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Evolution of the Neogene-Pleistocene Basins of Macedonia

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INTRODUCTION

Macedonia lies within the Cenozoic Southern Balkan Extensional regime that forms the northern part of the more regional Aegean extensional regime (Fig. 1). Study of the late Cenozoic basins of Macedonia provides important data that contributes to the unravelling of the tectonic evolution of the Southern Balkan extensional regime (see for example, Burchfiel et al., 2000, Nakov et al., 2001). The present study is complimentary and adjoins the study in Bulgaria by Nakov et al. (2001). Although Macedonian geologists have a long history of study of the late Cenozoic basins in Macedonia, this is the first detailed presentation of maps, stratigraphic sections, and discussions of the geology of the basins in English. The data presented here form the basis for a tectonic analysis of Macedonian graben and basin formation and how it relates to more regional processes of late Cenozoic extension in the Southern Balkan region.

The map that accompanies this report, *Cenozoic Sedimentary and Volcanic Rocks of Macedonia*, was compiled from the 1:100,000 geological map series, the Regional Geological Map of Socialist Federal Republic of Yugoslavia (SFRY), and from the results of the many years of research by the authors of this paper. The illustrated lithostratigraphic sections in the Neogene–Quaternary basins were compiled from previous research, especially from exploration drilling within Macedonia, and our own field studies. The significant papers used for our compilation are presented as references below.

GEOLOGICAL SETTING

The Cenozoic tectonic evolution of Macedonia consists of two periods of extension, the earlier in Paleogene time and the later in Neogene time, separated by two episodes of shortening. The Paleogene period of extension is not the major focus of this study, but is reviewed briefly for completeness because it is the time when extension was initiated in the Aegean extensional regime (Zagorchev, 1992, and Burchfiel et al., 2000). Paleogene extension and related basin development was diachronous and began in late Eocene time and continued into early Oligocene time. The Paleogene basins trend generally NW-SE and were formed mainly within the Vardar zone and Serbo-Macedonian tectonic units (Fig. 2). They are filled with Eocene–Oligocene molassic sediments, which reach a thickness of 3500–4000 m and can be divided into five lithologic units that are paleontologically well-dated. Abundant fossils indicate a late Eocene (Priabonian) and early Oligocene age for these strata. They contain a rich macrofauna of gastropods, bivalves, corals, and macro and micro foraminifera (see, for example, Maksimovic and Sikosek, 1954; Rakicevic et al., 1976; Karajovanovic and Hristov, 1976; Dzuranov et al., 1999).

Within Macedonia, SW-vergent folding and thrusting occurred during late Eocene (Pyrenean deformational phase) and latest Oligocene–early Miocene times (Savian deformational phase). Following shortening deformation, orogenic topographic relief was greatly reduced during the regional development of a low relief landscape (peneplain), which lasted until the end of early Miocene time. The low-relief erosional surfaces were disrupted during the second period extensional tectonism, the dominant mode of deformation from the early Miocene to present, and are presently preserved at different elevations. The highest surface is preserved at 2000 m in the mountains of Jakupica (Fig. 3). Volcanic activity within eastern Macedonia occurred during the first period of extension, the two shortening deformational periods, and continued into the second period of extension in the late Cenozoic during deposition in the Neogene extensional basins.

The second period of extensional deformation in Macedonia, which continues to present day, began in early to middle Miocene time and is marked by the deposition of middle Miocene strata in the deepest basins. The beginning of extension in Macedonia is contemporaneous with widespread extensional deformation throughout the central Balkan Peninsula (see Zagorchev, 1992; Burchfiel et al., 2000; and Nakov et al., 2001). Late Cenozoic extension and associated basin formation is characterized by dif-

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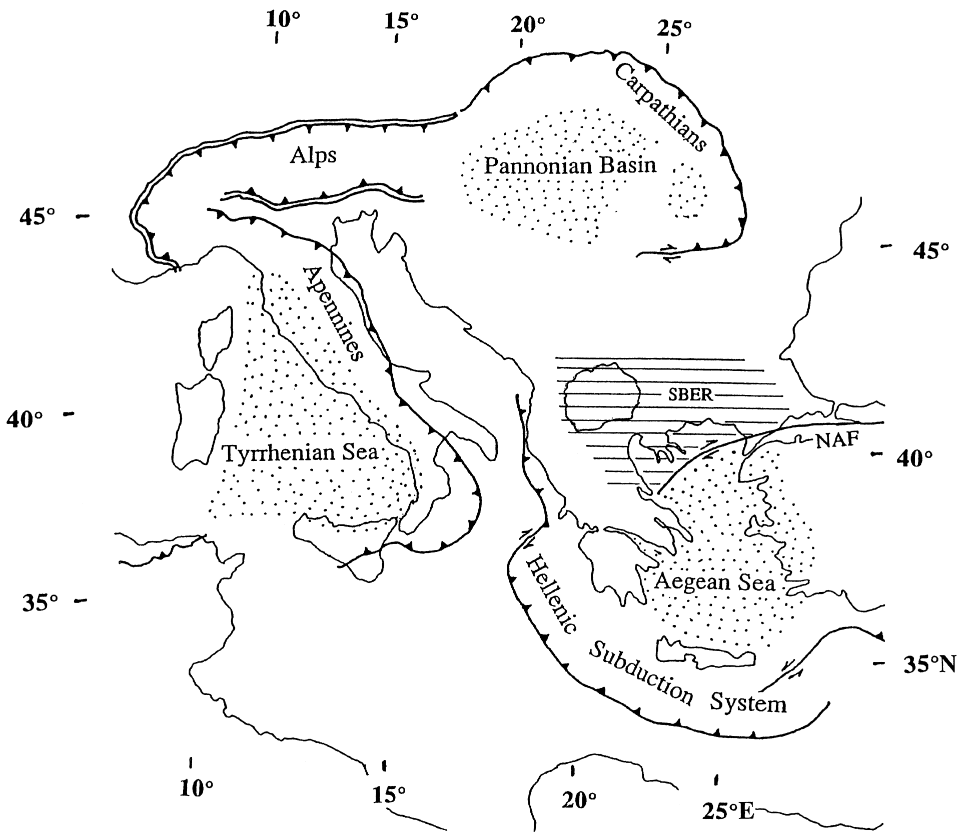

Figure 1. Generalized tectonic map of the eastern Mediterranean region showing Aegean extensional province and tectonic areas of similar origin (stippled). Southern Balkan Extensional region (SBER), northern continuation of the Aegean extensional province is shown with horizontal lines north of the North Anatolian fault (NAF). Location of Macedonia is indicated in black outline.

ferential vertical tectonic motions related to normal, oblique, and strike-slip faulting. The faults are both reactivated old faults and newly formed normal faults, which produced the first uplifted horsts and subsiding grabens that rapidly became sites of freshwater lakes. The first sediments related to these lakes and their associated depositional environments were developed in the Skopje, Kumanovo, Probistip, and Kocani grabens (see map) during middle Miocene time. Later deformation is characterized by periods of intensive tectonic activity, and the older grabens and lakes became more extensive and deeper and new grabens were formed. During intervening periods of weak tectonic activity, pelite and siltstone were deposited in the lakes and some disappeared. This second period of extension is contemporaneous with late Cenozoic volcanic activity in eastern Macedonia that is a continuation of volcanism from Paleogene time.

Late Cenozoic extension was superposed on a crust within Macedonia and the adjacent parts of the Balkan Peninsula that consists of four major tectonic units: (1) the Serbo-Macedonian massif, (2) the Vardar zone, (3) the Pelagonian massif, and (4) the West-Macedonian zone (Fig. 2). The bounding faults of many of the late Cenozoic basins generally do not follow the boundaries of these tectonic units, and most of the basins are located within the same tectonic unit. However, the grabens in western Macedonia, particularly those around the Pelagonian massif, show important relations to older structures. The Pelagonian massif, a Precambrian crystalline massif elongated N-S with an ellipsoidal shape, shows continuous relative uplift from the end of early Miocene time to the present. Numerous erosional planation surfaces are present at different levels on the massif. Miocene-Pliocene grabens occur in three rings around the massif. An inner ring of grabens consists of the Skopje, Porecje, Pelagonian, Mariovo, Tikves, and Veles grabens. The middle ring of grabens is formed by the Polog and Kicevo grabens and partially developed in the Demir Hisar graben in Pliocene time. A partial outer ring of grabens is formed by the Prespa, Ohrid, Piskupstina, and Debar grabens, some of which extend into northern Greece and Albania. Characteristic of this region are grabens and adjacent mountains that developed around and generally parallel to the rock units and structures in the Pelagonian massif.

STRATIGRAPHY OF CENOZOIC ROCKS

Neogene-Quaternary

The nomenclature of Neogene strata in the Republic of Macedonia is in a state of revision. Restudy of some mammalian fossils has shown that a fauna previously regarded as Pliocene in age is late Miocene. New geochronological data has established a new boundary between the Miocene and the Pliocene at 5.4 Ma (Fig. 4). Thus, much of the basinal strata previously considered

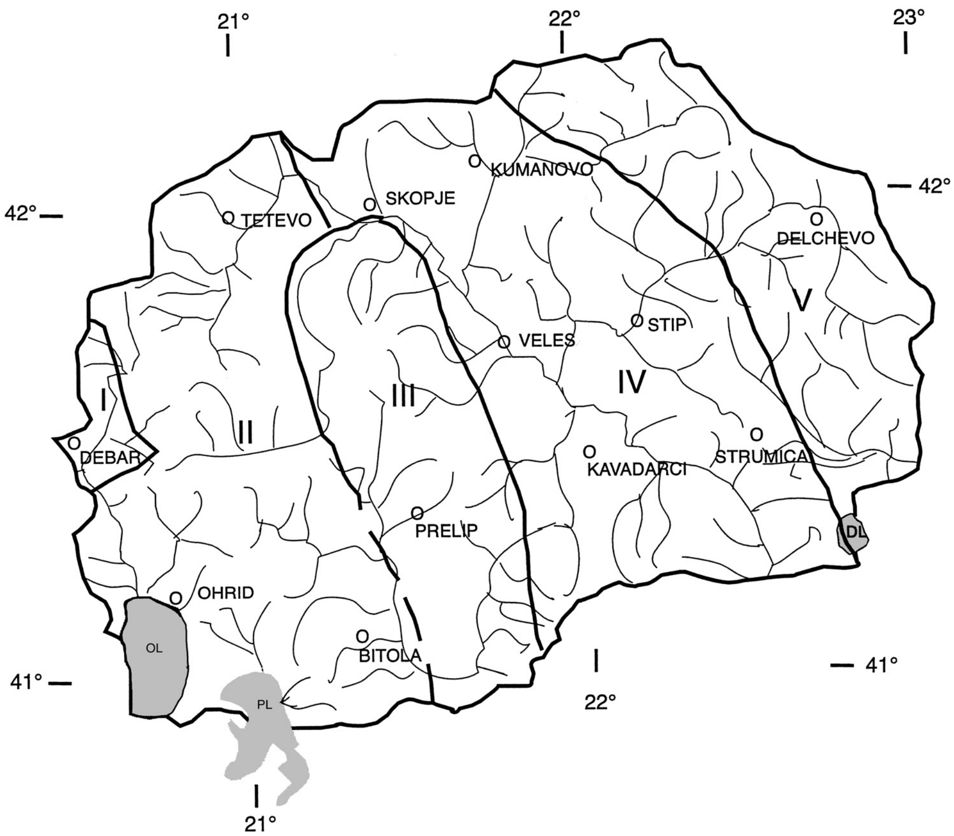

Figure 2. Major tectonic units of Macedonia. River systems are shown in thin lines. I—Chukali-Krasta zone, II—Western Macedonian zone, III—Pelagonian anticlinorium, IV—Vardar zone, V—Serbo-Macedonian massif, OL—Ohrid Lake, PL—Prespa Lake, DL—Dojran Lake.

to be Pliocene, must now be considered late Miocene in age. Studies by Dumurdzanov (1995, 1997), Dumurdzanov et al. (1997), Dumurdzanov and Krstic (1999), and Dumurdzanov et al. (1998) have begun to redefine the stratigraphy of the Neogene basins in Macedonia.

Polyphase Neogene deformation manifested by relative vertical displacement creating topographic relief, and in some regions associated with volcanic activity, directly influenced the gradual formation of the grabens and the type of sedimentary deposits in the basins. From the middle Miocene until the end of the Pleistocene, there were alternating periods of rapid and slow subsidence accompanied by accordingly variable sedimentation rates (and at times basinal sedimentation ceased). Kujumdgieva (1987) and Zagorchev (1992) have discussed Neogene polycyclic sedimentation in Bulgaria, and Dermitzakis (1990) has described similar lithostratigraphy in Greece. Dumurdzanov (1995, 1997) discussed and distinguished four sedimentary cycles in Macedonia: (1) middle Miocene (Badenian–Sarmatian), (2) late Miocene (Sarmatian–Meotian), (3) late Miocene–Pliocene (Pontian–Pliocene), and (4) Pleistocene. (For time terminology used in this paper, see Figure 4). Our study of the lithostratigraphy and associated volcanism of Neogene and Quaternary strata in separate Macedonian basins expands the work of Dumurdzanov and recognizes five cycles. Cycle I commenced in the Badenian and lasted to the beginning of the late Sarmatian, cycle II occurred in late Sarmatian and Meotian (Turolian) time, cycle III occurred during the late Meotian and Pontian time, cycle IV commenced in the early Pliocene and extended into late Pliocene time, and cycle V is Pleistocene in age.

Each of the cycles is a new phase in the formation of the grabens that widened or renewed lacustrine sedimentation after a hiatus. In many of the grabens, a hiatus can be identified either throughout the entire basin or over a large part of the basin between cycles. The division between cycles is especially well expressed between cycles I and II and cycles III and IV, where coarse-grained clastic proluvial–alluvial gravel or conglomerate or a paraconformity mark the beginning of cycles II and IV.

During cycle I, the Skopje, Kumanovo, Probistip, Kocani, and perhaps the Slaviskigrabens were developed. Within the Skopje graben, the sedimentary section is 1400 m thick, and in the Kumanovo graben it is 400 m thick; both are dominated by marl and marly claystone. The age of these deposits has been determined by macroflora imprints, ostracod fauna, and radiometric ages of interbedded volcanic rocks that are within or at the top of the sedimentary section

During cycle II, the Skopje and Kumanovo grabens were widened, and in the Probistip, Kocani, and Slaviski, grabens are dominated by the accumulation of volcanic and associated volcaniclastic rocks. At the same time, new grabens were formed that include the Pelagonian, Strumica, Veles, Tikves, Mariovo,

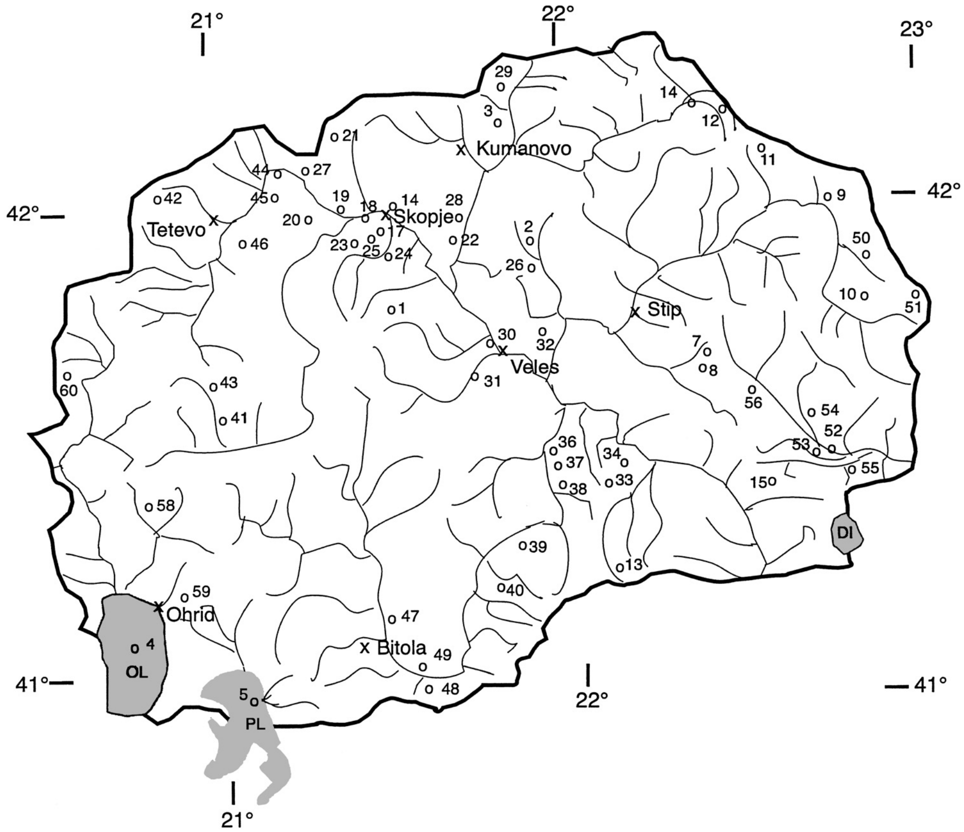

Figure 3. Location of localities mentioned in the text, but not shown on the map. OL—Ohrid Lake, PL—Prespa Lake, and Dl—Dojran Lake. 1—Jakupica, 2—Gjuriski monastery, 3—Mlado Nagoricani, 4—Ohrid Lake (OL), 5—Prespa Lake (PL), 6—Dojran Lake (DL), 7—Bucim, 8—Borov Dol, 9—Delcevo, 10—Pehcevo, 11—Sasa, 12—Toranica, 13—Kozuf, 14—Kriva Palanka, 15—Valandovo, 16—Usje, 17—Sopiste, 18—Nerezi, 19—Saraj, 20—Semeniste, 21—Blatse, 22—Katlanovo, 23—Govrlevo, 24—Markovo Reka, 25—Solnje, 26—Sveti Nikole, 27—Lepenec River, 28—Studena Bara, 29—Staro Nagoricani, 30—Veles, 31—Babuna River, 32—Kisino, 33—Barovo, 34—Vesje, 36—Vozaric, 37—Besava, 38—Begniste, 39—Vitoliste, 40—Gradesnica, 41—Oslomeh, 42—Sar Plania, 43—Tuin, 44—Kopanica, 45—Zilce, 46—Suva Gora, 47—skuvodol, 48—Zivojno, 49—Brod, 50—Pancarevo, 51—Bukovik, 52—Monospitovo, 53—Murtino-Bosilevo, 54—Saraj, 55—Belasica Mountain, 56—Galicica (between 4 and 5), 58—Arbinovo, 59—Vapila, 60—Debar.

Delcevo–Pehcevo, Berovo, Polog, Kicevo, and Piskupstina grabens. Because of the great thickness of the sediments in the Pelagonian and Strumica grabens, it is possible they formed at an earlier time, but because there is no direct evidence for an older age, they are included in cycle II. In the Skopje graben, the age of this cycle was determined for the Nerezi Formation by the presence of *Mastodon angustidens*, *Gomphotherium angustidens*, and other distinctive species (Laskarev, l937). In the Veles, Tikves, Mariovo, Delcevo–Pehcevo, and Berovo grabens, a Turolian age was established by the presence of the Pikermian fauna (Schlosser, l921). In all these grabens, coal-bearing units of dated Meotian age are typically developed. It is interpreted that there was a short period of hot and humid climate during Meotian time (biological climate optimum) that was very favorable for the regional formation of coal within Mediterranean basins. The development of the “lignite series” in Tuskana, Italia, where the coal layers alternate with gypsum layers (Bossio et al., 1981), is an example.

During cycle III, the Prespa, Ohrid, Debar, and Dojran grabens were formed, the Polog, Skopje, Kumanovo, Veles, Tikves, and Mariovo grabens were connected, and the lakes in the Probistip and Kocani grabens were drying up. The Pontian age for strata of this cycle is determined by some diatomaceous flora and leaf imprints of macroflora. At the end of this cycle, a hiatus occurred beyond the freshwater lakes in the basins, and the lakes in the Piskupstina, Mariovo, Veles, Kumanovo, Kicevo, and Pelagonian grabens completely dried up.

A partial or complete depositional hiatus occurred after cycle III, and the Pliocene sediments of cycle IV began with coarse-grained gravel and sandstone that overlie different stratigraphic levels of cycle III strata. Widespread thick deposits or remnants of Pliocene sediments of cycle IV demonstrate that new grabens and freshwater accumulations were formed, for example, in the Lakavica and Porecje grabens as well as in the smaller Mavrovo, Demir Hisar, and Raec grabens, and that many of the lakes became interconnected. During this cycle, the Pliocene sediments in many of the grabens characteristically contain similar polymict gravel and coarse-grained sandstone that are assigned to the same formation, the Solnje Formation, first described from the Skopje graben (Dumurdzanov et al., 1997). Strata of this cycle have not been well determined paleontologically in many of the grabens, and the Pliocene age given to this formation has been defined by lithological correlation with strata in the Mariovo and the Tikves grabens that have yielded diatoms and macrofloral imprints of Pliocene age. Radiometric ages (both K/Ar and Ar/Ar) of 4 ± 0.2 Ma to 1.8 ± 0.1 Ma from pyroclastic strata that are present throughout the Solnje Formation in the Mariovo basin and from agglomerate and tuff within sandstone

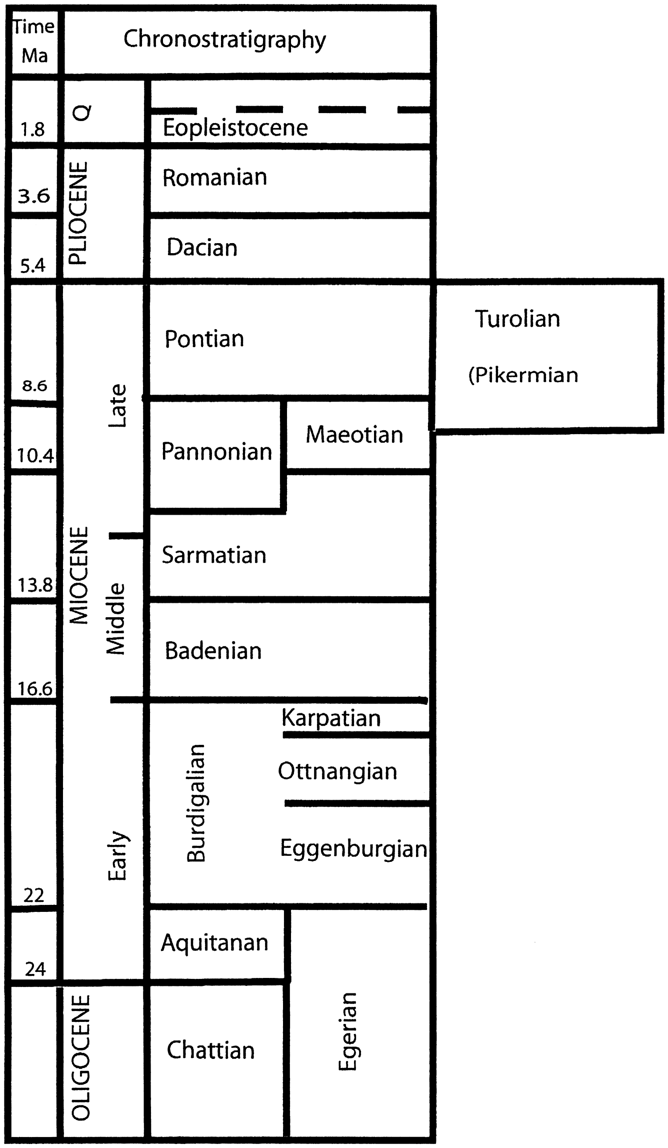

Figure 4. Nomenclature of time units used in the text.

and travertine deposits in the Tikves basin date these deposits as Pliocene. Also within upper Miocene strata of the Kumanovo graben at the Gkuriski Monastery, Mlado Nagoricani (Fig. 3), are calc-alkaline basalt flows dated at 8 Ma (Boev and Yanev, 2001) that are unconformably overlain by sediments of the Solnje Formation and which yield an upper age limit for the formation.

Cycle V of Quaternary age is characterized by a general uplift and formation of glacial deposits at elevations greater than 1800 m. The remains of moraine and glaciofluvial strata glacially sculptured landscapes are evidence for the glacial activity. Subsidence and shaping of 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 lakes. Within Macedonia, the lakes were drained by the formation of the through-going Vardar River and its important tributaries such as the Crna, Treska, and Bregalnica rivers, which flow into the northern Aegean Sea. Most of the Pleistocene and Pliocene strata have been deeply incised and weathered in the grabens, and they are preserved largely in terraces at different elevations due to uplift and incision by the Vardar River and its tributaries. Although there is no reliable data, uplift and incision probably occurred after the middle Pleistocene. The Ohrid, Prespa, and Dojran lakes, as well as the preserved lacustrine travertine masses in the Tikves, Mariovo, and the Skopje grabens, are the remnants of the extensive Pleistocene lake system.

MAJOR CHARACTERISTICS OF THE CENOZOIC VOLCANISM

Cenozoic volcanism is contemporaneous with extension in the Vardar zone and the Serbo-Macedonian massif. The oldest volcanic rocks occur in the areas of Bucim, Damjan, and Borov Dol (26.4–24.9 Ma), Kratovo and Zletovo (32–29 ± 2 Ma to 16 ± 2.0 Ma) and in the zone Toranica, Sasa, and Delcevo–Pechevo (25–17 Ma; Fig. 3). These older volcanic rocks are overlain by middle Miocene sedimentary rocks that provide an upper age limit, thus the age of these oldest volcanic rocks is Oligocene–early Miocene. The volcanic rocks are andesite, latite, quartz-latite, dacite, and rarely, trachyte and rhyolite (Karamata et al., 1992). The volcanism took place in several phases and occurs as subvolcanic bodies, flows and abundant pyroclastic deposits. The sequence is characterized by interbedded stratified tuff, agglomerate and flows of andesite, latite, and quartz-latite. Pyroclastic rocks are particularly abundant in the Kratovo-Zletovo volcanic area, where dacite and andesite ignimbrite occur as the oldest products.

A younger large volcanic area is present at Kozuf (Fig. 3) in the southern part of the Vardar zone. K/Ar radiometric data indicate volcanic activity commenced at the end of late Miocene time and continued through Pliocene and into the beginning of Pleistocene time. Kolios et al. (1980) report ages of 4 ± 2–1.8 Ma, and Boev (1988) and Karamata et al. (1992) present ages of 6–1.8 Ma for these rocks. The geological data are consistent with these ages. In the Tikves basin, the first Turolian volcanic pyroclastic rocks lie above Turolian–Pontian sediments, and in the Mariovo basin, they overlie Pliocene gravel and sandstone of the Solnje Formation. The volcanic rocks are characterized by latite, quartz-latite, and andesite, and more rarely by trachyte and rhyolite. Pyroclastic tuff, agglomerate, and breccia are common within this succession.

Beside this intermediate to felsic volcanism, basaltic magmatism is present, but only in the Vardar zone, where it has been radiometrically dated as Miocene-Pliocene in age, yielding K/Ar ages that range from 5.5 to 13 Ma at different localities. These mafic rocks occur as large, irregular bodies, necks, and lava flows at several levels in the Miocene sediments of the Kumanovo graben.

LITHOSTRATIGRAPHY OF THE EOCENE-OLIGOCENE BASINS

The upper Eocene–Oligocene sedimentary rocks deposited during the first extensional period are preserved in the two large basins of Ovce Pole and Tikves and in smaller basins at Delcevo, Kriva Palanka, and Valandovo-Dojran. Even though these rocks have been strongly folded and thrusted during late Eocene and late Oligocene time (Pyrenean and Savian orogenic phases, respectively) their lithostratigraphy is well understood. In all these basins, the rocks are well exposed at numerous locations, and their lithostratigraphy is the same or similar. These rocks are also known from deep drilling for oil and gas in the Tikves and Ovce Pole basins, where the deepest borehole reaches 2703 m. The total thickness of the Eocene–Oligocene strata has been estimated to be 3500–4000 m. The section can be divided into five lithological units referred to as the basal lithozone, the lower flysch lithozone, the lithozone of yellow sandstone, the upper flysch lithozone, and the uppermost (or Oligocene) lithozone.

The basal lithozone begins with a red and violet basal conglomerate and sandstone overlain by claystone and calcarenite. Its thickness ranges from 600 to 1000 m. The age of this lithozone has not been determined.

The lower flysch lithozone is 1200 m thick and consists of rhythmically interbedded red and grey conglomerate, sandstone, claystone, marl, and siltstone. Within the upper 500 m of this lithozone occur the gastropods *Cerithium diaboli*, *C. vivari*, *Natica vulcaniformis*, *N. vulcanica*, and *Spondilus bifrons*, and the pelecopods *Ostrea gigantica* and *Pecten* sp. of Priabonian age.

The lithozone of yellow sandstone is 500–700 m thick, but it lacks aerial continuity. It is well developed in the Tikves basin, where it grades both laterally and vertically into the overlying upper flysch lithozone. It contains the large foraminifera *Operculine granulosa*, *O. alpina*, *Nummulites incrassatus*, the gastropod *Trochus lucasianus*, and the corals *Stilocoenia taurinensis*, and *Dyctyarea octopartira* of Priabonian age.

The upper flysch zone is ~1300 m thick and consists of alternating grey sandstone, siltstone, claystone, and marl. At the top, these rock types grade into limestone with typically convoluted and deformed bedding. Abundant gastropods, bivalves, and both micro and large foraminifera are present. For example, the upper limestone beds contain the foraminifera *Nummulites fabiani*, *N. incrassatus*, *N. budensis*, *Operculina alpina*, and *Discocyclina angastae* (Maksimovic and Sikosek, 1954, Rakicevic at al., 1976), and micro foraminifera (Dzuranov et al., 1999) of Prabonian age.

The Oligocene strata at the top of the section are at least 300–400 m thick in some parts of the Ovce Pole basin (Kocani) and in the Skopje and Kumanovo area. This lithozone begins with grey and white biohermal limestone overlain by sandstone and at the highest level claystone. Oligocene species of nummulites, corals, gastropods, bivalves, and echinoderms are present (Karajovanovic and Hristov, 1976).

LITHOSTRATIGRAPHY OF THE NEOGENE-QUATERNARY GRABENS

Skopje, Kumanovo and Veles grabens (Figure 5)

The Skopje, Kumanovo and Veles grabens are located in the central part of the Vardar zone. The Skopje and Kumanovo grabens began to develop in Badenian time (cycle I) and with periods of nondeposition or erosion, lacustrine deposition within the grabens continued to the Pleistocene. The Veles graben formed in late Miocene time during cycle II.

The **Skopje graben** (1; numbers refer to the sections in the figures) is bounded by a system of normal faults that strike NW-SE and NE-SW to E-W. It occupies a surface area of ~550 km^2 and the basin sediments have been studied from both well-exposed outcrops and deep drill holes IB-SKG-1 and IB-SKG-4 that are 1655 m and 2000 m deep, respectively.

Combining data from outcrop profiles, deep drilling, and some gravity studies, the total sedimentary section is ~2200–2300 m thick. The basal units of the section unconformably overlie Precambrian and Paleozoic metamorphic rocks and Upper Cretaceous sedimentary rocks. The transgressive basal conglomerate, gravel and sandstone contain clasts from the underlying rock units. Strata of all five cycles are present in the Skopje basin and are assigned to three formations of Miocene and Pliocene age and one informal unit of Quaternary age at the top (Fig. 5).

The **Usje Formation (UsF)** is the oldest formation and consists of terrigenous marly strata, ~1400 m thick, that were deposited in Badenian-Sarmatian time. The best lithostratigraphic information comes from exposures in an open pit cement mine at Usje (Skopje) and from deep boreholes. The age of the formation is not well documented paleontologically with the exception of some collections of *Limnea (Galba)* sp., *Planorbarius ex. gr. corneus*, *Bithynia*, and other fauna and flora that are of Badenian age (Dumurdzanov and Krstic, 1999). This formation contains two informal lithological units from the base to the top:

(*a*) an upper gravel-conglomerate unit, 50–100 m thick; and

(*b*) an upper marl, marly claystone and siltstone unit, 1300–1350 m thick, that contains intercalations of sandstone and rare coal beds.

The **Nerezi Formation (NeF)** is partially exposed in the peripheral parts of Skopje, for example, at the villages of Nerezi and Usje-Sopiste, on the highway from Saraj to Semeniste, and in the southern parts of the Skopska Crna Gora mountain (Fig. 3). The name Nerezi Formation was given to this unit with the first discovery and identification of *Mastodon angustidens Cuv.* by Laskarev (1937) from strata at Mali Most in the village of Nerezi. The formation is ~530 m thick and in some parts of the Skopje basin it rests transgressively above pre-Cenozoic rocks, and in the borehole IB-SKG-1 it lies above the Usje Formation. It was deposited in cycles II and III and is Late Sarmatian-Meotian-Pontian in age. Three informal lithological subdivisions are recognized, from the base to the top.

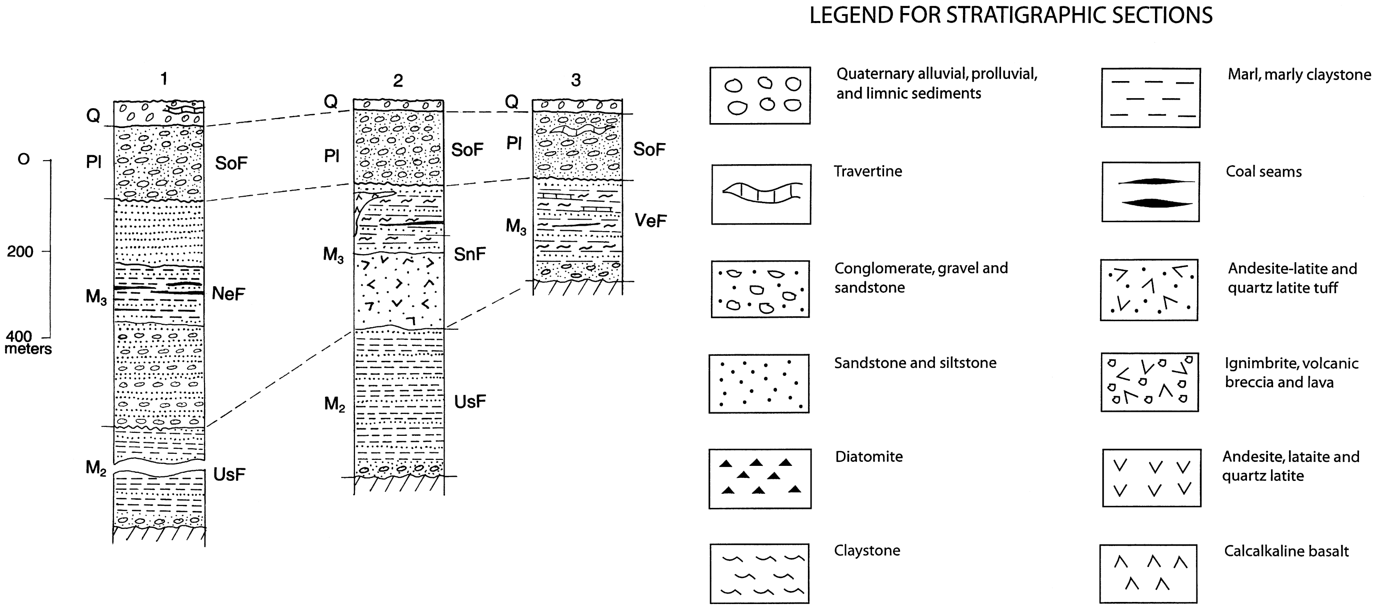

Figure 5. Stratigraphic sections of the Skopje (1), Kumanovo (2), and Veles (3) grabens. Q—Quaternary. Pliocene (Pl): SoF—Solnje Formation. Miocene (M): VeF—Veles Formation, SnF—Staro Nagoricani Formation, NeF—Nerezi Formation, UsF—Usje Formation. A: Legend for lithological symbols used in the stratigraphic sections for Figures 5 through 12.

(*a*) A basal gravel, sandstone and siltstone unit that is ~250 m thick.

(*b*) A middle silty-marly coal-bearing unit that consists of ~130 m of siltstone, marly claystone, marl, and coal beds. Beneath the lowest coal layer at Mali Most, *Mastodon angustidens* was discovered by Laskarev (1937), and above the upper coal layers, *Melanopsis*, *Prosothenia*, *Unionidae,* and other fauna of late Miocene age were described (Dumurdzanov and Krstic, 1999).

(*c*) An upper sandy-siltstone unit that consists of interbedded yellow and grey sandstone and siltstone with gradations into silty claystone. It has a total thickness of ~150 m. At the village of Zelezarnica (Skopje), *Gomphotherium angustidens* of Late Sarmatian–Turolian age was discovered and determined by Garevski (1985). In siltstone at Skopje Kale, an ostracod microfauna was determined by Krstic and other explorers and species of mollusk and imprints of macroflora leaves have been found (Dumurdzanov and Krstic, 1999), which yield a Meotian-Pontian age for this unit.

The **Solnje Formation (SoF)** was deposited above a hiatus that occurred probably after Pontian sedimentation and terminated much of the lacustrine environment in the Skopje graben. Following the hiatus, coarse-grained sediments were deposited and indicate increased topographic relief surrounding the graben caused by an increase in activity of the graben bounding faults during Pliocene time. The coarse-grained deposits interfinger with renewed lacustrine deposition. The coarse-grained deposits consist mainly of gravel, gravelly sandstone, and sandstone with transitions into siltstone deposited in an alluvial, proluvial, and lacustrine environment. The sandstone and gravelly sandstone of the Solnje Formation is well stratified and lies above marl of the Nerezi Formation. At Katlanovo, the gravel and the sandstone rest directly above the coal horizon of the Nerezi Formation. The Pliocene section is preserved mainly in the peripheral parts of the Skopje graben and is best studied at the villages: Solnje and Govrlevo and along the Markova River (Fig. 3) where its thickness reaches 150 m. In the Skopje graben, the age of the Solnje Formation in the Skopje graben has not been determined, but it correlates well with the same formation in the Kumnaovo graben where a Pliocene age is established.

The **Pleistocene cycle** (cycle V) is developed in the Skopje graben where relicts of glaciofluvial sediments are in the high parts of the surrounding mountains and travertine deposits 10–20 m thick occur at many locations, such as at the villages of Svilare, Kuckovo, Matka, and Bojanekkk (Fig. 3). The travertine deposits lie in places above the Solnje Formation, and at other places, directly above the Nerezi Formation, but these deposits are remnants of more extensive travertine units that have been extensively eroded. In the central parts of the graben, the Pleistocene sediments locally reach 60–80 m thick and consist of alluvial gravel, sand, and sandy clay deposited by the Vardar, Treska, Lepenec, and Markova Reka rivers (Fig. 3).

The **Kumanovo graben (2)** in northern Macedonia trends N-S (see map) and was connected with the Skopje graben to the west, to the Veles graben to the southeast, and to the Slaviski graben to the east. Good surface exposure of basinal strata occurs along the road between Kumanovo and Kriva Palanka, Kumanovo, and Sveti Nikole and along the valley of the Pcinja River. Lithostratigraphic data has also been obtained from many exploration boreholes for fresh and geothermal water. From these data sources, the total thickness of Neogene rocks in the Kumanovo graben is ~840 m thick. The stratigraphic section contains deposits from all five cycles of sedimentation and in most areas the basal strata lie transgressively above Jurassic, Upper Cretaceous, and Eocene-Oligocene sedimentary and igneous rocks. Three formations and undifferentiated Quaternary sediments (Fig. 5) are distinguished in the graben.

The **Usje Formation (UsF)** is lithologically similar to the same formation in the Skopje graben, but differs locally by the presence of bentonite clay because of its proximity to the volcanic rocks to the east. The formation contains *Eucypris* sp., *Candona* aff. *pokornyi*, and *Candona* sp. at the Studena Bara locality (Fig. 3) and is assigned a middle Miocene age. The thickness of the formation is ~400 m.

The **Staro Nagoricani Formation (SnF)** is ~330 m thick and was deposited during cycles II and III. It is composed of two lithological units.

(*a*) The lower unit consists of partially stratified andesite and latite tuff that is ~150 m thick. It is poorly exposed and in exploration boreholes it lies directly above the Usje Formation. The tuffaceous material has been genetically related to the Miocene volcanism in the Kratovo-Zletovo area (Fig. 3).

(*b*) The upper unit consists of a sandstone, claystone, and siltstone unit, in which calc-alkaline basalt flows occur at Mlado Nagoricani. These basalt flows have yielded a K/Ar age of 8.0–8.5 Ma (Boev and Yanev, 2001). In some parts of the basin, a thin coal layer occurs. There is no paleontological data for the age of this unit, but the radiometric ages from the basalt indicate a late Miocene age, and it directly lies above andesite and latite tuff at Staro Nagoricani dated at 8–8.5 Ma (Karamata et al., l992).

The **Solnje Formation (SoF)** in the Kumanovo basin is ~150 m. thick and is preserved along the peripheral parts of the graben. It consists of coarse gravel and sandstone above which lie travertine deposits that locally contain *Lymnea peregra*, *L. stagnalis*, and *Planopbarius corneus* that indicate a late Pliocene to Pleistocene age (Karajovanovic and Hristov, l976). At the Guriski Manastir this formation lies transgressively above the calc-alkaline basalt from the Staro Nagoricani Formation.

The **Quaternary sediments (Q)** are represented by locally thin travertine deposits and proluvial, alluvial, and deluvial sediments that range up to 20 m thick.

The **Veles graben (3)** has an irregular shape, but is generally elongated NE-SW. Determined from outcrop profiles and shallow boreholes, the thickness of the sedimentary section varies from 300 to 350 m. The strata of the graben lie unconformably above Paleozoic metamorphic rocks, Triassic, Upper Cretaceous, and upper Eocene sedimentary rocks and Jurassic ultrabasic rocks. The upper Miocene strata have been preserved in the central parts and the Pliocene and Pleistocene strata in the peripheral parts of the graben. Sedimentation began in the Meotian, continued in the Pontian, and, following a clear hiatus between the Pontian and the Dacian stages, Pliocene sedimentary rocks (Fig. 5) were extensively developed.

The **Veles Formation (VeF)** is 200–250 m thick and it is composed of sandstone, gravelly sandstone, claystone, and sandy claystone, much of which appears to have been deposited in a deltaic environment. In the upper part of the formation, layers of marly limestone 2.5 m thick occur. In the upper 100 m of the formation, at the localities Prevalec, Brca, and Beluska (brick plant), Umin Dol, and the villages of Kumarino and Karaslari (Fig. 3), a rich Pikermian fauna of late Miocene age (Turolian-Pont) is present. It contains a very rich mammalia fauna consisting of *Dicerhinus orientalis*, *Hipparion gracile*, T*etralophodon longirostris*, *Mesopithecus pentelici*, *Microstonix major*, *Helladotherium duvernoyi*, *Gazella deperdita*, *Gazella brevicornis Palaeoreas lindermayeri*, *Ictitherium robustum*, *Ictitherium hipparionum*, *Cameleopardalis parva*, *Machairodus orientalis*, *Machairodus aphanistus*, *Dinotherium giganteum*, *Xystrix primigenia*, *Symocion primigenius*, *Chalicotherium gollfussi Kaup*, and *Aceratherium incisivum* that was described by Schlosser (1921), Laskarev (1921, 1937), Brunner (1939), Papp (1939) and Garevski (1956, 1960, 1976, 1985, 1990). Forsten and Garevski (1989) have described *Anculotherium pentelicum*, *Hipparion matthewei*, *H. proboscideum*, *H. prostylum gervaies*, and *H. gromova gabunia* from the Veles Formation. In the Ovce Pole part of the Veles graben at the village of Kisino, the Veles Formation is intruded by calc-alkaline basalt.

The **Solnje Formation (SoF)** has its typical section exposed in the western and northern part of the Veles basin, where it extends into the Skopje and Kumanovo grabens. In the western part of the Veles graben, strata of these Pliocene sediments also lie above pre-Miocene rocks that suggest increased tectonic activity and enlargement of the graben to the west during cycle IV sedimentation. The formation consists of 100–150 m of poorly stratified coarse gravel and sandstone, and rarely from sandy claystone. In the SW part of the graben, south of the village of Izvor, there are two deposits of clayey and sandy travertine. There is no direct evidence for the age of this formation in the Veles graben, but it is assigned a Pliocene age based on lithological correlation with the dated rocks in the Kumanovo graben.

The **Quaternary sediments (Q)** are 10–30 m thick and are preserved in the western part of the Veles graben, particularly along the Babuna River where they consist of glacialfluvial gravel, transported by the glaciers from Jakupica Mountain. Alluvial-proluvial Quaternary sediments are developed along the Vardar River.

Slaviski, Probistip and Kocani grabens (Figure 6)

The Slaviski, Probistip and Kocani grabens occur along the boundary between the Vardar zone and the Serbo-Macedonian massif (Fig. 2 and map). The Slaviski and Kocani grabens trend E-W and the Probistip graben trends NW-SE. Basinal sedimentary and volcanic rocks in the grabens lie above metamorphic rocks of Precambrian age, sedimentary rocks of Eocene-Oligocene age, and locally, igneous rocks of Oligocene–lower Miocene age. All three basins were initiated during cycle I (Badenian-Sarmatian

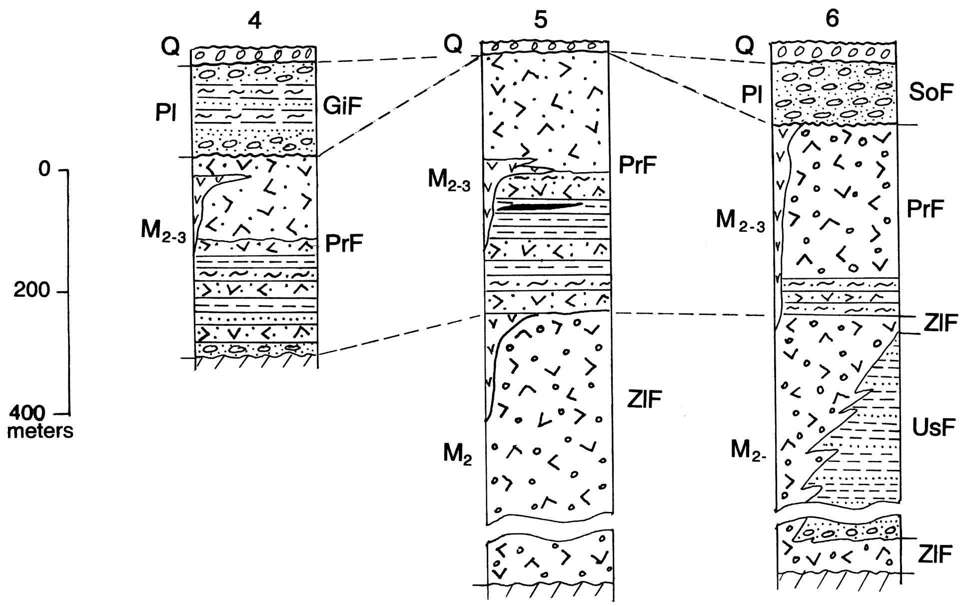

Figure 6. Stratigraphic sections of the Slaviski (4), Probistip (5), and Kocani (6) grabens. Q—Quaternary. Pliocene (Pl): GiF—Ginovci Formation, SoF—Solnje Formation. Miocene (M): PrF—Probistip Formation, ZlF—Zletovo Formation, UsF—Usje Formation.

time) and have similar Miocene sedimentary sequences and structure (Fig. 6).

The **Slaviski graben (4)** has a small aerial extent and the graben is bounded on the south side by part of the steeply dipping, seismically active Kustendil-Skopje-Debar-Elbasan fault. This major fault line strikes WSW-ENE and has important left-lateral displacement. The thickness of strata is estimated at ~500 m. The best exposed sections are along the road from Kumanovo to Kriva Palanka in an active open pit mine for bentonite clay. Some data are present from boreholes. The age of the sedimentary and volcanic section is assigned by correlation with dated volcanic rocks in the Probistip graben. The section includes two formations and Quaternary sediments.

The **Probistip Formation (PrF)** is estimated to be ~330 m thick, but only the upper part of the formation is exposed. It is of middle and late Miocene age and is composed of two lithological units.

(*a*) The basal marl and marly claystone, clay, tuff and sandstone unit is ~200 m thick.

(*b*) The upper unit of tuff and tuffite of andesite, latite, and quartz-latite composition is 150 m thick.

The **Ginovci Formation (GiF)** is assigned a Pliocene age based on its stratigraphic position and lithology that is similar to dated rocks in the Kumanovo graben. Its lower part consists of gravel and sandstone, and its upper part contains bentonite clay layers interbedded with sandstone, siltstone, and gravel.

The **Quaternary sediments (Q)** consist of a thin section of alluvial, proluvial, and diluvial strata.

The **Probistip graben (5)** is locally bounded on its east side by a NW-SE striking normal fault. Rocks in this graben are well exposed and there is abundant data on the rock sequence from exploration boreholes for polymetallic and non-metallic deposits and bituminous siltstones. The total thickness of basinal rocks is estimated to be more than 1000 m. The graben fill is composed of two lithologically distinct formational units (Fig. 6).

The basal unit, the **Zletovo Formation (ZiF)**, is composed of ignimbrite, volcanic breccia, and lava flows of dacite and andesite-latite composition. The formation is ~800 m thick and K/Ar radiometric data (Karamata et al., 1992) yield an age of middle to early Miocene and perhaps late Oligocene.

The **Probistip Formation (PrF)** is 300 m thick and can be divided into two lithological units.

(*a*) The lower unit consists of interbedded tuff, sandstone, claystone, marl, bituminous siltstone and coal layers. In the uppermost 50 m are bituminous siltstone and a thin layer of coal. A macroflora containing *Salix angusta*, *Myrica lignitum*, *Salix longa*, and *Pinus hepion* from marly claystone was described by Rakicevic et al. (1976) and was assigned a middle Miocene age.

(*b*) The upper unit is composed of tuff and volcanic breccia with travertine layers. This unit begins with stratified andesitic tuff overlain by volcanic breccias and a 10–25 m layer of travertine in which the gastropods *Planorbis corneus*, *P. species*, *Lymneus* cf. *pereger*, and *L.* cf. *Stagnalis* occur.

The thick deposits of pyroclastic material that filled the graben ended lacustrine deposition in Probistip Lake in late Miocene time. Pliocene rocks are missing, with an exception of travertine deposited in the uppermost part of the section above the volcanic breccia and containing Lithoporella algae, which are perhaps Pliocene or Pleistocene in age.

Quaternary sediments (Q) consist of thin river and deluvial-proluvial sediments.

The Kocani graben (6) is a typical symmetrical graben bounded by normal faults on both its south and north sides (see map). The sedimentary and volcanic rocks in the graben are incompletely exposed, but the lithostratigraphy of the section has been well studied from several geothermal exploration boreholes, the deepest of which is 1100 m.

The graben was initiated in middle Miocene time (cycle I) as a lacustrine basin that persisted until the late Miocene when lacustrine sedimentation was terminated by the influx of pyroclastic material, volcanic breccia, and lava flows. In Pliocene time, a lacustrine environment was re-established and coarse-grained gravel and sandstone were deposited. Four formations can be distinguished, three of which are in superposition (Fig. 6).

The **Zletovo Formation (ZlF)** is composed of ignimbrite, breccia, and lava flows of dacite, andesite, and latite. These volcanic units created relief within the graben, similar to the deposits in the Probistip graben, were erupted contemporaneously, and interfinger with sediments of the Usje Formation. The rock units of this formation are similar to that in the Probistip graben.

The **Usje Formation (UsF)** is not exposed but is known from several deep boreholes. It is recognized as the Usje Formation by its lithology and stratigraphic position similar to the rocks in the Skopje graben. It consists of 580 m of marl, marly claystone, claystone, sandstone, and siltstone that was deposited in one part of the graben simultaneously and interfingered with the volcanic rocks of the Zletovo Formation. The middle Miocene age for this formation is based on the interfingering with middle Miocene volcanic rocks (Karamata et al., l992).

The **Probistip Formation (PrF)** in the Kocani graben is ~280 m thick and consists of two lithological units.

(*a*) The lower unit contains tuff and claystone. It is not exposed but is known from drill hole data and is up to 80 m thick. Correlation of similar rocks in the Probistip graben indicates a middle Miocene age for this unit (Karamata et al., l992).

(*b*) The upper unit consists of up to 230 m of andesitic breccia and tuff with lava flows mostly of andesite, latite, and quartz-latite. Radiometric data indicate a middle to late Miocene age (Karamata et al., l992)

Rocks of the **Solnje Formation (SoF)** are exposed mostly in the eastern parts of the graben where they are up to 100 m thick. The presence of a hiatus at the base of this formation is suspected. Intensive tectonic movements occurred during deposition of these strata lacustrine environments were reestablished. The cycle IV strata of the Solnje Formation are composed of sandstone and gravel. There is no paleontological data about the age of this formation, and, like the Solnje Formation elsewhere, it is assigned a Pliocene age based on its stratigraphic position and correlation with similar strata in the Kumanovo graben.

The **Quaternary sediments (Q)** are developed on the margins of the graben and represent alluvial-proluvial terraces. Locally, thin travertine layers occur in the southern part of the basin.

The Tikves and Mariovo Grabens (Figure 7)

The Tikves and Mariovo grabens are located in central southern Macedonia and are developed above rocks of the Vardar zone or at their margins above the Pelagonian Massif.

The northern part of the **Tikves graben (7)** is elongated N-S and is bounded on its western side by normal faults of N-S and NW-SE strike (see map). Two NE-striking parallel faults bound its northwestern and southeastern sides. The graben was initiated during cycle II, and during cycle III, it was connected with Central Macedonian Lake that extended across the Skopje, Kumanovo, Veles, and Tikves grabens. A major part of the sedimentary sequence in the Tikves basin is exposed and deeper parts of the Miocene section have been explored by drill holes exploring for coal deposits. Strata in the Tikves basin mostly lie unconformably above Eocene flysch, but in the western and southern part of the basin they overlie Triassic, Jurassic, and Cretaceous sedimentary rocks and Jurassic ophiolites. During late Pliocene time, the lake deposits of the basin were greatly enlarged and extended to the west into the Raeci graben where the basinal strata consists of sandstone, gravel, and sandy claystone with travertine beds of Pliocene and Pleistocene age.

Three formations are recognized in the central and southern part of the Tikves basin (Fig. 7).

The **Nerezi Formation (NeF)**, the oldest formation in the Tikves basin, was deposited during cycles II and III, and sedimentation was continuous to the end of Miocene time. This coal-bearing formation is composed of three superposed lithological units that rest unconformably on Eocene sedimentary rocks.

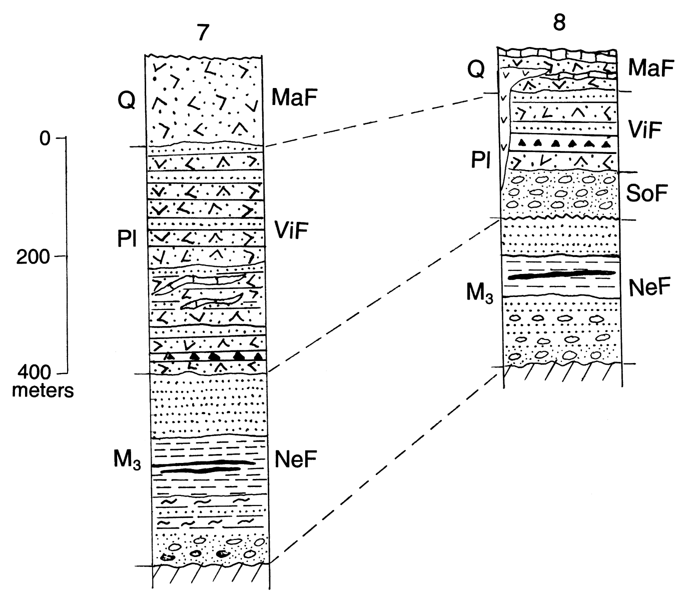

Figure 7. Stratigraphic sections of the Tikves (7) and Mariovo (8) grabens. Q—Quaternary, MaF—Mariovo Formation. Pliocene (Pl): ViF—Vitacevo Formation, SoF—Solnje Formation. Miocene (M): NeF—Nerezi Formation.

(*a*) The basal unit is ~l40 m thick, but is not exposed and it is known only from drill hole data. It consists of a basal conglomerate with gravel, sandstone, and brown claystone overlain by 100 m of sandstone and mottled claystone. No fossils have been recovered from this unit

(*b*) The middle unit is ~100 m thick and is mainly developed in the center of the basin. The basal strata are interbedded grey claystone, coal-bearing claystone and coal beds overlain by marl and marl-rich beds 40–50 m thick. The main coal-bearing sequence is ~27 m thick. The strata are subhorizontal except near the edges of the basin where they become gradually inclined toward the basin. Within the coal layers, *Ilyocypris* and *Hungarocypris* are found yielding a probable late Miocene age.

(*c*) The upper unit is 120 m thick and occupies a large area of the basin but is well exposed in only a few locations. It consists of interbedded sandstone, siltstone, and silty claystone. In the upper layers near the villages of Barovo and Vozarci, *Hipparion matthewei*, *H. proboscideum*, *H. verae*, and *H. gracile* were collected and described by Forsten and Garevski (1989). Near the village of Veshje, *Mastodon (Anancus) arvenensis* was collected and described by Garevski (1960). This fauna is assigned a Turolian (Meotian) age.

During the deposition of the **Vitacevo Formation (ViF)**, tectonic activity increased, causing widening of the Tikves graben to the west and deposition of volcanic and volcaniclastic rocks that cover a large part of the basin. The formation is 400 m thick and is best exposed in the area of Vitacevo. Basal beds, 100 m thick, consist of sandstone overlain by tuff and agglomerate with diatomite and tuff at the top. These beds are overlain by interbedded yellow sandstone, tuff, and agglomerate, locally containing travertine. One travertine bed is 15 m thick and extends laterally 40 m. In the travertine beds exposed in the villages Resava and Begnishte and at the locality of Ljubash (Fig.3), *Lymnaeus stagnalis* and *Planorbis corneus* of Pliocene age was collected and described by Hristov et al. (1973). The topmost part of the formation consists of ~100 m of agglomerate and tuff. The Pliocene age of the Vitaceov Formation was confirmed by K/Ar radiometric ages from the volcanic rocks that range from 5 to 1.8 Ma (Boev and Yanev, 2001).

The **Mariovo Formation (MaF)** consists of strata deposited in a lacustrine environment that was terminated during Pleistocene time by deposition thick beds of breccia conglomerate with volcanic material that reaches ~100 m thick in the western parts of the graben. Above these beds is 150 m of agglomerate, tuff, volcanic breccias, and locally travertine. There are good exposures of the Mariovo Formation in the area of the Mariovo graben that forms the SW extension of the Tikvis graben.

The **Marivo graben (8)** was formed along the boundary between Vardar zone and Pelagonian Massif. Much of the basinal fill in this graben has been eroded, but the best preserved sections are between the villages of Vitoliste and Gradesnic. Relicts of the Pliocene strata along the Crna River indicate a possible connection of the Mariovo Lake with the Tikves Lake and eventually with the Pelagonian Lake.

The graben started to form during late Miocene (Meotian) time and deposition continued until the end of Pontian time, when a hiatus occurred. Increased vertical movements during the Pliocene lead to widening of the lake and its persistence into middle Pleistocene time.

Deposits of the Mariovo graben are well known from outcrops and the deeper parts of the section are known from a detailed network of drill holes exploring for coal. The section in this graben can be divided into four formations (Fig. 7).

The **Nerezi Formation (NeF)** in the Mariovo graben is lithologically identical with the same formation in the Skopje graben. In the Mariovo graben, the formation can be divided into three units.

(*a*) A basal unit ~120 m thick is known only from drill hole data. It consists of gravel and sandstone beds, but no data is available on its age.

(*b*) The middle unit consists of ~70 m of siltstone and silty claystone that grades upward into coal and claystone and finally into a continuous coal later 6–15 m thick. Above the coal layer are marly and silty claystone rich with macrofloral imprints of *Taxodium distichum*, *Juglans acuminata*, *Castanea atavia*, and *Quercus pseudocastanea* described by Dumurdzanov et al. (1976). More recently, Mihajlovic and Lazarevic (2004) have determined *Pinus hepios*, *Glyptostrobus europius*, *Ulmus* cf. *ruskovensis*, *Ulmus* sp. *Quercus cerisaecarpa*, *Q. sosnowkyi*, *Q mediteranea*, *Q. species 1*, *Q species 2*, and *Dictylophullum* sp., which yield a late Miocene age. Also above the coal beds the planktonic algae association of *Actinocyclus (Cyclotella)*, determined by Ognjanova-Rumenova (2000), are very similar to those in the Novoiskar Formation of the Sofia Basin and considered to be late Miocene in age.

(*c*) The upper unit consists of ~60 m of well-bedded siltstone and sandstone followed by a hiatus. Near the village of Gradesnica a tooth of *Zygolophodon borsoni* was found and determined by Petronijevic (1952) to be a *Mastodon borsoni*. Stratigraphic position of the tooth remains uncertain and its position in this unit could be a slightly higher than reported. According to Nikolov (1985), *Zygolophodon borsoni* is Meotian-Pliocene in age.

The **Solnje Formation (SoF)** unconformably overlies Miocene strata and is characterized by ~60–80 m of yellow-red and grey, poorly stratified gravel and sandstone. Clasts in the gravel consist mostly of quartz, gneiss, and other metamorphic rocks, and lack volcanic material. The age is of the Solnje Formation is Pliocene (cycle IV), based on its correlation with similar rocks in the Kumanovo graben.

The **Vitacevo Formation (ViF)** overlies the Solnje Formation without a break and begins with stratified tuff. The tuff is overlain by ~50 m sandstone and gravel interbedded with beds of diatomite, tuff, and sandy claystone Above these strata are travertine deposits followed by ~80 m of tuff-agglomerate and sandstone. The diatomite beds are ~5–30 m thick, with the thickest diatomite layer being 7 m. From the diatomite, Ognjanova-Rumenova (2000) determined a well-developed association of *Actinocyclus Ehr.* and *Cyclotella castracanei*, and from the upper part of the section, she determined *Cyclotella macedonica Jur.* and *Stephanodiscus careonensis Ehr.*, which establish a Pliocene age for the Vitacevo Formation. Diatomite from the Pulic locality yielded *Poacitea equalis*, *Castanea atavia*, *Quercus pseudocastanea*, *Fagus pliocenica*, and *Acer pseudoplatanus* considered to be of Pliocene age (Dumurdzanov et al., l976)

The Pliocene age of the Vitacevo Formation was also confirmed by K/Ar radiometric data determined presented by Kolios et al. (1980) on nearby volcanites that range from 4.0 ± 0.2 to 1.8 ± 0.1 Ma.

The **Mariovo Formation (MaF)** probably was very widespread, but presently only relicts remain in the western part of the basin. Well-exposed sections contain pyroclastic rocks with nine travertine layers and a 20-m-thick travertine deposit covering 20 km^2, confirming the existence of the Mariovo Lake. The total thickness of the formation is 60–70 m. Shelly fossils indicate a Pleistocene age for the formation (Dumurdzanov et al., 1976).

The Kicevo and Polog Graben (Figure 8)

Kicevo and Polog grabens are developed in the NW part of the Western Macedonian zone (see map), and both grabens were initiated during sedimentation cycle II.

The **Kicevo graben (9)** consists of two minor depressions in the north connected by a N-S trending central segment to an E-W trending southern graben giving the graben a very irregular shape. The central and northern parts of the graben are bounded by a NNW-striking fault, whereas the southern E-W trending graben is bounded on its south side by a fault of the same strike. This irregular graben started to form during late Miocene time on a basement of early Paleozoic metamorphic rocks and locally on Triassic carbonate rocks. The section in the Kicevo graben is well known from the Oslomej open pit coal mine (Fig. 3) where there are good cross-sectional exposures and numerous exploration drill holes. Lacustrine strata are horizontal and are of late Miocene, Pliocene, and Quaternary age. The total sequence is 360 m thick and can be divided into two formations and Quaternary sedimentary rocks (Fig. 8).

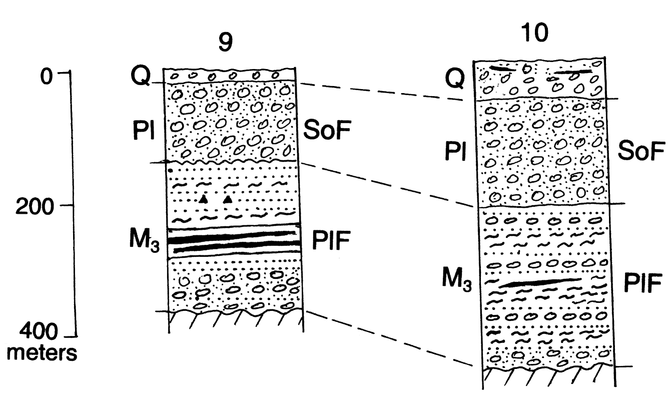

Figure 8. Sratigraphic sections of the Kicevco (9) and Polog (10) grabens. Q—Quaternary. Pliocene (Pl): SoF—Solnje Formation. Miocene (M): PlF—Pelagonian Formation.

The **Pelagonian Formation (PlF)**, typically known from the Pelagonian graben, is exposed in the Oslomej open pit mine, whereas the lower parts of the formation have been studied from drill holes. This formation consists of three superposed lithological units:

(*a*) The lowest unit consists of 80 m of proluvial-alluvial gravels overlain by lacustrine sandstone and claystone. No age data are available for this unit.

(*b*) The middle unit is composed of 50 m of coal-bearing claystone, siltstone, and few coal layers.

(*c*) The upper siltstone and claystone unit is ~100 m thick. In its lower part and in the siltstone below an upper coal layer, a diatomite flora is present. Ognjanova-Rumenova distinguished benthic species of diatoms, such as *Fragilaria*, *Tabellaria*, *Tetracyclus*, *Eunotia*, *Gomphonema*, and *Cymbela* (Dumurdzanov, 1997). The most important species in this association is *Tetracyclus japonicus (Petit)*, *Tempere et Peragallo*, which is very characteristic for the late Miocene and identical to the association of Alino Formation in Bulgaria (Ognjanova-Rumenova, 2000).

The Pliocene **Solnje Formation (SoF)** discordantly overlies the Miocene strata and is represented by 100 m of yellow, poorly stratified, and poorly sorted gravel and sandstone. The clastic material in these strata consists mostly of quartz and quartzite, and in general the formation is similar to the same formation in the Skopje and Kumanovo grabens.

Quaternary sediments (Q) are developed in a proluvial and alluvial facies, whereas in the village of Tuin (Figure 3), they are developed as glaciofluvial deposits. Thickness of these sediments varies from 10 to 30 m.

The **Polog graben (10)** is a NE-SW trending symmetrical depression ~65 km long and 8 km wide. It lies between the Sar Planina horst, with peaks more than 2500 m high to the NW, and the Suva Gora horst, bounded by normal faults on both sides to the SE. The thickness of sediments in the graben is ~470 m. The basinal sediments are not deeply incised by rivers and most of the surface outcrops are Quaternary sediments, thus the lithostratigraphy of the Miocene-Pliocene strata is constructed from drill hole data and rare surface occurrences near the margins of the graben. The graben sedimentary sequence can be divided into two formations and undifferentiated Quaternary sediments (Fig. 9).

The **Pelagonian Formation (PlF)** is ~240 m thick and is lithologically identical to the Pelagonian Formation in the Pelagonian valley to the south. Basal strata consist of gravel and sandstone followed by sequences of interbedded sandstone, claystone, sandy claystone, and gravel of different thickness. Coal layers are present in the lower part of the formation. Near the villages of Kopanica and Zilce, the fossil *Planorbis* has been found, but a late Miocene age for the Pelagonian Formation was determined by correlation with similar fossiliferous strata in the Kicevo and Pelagonian grabens.

The **Solnje Formation (SoF)** contains 130 m of gravel and sandstone that is similar to the same formation in the Skopje

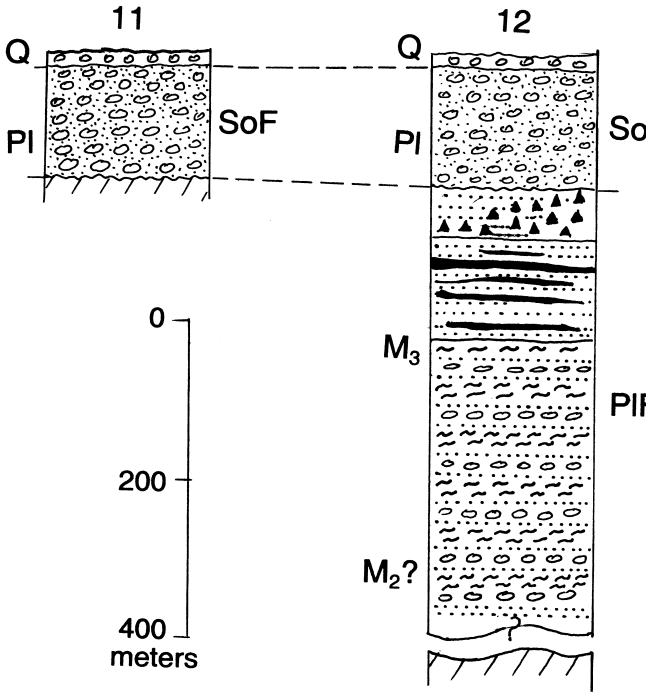

Figure 9. Stratigraphic sections of the Porecje (11) and Pelagonian (12) grabens. Q—Quaternary. Pliocene (Pl): SoF—Solnje Formation. Miocene (M): PlF—Pelagonian Formation.

graben. There is no direct evidence for the age of the Solnje Formation.

Quaternary sediments (Q) are developed across the entire graben and have a greater thickness along the western side of the graben adjacent to the high Sar Plannia range. Near the village of Neraste, a Pleistocene age for the sediments was determined from the presence of the ostracods *Candona ex. gr. neglecta* and *Candona ex. gr. Pafabaeformis* (Petkovski et al., 1985).

The Porecje and Pelagonian grabens (Figure 9)

The Porecje and Pelagonian grabens are located on the border between the Pelagonian massif and Western-Macedonian zone. The Pelagonian graben was initiated first during late Miocene time, whereas the Porecje graben was initiated during Pliocene time.

The NNW-SSE–trending **Porecje graben (11)** of west central Macedonia is ~50 km long and 5–6 km wide. Its basement consists of Precambrian marble and schist of the Pelagonian massif and Paleozoic schist of the Western-Macedonian zone. A steeply dipping active fault bounds its west side. The sedimentary fill is 130–150 m thick and is composed of Pliocene gravel and sandstone of the Solnje Formation (Fig. 9) containing abundant quartz, schist, and marble detritus. The sedimentary section is well exposed through incision by the Treska River in Pleistocene time. The Pliocene age of the sediments is assigned by correlation with the Solnje Formation in adjacent grabens.

The N-S–trending **Pelagonian graben (12)** is ~100 km long (including a part in the Northern Greece) and up to 25 km wide. It is a complex graben developed on Precambrian gneiss and schist and Paleozoic schist and granite of the Pelegonian tectonic unit. Within the graben are small horsts and one intragraben horst that divides the main graben into northern and southern parts containing 450–500 m and 700–800 m, respectively, of sedimentary fill. The graben is bounded on all sides by normal faults. Along the eastern side of the graben the youngest sedimentary layers are displaced up to 70 m.

The basal units in Pelagonian basin are proluvial-alluvial sediments based on drill hole data. Seismic studies indicate that these sediments were deposited in narrow river valleys rather than with a fault controlled graben. Paleontological data from higher stratigraphic levels indicate the graben was initiated in late Miocene time and contained a lacustrine environment from late Miocene to the end of the end of Pliocene and Pleistocene time locally. Considering there is probably more than 1000 m of section in the southern part of the graben, it can be suggested that this part of the graben may have been initiated during middle Miocene (Badenian-Sarmatian) time. The Miocene-Pliocene section is covered by 5–15 m of Pleistocene alluvial-proluvial sediments, except in the southeastern part of the graben, where upper Miocene strata are exposed by uplift and erosion. In this area, the section has been well studied in the Suvodol open pit coal mine and in drill holes in numerous water wells. The sequence is divided into two formations and undifferentiated Quaternary strata (Fig. 9).

The **Pelagonian Formation (PlF)** consists of ~600 m of terrigenous coal-bearing strata that can be divided into three superposed lithological units deposited in sedimentary cycles II and III.

(*a*) The basal unit consists of gravel, sandstone and silty claystone. This unit is 150–200 m thick in the part of the graben abound Prilep and 400–500 m thick in the part around Bitola, but the maximum thickness of this unit is unknown. It begins with alluvial-proluvial gravel and sandy claystone overlain by well stratified interbedded gravel, sandstone, silty claystone, and siltstone. The age of these strata are unknown.

(*b*) The middle coal-bearing unit consists of interbedded siltstone, silty claystone and a few coal-bearing layers. In the Prilep area coal-bearing layers in the middle of this unit are 6–7 m thick. In the Bitola area are two levels of coal-bearing strata, up to 58 m thick, with numerous coal layers. The coal layers are well developed in the eastern part of the graben between the villages Suvodol, Vranjevci, Brod, and Zivojno (Fig. 3), and thin to the west and north (Andreevski, 1990). There is no direct evidence for the age of these strata, but correlation with the similar strata in the Kicevo, Tikves, Mariovo, and Skopje grabens suggests they are probably of Meotian age.

(*c*) The upper unit, consisting of diatomite, siltstone, and claystone, has been well studied in the southern part of the graben from outcrops and in the Suvodol coal mine. In the Bitola area, there is a 70 m continuous section that begins with few meters of sandstone overlain by diatomite, siltstone, and silty claystone rich in macroflora and diatoms. Ognjanova-Rumenova (Dumurdzanov, 1997) determined the diatoms contain the association *Cyclotella elymaea Ec.-Am.* and *Aulocoseira* that is of Miocene (Pontian) age. Mihajlovic and Lazarevic (2004) determined the macroflora *Zelkova zelkovifolia*, *Quercus pseudocastanea*, *Q. sosnowskyi*, *Q. lucidensis*, *Q. kubynyi*, *Alnus nanzelli*, *Caprinus cf. neilrechii*, and *Dicotylophyllum* sp. that are probably of early Pliocene age. Also, near the village of Zivojno, *Tapirus priscus macedonica* of Pontian age was determined by Laskarev (1950).

The **Solnje Formation (SoF)** is present in most parts of the basin except along the eastern margin around Bitola where they have been removed by erosion. The 150-m-thick formation always begins with yellow-brown gravel and sandstone, which suggests a possible hiatus at its base. Above are poorly stratified and poorly sorted sequences of interbedded gravel, sandstone, and sandy claystone. A Pliocene age is assigned to the Solnje Formation by correlation with similar rocks in the Mariovo and other grabens.

Quaternary sediments (Q) are present over the entire Pelagonian graben. They consist of alluvial and proluvial sediments, 2–10 m thick in the Bitola part and 10–20 m thick in the Prilep part of the graben. In the western part of the graben in the Bitola area, glaciofluvial sediments were deposited.

The Delcevo-Pehcevo and Berovo Grabens (Figure 10)

The Delcevo-Pehcevo and Berovo grabens are located in southeastern Macedonia within the Serbo-Macedonian tectonic unit (see map). The Delcevo-Pehcevo graben is bounded by older NW-SE-striking reactivated faults, whereas the Berovo graben is bounded by new faults that strike NE-SW and E-W. The lithostratigraphy of these grabens is very similar. The Delcevo-Pehcevo graben was the first of the two grabens to form. The sedimentary sequence in both grabens began during late Miocene time (cycles II and III), and following a hiatus, Pliocene and Quaternary sediments were deposited.

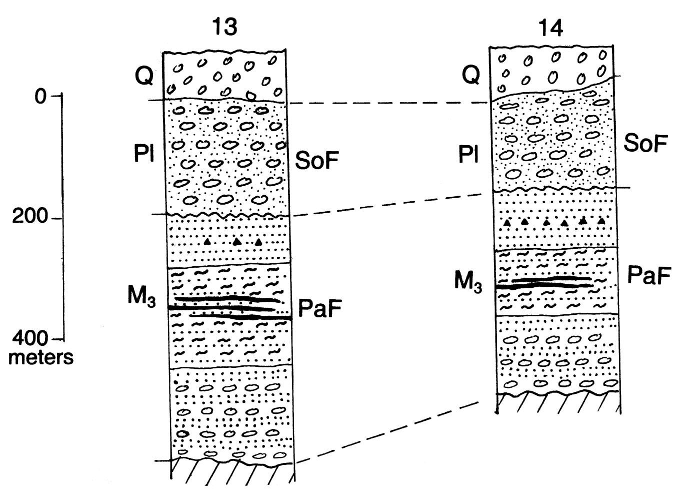

Figure 10. Stratigraphic sections of the Delcevo-Pehcevo (13) and Berovo (14) grabens. Q—Quaternary. Pliocene (Pl): SoF—Solnje Formation. Miocene (M): PaF—Pancerevo Formation.

The NW-SE-trending **Delcevo-Pehcevo graben (13)** is 32 km long and 6 km wide. The sedimentary sequence is only partly exposed, and the deeper parts of the basin are known from exploration drill holes. The basin fill is 600 m thick, and two formations can be distinguished: the upper Miocene Pancerevo Formation and the Pliocene Solnje Formation. These are covered by undifferentiated Quaternary strata (Fig. 10).

The **Pancerevo Formation (PaF)** is an upper Miocene coal-bearing formation very similar to the Nerezi Formation in the Skopje and Tikves grabens. This formation is composed of three lithological units.

(*a*) The basal unit is ~150 m thick and consists of gravel, sandstone, and claystone. It is only partly exposed, but is known at depth from a few drill holes. The basal part of the formation consists of 40 m of conglomerate that contains clasts of gneiss, granite, greenschist, and meta-gabbro. It is overlain by claystone, sandstone, and siltstone more than 100 m thick.

(*b*) The middle coal-bearing gradational unit overlies the basal unit. It consists of siltstone, marly claystone, and few coal layers. Near the villages of Zvegor and Stamer, it is ~170 m thick with three coal-bearing horizons: the lower horizon is 20 m thick, with few coal layers; the main coal horizon is 10–25 m thick, with two coal layers; and the upper horizon has only a few thin coal layers. In the area of the Star Istevnik-Pancarevska River, the coal-bearing beds form one horizon 80 m thick. Above the main coal horizon near the village of Star Istevnik, a *Hipparion* tooth was discovered and determined by Garevski (Dumurdzanov et al., 1998) to be Turolian in age.

(*c*) The upper unit consists of ~80 m of interbedded sandstone, siltstone, and claystone containing thin layers of diatomite. Locally, in the upper part of this unit near the village of Stamer, are carbonate rich claystone and a travertine layer 1 m thick that indicate evaporation of the lake water and the beginning of a hiatus. A Meotian-Pontian age is assigned to this unit by correlation with the same horizon in the Berovo graben that contains a diatom microflora.

The **Solnje Formation (SoF)** rests discordantly on the upper Miocene strata. It is deeply eroded, but locally, in the marginal parts of the graben, the formation is 100–200 m thick. It is lithologically similar to the same formation in the Skopje graben and consists of gravel and sandstone with gravel clasts of quartz, granite, greenschist, Triassic carbonate rocks, and volcanic rocks.

Quaternary sediments (Q) are represented by proluvial-alluvial, lake, and swamp sediments and limonite breccias in southeastern part of the graben which are 80 m thick.

The NE-SW-trending **Berovo graben (14)** extends 15 km south from the Bukovik volcano that forms the boundary with the Delcevo-Pehcevo graben The sedimentary fill of the graben crops out across an ~6 km width, but the sedimentary section near the

Brik coal mine and other smaller relicts of Neogene sediments to the south and west suggest that the area covered by the basin was much larger. The sedimentary section in the Berovo graben is more than 500 m thick and is composed of two formations and Quaternary sediments.

The **Pancarevo Formation (PaF)** is ~330 m thick and its stratigraphic section is similar to that of the same formation in the Delcevo-Pehcevo graben, but with fewer coal layers and more widespread diatomite, bituminous siltstone and kaolinitic claystone. Three superposed lithological units are present in the Pancarevo Formation (Fig. 10).

(*a*) The basal 125-m-thick unit of gravel, sandstone, and claystone is very similar to the basal unit the Delcevo-Pehcevo graben.

(*b*) The middle coal-bearing unit is ~100 m thick and is composed of siltstone, grey and green-grey claystone, and 1–2 layers of coal developed at the SW margin of the basin at the Brik mine. In the more central parts of the basin, the coal-bearing beds are mainly coal-bearing claystone and thin beds of bituminous siltstone.

(*c*) The upper unit consists of ~100 m of interbedded sandstone, siltstone, and claystone. The uppermost part contains diatomite, such as near the village of Umlena (east of Smojmirovo), and kaolinitic claystone near Pehcevo. Ognjanova-Rumenova (2000) determined the *Actinocyclus/Cyclotella* association of planktonic diatom flora from the diatomite that belongs to late Miocene *Actinocyclus makarovae* Zone (correlative with the Novi Iskar Formation in the Sofia basin). The presence of the kaolinitic claystone, diatomite, and rare occurrences of bituminous siltstone could be related to sedimentation following the activity of the Bukovik volcano, but the age of this volcano has not been determined. Pyroclastic material from the volcano is not present within the basin, which suggests an age for the volcano older than late Miocene. A K/Ar radiometric age of 25–17 Ma (Serafimovski, 1993) and four new ages that range from 28 to 29 Ma (T. Serafimovski, 2002, personal commun.) have been determined for the Sasa volcanic rocks. The Bukovik volcano lies within this volcanic zone suggesting it is older than late Miocene.

The **Solnje Formation (SoF)** is more than 150 m thick, and in most inner parts of the basin it is deeply eroded. It consists of gravel, sandstone, and sandy claystone. Clasts in the gravel are composed of quartz, granite, gneiss, greenschist, and quartz-latite eroded from the Bukovik volcano.

Up to 80 m of **Quaternary sediments (Q)** are developed in northeastern part of the graben and consist of proluvial sediments, while in the higher parts of Bukovik Mountain, they consist of thick limonitic breccia. The limonitc breccia was developed during the activity of the Bukovik volcano by hydrothermal activity, but the breccia has been reworked into similar appearing breccias of Quaternary age.

The Lakavica, Strumica, and Dojran Grabens (Figure 11)

The Lakavica, Strumica, and Dojran grabens are located in southeastern Macedonia (see map). The Lakavica and Strumica grabens are long and narrow, whereas the Dojran graben is more equidimensional and lies mainly in northern Greece. The Lakavica and Strumica grabens are partly developed above upper Eocene sediments.

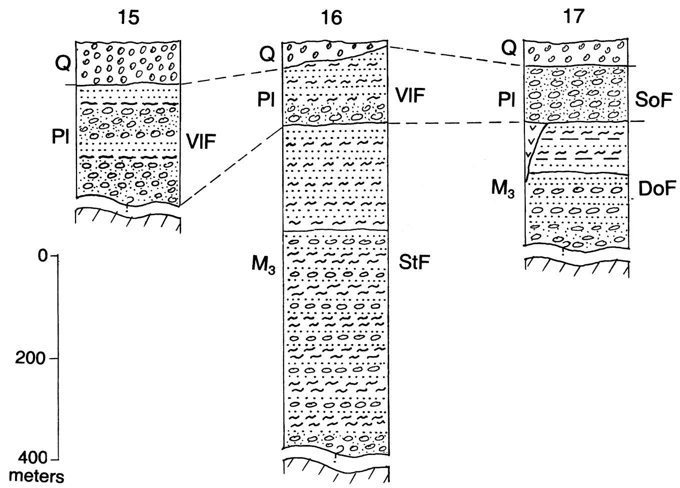

Figure 11. Stratigraphic sections of the Lakavica (15), Strumica (16), and Dojran (17) grabens. Q—Quaternary. Pliocene (Pl): SoF—Solnje Formation, ViF—Vladilovice Formation. Miocene (M): DoF—Dojran Formation, SrF—Strumica Formation.

The NW-SE–trending **Lakavica graben (15)** is 70 km long and 7 km wide and is bounded by a normal fault with a left-lateral strike-slip component on its SW side and a discontinuous normal fault on its NE side. The graben formed during Pliocene time along reactivated older faults. The sedimentary section is ~300 m thick and is composed of the poorly exposed Vladevci Formation overlain by undifferentiated Quaternary sediments (Fig. 11).

The **Vladevci Formation (VlF)** consists of more than 200 m of gravel and sandstone alternating with claystone and sandy claystone. These rocks are rarely exposed at the surface and most information about this formation comes from exploration drill holes and comparison with rocks in the same stratigraphic position in the Strumica graben. To the east, the sedimentary graben fill overlaps the Bucim-Damjan-Borov Dol volcanic complex (K/Ar age of 26–29 Ma). The sediments contain detritus of quartz, gneiss, granite, andesite, latite, and quartz-latite. A Pliocene age for Vladevci Formation is inferred.

In some parts of the graben the **Quaternary sediments (Q)** are 100 m thick and consist of poorly sorted and poorly stratified gravel containing clasts of quartz, gneiss, granite, carbonates, and volcanic rocks.

The **Strumica graben (16)** in SE Macedonia trends E-W and is a continuation of the Strumesnica graben in Bulgaria. To the west, it changes trend to the NW and cuts diagonally across the boundary between Serbo-Macedonian massif and Vardar zone. Within Macedonia, the graben is 60 km long and 13 km wide. The sedimentary section in the graben rests unconformably above Precambrian gneiss, Paleozoic metamorphic rocks, and granite, and partly above upper Eocene flysch. The basin strata are rarely exposed and have been studied mainly from deep exploration drill holes for fresh and thermal waters. Gravity anomalies in the central part of the graben, between the villages of Monospitovo, Murtino, and Bosilovo (Fig. 3), suggest the basin fill is more than 1800 m thick. At the periphery of the anomaly in one drill hole near the village of Saraj, the Neogene sedimentary section was 713 m thick. There is a clear fault along the south side of the graben and the Belasica Mountains to the south are a horst, with a clear fault on their south side in Greece. These mountains reach an elevation of more than 1800 m and with the depth of the basin indicated by gravity data, there is evidence for more than 2000 m of relative displacement along the southern boundary fault of the graben. The graben is asymmetric as the northern boundary is limited by normal faults of small displacement and the mountains to the north have a long gentle surface that slopes south into the graben.

Data from outcrops, drill holes, bounding faults, and lithological composition of the sedimentary sequence indicate that the fault along the south side of the graben was active from the initiation of the graben to the present. The sediments in the graben indicate rapid accumulation of coarse clastic material. From exposures and drill hole data, the section can be divided into two formations and Quaternary sediments (Q).

Deposition of the **Strumica Formation (StF)** at the base of the section began in late Miocene time and was continuous until the end of the Miocene (cycle IV, Fig. 11). Two lithological units can be distinguished.

(*a*) The basal unit consists of gravel, sandstone, and claystone that is more than 400 m thick. At the bottom is coarse rubble overlain and mixed with gravel and sandstone. Above are sequences 10–20 m thick of interbedded stratified sandstone, gravel, and claystone. There is no direct evidence for the age of this unit.

(*b*) The upper unit consists of more than 200 m of sandstone, siltstone, and claystone, and in places interbedded yellow and grey claystone and marly claystone are present. This unit is considered late Miocene by correlation with rocks in adjacent Berevo graben, but there is no direct data on its age

The **Vladevci Formation (VlF)** has a characteristic yellow to brownish-red color. It begins with gravel beds overlain by an alternation of sandstone, claystone, and gravel. The formation is exposed near the village of Vladevci and at a few other localities and is known from drill holes. The formation is assigned a Pliocene age based on the assumption that coarse clastic deposits begin in all other basins (Solnje Formation) during Pliocene time, but its boundary with the Miocene rocks is gradational and not distinctive. The formation begins with gravels and continues with an alternation of sandstone, claystone, and gravel, but contains claystone than Pliocene rocks elsewhere thus the name Solnje Formation is not used.

The **Quaternary sediments (Q)** in the central parts of the graben consist of alluvial and proluvial sediments, whereas near Monospitovo Lake, lacustrine and marsh deposits are ~20 m thick. In the southern part of the graben near the Belasica Mountains, the Quaternary strata are composed of proluvial breccia and glaciofluvial sediments that are ~50–60 m thick.

The sedimentary rocks in the **Dojran graben (17)** were widespread, but today they are known only from limited exposures surrounding Dojran Lake and by more extensive exposures to the SE in Greece. Garevski (1956, 1976) first described the Pikermian fauna near the villages of Prsten and Bashibos (Anska River), and he showed that the lake was initiated during late Miocene time. This age assignment has been confirmed by a K/Ar radiometric age of 8 Ma (R. Stoyanov, 2002, personal commun.) from quartz-latite that intrudes the lower part of the Miocene sedimentary section. Two formations and undifferentiated Quaternary sediments form the graben fill (Fig. 11).

The **Dojran Formation (DoF)** is not exposed and is only known from drill holes which, unfortunately, did not reach bedrock. The Dojran Formation lies unconformably on Paleozoic schist and marble and locally on Precambrian gneiss of the Serbo Macedonian tectonic unit that surround the Dojran graben. It is composed of two lithological units.

(*a*) The basal unit consists of more than 200 m of gravel, sandstone, siltstone, and claystone.

(*b*) The upper unit has an estimated thickness of 100 m and consists of sequences of interbedded claystone, marly claystone, marl, and siltstone that have varying thickness. In Greece, these sediments are cut by latite dikes that yield K/Ar ages of 8 Ma (R. Stojanov, 2002, personal commun.). The fauna Machairodus aphanistus determined by Garevski (1990) near the village of Prsten (Anska River) indicates a late Miocene age for the upper unit.

The **Solnje Formation (SoF)** is known from only rare outcrops, but its presence is known from a few drill holes on the west side of the lake. It consists of ~100 m of gravel, sandstone, and sandy claystone. A Pliocene age for the formation is assigned by correlation with similar dated units in the Skopje graben.

The **Quaternary sediments (Q)** consist of 50–60 m of sandstone, claystone, and siltstone overlain by clay, mud, and sand deposited in swamp and marsh environments

Prespa, Ohrid, Piskupstina, and Debar Grabens (Figure 12)

The Prespa, Ohrid, Piskupstina, and Debar grabens are located in the western border region of Macedonia (see map). The Ohrid, Piskupstina, and Debar grabens are grouped together as the Drim grabens that originated near contact between the Western-Macedonian zone and Albanian Merdita ophiolite zone. They are aligned along the same important N-S striking fault zone that continues into Albania to the north and Greece to the south. The Korca graben in Albania is also aligned along a fault of similar strike, but to the southwest. The Prespa graben lies SE of the Ohrid graben. All these grabens are bounded by N-S–striking faults, and the Debar graben is also cut by the western part of the seismic and very active NE-SW–striking Kustendil-Skopje-Debar strike-slip fault. The Piskupstina graben probably was initiated first in cycle II (Upper Sarmatian-Meotian), whereas the Prespa, Ohrid, and Debar grabens were formed during cycle III (Uppermost Meotian-Pontian).

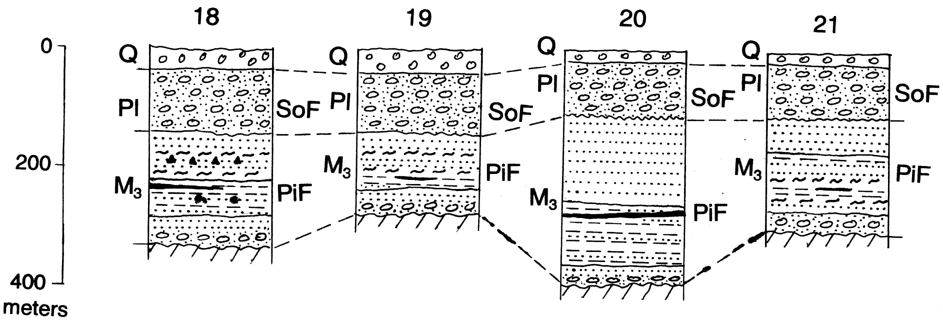

Figure 12. Stratigraphic sections of the Prespa (18), Ohrid (19), Piskupstina (20), and Debar (21) grabens. Q—Quaternary. Pliocene (Pl): SoF—Solnje Formation. Miocene (M): PiF—Piskupstia Formation.

The N-S trending **Prespa graben (18)** is 35 km long and 13 km wide and extends southward into northern Greece. The central part of the graben is covered by Lake Prespa. The sedimentary section of the graben fill is rarely exposed and most information on its lithostratigraphy comes from drill hole data. The sequence is ~330 m thick and can be divided into two formations and undifferentiated Quaternary sediments (Fig. 12).

From partial exposures and drill hole data, the **Piskupstina Formation (PiF)** can be divided into three superposed units.

(*a*) The lowest unit consists of 50 m of gravel, sandstone, and siltstone that rests unconformably on Paleozoic metamorphic rocks and Triassic carbonate and clastic rocks.

(*b*) The middle coal-bearing unit, known only from drill hole data, is ~70 m thick and is composed of siltstone and silty claystone with two coal layers present within a 15–20 m part of the section

(*c*) The upper unit is ~80 m thick and consists of siltstone and marly claystone with diatomite. Probably during Pontian time, lacustrine sedimentation became more widespread. In one small uplifted block on eastern slopes of the Galicica Mountain, near the village of Leskovec, in yellowish diatomitic and marly claystone a fossil flora was discovered and was described by Ognjanova-Rumenova (in Dumurdzanov, 1997) who determined different forms of genius Aulacoseira, of Pontian–early Pliocene age. This age determination was also confirmed with a rich leaf macroflora containing, for example, *Betula prisca*, *Caprinus grandis*, *Castanea atavia*, *Quercus* cf., *Quercus pseudocastanea*, *Juglans acuminata*, *Caria serreofolia*, *Zelkova ungeri*, *Ulmus longifolia*, and *U. caprinoides* determined by Pantic et al. (1973).

The **Solnje Formation (SoF)** consists of ~100 m of gravel and sandstone. Its Pliocene age is assigned based on correlation with similar strata in the Skopje and Kumanovo grabens.

The **Quaternary sediments (Q)** consist of 50–60 m of lacustrine gravel, sandstone, and sandy claystone, and mixed lacustrine-marsh sediment at the northern end of the lake.

The **Ohrid graben (19)** is 40 km long and 13 km wide and contains the Ohrid Lake that is ~285 m deep in its southern part adjacent to Galicia Mountain. Formerly, the lake continued farther north into the Piskupstina graben. The graben is bounded on both sides by large normal faults with more than 1400 m of relief along its eastern side adjacent to Galicia Mountain.

The sedimentary sequence in the graben is rarely exposed, and the lithostratigraphy of the basin fill is studied at rare surface occurrences, in drill holes, and by comparison with the sediments in the Prespa graben. Triassic carbonate rocks, claystone, and conglomerate, and partly locally Paleozoic schist unconformably underlie the Ohrid basin fill. The section is ~270 m thick and can be divided into two formation and undifferentiated Quaternary sediments (Fig. 12).

In a rare exposure of the **Piskupstina Formation (PiF)** at the base of the section near the village of Vapila and at the brick factory at Arbinovo, the formation can be divided into two parts: (a) the lowest part consists of gravel, sandstone, and siltstone overlain by (b) siltstone, claystone, marly claystone, and locally thin coal layers.

The formation is estimated to be 130 m thick and its Pontian age is assigned by correlation with the similar well-dated rocks in the Prespa graben.

The **Solnje Formation (SoF)** is exposed in marginal parts of the graben where it consists of gravel and sandstone composed of clasts and grains of quartz, carbonate, quartzite, and schist.

The **Quaternary sediments (Q)** consist of 50–60 m of lake gravel, sandstone, and mudstone and in the northern coastal part of the lake peat deposits are also present.

The **Piskupstina graben (20)**, a small graben 6–8 km long and 1–2 km wide, is bounded on its west side by a fault that is probably continuous with the fault along the west side of the Ohrid graben. Its sedimentary fill is largely eroded and clearly represents a relict of a much more extensive basin. The Neogene section that is preserved is 380 m thick—thicker than the Neogene deposits in the larger Ohrid graben to the south—indicating that lacustrine sedimentation initiated first in the Piskupstina graben during cycle II in Late Sarmatian to Meotian time. The section is well exposed in a large open pit coal mine, and its deeper parts are known from drill holes that extend to 200 m depth. Two formations can be distinguished (Fig. 12).

The **Piskupstina Formation (PiF)** consists of 280 m of terrigenous coal-bearing strata whose lithostratigraphy is very similar to the Nerezi Formation in the Skopje graben, and can be divided into three units.

(*a*) The basal conglomerate and sandstone unit has a thickness of 30–40 m determined from drill holes. It overlies folded Paleozoic and Triassic rocks.

(*b*) The middle coal-bearing unit is gradational from the basal unit below and consists of 100 m of grey siltstone and pure marl in the lower part and with coal layers that total 3–10 m thick in the upper 10 m.

(*c*) The upper unit consists of 140–150 m of interbedded sequences of varying thickness of poorly cemented grey siltstone and sandstone. The siltstone contains a rich fauna with *Alnus* cf. *adscendens* (Goepert) and *Zastavniak-Walther* of Pontian age, very similar to the Suvodol fauna and associated flora in the Pelagonian graben.

The **Solnje Formation (SoF)** transgressively overlies different stratigraphic levels of the Piskupstina Formation. It is characteristically yellow-brown with clearly differentiated layers of poorly sorted gravel that grade into sandstone. The Solnje formation is 130 m thick. As a result of recent uplift and tilting of the Jablanica block in western Macedonia, the entire Neogene section dips 12–20° to the WNW.

The **Quaternary sediments (Q)** consist of alluvial and proluvial strata 10–15 m thick.

The Debar graben (21) lies north of and along the trend of the Piskupstina graben within Macedonia, and farther to the NW it enters Albania where it has a slightly more northerly trend. It is 20 km long and 7 km wide and is bounded by the same NW-trending fault that bounds the Piskupstina graben, but on the opposite side of the graben. Graben sediments unconformably overlie Paleozoic schist, Triassic carbonate rocks, Upper Cretaceous carbonate rocks, and claystone. The upper part of the Neogene section is mostly exposed and drill holes provide data on the deeper part of the sequence. Drill hole data indicate the sequence is 300 thick and consists of two formations and undifferentiated Quaternary sediments (Fig. 12).

The **Piskupstina Formation (PiF)** is not exposed, but from drill hole data is known to consist of a basal gravel and sandstone 30 m thick.

(*a*) It is overlain by 100 m of siltstone and marly claystone with local coal beds.

(*b*) The upper unit consists of 60 m of siltstone and sandstone.

There is no direct data the age of the Piskupstina Formation in the Debar graben, but it is considered of probable Pontian age by correlation with similar rocks in the Piskupstina graben.

The **Solnje Formation (SoF)** is mostly exposed and is ~100 m thick. Its relation with the Miocene strata is not clear, but its contact is probably an unconformity. The formation consists of gravel and sandstone. A Pliocene age is suspected for the formation.

The **Quaternary sediments (Q)** consist of 10–15 m of alluvial, proluvial, and glaciofluvial sediments. These strata are extensively eroded and consist mainly of relicts of more widespread deposits.

SUMMARY

The Neogene tectonic evolution of Macedonia, as in the other parts of the Balkan Peninsula, commenced at the end of lower Miocene time and became very active in Badenian time, when the first grabens were formed. The first freshwater lakes and associated sediments were deposited in the Skopje, Kumanovo, Probistip, and the Kocani basins. At the end of Sarmatian time and the beginning of Meotian (Tyrolian) time, vertical displacements became more intensified. Existing grabens, as well as the fresh basins, were widened, and many new basins, such as the Pelagonian, Tikves, and Strumica basins, were formed (most probably in Middle Sarmatian time) followed in Meotian time by the Veles, Mariovo, Delcevo–Pehcevo, Berovo, Kicevo, Polog, and Piskupstina basins, and later at the end of Meotian and Pontian time by the Prespa, Ohrid, and Debar basins. Sedimentary and structural data indicate these basins were developed as grabens or half-grabens.

During Pliocene time, vertical displacements along basin-bounding normal faults increased resulting in a corresponding increase in topographic relief that is reflected in the basins by the accumulation of coarse-grained clastic molassic type strata. During this time, lakes widened and deepened, and new basins, such as the Porecje, Lakavica, Mavrovo, Demir Hisar, and Raec basins, were formed. Some of these basins had their inception in early Pliocene time (probably in latest Pontian time), whereas others were formed in late Pliocene time.

Vertical displacements and a corresponding increase in topographic relief continued into the Pleistocene and with lesser intensity to the Recent. Thus, Macedonia and the central part of the Balkan Peninsula was the site of increased relative uplift, including the basins, and increased topographic relief at a time when the region of the Aegean Sea was undergoing continued subsidence. Within Macedonia, influenced by increased relief and Pleistocene glacial and interglacial erosion, many of the lakes were buried and disappeared. Equally important during Pleistocene time was the formation of the Vardar River. Prior to this time, most of the basins of central Macedonia were part of an enclosed and partly interconnected interior drainage system. A low sill of Jurassic limestone formed a dam in southern Macedonia at the southeast corner of the Tikves graben for this interior drainage system. During Pleistocene time, the sill was breached and the Vardar River and its drainage system developed by rapid headward erosion so that at present the Vardar drainage system covers more than 80% of Macedonia. Lakes present before the sill was breached were rapidly drained and basinal sediments were deeply eroded by capture from the Vardar River system. Only the Ohrid and Prespa lakes remain as remnants of this former extensive system of lakes. These two lakes are just being tapped by the Struga and Crna rivers and are destined in the near future also to be drained. The Struga River flows to the Adriatic Sea through Albania, and the Crna River is part of the Vardar system which flows to the Aegean Sea. Dojran Lake, in southeastern Macedonia, remains an enclosed basin, possibly caused by recent tectonic displacements, but it has a very low sill at its southern end and will probably be drained in the near future.

The Neogene tectonic evolution of Macedonia will be the subject of another paper and is only briefly commented on here. The basins in Macedonia are fault-controlled grabens and half-grabens. Faults which control these grabens strike NW-SE, E-W, and WSW-ENE. Most of the faults have normal dip-slip displacement, but some have components of strike-slip and are oblique-slip faults. Some of the faults clearly are related to reactivation of older structures, whereas others are not controlled by pre-existing anisotropy. Fault initiation and direction of slip changed with time, and the temporal and spatial evolution is complex and requires more discussion than can be presented in this contribution. Once formed, the Neogene basins were not subjected to shortening deformation and their sediments are either horizontal or tilted by extensional faults, but they are not folded. The local folding does occur, but is associated with displacement on faults related to extension.

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