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The Unaz Formation: A Key Unit in the Western Black Sea Region, N Turkey

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Abstract: The Pontide magmatic belt in the Western Pontides, which developed in response to the northward subduction of the northern branches of the Tethys Ocean, consists of two different volcanic successions separated by an Upper Santonian pelagic limestone unit, the Unaz Formation. The first period of volcanism and associated sedimentation started during the Middle Turonian and lasted until the Early Santonian under the control of an extensional tectonic regime, which created horst-graben topography along the southern Black Sea region. The lower volcanic succession, the Dereköy Formation, was deposited mainly within these grabens. This extensional period probably represents the rifting of magmatic arc, giving rise to the opening of the Western Black Sea back–intra-arc basin.

The Unaz Formation commonly covers horsts and grabens developed before its deposition. This formation implies sudden subsidence of the region and termination of the volcanism during the Late Santonian. This period was interpreted as the time of the beginning of the oceanic spreading in the Western Black Sea Basin. The second period of magmatism developed on the Unaz Formation was more voluminous and was active during the Campanian.

Stratigraphy, contact relationships and regional correlations indicate that the deposition of the Unaz Formation and similar deep marine red pelagic sediments in the Black Sea and Eastern Mediterranean region were probably controlled by local and regional tectonic events and sea level and/or climate changes.

Key Words: Pontides, Late Santonian, Cretaceous oceanic red beds, Black Sea

Batı Karadeniz Bölgesinde Anahtar Bir Birim: Unaz Formasyonu

Özet: Tetis Okyanusu'nun kuzeye doğru dalmasının bir ürünü olan Pontid magmatik kuşağı Batı Pontidler'de Unaz Formasyonu'nun Üst Santoniyen pelajik kireçtaşları ile birbirinden ayrılmış iki farklı volkanik istiften oluşur. İlk evre volkanitleri ve buna eşlik eden çökeller Orta Turoniyen ile Erken Santoniyen arasında Güney Karadeniz bölgesi boyunca horst-graben yapısının oluşmasına neden olan genişlemeli bir tektonik rejimin kontrolünde gelişmişlerdir. Dereköy Formasyonu adı ile bilinen bu alt volkanik topluluk genellikle grabenler içerisinde çökelmiştir. Bu genişlemeli dönem olasılıkla magmatik yayın riftleşmesini ve bunun sonucunda Batı Karadeniz Havzası'nın bir yay içi/yay ardı havzası olarak açılmasını temsil etmektedir.

Unaz Formasyonu, ilk evrede gelişmiş olan horst ve grabenlerin ortak örtüsünü oluşturur. Bu formasyon, Geç Santoniyen'de ilk evre volkanizmasının sona erdiğini ve bölgenin ani olarak çöktüğünü işaret etmektedir. Bu dönem Batı Karadeniz Havzası'nda okyanusal yayılmanın başlama zamanı olarak yorumlanmıştır. Unaz Formasyonu üzerinde Kampaniyen boyunca sürmüş olan olan ikinci evre volkanizması ise öncekine oranla çok daha şiddetli ve hacimli olmuştur.

Unaz Formasyonu'nun stratigrafisi, dokanak ilişkileri ve bölgesel korelasyonu, Karadeniz ve Doğu Akdeniz'deki bu ve benzeri derin denizel birimlerin çökeliminin yerel ve bölgesel tektonik yanında deniz seviyesi/iklim değişiklikleri tarafından da kontrol edildiğini işaret etmektedir.

Anahtar Sözcükler: Pontidler, Geç Santoniyen, Kretase okyanusal kırmızı kayaları, Karadeniz

Introduction

The Cretaceous is a critical time to understand the tectonic evolution of the Black Sea and the mountain ranges surrounding this landlocked oceanic basin. It is generally accepted that the Black Sea region was affected by an extensional tectonic regime during the Early Cretaceous (Letouzey *et al.* 1977; Zonenshain & Le Pichon 1986; Görür 1988; Manetti *et al.* 1988), resulting in the development of the Western and Eastern Black Sea basins and other sedimentary basins on its southern continental margin.

The Pontides (Ketin 1966; Şengör & Yılmaz 1981; Okay & Tüysüz 1999), forming the southern continental margin of the Black Sea, can be separated into the Western, Central and Eastern Pontides. The Western Pontides corresponds to the İstanbul Zone and Central and Eastern Pontides correspond to the Sakarya Zone of Okay (1989). The Zonguldak and the Ulus basins on the İstanbul Zone and the Sinop Basin on the Sakarya Zone (Figure 1) were mainly filled by Cretaceous sedimentary and volcanic units. Tüysüz (1999) concluded that the stratigraphy of the Lower Cretaceous units of both the Zonguldak and the Ulus basins (Figure 1) is different from that of the Sinop Basin, while the stratigraphy of the Upper Cretaceous and younger units of all these basins are the same. Based on this, Tüysüz (1999) deduced that the İstanbul and the Sakarya zones were juxtaposed at the end of the Early Cretaceous.

Sedimentary fill of the Zonguldak, Ulus and Sinop basins (Figure 1; Tüysüz 1999) reflects opening and deepening periods of these basins east of the Bolu-Ereğli line (Figure 1) during the Late Barremian to Cenomanian interval (Tüysüz 1999; Masse *et al.* 2009). At that time, the western part of this line remained as an erosional area. The Upper Barremian–Aptian basal parts of the fills of the basins are mainly represented by siliciclastics and carbonates deposited during the rifting of these basins (Figure 2). The Aptian–Cenomanian sediments are mainly composed of ammonite-bearing dark shales, marls and siliciclastic turbidites reflecting anoxic basin conditions. Following a short uplift and erosional period within the Cenomanian, the nature of the sedimentation totally changed; deposition of dark shales and siliciclastic turbidites were replaced by volcanics, volcaniclastics and alternating red pelagic shales and limestones indicating oxic conditions (Görür *et al.* 1993). This new period of sedimentation was mainly associated with extensive volcanism, produced by a magmatic arc extending from the Srednagorie Zone in Bulgaria to the Caucasus in Georgia. It is generally accepted that this arc trending parallel to the southern Black Sea coast was established in response to northward subduction of the Intra-Pontide and Ankara-Erzincan-Sevan branches of Tethys Ocean from west to east, respectively (Peccerillo & Taylor 1975; Şengör & Yılmaz 1981; Manetti *et al.* 1988; Aykol & Tokel 1991; Tüysüz 1993; Okay & Tüysüz 1999; Karacık & Tüysüz 2010).

The Pontide magmatic arc comprises mainly volcanics, volcaniclastics and alternating clastics and carbonates and granitic intrusions in its western and eastern parts. The thickness of the volcanic succession exceeds a few kilometres in places. Both radiometric and fossil age data from different parts of the magmatic belt imply that the volcanism was active between the Middle Turonian and Maastrichtian (Çoğulu 1975; Akın 1978; Moore *et al.* 1980; Stanisheva-Vassileva 1980; Popov 1981; Akıncı 1984; Ohta *et al.* 1988; Aykol & Tokel 1991; Çamur *et al.* 1996; Berza *et al.* 1998; von Quadt *et al.* 2005; Karacık & Tüysüz 2010).

Görür *et al.* (1993) concluded that the rifting of the Black Sea back-arc basin was initiated during the Aptian and this was followed by syn-rift sedimentation and subsidence until the late Cenomanian, when ocean floor spreading and thermally induced subsidence started. After the breakup of the continental crust in the late Cenomanian, basinward tilting and subsidence of the southern margin of the Black Sea caused widespread transgression and a major post-breakup unconformity, above which pelagic limestones and marls were deposited. Following the onset of spreading in the Black Sea, the euxinic conditions of the rift stage were replaced with oxic conditions, giving way to the deposition of red pelagic carbonates and marls.

Tüysüz (1999) and Tüysüz *et al.* (2004) indicated that post-breakup sequence of Görür *et al.* (1993) in the Western Pontides is represented by two different volcanic successions separated by the Unaz Formation. According to fossil data, the lower volcanic succession, the Dereköy Formation (Tüysüz

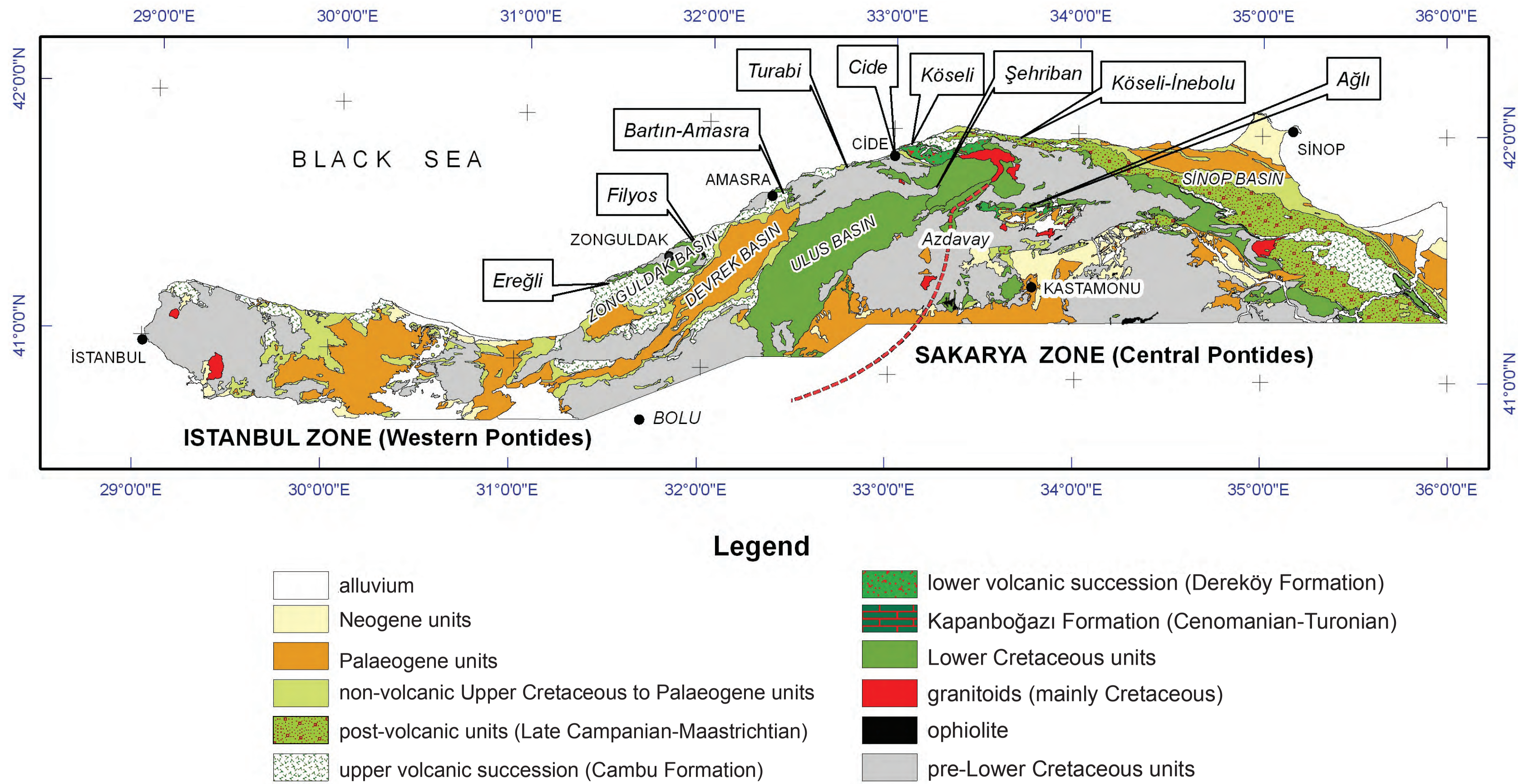

Figure 1. Simplified geology map of the Western and Central Pontides. Red dashed line is the Intra-Pontide suture separating the İstanbul and the Sakarya zones. Labels indicate the locations of the stratigraphic sections of the Unaz Formation.

1999), was deposited between the Middle Turonian and the Early Santonian (Figure 2). In places, where its base is visible, this formation rests unconformably on the Lower Cretaceous and older units and starts with a thick basal conglomerate grading upward into an alternation of calc-alkaline and acidic to intermediate porphyritic lavas and pyroclastics, pelagic micritic red to whitish limestones and turbiditic clastics. The oldest Middle Turonian age comes from the first pelagic limestone horizons and the matrix of debris-flow horizons in the middle part of the formation; thus lower parts of the formation can be as old as Late Cenomanian or Early Turonian. Geochemical features of the Dereköy Formation magmatic rocks imply that they were produced by a depleted mantle bearing the signature of a subduction zone (Keskin & Tüysüz 1999, 2001).

The Dereköy Formation comprises abundant blocks (olistoliths) and debris-flow horizons (olistostromes) in some locations (Figure 3). The matrix of these debris horizons is composed of micritic limestones and siltstones with abundant planktonic foraminifera including *Marginotruncana coronata, Marginotrunca pseudolinneiana; Marginotruncana schneegansi, Muricohedbergella flandrini; Dicarinella* cf. *hangi-primitiva, Dicarinella* cf. *concavata, Dicarinella canaliculata, Dicarinella imbricata, Praeglobotruncana* cf. *stephani, Hedbergella* sp., indicating an age between Middle Turonian and Early

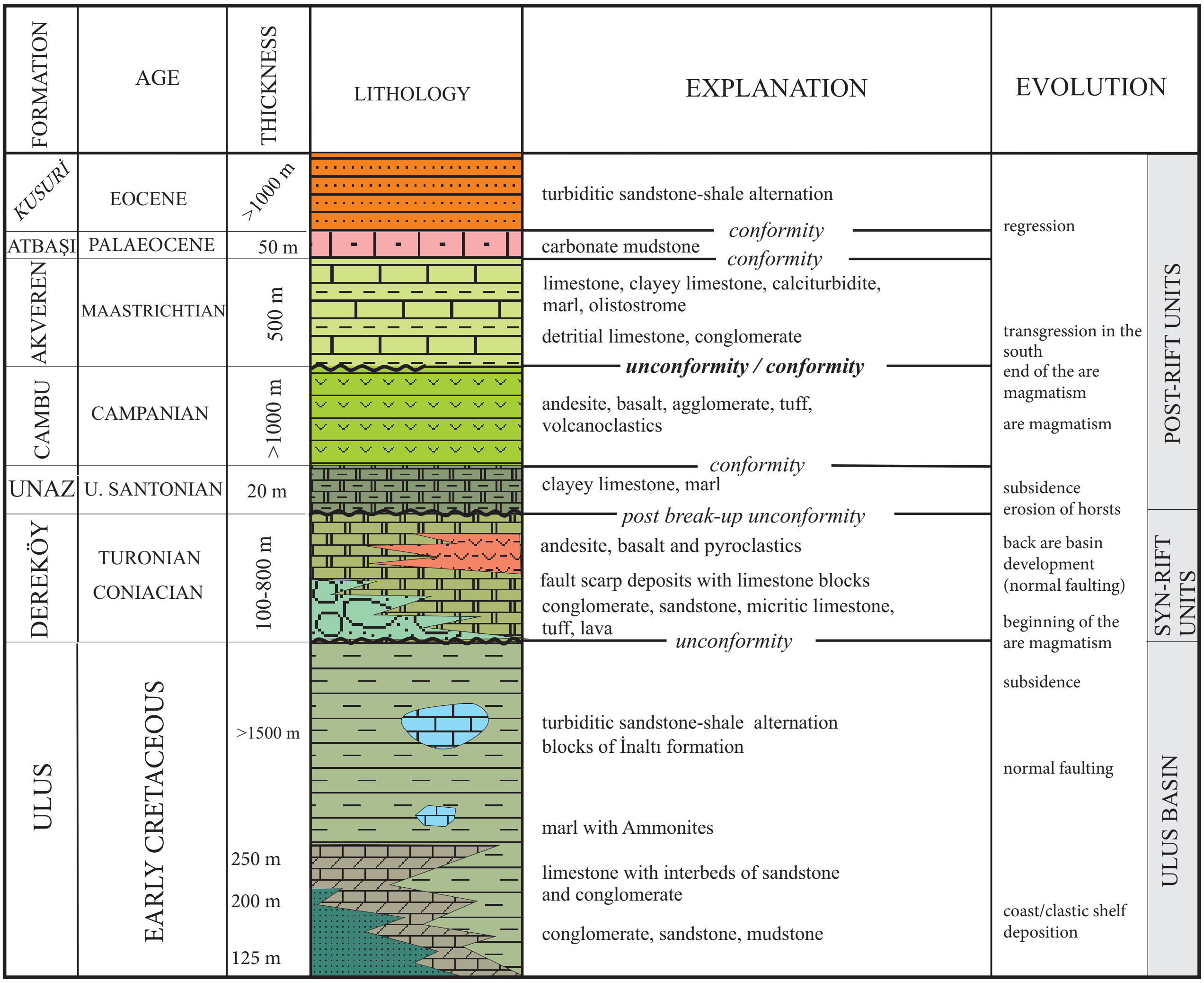

Figure 2. Generalized Cretaceous–Palaegene stratigraphic chart of the İstanbul Zone.

Figure 3. Debris-flow horizon within the Dereköy Formation. Angular and unsorted Lower Cretaceous neritic limestone pebbles and blocks are embedded within pink Middle Turonian–Lower Santonian pelagic limestones and siltstones.

Santonian. Blocks and pebbles embedded within this matrix are angular, poorly sorted and composed of Lower Cretaceous and Upper Jurassic shallow water platform limestones (Figure 3). In the light of the lithology and geometry of these debris-flows and blocks, together with sudden thickness and facies changes of the formation, Tüysüz (1999) concluded that these chaotic units were deposited in front of normal faults around the shelf margin facing towards a deep marine environment. The deepening and fining upward character of the Dereköy Formation in the debris-flow horizons support this interpretation.

The second magmatic series, the Cambu Formation (Figure 2), started after the deposition of the Unaz Formation. The Cambu Formation is represented by an alternation of basaltic and andesitic lava, pyroclastics, volcaniclastics and pelagic micritic limestones. This second episode of magmatism was more voluminous than the first stage and was active throughout the Campanian. The lavas belonging to this second episode are both tholeiitic/calcalkaline and within-plate high-K shoshonitic series following two different trends. The amphibole-bearing first series is similar to lavas of the Dereköy Formation and derived from a mantle source. The second series displays within-plate characteristics and implies thinning of the lithosphere and upwelling of the asthenosphere in the region, probably due to back-arc opening (Keskin & Tüysüz 1999, 2001).

The Late Santonian Unaz Formation (Figure 2), separating two stages of the volcanism (the Dereköy and the Cambu formations), is the subject of this paper. This formation is represented by a 5–20-m-thick micritic limestone and extends throughout the Western and Central Pontides as a marker horizon. Although both the Dereköy and Cambu formations contain several pelagic limestone horizons, it is easy to distinguish the limestones of the Unaz Formation from these horizons by using following criteria: (1) Volcanic rocks of the Dereköy and the Cambu formations can be distinguished in the field by their different mineralogical and textural properties (Keskin & Tüysüz 1999, 2001), the Unaz Formation occurs stratigraphically between these two different formations, (2) The Unaz Formation rests on an unconformity/disconformity surface in most places, (3) There is a 0–10-m-thick clastic sequence, the Kökyol Formation, below the Unaz Formation in some areas (4) None of the pelagic limestone horizons within the Dereköy and Unaz formations is laterally as continuous as those of the Unaz Formation, (4) Fossils from each of these formations indicate different ages.

During the deposition of the Unaz Formation, the volcanism ceased and no volcaniclastics and/or siliciclastics were produced, implying that the Unaz Formation marks the end of the first period of volcanism and submergence of the whole region. The geochemical nature of the magmatism changed after the deposition of the Unaz Formation (Keskin & Tüysüz 1999, 2001). These data imply that the Unaz Formation is a key unit in understanding the Late Cretaceous evolution of the Pontides.

In this paper we follow the stratigraphic nomenclature of the Western Pontides published by the Turkish Stratigraphy Commission (Tüysüz *et al.* 2004). Recently Hippolyte *et al.* (2010) suggested a revision of the Cretaceous to Palaeogene stratigraphy of the Western and Central Pontides based on nannofossil determinations. They did not take account of the formal stratigraphic nomenclature (Tüysüz *et al.* 2004) and instead of the Dereköy Formation of Turonian–Coniacian age they show non-deposition. However, as shown here, this period is represented by a thick volcanic succession corresponding to the Dereköy Formation (Akyol *et al.* 1974; Tüysüz 1999).

They terminated the second period of magmatism at the end of Santonian although it extends in the north to the Campanian (Akyol *et al.* 1974; Tüysüz 1999 and references therein).

In this study, we examined different stratigraphic sections in the Western Pontides and investigated the basal contacts of the Unaz Formation with the underlying units, which allowed us to obtain a palaeogeographic picture of the region just before and during the deposition of the Unaz Formation, and to interpret the Late Cretaceous geological events.

Stratigraphy of the Unaz Formation

The Unaz Formation is a rather uniform unit. It is represented by red to pinkish, thinly-bedded, sometimes laminated bioclastic micritic limestones. Stylolites parallel to the bedding are common. A few-mm-thick red shale interbeds can also be seen. Some slump structures within the Unaz Formation have also been observed. In thin sections, well-preserved microfossils are seen scattered within the micritic matrix. Hematite concentrations along the lamina surfaces and scattered hematite fragments are common. Minor amounts of quartz, feldspar and echinoid fragments were also observed. Some sections of the Unaz Formation will be described briefly in the following paragraphs from west to east (Figure 4).

In the east of Ereğli town, on the road from Ereğli to Zonguldak (36T 373500/4570310), the Unaz Formation is seen between two volcanic successions (Figure 5). Tokay (1952), who mapped this region in detail, separated the lower volcanic succession into two members: Lower Series (La Série inférieure de Crétacé supérior) and Agglomerates, both of which correspond to the Dereköy Formation. He named the overlying pelagic limestones and marls together as 'İkse-Köristan marnocalcaires'. The pelagic limestones at the base of the 'İkse-Köristan marnocalcaires' correspond to the Unaz Formation while the marls and overlying four volcanic-volcanogenic members correspond to the Cambu Formation.

The Dereköy Formation, consisting of tuffs, agglomerates, marls and thinly-bedded pelagic limestones, transgressively overlies both the Cenomanian marls and the Palaeozoic substratum. Tokay (1952) identified *Globotruncana* ex gr. *lapparenti* and *Globotruncana* ex gr. *helvetica* from the basal part, and Cephalopoda specimen *Peroniceras moureti* De Gros from the upper part of this succession and assigned an Early Turonian to Coniacian age for the deposition of the lower volcanic succession. He also indicated the occurrence of submarine slump structures, olistoliths and 15–20-cm-thick radiolarites within this unit, implying deepening upward and a tectonically active environment of deposition.

The red pelagic limestones of the Unaz Formation rest on the agglomerates, pillow lava and alternating volcaniclastics of the Dereköy Formation. There is a thin conglomeratic horizon at the base of the Unaz Formation, which can be compared to the Kökyol Formation in the Amasra section described below. This conglomeratic horizon probably indicates a disconformity separating the Unaz Formation from the underlying Dereköy Formation. The Unaz limestone is pink to red, micritic, thinly bedded, laminated and is about 8–10 metres thick. It grades upward into red pelagic marls, shales, andesites, basalts and tuffs of the Cambu Formation (Figure 5). Tokay (1952) reported *Globotruncana* ex gr. *lapparenti*, Stomiosphaeridae and Cadosinidae fossils from the Unaz limestones.

Tokay (1952) separated different members within the Cambu Formation and described fossils indicating a period between Late Santonian and Late Campanian for its deposition. These data bracket the age of the Unaz Formation in the Ereğli region between the Late Coniacian and Late Santonian.

Filyos Section (Figures 1 & 4)

The Upper Cretaceous units rest unconformably on Upper Albian blue marls and Lower Aptian limestones in this area (Altınlı 1951; 36T 420830/4592100). At the base of the Upper Cretaceous succession, there is a thick unit consisting mainly of conglomerates, sandstones, siltstones, clays, limestones, marls, tuffs, volcanic breccia and agglomerates. Within this unit, there are coal fragments derived from the Carboniferous basement. Lower parts of the sequence consist of Pelecypoda and Bryozoa coralline algae indicating a shallow and warm

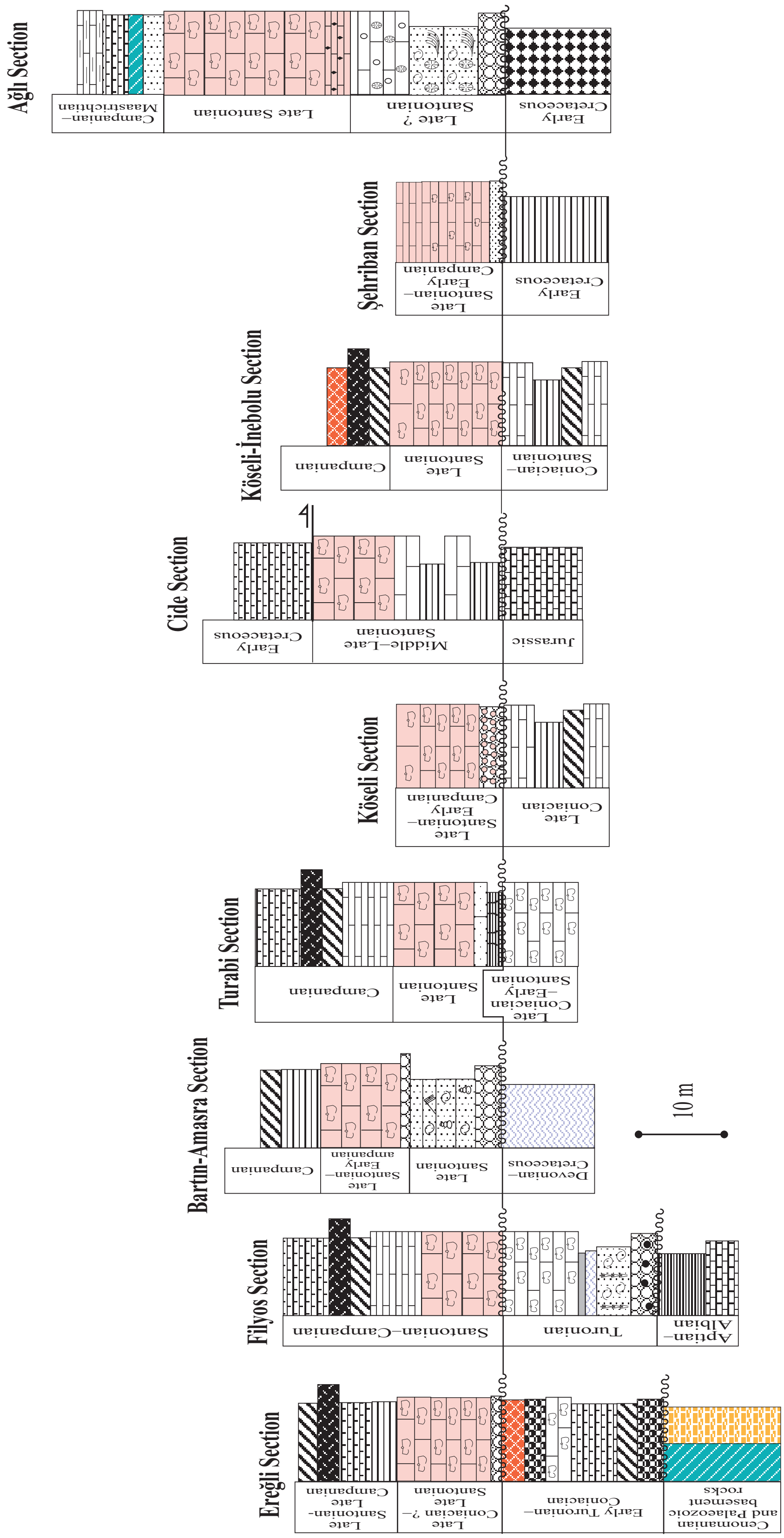

Figure 4. Measured stratigraphic sections of the Unaz Formation (Locations of the sections are shown on Figure 1).

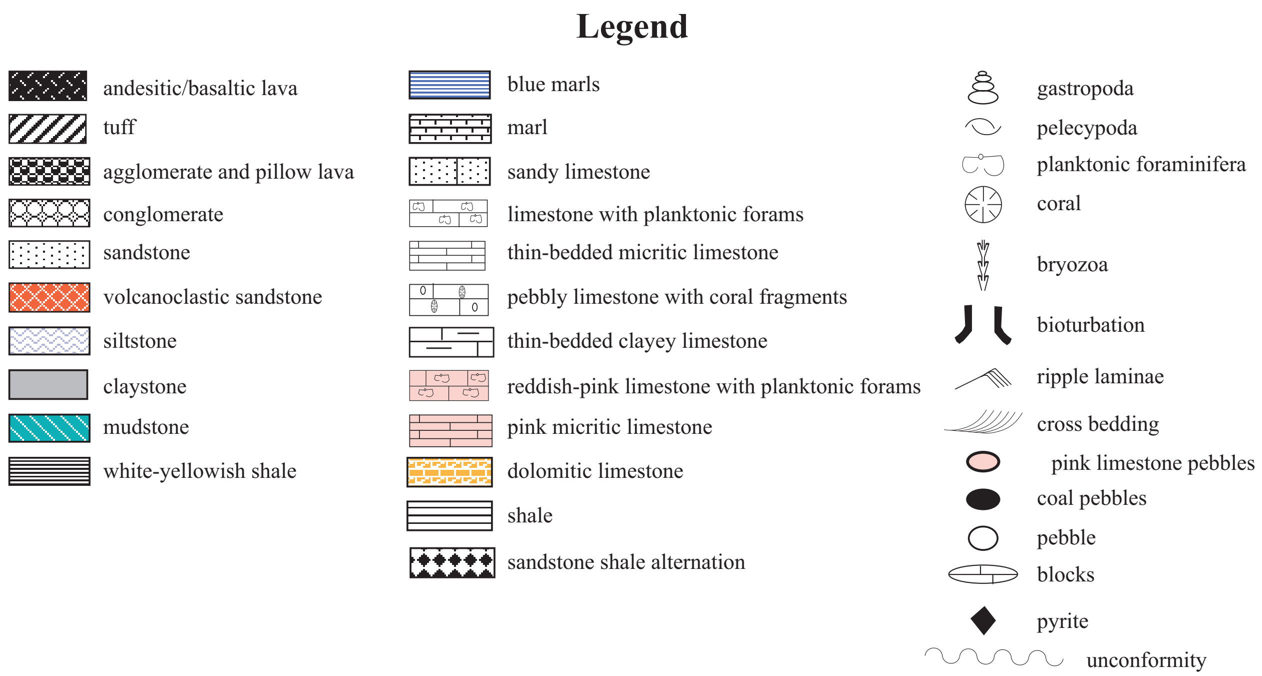

Figure 4. Continued.

Figure 5. The Unaz Formation and overlying Cambu Formation on the Ereğli-Zonguldak road.

depositional environment. Higher in the section micritic limestone interbeds start to be seen. Based on *Globotruncana* species Altınlı (1951) assigned a Turonian age to these limestones.

The Turonian sequence is disconformably overlain by red to pink, hard, thinly-bedded and conchoidally fractured micritic limestones of the Unaz Formation. The thickness of this unit varies between 10–20 m. These red limestones grade upward into an alternation of white, thinly-bedded pelagic limestones, tuffs, andesitic lava and marls belonging to the Cambu Formation. In most of the previous studies, these white limestones alternating with volcanics and volcaniclastics were regarded as the upper part of the Unaz Formation. Based on the occurrences of *Globotruncana* and *Gumbelina* species and *Radiolaria* Altınlı (1951) assigned a Santonian to Campanian age to these limestones.

Bartın-Amasra Section (Figures 1 & 4)

The Unaz and underlying Kökyol formations rest unconformably on different units such as Devonian carbonates and Carboniferous clastics to the north of Bartın (36T 443225/4612450), Lower Cretaceous carbonates and ammonite-bearing blue marls occur around Amasra (Figure 3; 36T 452465/ 4620880), and Triassic clastics southeast of Amasra (36T 453320/4618460). Although this outcrop of the Unaz Formation can be traced for about 60 km laterally, stratigraphically it is very uniform.

The Kökyol Formation below the Unaz Formation is a 0.2–15-m-thick clastic unit consisting of grey to yellowish sandstones and conglomerates. The sandstones are rich in quartz and lithic fragments, medium bedded, and well to medium sorted. Its matrix is composed mainly of yellowish silt and clay. The presence of symmetrical ripple marks indicates a shallow environment of deposition. Conglomerates are less dominant compared to sandstones within the formation. Most of the pebbles are rounded, semi-spherical, medium to poorly sorted and tightly cemented with calcite. They are 1–5 cm in diameter. Although the lithology of the pebbles varies laterally, Devonian limestones are dominant in the west, while Jurassic and Lower Cretaceous limestones dominate towards the east. In general, the conglomerates are seen as laterally discontinuous lenses, reflecting channel-type geometry. Within this clastic unit, there are abundant macrofossils such as Gastropods, Pelecypods and Brachiopods. Hippolyte *et al.* (2010) reported Santonain and Coniacian–Santonian nannofossils from this unit.

Higher in the section, this clastic sequence is overlain by red pelagic limestones. The contact between the clastics and the limestones is very sharp. In places, the fine clastic sequence is absent and there are 10–30 cm of thick grey to mottled basal conglomerate at the base of the pelagic limestones resting unconformably on the older units (Figure 6). The pebbles of this conglomerate are 1–2 cm in diameter, poorly sorted, elongate and rounded. Most of them are reworked intraformational red pelagic limestones. They are tightly cemented by calcite. Some sole marks at the base of the conglomerates and a fining-upward structure are interpreted as evidence of a turbiditic origin.

The pelagic limestones of the Unaz Formation are red, pink or whitish and thinly bedded. Bedding is smooth, parallel and well exposed in most places, but some undulating bedding was also observed. In the lowest 10–20 cm of the section, the thickness of the bedding is about 1–3 cm, but it reaches to 5–8 cm in the upper part. The total thickness of the limestone varies between 3 to 10 metres. Nannofossils and *Calculites obscurus* (Deflandre) Prinsand Sissingh from this outcrop indicate a Late Santonian–Early Campanian age for the pelagic limestones.

Figure 6. Pink pelagic limestones of the Unaz Formation resting unconformably on the Ammonite-bearing Lower Cretaceous bluish-grey marls, east of Amasra town. 20-cm-thick single bed at the base of the limestones is conglomerate (for detailed description see text).

Higher up the section, some tuff and red shale horizons start to be seen; they increase toward the top and the limestones grade into the volcanic-volcaniclastics of the Cambu Formation.

Turabi Section (Figures 1 & 4)

The Turabi section is seen on a road cut in Turabi village (36T 472600/4629380). Here, the Unaz Formation rests unconformably on the top part of the Dereköy Formation, which consists of thin-bedded white micritic limestones. The following nannofossil assemblage has been identified from the Dereköy Formation below the unconformity: *Watznaueria barnasiae* (Black) Perch-Nielsen, *Cribrosphaerella ehrenbergii* (Arkhangelsky) Deflandre, *Micula staurophora* (Gardet) Stradner, *Lithraphidites carniolensis* Deflandre, *Lucianorhabdus* ex gr. *cayeuxii Deflandre*, *L. maleformis* Reinhardt, *Calculites obscurus* (Deflandre) Prins and Sissingh, *Grantarhabdus coronadventis* (Reinhardt) Grün, *Gartnerago obliquum* (Stradner) Noël, *Tranolithus minimus* (Bukry) Perch-Nielsen, *T. orionatus* (Reinhardt) Reinhartd, *Eiffellithus eximius* (Stover) Perch-Nielsen, *E. turriseiffelii* (Deflandre) Reinhardt, *Retacapsa angustiforata* Black, *Microrhabdulus attenuatus* (Deflandre) Deflandre, *Chiastozygus litterarius* (Górka) Manivit, *Broinsonia enormis* (Shumenko) Manivit, *Helicolithus trabeculatus* (Górka) Verbeek, *Braarudosphaera bigelowii* (Gran and Braarud) Deflandre, *Biscutum ellipticum* (Górka) Grün, *Zeugrhabdotus biperforatus* (Gartner) Burnett, *Z. embergerii* (Noël) Perch-Nielsen, *Z. bicrescenticus* (Stover) Burnett, *Z. diplogrammus* (Deflandre) Burnett, *Cretarhabdus conicus* Bramlette and Martini, *Tegumentum stradneri* Thierstein, *Prediscosphaera cretacea* (Arkhangelsky) Gartner, *Manivitella pemmatoidea* (Deflandre) Thierstein.

According to the association of *Lucianorhabdus* ex gr. *cayeuxii* and *Grantarhabdus coronadventis* the top of the Dereköy Formation in this outcrop has been assigned to the Uppermost Coniacian–?Lower Santonian, zone interval from UC11c to the lower part of UC12 (Burnett 1998).

There is a slight angular unconformity between the Dereköy and the Unaz formations (Figure 7a). At the top of the Dereköy Formation, there is a 10–15-cm-thick, loose, greyish to pinkish, intensively bioturbated marl horizon just below the Unaz Formation (Figure 7b). Within this horizon, there are abundant borings filled with grey to pink hardened marls. In general, borings are parallel to the unconformity surface but some of them are vertical and penetrate into the unconformity surface. This horizon represents a hard ground surface and implies subaerial exposure of the Dereköy Formation just before the deposition of the Unaz Formation.

The localization of bored surfaces (hard grounds) at the top of the thin-bedded carbonates of the Dereköy Formation is interpreted as being the result of regression and following transgression and lithification prior to the onset of the deep marine sedimentation of the Unaz Formation. In addition, the presence of the genera *Lucianorhabdus* and *Braarudosphaera* just below the unconformity also indicates shallow-marine conditions (regression).

On top of the marl horizon there is a single bed of sandy micritic limestone belonging to the Unaz Formation, which is overlain by homogeneous pink, thin-bedded biomicritic limestone 8 metres thick (Figure 7b). Within these limestones foraminifera *Dicarinella asymetrica*, *Dicarinella concavata*, *Globotruncanita stuartiformis*, *Muricohedbergella flandrini*, *Globotruncanita* cf. *elevata* and radiolarians have been found indicating a Late Santonian age (Tüysüz *et al.* 1997). The limestone grades upward first into a micritic limestone, shale and tuff alternation and then lava and pyroclastics of the Cambu Formation.

Cide Section (Figures 1 & 4)

South of Cide, around Kayaarkası Hill (36T 497150/4633200), the Unaz Formation starts with a white-yellowish shale and micritic limestone alternation unconformably overlying the Jurassic limestones. This basal part grades upward into red, thinly-bedded porcellanous limestones. The upper part of the section is tectonically overlain by Lower Cretaceous marls SW of Kayaarkası Hill. Within the red micrites *Dicarinella asymetrica*, *Marginotruncana coronata*, *Marginotruncana pseudolinneiana*, *Heterohelix* sp., *Hedbergella* sp. have been determined and a Middle to Late Santonian age has been assigned for the deposition of the Unaz Formation (Tüysüz *et al.* 1997).

Köseli Section (Figures 1 & 4)

The Köseli section is located east of Cide, at the eastern edge of Köseli village on the Cide-İnebolu road (36T 502200/4640340). Due to intense Middle to Late Eocene imbrications in the region, bedding is vertical to steep in the area. At the base of the section, there is an alternation of red micrites, shales, tuffs and other pyroclastics of the Dereköy Formation. In the uppermost parts of the Dereköy Formation the following nannofossils have been determined: *Quadrum gartneri* Prins and Perch-Nielsen, *Q. intermedium* Varol, *Q.* cf. *svabenickae* Burnett, *Micula* cf. *swastica* Stradner and Steinmetz, *M. staurophora* (Gardet) Stradner, *Eiffellithus eximius*

Figure 7. **(a)** Angular unconformity separating the Dereköy Formation at the base (thinly-bedded, light coloured limestone and marl alternation) and the Unaz Formation at the top (pink pelagic limestones) in the Turabi Section. **(b)** Close-up view of the unconformity in (a). Bioturbated marls at the base belong to the Dereköy Formation. Pinkish to greyish boudin-like features within the marls are burrows. At the base of the Unaz Formation there is a single bed of sandy micritic limestone (behind of the pencil), which is overlain by pink biomicritic limestones.

(Stover) Perch-Nielsen, *E. turriseiffelii* (Deflandre) Reinhardt, *Helicolithus trabeculatus* (Górka) Verbeek, *Tegumentum stradneri* Thierstein, *Lucianorhabdus* ex gr. *maleformis* Reinhardt, *L. cayeuxii* Deflandre, *Retacapsa angustiforata* Black, *Gartnerago obliquum* (Stradner) Noël, and *Watznaueria barnasiae* (Black) Perch-Nielsen. Based on the joint occurrence of *M. staurophora, Lucianorhabdus.* ex gr. *cayeuxii* and *Quadrum gartneri* deposition of the uppermost part of the Dereköy Formation in this outcrop is assigned to the uppermost Coniacian (zone UC11c by Burnett 1998).

The Unaz Formation rests disconformably on the Dereköy Formation. At the base of the Unaz Formation is a 10–30-cm-thick conglomerate. Pebbles of this conglomerate consisted totally of red pelagic limestones tightly embedded within a red micritic carbonate matrix. Pebbles are 3–10 cm in diameter and rounded. The internal structure of the pebbles displays convolute laminae, probably developed by disturbance of soft carbonate mud by turbiditic currents/ground instability. Higher in the section, there are 5–7 metres of thick pink-red, thinly-bedded micritic limestone with laminae and stylolite structures. Red micritic limestones of the Unaz Formation comprise foraminifera *Dicarinella canaliculata, Dicarinella concavata, Dicarinella asymetrica, Hedbergella* sp., *Heterohelix* sp., and *Globotruncanita* div. spec indicating an age between the Latest Santonian and the Earliest Campanian.

Between Köseli and İnebolu (Figures 1 & 4)

The road between Köseli and İnebolu exposes in many places the Unaz Formation, which consists here of a laterally continuous, red to pink, thinly-bedded and homogeneous micritic limestone horizon. In this large area, the Unaz Formation conformably overlies the Dereköy Formation, except locally where a disconformity separates these two formations. The upper contact of the Unaz Formation with the Cambu Formation is always gradational.

In places, some slump structures and soft sediment deformation have been observed within the Unaz Formation. The fossil assemblage from this area is the same as in the Köseli section and indicates a Late Santonian age for the deposition of the Unaz Formation.

Şehriban Region (Figures 1 & 4)

The Unaz Formation crops out in a limited area north of Azdavay town (36T 522550/4613375), where it lies unconformably on Lower Cretaceous rocks around Memremi Village. The sequence starts with white to cream carbonaceous sandstones a few tens of centimetres thick, and grades upward into white, thin-bedded, homogeneous micritic clayey limestones. The upper part of the sequence is eroded. The visible thickness of the Unaz Formation is about 6–9 metres in this area. A foraminifera assemblage with *Marginotruncana coronata*, *Marginotruncana pseudolinneiana*, *Hedbergella* sp., *Globotruncanidae* and radiolarians has been identified within this sequence. This assemblage indicates an age span between Turonian and Maastrichtian. However, for the same outcrop, Kuru *et al.* (1994) reported a Late Santonian–Early Campanian age based on nannofossils and radiolarians.

Ağlı Basin (Figures 1 & 4)

The Ağlı Basin is a small sedimentary basin lying unconformably on Lower Cretaceous and older units of the Central Pontides (the Sakarya Zone). It is filled by a continuous Upper Cretaceous to Middle Eocene sedimentary sequence (Tüysüz *et al.* 2000). At its base (36T 542050/4617750) is a detrital limestone and carbonaceous sandstone 20–30 metres thick, named the Kayıkçı Formation. In places, at the base of the Kayıkçı Formation, there is a grain-supported coarse conglomerate horizon. Angular and disordered pebbles and blocks of this conglomerate are very poorly sorted. Grain size ranges between a few millimetres to one metre. The conglomerate has a lensoid geometry and grades upward and laterally into cross-bedded sandstones and carbonaceous pebbly limestones, which unconformably rest on the older rocks. The nature of the conglomerate implies very rapid deposition close to a tectonically controlled uplift and very rapid deepening, probably on a downthrown fault block. Large-scale cross bedding, thick bedding and abundant benthic fossil and coral fragments within the sandstones imply a shallow marine environment for the deposition. Similarly, the presence of abundant coral fragments and binding algae within the pebbly limestones imply a depositional environment close to a reef front. No characteristic fossil had been found within the Kayıkçı Formation. This unit can be correlated with the clastic Kökyol Formation just below the Unaz Formation in the Amasra region on account of its stratigraphic position and depositional conditions.

The Kayıkçı Formation is disconformably overlain by white, pink and red, thinly-bedded micritic limestones of the Unaz Formation. The contact between these two formations is very sharp and probably indicate a sudden subsidence of the region or, alternatively, sudden rise of the sea level. In places, the Kayıkçı Formation is missing and the Unaz Formation rests directly on older units, which supports this idea.

The Unaz Formation is about 30–40 metres thick in the Ağlı Basin. It sits on different lithologies of the Kayıkçı Formation, including conglomerates, sandstones and limestones. In most places, the lowest part of the sequence 5–25 cm thick consists of white clayey and micritic limestones rich in pyrite crystals, which are mostly oxidized. This lower part indicates deposition under partly anoxic conditions, grading upward into reddish to pink, homogenous thinly-bedded micritic limestones indicating oxic conditions. Foraminifera *Globotruncanita elevata, Globotruncanita stuartiformis, Dicarinella asymetrica, Marginotruncana coronata, Globotruncana linneiana, Heterohelix* sp., *Hedbergella* sp. and radiolarians have been found within these limestones and a Late Santonian age has been assigned for the deposition. The same age has also been determined in this location based on nannofossils (Hippolyte *et al.* 2010). In the Ağlı Basin, the Unaz Formation grades upward into the Ağlı Formation consisting of sandstone, mudstone, marl and clayey micritic limestones. According to fossil findings from its upper parts, the Ağlı Formation is Maastrichtian in age and its lower parts may be Campanian.

Interpretation

Pre-Unaz Formation Evolution of the Southern Black Sea Region

The Pontides consists of two tectonic units, the İstanbul Zone in the west and the Sakarya Zone in the east. These two zones are separated by Araç-Daday Shear Zone, which has been regarded as the eastern continuation of the Intra-Pontide suture (Şengör & Yılmaz 1981; Tüysüz 1999; Okay & Tüysüz 1999). In the eastern part of the İstanbul Zone, the Zonguldak and Ulus sedimentary basins started to open during the Late Barremian. Upper

Barremian–Cenomanian deposits in these basins represent the opening and deepening of the basins, probably contemporaneously with the opening of the Western Black Sea Basin. Based on data provided by Masse *et al.* (2009), Tüysüz (2009) concluded that an archipelago separated the Western Black Sea Basin from the Zonguldak-Ulus Basin and a short-lived carbonate platform developed in this archipelago during Late Barremian time. A regional Late (?) Cenomanian unconformity separates mainly anoxic basin sediments from the overlying volcanics and volcanic-rich sediments (Görür 1997). The tectonic meaning of this unconformity is not clear due to insufficient data. This event may be attributed either to a regional thermal doming just before the start of arc magmatism produced by northward subduction of the Intra-Pontide Ocean (Şengör & Yılmaz 1981; Aykol & Tokel 1991; Tüysüz 1999; Karacık & Tüysüz 2010), or to the juxtaposition of the İstanbul and Sakarya zones. This subject is beyond the scope of this paper.

Although the fossil data indicate that the beginning of the magmatism on the İstanbul Zone is Middle Turonian, it may be as early as Late Cenomanian or Early Turonian as fossil findings come from the pelagic limestones in the middle part of the succession (Tüysüz *et al.* 1997).

The early Cretaceous stratigraphy of the Sakarya Zone in the Central Pontides is different from that of the İstanbul Zone (Tüysüz 1999). In that area, Upper Barremian to Cenomanian sediments filling the Sinop Basin record the opening of the north-facing asymmetric Sinop Basin. The basin started to open under the control of horst-graben topography and rapidly deepened, especially in its northern part, towards the Eastern Black Sea Basin (Tüysüz 2009). In contrast to the İstanbul Zone, the Cenomanian–Turonian transition is represented by radiolaria-bearing deep marine red carbonates and red shales resting conformably or, in most outcrops, disconformably on Albian–Cenomanian dark shales (Tüysüz 1999; Luo 2005; Yılmaz *et al.* 2010). In contrast to pre-magmatic period, units deposited during the late- and post-magmatic period on both the İstanbul and the Sakarya zones are very similar and can be correlated with each other. Based on these stratigraphic data, Tüysüz (1999) concluded that the Intra-Pontide Ocean separating the İstanbul and Sakarya zones closed during the Albian–Cenomanian period, definitely before the deposition of the Unaz Formation, or probably before the deposition of the Dereköy Formation.

The Turonian–Santonian period is represented by extensive magmatism throughout the Pontides. In both the İstanbul and the Sakarya zones, and even in the Thrace Zone in the west, this magmatic activity is mainly represented by submarine extrusives. The geochemical properties of the first magmatic stage indicate a subduction-related magmatic origin. Blocks and debris-flow horizons within the Dereköy Formation imply the development of normal faulting associated with the arc magmatism. This extensional tectonic regime was probably created by a roll-back mechanism of the subducting oceanic plate in the south of the Pontides.

The stratigraphic relationships between the Unaz and the underlying Dereköy formations imply that just before the deposition of the Unaz Formation some areas in the southern coast of the Black Sea were elevated as horsts and eroded (for example Cide area) or remained covered by a very shallow sea (Amasra), while others remained or deepened as grabens (Turabi, Köseli and the area between Cide and İnebolu), where the volcanism is associated with deep marine sedimentation (Figure 8).

Stratigraphic Relationships of the Unaz Formation with the Underlying Units and Depositional Conditions

The Unaz Formation itself is a quite homogeneous unit extending for about 250 km between Ereğli and İnebolu. Although there is no detailed map of this unit in the Central and Eastern Pontides, our field observations indicate that it is possible to trace it eastward for hundreds more kilometres.

In the west, north of İstanbul, Upper Cretaceous rocks are represented only by the Cambu Formation and the Dereköy Formation is absent. Gedik *et al.* (2005) indicated that, in the European part of İstanbul, Palaeozoic rocks are thrust over the Upper Cretaceous volcanics, but in the Asian part of the city, on the Bithynian Peninsula, the Cambu Formation rests unconformably on Triassic rocks. Gedik *et al.* (2005) found a rich nannofossil and foraminifera

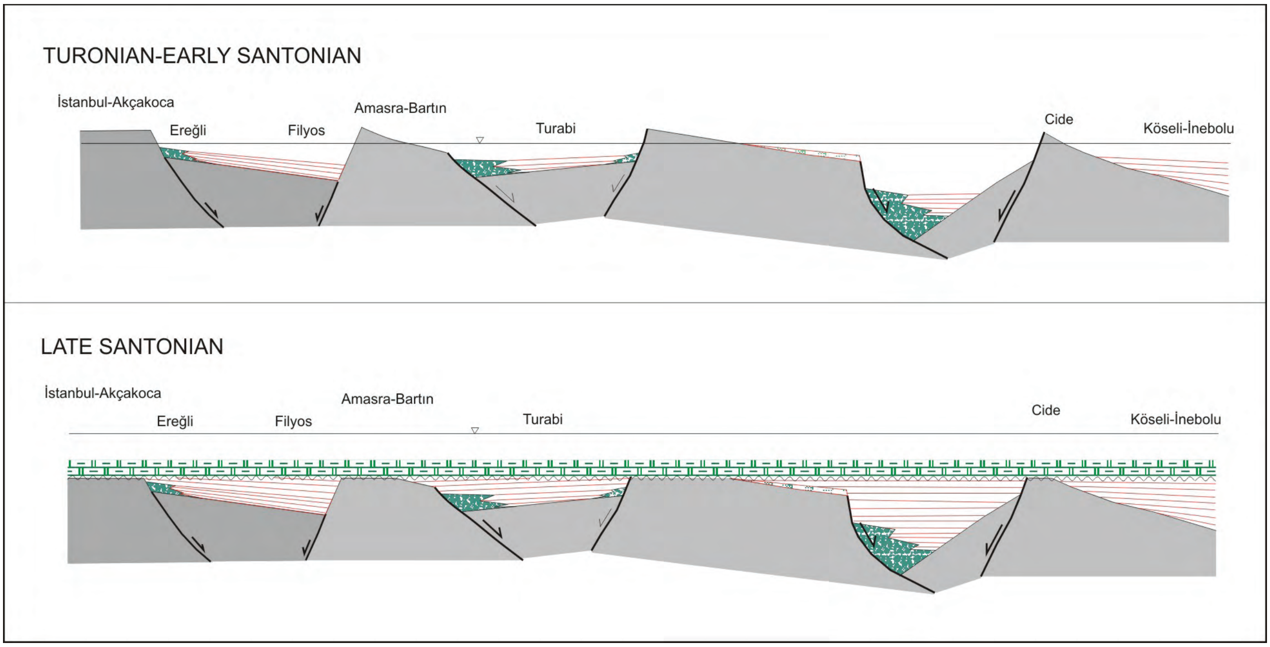

Figure 8. Schematic cross-sections showing the Turonian to Late Santonian tectonic evolution of the İstanbul Zone (not to scale). Grey shaded areas represent the Lower Cretaceous and older units. Red lines and green dotted areas represent the Dereköy Formation and debris-flow deposits within this formation, respectively. Green limestone symbol on the lower figure represents the Unaz Formation.

fauna from this formation and based on this data gave a Late Santonian–Early Campanian age. They did not map the Unaz Formation as a separate unit in this area but indicated the occurrence of the red pelagic micrites within the volcanic succession. As they did not find any fossil data older than Late Santonian, we interpret that the Unaz and Cambu formations rest directly on the pre-Upper Cretaceous basement in this area without the Dereköy Formation, as in the Bartın and Amasra regions. In the upper parts of the volcanic succession (the Cambu Formation) Gedik *et al.* (2005) found calcareous nannoflora and assigned it a Late Campanian age.

Between İstanbul and Ereğli, the base of the Upper Cretaceous volcanic succession cannot be seen. In that area, there are some volcanic interbeds within the carbonate-dominant Campanian units.

The lower volcanic succession transgressively overlies the Cenomanian marls and older units and is disconformably overlain by the Unaz Formation between Ereğli and Filyos (Figure 1). East of this area, from west of Bartın to east of Amasra, the Dereköy Formation is absent. From east of Amasra to Cide (Figure 1), as seen in the Turabi section, the lower volcanic succession was deposited in a deep, but shallowing-upward marine environment. Around Cide, the Unaz Formation directly overlies Jurassic limestones: the Dereköy Formation is absent. East of Cide, a disconformity separates the Dereköy and the Unaz formations, which were deposited in deep marine environments.

As can be seen from these relationships, in places there is a thick sequence of Upper Cenomanian (?)–Turonian to Santonian sedimentary and volcanic rocks at the base of the Unaz Formation. The Unaz Formation unconformably or conformably overlies the Lower Cretaceous to Palaeozoic units. In the latter case, there is a shallow-marine clastic sequence a few metres thick at the base of the formation. In the light of these stratigraphic data and the evidence of syn-sedimentary faulting within the Dereköy Formation, we deduce that the southern Black Sea margin was dissected by normal faults and the area formed horsts and grabens during the Middle Turonian–Coniacian.

The areas where the Dereköy Formation is absent are interpreted as horsts. In these areas, shallow marine clastics were deposited while deep marine deposition was continuing within the grabens. By using these stratigraphic properties it is possible to conclude that the İstanbul-Ereğli, Bartın-Amasra and Cide areas were emergent horsts, while the Ereğli-Bartın, Kurucaşile-Cide and Cide-İnebolu regions were covered by deep water during Turonian-Coniacian times (Figure 8).

Pelagic micrites of the Unaz Formation overlie different units as a common cover. Except for a shallow-marine clastic or siliciclastic turbidite horizon in its base, there are neither volcanic nor clastic fragments within the Unaz Formation. The lower contact of the micritic limestones, including the contact with its clastic basal part, is quite sharp. These imply:

(1) *Termination of the First Period of the Magmatism* – During the deposition of the Unaz Formation magmatism stopped but it restarted after the deposition of the limestones. The geochemical natures of magmatism in these two periods, separated by the Unaz Formation, are different. The pre-Unaz period is represented by typical arc magmatism, while the post-Unaz period bears the clues of within-plate signature which can be attributed to an uplifted asthenosphere due to rifting and oceanic spreading in the Western Black Sea Basin (Keskin & Tüysüz 1999, 2001). This change can be attributed to a southward jump of the magmatic arc axis as a result of slab roll-back, and relaxation and subsidence in the north, corresponding to the present location of the Western Black Sea Basin.

(2) *Sudden Change in the Physical Conditions of Deposition* – The Unaz limestone implies a rather quiet and deep depositional environment developed after an intense extensional tectonic period. The presence of slump structures indicates that the effect of this tectonic activity was still continuing in some places. The absence of any siliciclastic fragments during the deposition of these limestones implies that all emergent areas that provided siliciclastics to the Dereköy and Kökyol formations during Turonian–Santonian time were submerged during the Late Santonian due to either sudden submergence of the whole region or sudden sea-level rise. The red colour of the Unaz limestones indicates oxygenated conditions during deposition (Görür *et al.* 1993; Hu *et al.* 2005; Yılmaz 2008).

Tectonic and Depositional Interpretations of the Unaz Formation

Data presented above clearly indicate that the Unaz Formation represents a sudden change in the depositional system along the southern coast of the Black Sea Basin. Görür *et al.* (1993), Görür (1997) and Tüysüz (1999) attributed this change to the tectonic evolution of the Western Black Sea Basin. According to these authors, the unconformity at the base of the Unaz Formation represents the break-up of continental crust in the Black Sea Basin and indicates the onset of oceanic spreading. Görür *et al.* (1993) considered different red pelagic micrite horizons within the lower and upper volcanic successions as a unique sequence, the Kapanboğazı Formation, and they produced a model based on these data. Our recent observations (Tüysüz *et al.* 2004) indicated that the name Kapanboğazı Formation is applied, incorrectly, to different pelagic micrite horizons without regard to stratigraphic position and age. In fact, the Kapanboğazı Formation occurs only in the Sinop Basin (Sakarya Zone) and its age is Turonian (based on radiolarians, Luo 2005) or Late Cenomanian–Early/Middle Turonian (based on nannofossils Tüysüz and Melinte, unpublished data and based on radiolaria and planktonik forminifera, Yılmaz *et al.* 2010). In this study, we agree with the tectonic model of Görür *et al.* (1993), except for the timing. Görür *et al.* (1993) implied that the unconformity at the base of the oxic sediments and volcanics separate the faulted syn-rift sequence from the unfaulted post-rift sequence. Our data shows that the rifting was effective until the deposition of the Unaz Formation during the Late Santonian. Extensional tectonics and the consequent faulting period before the deposition of the Unaz Formation can be attributed to the rifting period; and sudden deepening of the region during the deposition of the Unaz Formation can be attributed to break up of the already thinned continental crust. This tectonic model is also supported by the geochemical nature of the volcanism, indicating uplift of asthenosphere (Keskin & Tüysüz 1999, 2001).

Discussion

The Unaz Formation clearly indicates sudden deepening of the region and/or sudden sea-level rise during the Late Santonian. Although the tectonic model presented above fits the stratigraphic and palaeogeographic data well, regional distribution of Upper Santonian micritic carbonates indicate that this event is not only limited to the Black Sea region. Deposition of Upper Santonian red pelagic limestones and/or shales is very common in different parts of the Tethyan realm (Hu *et al.* 2005). This indicates that purely local tectonic events cannot explain the sudden regional change of physical conditions during the Late Santonian.

Upper Santonian red pelagic sediments are also recorded in the Mudurnu-Göynük and Haymana basins in the western and central parts of the Sakarya Zone. In the Mudurnu-Göynük Basin, which is a rift basin along the Sakarya continental margin (Koçyiğit *et al.* 1991), Upper Santonian red pelagic micrites (Değirmenözü Member of the Yenipazar Formation, Timur & Aksay 2002) unconformably overlie the Albian to Coniacian basinal facies and older elevated areas (Yılmaz 2008). In the Haymana Basin, which is an 'accretionary fore-arc basin' (Koçyiğit 1991) near Ankara, NW Turkey, the same Upper Santonian red pelagic limestones and marls (Kocatepe Formation, Yüksel 1970; Ünalan *et al.* 1976) rest unconformably on the Tethyan accretionary complex (Ankara Mélange). This formation approximately marks the base of the Haymana Basin and turbiditic sequences lie above. This indicates deep slope environments after the deposition of the red pelagic limestones.

In the Kargı Massif, in the southern part of the Central Pontides (Sakarya Zone) Late Santonian pelagic limestones lie unconformably on Early Cretaceous sediments (Okay *et al.* 2006). Although red pelagic limestones were also reported from the southern part of the Kargı Massif (Yiğitbaş *et al.* 1990; Okay *et al.* 2006; Tüysüz & Tekin 2007), those were deposited on an active continental margin facing the Tethyan Ocean to the south. Tüysüz & Tekin (2007) clearly demonstrated that this margin was active between the Late Valanginian and Campanian.

Some authors attributed the Late Santonian event to a sea-level change, as the Late Cretaceous is the time of globally high sea level, high sea-surface temperatures and a peak in the production of organic matter. Larson (1991a, b) postulated that massive upwelling of magma from the core/mantle boundary to the surface of the Earth brought these extraordinary circumstances. The elevated young oceanic crust resulted in a sea level rise (Hays & Pitman 1973). Furthermore, the augmented release of CO_2 raised atmospheric CO_2-levels to about four times higher than at present, causing warming of the Earth's atmosphere and subsequent additional sea level rise (Huber *et al.* 2002).

Data from different parts of Tethys indicate that the Late Santonian event is regional rather than local. For example, Late Santonian sea level changes have been described by Flexer *et al.* (1986) from Israel, Bosworth *et al.* (1999) from Syria, Bilotte *et al.* (2005) from the Pyrénéés, Liu (2007) from the Gulf of Mexico, Ghabeishavi *et al.* (2008) from the Zagros area, and Voigt *et al.* (2008) from Central Europe. Dercourt *et al.* (1986) mentioned that differential changes in the rotation of poles between Africa and Eurasia during Santonian effected the reorganization of spreading ridges and the closure rate of Neotethys.

Hu *et al.* (2005) demonstrated the widespread occurrence of Upper Cretaceous Red Beds (CORBs) within the large geographic belt extending from the Caribbean across the central North Atlantic, southern and Eastern Europe to Asia. They indicated that oceanic red bed occurrences are generally associated with Alpine tectonic deformations creating changes in oceanic circulation and/or palaeoclimate. Ogg *et al.* (2008) indicated a major global sequence boundary in the Late Santonian within the *Dicarinella asymetrica* biozone and this sequence boundary is followed by a major maximum flooding surface within the same biozone. Forster *et al.* (2007) mentioned the pronounced cooling in the Santonian and related this event to the first progressive opening of a deep-water passage through the equatorial Atlantic gateway. Friedrich & Erbacher (2006) reported sudden changes in benthic foraminifera population within the Late Santonian to Early Campanian interval in the Demerara Rise in association with anoxic shale deposition in the South Atlantic and interpreted this event as recording progressive opening of the Equatorial Atlantic Gateway.

In the light of all these data and interpretations, it can be stated that the acceleration in the opening of the equatorial Atlantic Gateway gave rise to the formation of background tectonic forces recorded even in far distant areas and changed the oceanic circulation in the Atlantic and triggered an increase in the heat transfer between the ocean-atmosphere interactions. Therefore, a drop in temperature of the surface ocean water appeared in parallel with the increase in the nutrient influx due to ventilation and caused some red colouring in slope and elevated offshore equatorial areas. Overprinting of change in heat budget/climate, sea level and accelerated opening of the South Atlantic caused the formation of a widespread Upper Santonian red pelagic succession. In our case, deposition of the red pelagic sediments of the Unaz Formation was controlled mainly by local tectonics related to the start of oceanic spreading in the Western Black Sea Basin and this event was probably overprinted by the regional Late Santonian sea level rise.

Conclusions

The Pontide magmatic arc was established in response to the northward subduction of the northern branches of the Tethys Ocean and its first eruptions occurred in the İstanbul Zone during the Middle Turonian. This arc persisted until the collision of the İstanbul, Sakarya and Kırşehir zones during the Maastrichtian. Arc magmatics and associated sediments in the İstanbul Zone are represented by two different sequences separated by the Upper Santonian Unaz Formation. During the deposition of the lower volcanic sequence, an extensional tectonic regime prevailed in the region and created a horst-graben topography. The lower volcanic succession was mainly deposited within the grabens during Late Cenomanian (?)–Turonian–Santonian time.

During the Late Santonian the whole region subsided suddenly and the pelagic limestones of the Unaz Formation were deposited on both horsts and grabens. Deposition of the Unaz Formation was a combined effect of extensional tectonics resulting in the break-up of continental crust, the onset of oceanic spreading in the Western Black Sea Basin and the global sea level change triggered by opening of the Equatorial Atlantic Gateway.

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