west that contained the continental crustal fragment consisting of the Western Macedonian and Pelagonian tectonic units beneath the Serbo-Macedonian tectonic unit and other tectonic units of Bulgaria and northern Greece (Pamic’i, 2002). Following the final suturing along the Vardar zone, subduction shifted westward into the Chukali-Krasta and Pindus zones of Albania and northern Greece, respectively (Fig. 12; Aubouin and Ndojay, 1964; Robertson and Shallo, 2000). During the Eocene and early Oligocene, oceanic or thin continental lithosphere continued to underthrust to the east along the Chukali-Krasta and Pindus zones of Albania and northern Greece, respectively (Fig. 12; Aubouin and Ndojay, 1964; Robertson and Shallo, 2000). The suprasubduction zone continental lithosphere developed extensional structures in southwest Bulgaria in the middle(? to late Eocene–Early Oligocene along the NW-trending Mesta detachment and numerous NW-trending, W-dipping normal faults in western Bulgaria and eastern Macedonia (Burchfiel et al., 2003; Kounov et al., 2004).

Somewhat earlier extension may have occurred farther east in the eastern Rhodope Mountains (Dimov et al., 2000), but the evidence needs clearer documentation. These E-tilted basins may have overlain a major W-dipping detachment system, but present evidence cannot confirm this interpretation. Coeval with this ENE-WSW extension was the development of a Paleogene magmatic arc that extended from eastern Serbia through eastern Macedonia and southwestern Bulgaria into northern Greece (Figs. 1 and 12; Harkovska, 1983, 1984; Boev and Yanev, 2001). West of the magmatic arc the marine and non-marine strata of the late Eocene to late Oligocene Tikves-Ovchepole basin were deposited and interfingered to the east with the arc rocks, placing the Tikves basin in a forearc basin position. The cause of the intra-arc/backarc extension may be related to gravitationally induced lateral spreading in a thickened hot crust along with trench rollback, but the relative contribution of the two mechanisms presently cannot be uniquely evaluated (Burchfiel et al., 2003) and other suggested mechanisms have been proposed by Kounov et al. (2004).

In the late Oligocene–early Miocene, strata in the Tikves basin were folded and several, but not all, of the half grabens to the east were deformed mainly by west-vergent structures. At the same time folding and thrusting occurred locally in Bulgaria (Burchfiel et al., 2000; Nakov et al., 2001). This shortening deformation is short-lived, perhaps only a few million years long, before the second period of extension began in middle Miocene time. The cause for this short period of shortening may be the arrival of the Kruja crustal fragment in the Chukali-Krasta subduction zone to the west (Fig. 12; Aubouin and Ndojay, 1964; Robertson and Shallo, 2000). Royden (1999) has shown that small crustal fragments entering a subduction zone can slow the rate of subduction and also change the stress regime in the suprasubduction crust from extension to compression. Following accretion of at least the upper part of the Kruja crustal fragment eastward subduction of oceanic or thinned continental crust continued and we postulate that the subduction rate was again increased and trench rollback was renewed.

During the middle Miocene, extension began within central and eastern Macedonia along mainly NW-trending faults forming grabens (Skopje and Probistip) and associated basins. The magmatic arc development appears to have continued from Paleogene time into Neogene time, although the igneous rocks temporally and spatially change their character (Boev and Yanev, 2001). The E-dipping subduction zone at this time was in western Albania (Roue et al., 1995; Robertson and Shallo, 2000). The graben formation at this time is both within (Probistip) and west of the magmatic arc (Skopje graben), and the surface expression of the backarc extensional detachment system in western Bulgaria migrated westward from the Mesta half graben to the Struma half graben and its southern extension, the Strymon Valley detachment, in northern Greece (Fig. 12; Burchfiel et al., 2003; Dinter and Royden, 1993).

Extension in Macedonia continued into late Miocene time with the development of NW-, NNW-, and N-S–trending grabens and half grabens that became progressively younger to the west. The magmatic arc continued to develop during this period and its rock types have different characteristics both spatially and temporally, some showing arc, others with plate characteristics (Boev and Yanev, 2001). There was also a tendency for the arc to migrate slightly to the west into late Cenozoic time. These relations suggest the extension was related to trench rollback as only some basins lie within the arc, but most lie west of it where the crust was neither hot nor thickened.

In Pliocene time there was further westward migration of extension and resultant graben formation into western Macedonia and eastern Albania, suggesting continued trench rollback was an important mechanism in their formation (Fig. 13). Coeval shortening was restricted to a narrow zone near the subduction zone in western Albania (Roue et al., 1995; Robertson and Shallo, 2000). At the same time there was a major tectonic change in eastern Macedonia with the formation of E-W-trending faults and associated basins. These form the S-tilted half grabens of Slaviski, Kocani, and Valandovo half grabens and the continued subsidence of the Strumica half graben. This change took place about the beginning of Pliocene time (ca. 6 Ma), which is the time that the North Anatolian fault extended into the northern Aegean Sea (ArmiJo et al., 1999). At this time a similar, but diachronous, change to E-W–trending grabens also occurred in Bulgaria (Burchfiel et al., 2000). These structures indicate N-S extension. This may be the beginning of the SSW movement of the Aegean crust as a single plate (Papanikalou and Royal, personal commun., 2004; Burchfiel 2004). Such movement south of the North Anatolian fault may have drawn the lithosphere in the Southern Balkan extensional regime along with it, but at a slower rate.

The Pliocene pattern of deformation in the Balkan region continues to the present where
the pattern of Pleistocene extension is similar (Fig. 13) and our preliminary GPS studies suggest it is active today. Thus, the present tectonic framework appears to have developed in Pliocene time with continued trench rollback associated with eastward subduction in offshore Albania along the Northern Hellenic trench and a narrow zone of shortening in western Albania (Roue et al., 1995; Robertson and Shallo, 2000). There are three areas of different tectonism; ENE-shortening along the Adriatic coast, ENE- to E-W extension in eastern Albania and western Macedonia, and N-S extension in eastern Macedonia and Bulgaria (Fig. 13). The western zone of extension we interpret to be related to continued trench rollback. At about the position of the Vardar zone, N-S extension begins and continues eastward into eastern Macedonia and through central and southern Bulgaria. Such extension probably has its cause in the northernmost effect of southward movement of the Aegean Sea as a single plate as shown by recent GPS studies.

CONCLUSIONS

During the late Cretaceous to Paleocene, oceanic crust in the Vardar zone was closed and amalgamated the basement units of most of Macedonia. Pre-Cenozoic basement tectonic units have a NNW-trending structural grain except in north-central Macedonia where foliations and structures curve around the north plunging Pelagonian anticlinorium. Basement structures have had a very profound influence on the trends of Cenozoic faults and associated basins.
Macedonia experienced two periods of extension separated by two abbreviated periods of shortening in Cenozoic time that we relate to the accretion of the Kruja continental crustal fragment at the convergence zone in central Albania. The first period of extension is late Eocene–early Oligocene and is characterized by two types of basins that lie east of the Pelagonian massif of central Macedonia. Numerous narrow NW-trending nonmarine basins are present in eastern Macedonia bounded by faults along their eastern side and represent the formation of extensional E-tilted half grabens. The marine and nonmarine strata of Tikves Ovchepole basin in east-central Macedonia is a forearc basin whose strata interfinger with arc volcanics rocks to the east and are related to east-dipping subduction in eastern
Albania. Both basin types are deformed along NW-trending thrust faults and folds during late Oligocene–Early Miocene time. This period of shortening is short-lived and is followed by a period of erosion producing a landscape of low relief.

The second period of extension began in the middle Miocene and has continued to the present. Basins formed during this period consist of several different types: grabens, half grabens, tectonically slided basins filling pre-existing topography and irregular, sometimes faulted, areas of subsidence. The development of most of these basins was dominated by NNE-SSW–directed extension that began in the middle Miocene in eastern Macedonia and migrated westward with the youngest basins initiated in Pliocene time in western Macedonia and eastern Albania. Coeval with both periods of extension is the NW-trending volcanic arc in eastern Macedonia. The arc migrated slightly westward in time as does the section of the Balkan Peninsula. Geology, v. 9, p. 15–22.

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