Zootaxa 4890 (4): 535–553
https://www.mapress.com/j/zt/

Article

ISSN 1175-5326 (print edition)
ZOOTAXA
ISSN 1175-5334 (online edition)

https://doi.org/10.11646/zootaxa.4890.4.6
http://zoobank.org/urn:lsid:zoobank.org:pub:36C04F2C-4C96-4C72-A746-01EB7ADDD167

Bioacoustics of poorly known *Poecilimon* taxa (Insecta: Orthoptera: Tettigoniidae) with redescriptions of *P. pechevi* and *P. stschelkanovzevi*

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Abstract

The genus *Poecilimon* has been object of several studies dealing with its systematics, sound communication and evolution. Yet, published data contradict in the classification, while many taxa are still insufficiently known. In the present study we supplement the knowledge of 13 poorly known species and one additional subspecies with data on their sound communication and/or morphology. Most species concerned here are classified within two acoustic groups. First group includes *P. celebi*, *P. obtusicercus* and *P. toros*, showing typical characteristics of the *P. syriacus* group. Second group is more heterogeneous. Among that, *P. pechevi*, *P. armeniacus*, *P. harveyi*, *P. guichardi*, *P. haydari*, *P. doga*, *P. davisi* and *P. excisus* present a song pattern similar to that of *P. ampliatus*. In addition, *P. ataturki* is also quite similar in basic song structure to the latter but differs in its fine song structure. *Poecilimon stschelkanovzevi*, with unclear relationships, is described morphologically in detail. The present study provides hints for solving some disagreement between recent revisions, proposing unification of the *Poecilimon celebi* with *P. syriacus* group and opening discussion based on close relationships of the groups *ampliatus*, *armeniacus*, *davisi*, *luschani* and the species *P. guichardi* on one hand, while the complex *P. ataturki/glandifer* shows significant differences on the other. The acoustic peculiarities of the *ampliatus* group allies are discussed in an evolutionary light.

Key words: Sound communication, sound production, morphology, bush-cricket, Barbitistini

Introduction

The genus *Poecilimon* Fischer is a member of the highly specialized phytophagous flightless bush-cricket tribe Barbitistini. This Palaearctic bush-cricket genus is richest in the number of taxa with almost 182 valid taxa (142 species, 40 subspecies; Cigliano *et al.* 2020). Most of these are concentrated in the Aegean, Anatolian and Ponto-Caspian region, the range of the genus extending north- and eastwards to Central Europe, Central Siberia and north-westernmost China, respectively. Many species represent local or regional endemics inhabiting isolated mountain summits or islands and thus being of high conservation value.

Several studies deal with the systematics and phylogeny of this group on a larger or smaller scale using morphological (Ramme 1933, 1951; Bey-Bienko 1954; Ünal 2010), a combination of morphological and behavioral (Heller 1984, 1988; Heller & Sevgili 2005; Heller *et al.* 2006, 2008, 2011; Chobanov & Heller 2010; Kaya *et al.* 2012, 2018; Sevgili *et al.* 2018), or molecular traits (Ullrich *et al.* 2010; Boztepe *et al.* 2013; Kaya 2018). Yet, some of those contradict in their conclusions and the proposed systematic arrangements.

The genus *Poecilimon* is quite diverse in its acoustic communication. In many species the females respond acoustically to the male song, but in others they have lost this capability, obviously several times independently (see Chobanov & Heller 2010). Within both sections many different song patterns exist, which prove the necessity of acoustic studies in combination to morphology to delimit taxa and solve certain systematic issues (compare Kaya *et al.* 2018; Sevgili *et al.* 2018). Due to the vast diversity within the genus and the multitude of rare and endemic taxa,

Accepted by D. Rentz: 17 Nov. 2020; published: 4 Dec. 2020

most of the proposed systems focus on certain groups of taxa or on certain geographic area (e.g., Heller 1984; Ünal 2010) and plenty of taxa are still insufficiently known, especially bioacoustically. With the present study we aim to contribute to the knowledge of *Poecilimon* through description of the previously unknown male calling songs of 12 and the redescription of two insufficiently known taxa.

Material and methods

Species were identified according to their descriptions. The classification follows Cigliano *et al.* (2020) and the group names are following Ünal (2010).

The studied specimens are deposited at the National Museum of Natural History, Sofia, Bulgaria (NMNHS), the Hungarian Natural History Museum, Budapest, the Regional History Museum in Blagoevgrad, Bulgaria (HMB), and in the collections of Chobanov (CC at the Institute of Biodiversity and Ecosystem Research, Sofia), Heller (CH) and Sevgili (HUZOM, Hacettepe University Zoological Museum).

The stridulatory files were analysed and photos taken partly using a dissecting microscope (OLYMPUS SZ Binocular Stereo Zoom Microscope) equipped with a digital camera (SONY Cyber-shot DSC-P120), Amplival microscope (Carl Zeiss Jena) equipped with a Canon EOS1300D camera, and Scanning Electron microscope imaging (SEM; performed in the Hungarian Natural History Museum, Budapest). The distance between two teeth in the stridulatory file (see Tab. 2) is given as mean of the ten largest consecutive inter-tooth intervals.

The male calling songs were recorded in the laboratory with a variety of analogous and digital recording equipment (UHER 4200 IC tape recorder; SONY WM-D3 cassette tape recorder; TransIt USB-external sound card connected to a PC; Sony DAT Recorder TCD-D7; Tascam DR-680MKII; Tascam HD2, Fostex FR 2; Pettersson D1000X) and microphones (UHER M 645; Sony PC-62; Knowles BT-1759-000 electret condenser microphone with a custom-made preamplifier; condenser microphone CMPA-P48/CM16, Pettersson D500 microphone; Grass 40 BF Bruel&Kjaer) with sampling rates of 100 or 192 kHz. After digitising the songs on a computer, oscillograms (after high pass filtering, typically around 1 kHz) and sound analyses were made using the programs Turbolab (TL 4.0, Stemmer, Puchheim, Germany), Amadeus (Amadeus II, Martin Hairer, http://www.hairersoft.com) and Audacity (Audacity 2.1.0; http://audacity.sourceforge.net) on Macintosh and PC.

For the frequency measurements, recordings made with ultrasound sensitive-equipment (Pettersson D1000X by Pettersson Elektronik AB, Uppsala, Sweden; frequency response flat 5–235 kHz; Tascam DR-680MKII with Pettersson D500 and Tascam HD2 with CMPA-P48/CM16, sampling rate 192 kHz) were evaluated using Fast Fourier Transformation (FFT) analysis with Hanning window, 512 points per frame, from one frame or the mean of several overlapping frames.

The singers were caged in plastic tubes or gauze cages with microphone fixed or hand held at distances between 5 and 60 cm.

Song terminology—Calling song: song produced by an isolated male. Syllable: the sound produced by one complete up (opening) and down (closing) stroke of the wing. Echeme: a first-order assemblage of syllables. Syllable period: time period measured from the first impulse to the first impulse of the next syllable (reciprocal value: syllable repetition rate SRR). Impulse: a simple, undivided, transient train of sound waves (here: the highly damped sound impulse arising as the impact of one tooth of a stridulatory file).

Results

The specimens studied were collected in Bulgaria, North Makedonia, Turkey and Turkmenistan (Fig. 1). General view of some of the studied taxa and some morphological features is shown on Figures 2–5. Except of *Poecilimon stschelkanovzevi* (Fig. 4), all species belong to the section of *Poecilimon* with wingless and mute females and have stridulatory files with relatively few teeth (40–95; Fig. 5). The calling songs of all species (no data for *Poecilimon stschelkanovzevi*) consisted of highly damped sound impulses ('non-resonant song'; Fig. 6–8) and had the peak of their carrier frequencies between 20 and 40 kHz (Fig. 9). According to amplitude pattern of their songs, the studied species belong to two groups, one of them with three subgroups. The songs of the first group (A1–3) (Fig. 6) are characterized by SRRs between 10 and 20 Hz, while those of the second (B) are much faster (40–50 Hz; Table 1; Fig. 8). The syllables of the second group contain only 1–2, that of the first from 5 to more than 20 impulses.

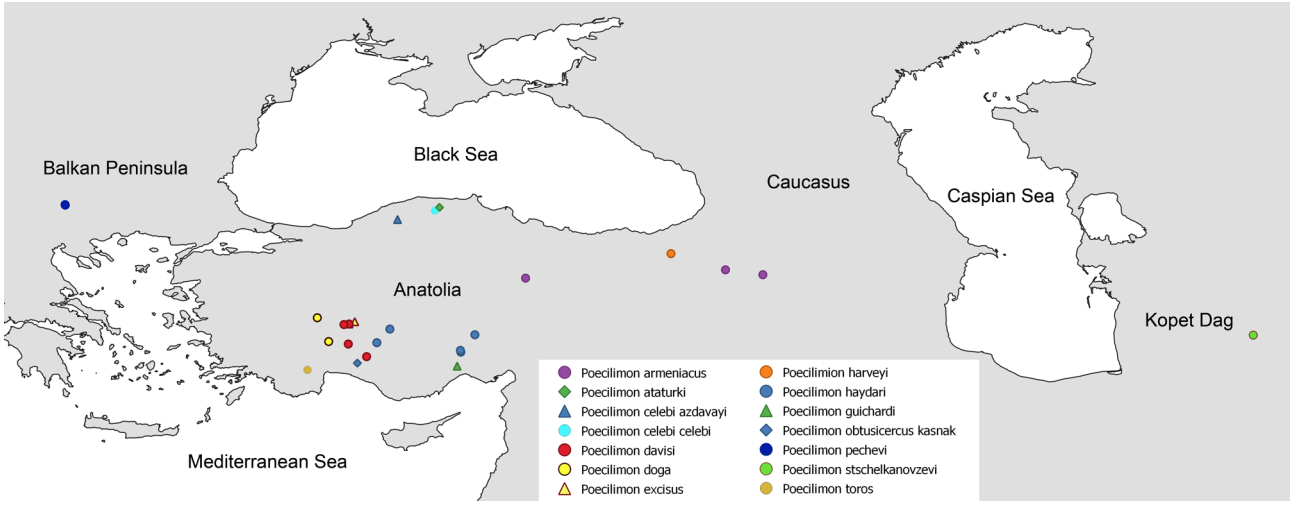

FIGURE 1. Map of the studied samples of taxa of *Poecilimon* concerned in this study (for locality details see redescriptions). Different symbols correspond to the name given in the figure legend.

TABLE 1. Review of the song characteristics (mean data)

Song type	Species	Syllable repetition rate	Duration of echemes/series	Impulses per syllable	Temperature
		Hz	s	n	°C
A1	*P. ataturki*	15	45	20 in 2 groups	27–28
A2	*P. pechevi*	11	13	13	25–27
A2	*P. armeniacus*	13	6	8	23–28
A2	*P. harveyi*	13	8	5	27
A2	*P. guichardi*	10	10	6	29
A2	*P. haydari*	12	20	6	25-29
A2	*P. doga*	13	8	22	(19.5–)27
A3	*P. davisi*	20	< 1s	5	25–26
A3	*P. excisus*	12	< 1s	14	25–30
B	*P. celebi azdavayi*	46	< 1s	2	23
B	*P. celebi celebi*	50	< 1s	2	23
B	*P. obtusicercus kasnak*	51	< 1s	1,5	24
B	*P. toros*	41	< 1s	2	23–24

A1) Song consisting of long (duration typically many seconds) series of bi-partite syllables

Poecilimon ataturki Ünal, 1999 (*ampliatus*-group)

TURKEY: Devrekani–Bozkurt road, 9.07.2011, 1200 m (41.70733ºN, 33.97399ºN), leg. B. Çıplak, S. Kaya & D. Chobanov, 1 male recorded.

P. aff. *ataturki*: Tokat, 10.07.2011, 700 m (40.2661ºN, 36.5494ºN), leg. Chobanov

The calling song of the recorded male consisted of long series (at least 26 to 62 s) of up to 875 syllables. In one case two series were separated by a very short interval (< 1 s). The syllables (duration 55 ms) were produced at a rate

of 14.6 Hz (Fig. 6) and contained about 20 impulses (T=26.7–28.2ºC). Except of a very few cases they had always a gap in the middle (Fig. 7) and the mean interval between the impulses was about 2.9 ms (gap included).

The stridulatory file carries 95 teeth (inter-tooth distance 31–38 µm) and is bi-partite by a distinct step in the middle of the file (Fig. 5A; Devrekani–Bozkurt). In this male the basal (proximal) part has 48 teeth and the anal (distal) 47, in a male from Tokat (*P.* aff. *ataturki*) the numbers are 34 and 36, respectively.

A2) Song consisting of long (duration often many seconds) series of syllables

This song type was described for European species of *Poecilimon ampliatus* group (Heller & Lehmann 2004).

Poecilimon pechevi Andreeva, 1978

Song recordings: BULGARIA / NORTH MACEDONIA border area: Vlakhina Mt., Kadiytsa summit, above the tree line (*F. sylvatica*), 04.–05.08.2006, 1700–1800 m alt. (41.77653ºN, 22.97026ºE), mesophytic herb and grass associations (*Chamaecytisus* sp., *Hypericum* sp., *Vaccinium* sp., *Thymus* sp., *Rubus idaeus*, etc.), leg. Chobanov, 3 males recorded.

NORTH MACEDONIA: Vlakhina Mts., Kadiytsa summit, 1890 m (N41.78815, E22.96332)–1930 m (41.78914ºN, 22.96490ºE), open meadows, 27.07.2019, leg. Chobanov, 1 male recorded.

Depending on the temperature the males are usually active at night and produced series of syllables with a duration of 4.3±1.3 s (n=32; range 1.2–8.1 s) at intervals of 11.8±7.6 s (n=15) (Fig. 6). After a short, soft and irregular beginning ca. 46 syllables followed (SRR 10.7 Hz; T=25–27ºC). The syllables had a duration of 73±7.9 ms (n=18) and contained 13.1±2.2 (n=18) impulses, resulting in a mean interval of 6.1 ms between the impulses. The largest intra-syllable impulse intervals, however, were nearly as large as the intervals between the syllables (e.g. 16 vs. 20 ms, 14 vs. 18 ms or 15 vs. 20 ms).

The spectrum of the song had its peak near 30 kHz (Fig. 9).

Redescription. Studied material. *Holotype*: ♂, Bulgaria, Blagoevgrad prov., Western Bordering Mountains, Vlakhina Mountain, Kadiytsa summit: Kadiytsa, 1700 m (Andreeva 1978) (labelled 1600–2000 m) (Peshev & Andreeva 1986), 31.07.1974. *Paratypes*: same locality, 3 ♂♂, 5 ♀♀, leg. E. Andreeva, NMNHS & 1 ♂, 1 ♀, leg. G. Peshev, NMNHS & 8 ♂♂, 5 ♀♀, leg. E. Andreeva, HMB; other material: same locality, 1700-1800 m, 41.797ºN, 22.969ºE, xerophyte low bush- and mesoxerophyte grass associations, 04. –05.08.2006, common, 4 ♂♂, 2 ♀♀, leg. D. Chobanov, NMNHS & CC.

Note: Andreeva (1978) presents a detailed but insufficient description of a new species, *Poecilimon pechevi*. The figures in the latter publication are quite schematic and, as found later, somewhat incorrect. The differential diagnosis is too brief and the new species is compared only with *P. zwicki* Ramme, 1933. Actually, from the figure of the apical part of cerci (Andreeva 1978: Plate I, 5), a similarity with *P. ampliatus* may be observed. As a result, *P. pechevi* remained a taxon with unclear status and position within the genus *Poecilimon*. Furthermore, its isolated population and local endemic status required definition of its conservation importance.

Small, stocky build, with moderately shiny integument. Measurements as shown by Andreeva (1978) or also slightly smaller.

Male (Fig. 3a, b, d, e). The fastigium verticis is half the width of the scapus, equal or wider and slightly longer than the second antennal limb, with parallel sides, moderately projecting fore- and upward. The pronotum is widest in its middle, the metazone is moderately dome-shaped bulging and slightly constricted backwards; its hind margin is concave. The mid sulcus passes just before the middle of pronotum. The lateral plates of pronotum have rounded corners. The acoustic stigma has small aperture. The tegmina are slightly covered by pronotum (<1/2 of their length), small, almost oval, with excision at the medial (anal) edge. The stridulatory vein is narrow, easily visible on the translucent membranous surface of the tegmen. The stridulatory file (Fig. 3g–i) is 2.2 mm long (if only the closely arranged teeth are measured) and 0.09 mm in its widest point. The file bears 68–73 (2 ♂♂) large, sparsely distributed stridulatory teeth, getting smaller towards the basal and apical end of the file. Few small isolated teeth/indentations are disposed at the apical and basal ends of the file, where CuP is strongly tapered (with those the file measures 2.4–2.5 mm). On 0.5 mm the basal part of file contains 17 teeth and the middle part—13 teeth.

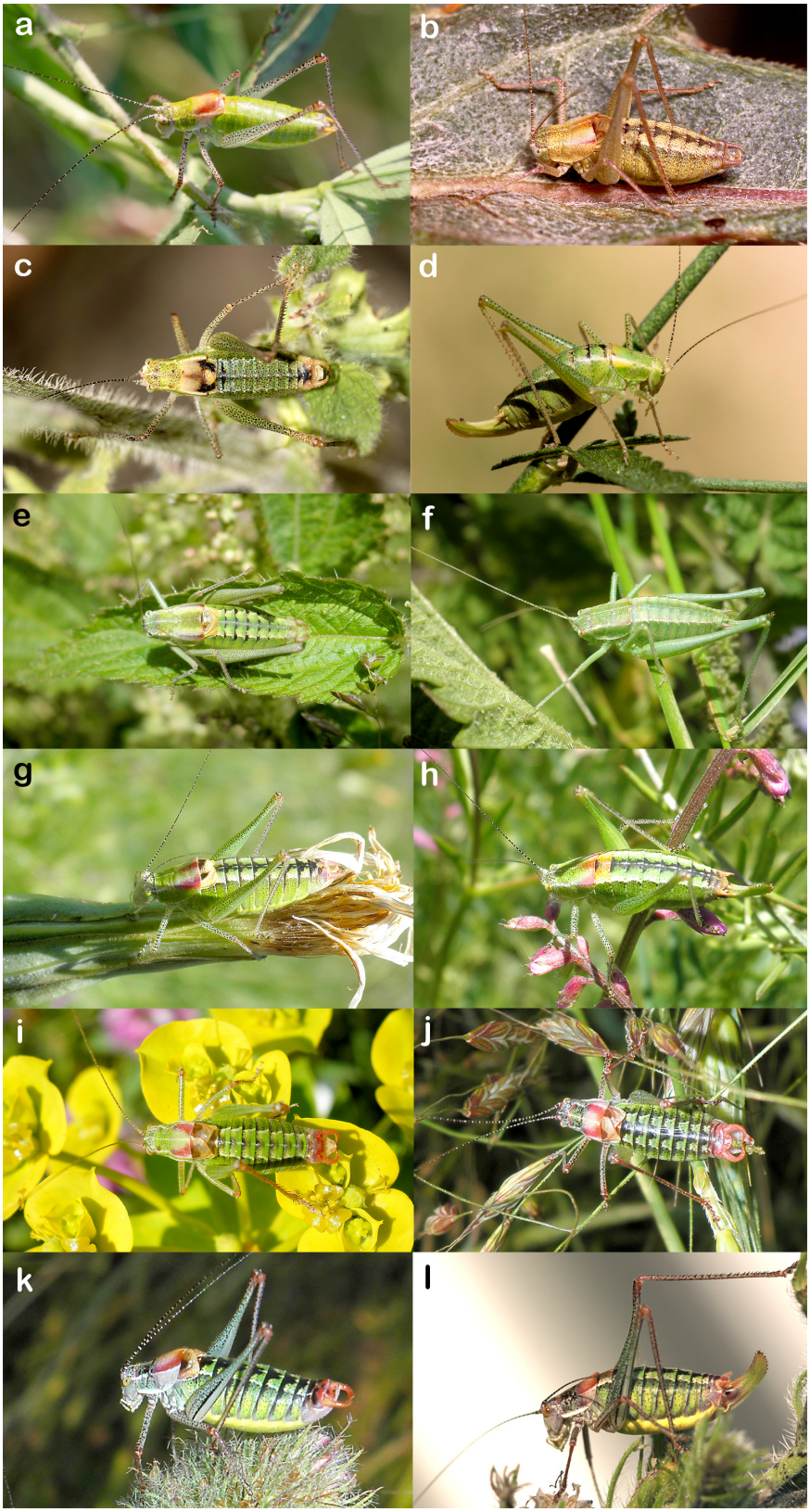

FIGURE 2. General appearance of taxa of *Poecilimon* concerned in this study (for locality details see redescriptions). **a**—*Poecilimon ataturki*, male, Turkey, Devrekani–Bozkurt road; **b**—*Poecilimon harveyi*, male, Turkey, Erzurum, Gölyurt Gecidi; **c, d**—*Poecilimon guichardi*, **c**, male, **d**, female, Turkey, Mersin, Güzelyayla; **e, f**—*Poecilimon doga*, **e**, male, **f**, female, Turkey, Afyonkarahisar, Suhut–Sandıkli road; **g, h**—*Poecilimon davisi*, **g**, male, **h**, female, Turkey, Isparta, Dedegöl Mt.; **i**—*Poecilimon celebi azdavayi*, male, Turkey, Karabük, Ağaçkesen vill.; **j–l**—*Poecilimon celebi celebi*, **j, k**, male, **l**, female, Turkey, Devrekani–Bozkurt road.

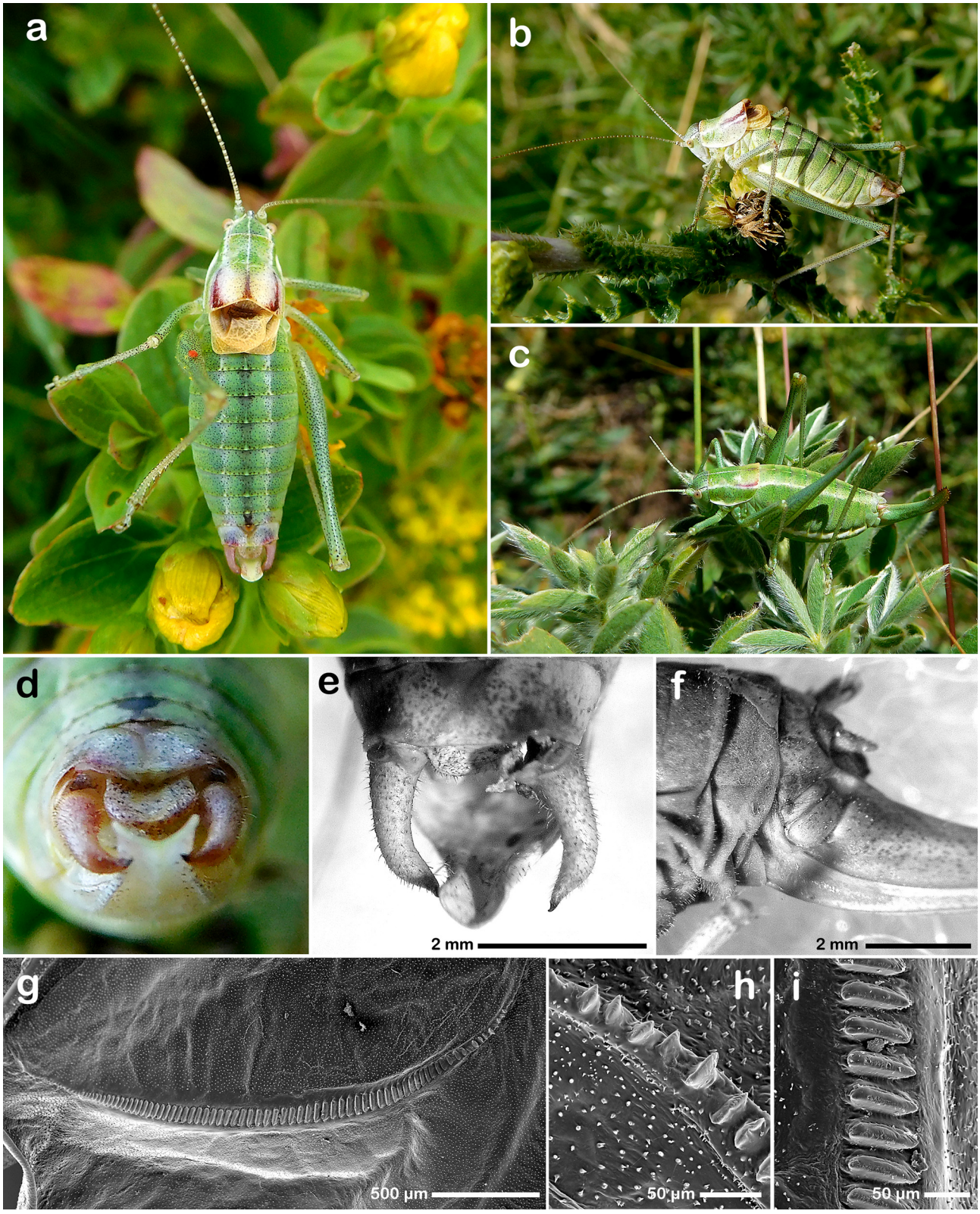

FIGURE 3. General appearance and details of the morphology of *Poecilimon pechevi* from Bulgaria, Kadiytsa summit. **a**—male, dorsal view; **b**—male, dorso-lateral view; **c**—female, dorsolateral view; **d**—male cerci, apical view; **e**—male cerci, dorsal view; **f**—female ovipositor base, lateral view; **g**—male stridulatory file; **h**—stridulatory file, proximal part; **i**—stridulatory file, middle part.

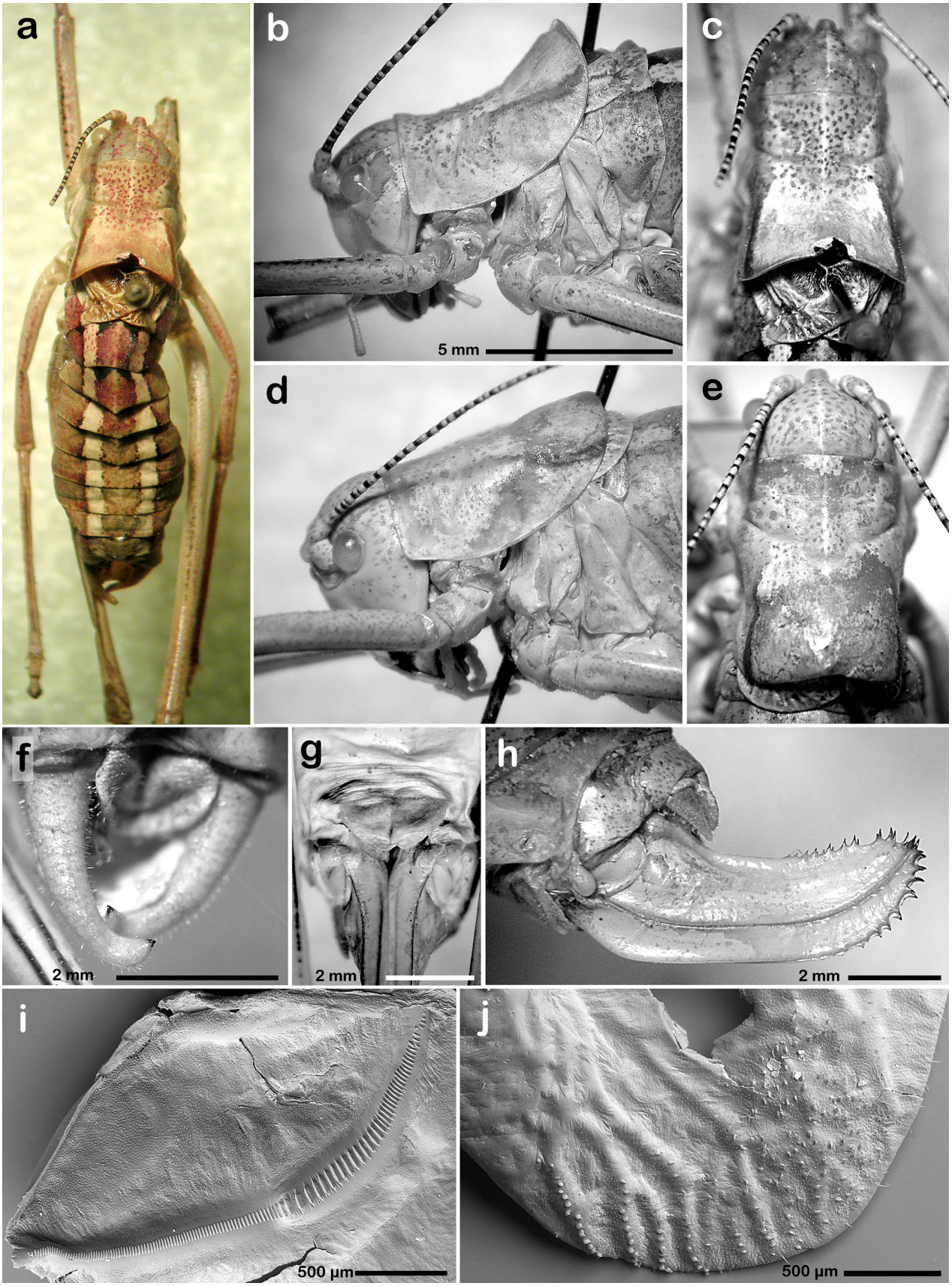

FIGURE 4. General appearance and details of the morphology of *Poecilimon stschelkanovzevi* from Turkmenistan, Ahal, Dushak-Erekdag Observatory. **a**—male, dorsal view; **b**—male pronotum, lateral view; **c**—male pronotum, dorsal view; **d**—female pronotum, lateral view; **e**—female pronotum, dorsal view; **f**—male cerci, dorsal view; **g**—female subgenital plate, ventral view; **h**—female ovipositor, lateral view; **i**—male stridulatory file; **j**—female stridulatory apparatus.

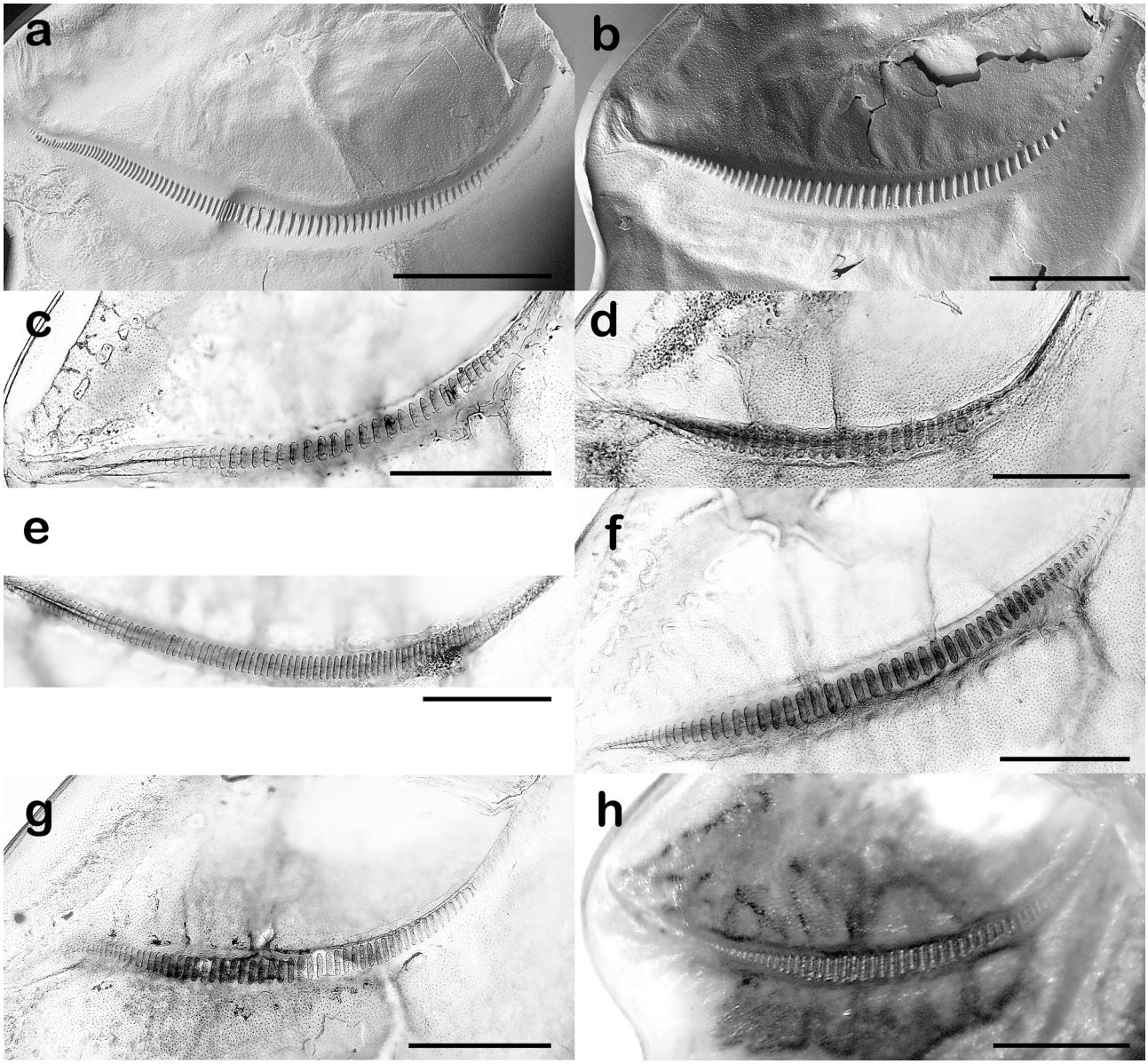

FIGURE 5. Stridulatory files of *Poecilimon* species; **a**—*P. ataturki,* **b**—*P. armeniacus*, **c**—*P. harveyi*, **d**—*P. haydari*, **e**—*P. doga*, **f**—*P. excisus*, **g**—*P. davisi*, **h**—*P. guichardi*.

The fore femur (4–4.5 mm) is slightly shorter than the pronotum (~4.5 mm). Hind femora lack spines on their ventral keels. Hind margins of the abdominal tergites are slightly triangularly protruded in the middle; first tergum (observe below tegmina) lacks glandular bulge. The epiproct is rounded, wider than long. The cerci (Fig. 3d, e) are short, stout, basally very wide and smoothly tapering towards apex. Their apical part (slightly shorter than the basal one) is angularly S-shaped and ends with a small, hook-shaped spine. The subgenital plate is very long (up to 5 mm), equal or fairly longer than pronotum and clearly surpasses the tip of cerci. The apical third of the subgenital plate is much narrower than the basal two-thirds, with parallel lateral margins and weak medial crest lacking in the basal part. The apical margin is angularly convex.

Coloration. The body is pale, yellowish-green, with many rusty-brown speckles. A thin whitish band passes along the middle of the vertex, occiput and the distal part of tergites. The sides of metazone are bordered by a reddish band, widened backwards. Sometimes such reddish band is developed along the middle of metazone and then it connects the lateral ones. The tegmina are yellowish with dark stridulatory area and dark brown CuP-vein. The dorsal side of abdominal tergites is paler and forms a longitudinal lighter area on abdomen. The abdominal tergites have a dark spot medio-basally, which has a tendency of elongation backwards.

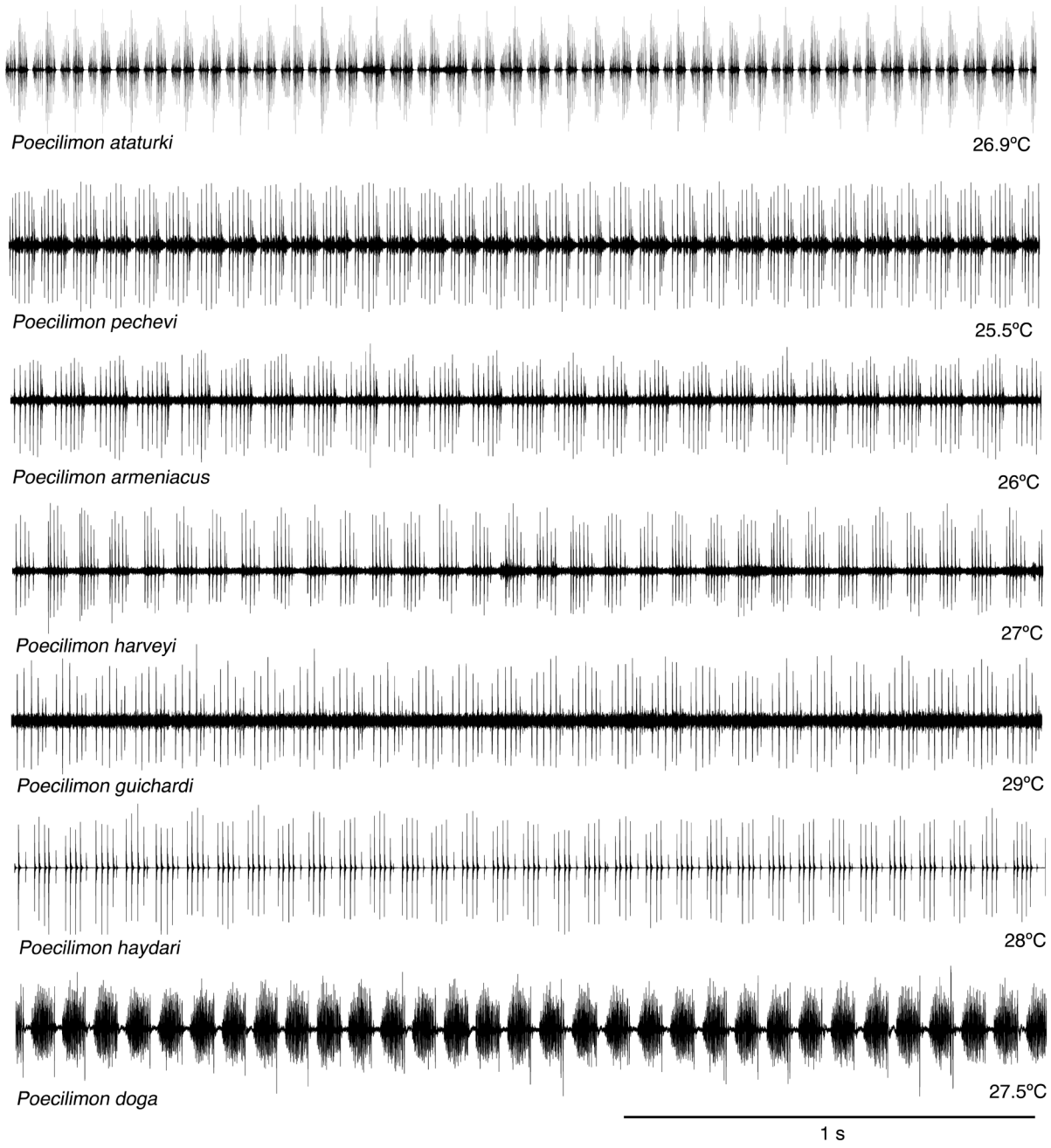

FIGURE 6. Oscillograms of male calling songs of *Poecilimon* species, an overview. Name of taxa and air temperature during recording provided below each oscillogram. Time scale in the lower right corner.

Female (Fig. 3c, f). The fastigium is slightly broader than in the male—about 2/3 of the width of scapus. The pronotum is almost cylindrical, weakly incurved dorsally, with slightly concave hind margin. The tegmina are strongly reduced, non-overlapping, pear-shaped, fully covered by pronotum. Abdominal tergites almost lack medial protrusion. The epiproct is tapered towards the end, longer than broad. The cerci are conical, wide at the base, slightly longer than the epiproct. The subgenital plate is short, widely rounded at the apex. The basal fold of the upper edge of lower ovipositor valve (lamella) is weakly flattened and laterally protruded and does not form clearly delimited groove above it (Fig 3f).

Coloration. Usually greener than in the male; the speckles are smaller and less dense. The reddish bands on pronotum are weakly developed.

Diagnosis. *P. pechevi* belongs to the *Poecilimon ampliatus* group, as defined by Heller & Lehmann (2004). It is most similar to *P. ebneri* by sharing various synapomorphies as the general coloration and body shape, the number

of stridulatory teeth, and especially the shape of female lamella. On the other hand, similarities exist with *P. ampliatus* in the shape of male cerci, in *P. pechevi* cerci being slightly shorter and thicker. Male calling song is typical for the group and strongly resembles the song of both *P. ebneri* and *P. ampliatus* (compare Heller 1988; Heller & Lehmann 2004).

The most important difference between *P. pechevi* and *P. ampliatus* is the presence of a glandular bulge at the first abdominal tergite of the latter, which is thus an autapomorphy of *P. ampliatus*. Other differences from *P. ampliatus* include: 1) the colouration of *P. pechevi* is paler, similar to that of *P. ebneri*; 2) lower number of stridulatory teeth (68–73 against 95 in *ampliatus*; but see below and Anichini *et al.* 2016); 3) the differences in song are weak (as typical for the group in general). Differences from *P. ebneri* include mainly male cerci. In *P. pechevi* cerci are very short and bulky with sinuate outcurved apex bearing a single hook-shaped tooth, while in *P. ebneri* cerci are longer, tip is gently incurved and bearing usually two (rarely 1 to 4) pointed teeth (compare with Heller & Lehmann 2004). Female lamella in *P. pechevi* closely resembles *P. ebneri* and *P. ampliatus* (compare Fig. 2A, B in Heller & Lehmann 2004; errors exist in the legend of that plate and Figs 2–5 should be read as 2—*P. ebneri*, 3—*P. marmaraensis*, 4—*P. amissus* and 5—*P. intermedius*) being dorso-ventrally flattened and triangularly pointed at the lower part of gonangulum..

Distribution, conservation importance and biological remarks. *P. pechevi* occurs only on Vlakhina Mountain, at the border between Bulgaria and North Macedonia, where it is found only on the summit of Kadiytsa. The latter strikingly dominates the landscape, rising from the surrounding crests of 1700–1750 m to 1924 m. The species is a local endemic for the pseudosubalpine meadows at Kadiytsa summit, unique for the central part of the Ossogovo-Ograzhden mountain group. The habitat appears to be naturally climatically deforested and belongs to habitat types 62D0 and 4060 (http://natura2000.moew.government.bg/Home/ProtectedSite?code=BG0000366&siteType=HabitatDirective). Its vegetation was determined as grass formations (Agrostideta capillaries, Nardeta strictae, Bellardiochloeta violaceae) replacing forests of *Fagus sylvatica* and *Abies alba* (Bondev 1991).

The occupied habitat is estimated to cover about 10 square km and is subjected to a disturbance by fruit pickers during the blueberry season. Recently, a significant pressure from cattle overgrazing was observed that visibly changed the habitat quality.

P. pechevi keeps into meso- and xeromesophyte grass associations and within tufts of small bushes of *Chamaecytisus*, even completely isolated from the neighbouring vegetation by soil patches with xeric character, between 1700 and 1900 m altitude. During the summer months the animals become active after dark (in the beginning of August higher activity was observed after 10 p.m.), while in the morning they dart within the vegetation where spend the day. Earlier in the year and during cool days the animals are active throughout the day. The nymphs emerge in May and the imagines occur from July to late August.

Poecilimon armeniacus (Uvarov, 1921) (*armeniacus*-group)

TURKEY: Malatya, Arapgir, 14.07.2002, leg. H. Sevgili, 1 male recorded; Erzurum, Askale–Tercan yolu, 11.07.2002, leg. H. Sevgili, 2 males recorded; Erzurum, Pasapinar, 11.07.2002, leg. H. Sevgili, 1 male recorded (Fig. 6); Tokat/Sivas prov. border, Çamlibel pass, 1600 m (39.6300ºN, 36.5075ºE), 10.07.2011, leg. D. Chobanov, B. Çıplak, S. Kaya, CC, 1 male recorded (Fig. 7); Agrı, Taslıcay, under Balık lake, 2200 m (39.7300ºN, 43.4856ºE), 16.07.2011, leg. D. Chobanov, B. Çıplak, S. Kaya, CC, 1 male recorded, stridulatory file studied; Agrı, Saclıdag, 2160 m, 16.07.2011 (39.8747ºN, 42.3856ºE), leg. leg. D. Chobanov, B. Cıplak, S. Kaya, CC, 1 male recorded.

The song is quite similar to that of *P. pechevi*. The males were active at night and produced series with a duration of 5.6±3,7 s (n=62; range 0.8–18.7 s) at intervals of 12.9±10.8s (n=28) s. After a short, soft and irregular beginning ca. 60 syllables followed (SRR 10.8 Hz; T=23.5–28ºC; Fig. 6). The syllables had a duration of 64±8.2 ms (n=28) and contained 8.25±1.2 (n=18) impulses, resulting in a mean interval of 9.1 ms between the impulses (Fig. 7).

For details of the stridulatory file see Table 2, Fig. 5.

Poecilimon harveyi Karabag, 1964 (*armeniacus*-group)

TURKEY: Erzurum, Gölyurt Gecidi, southwest of Ispir (40.35ºN, 40.783ºE), 2300 m, 7.08.1983, leg. K.-G. Heller; 2 males recorded, stridulatory file studied.

The song is quite similar to that of the closely related (Ünal 2010) *P. armeniacus*. In the short recording two males produced overlapping series with durations of ca. 8 s each. In these series they showed a SRR of 12.5 Hz (T=27ºC; Fig. 6). The syllables had a duration of 46 ms and contained 4–6 impulses, resulting in a mean interval of 11.5 ms between the impulses.

For details of the stridulatory file see Table 2, Fig. 5.

TABLE 2. Review about characteristics of stridulatory file and song of species of the *Poecilimon ampliatus* group s.l. (Ullrich *et al.* 2010). For specimen data see appendix.

species	teeth number	impulse number	tooth distance	impulse period	source
	n	n	µm	ms	
P. marmaraensis	80	15	32.2	4.8	Heller & Lehmann 2004; CH4581
P. amissus	79	17	36.9	5.8	Heller & Lehmann 2004; CH2975
P. ebneri	65	10	45.2	9.6	Heller & Lehmann 2004; CH0006
P. ampliatus	55	9.5	40.0	6.5	Anichini *et al.* 2016; CH0062*
P. doga	93	22	25.0	2.6	This paper
P. haydari	40	6	47.6	10.4	This paper
P. harveyi	51	5	42.9	11.5	This paper
P. armeniacus	48	8	41.1	9.1	This paper; CH7577
P. pechevi	70	13	38.8	6.1	This paper
P. davisi	59	5	33.4	7.8	This paper
P. excisus	55	14	56.0	4.4	This paper
P. guichardi	53	6	35.8	14.0	This paper
P. orbellcus	135	43	40.8	4.5	Boztepe *et al.* 2013, CH0381
P. tuncayi	94	27	38.7	4.1	Boztepe *et al.* 2013, CH0262
P. luschani birandi	131	45	28.4	3.3	Boztepe *et al.* 2013, CC (n=2),
P. helleri	113	33	49.0	2.4	Boztepe *et al.* 2013, CC

* tooth number of 95 for *ampliatus* (Montenegro, Durmitor; Heller 1988) not confirmed in other localities

Poecilimon guichardi Karabag, 1964

TURKEY: Mersin, Güzelyayla, Eskigüzle Mevkii, 12.07.1999, leg. H. Sevgili, 1 male recorded; Mersin, Güzelyayla, Eskigüzle Mevkii, 01.08.2020 (37.045ºN, 34.496ºE), leg. H. Sevgili & O. Sevgili, 1 male recorded.

The song is quite similar to that of *P. armeniacus*. In both recordings of this species a continuous series of syllables (up to 35 s) is heard, produced with SRRs of 9.2–10.4 Hz (T=29ºC; Fig. 6). The syllables had durations of ca. 67–85 ms and contained 6 impulses, resulting in a mean interval of 14 ms between the impulses.

The spectrum of the song had its peak between 30 and 40 kHz (Fig. 9).

For details of the stridulatory file see Table 2, Fig. 5.

Poecilimon haydari Ramme, 1951 (*armeniacus*-group)

TURKEY: Niğde, Bolkar Mt., Maden Köyü ,1278 m (37.50763ºN, 34.59105ºE) & Kanagol Lake, 1950 m (37.45749ºN, 34.60315ºE), xeromesophyte grass associations, 17.06.2014, nymphs last instar and imago, leg. D. Chobanov, 1 male recorded (Fig. 6, 7), stridulatory file studied; Niğde, Ulukısla, 24.06.2001, leg. H. Sevgili, 1 male recorded; Niğde, Buldurus (pass in Ala Dagh) (37.9667°N, 35.0167°E), 3.07.2002, leg. K.-G. Heller, 1 male recorded; Konya, Kizkayasi Mts., north of Konya, 1700 m (38.1333°N, 32.5167°E), 29.06.2002, leg. K.-G. Heller, 1 male recorded; Konya, west of Konya (Erenkaya), Bulumya yaylasi, 1500 m (37.7332°N, 32.1332°E), 30.06.2002, leg. K.-G. Heller, 1 male recorded.

The song is quite similar to that of *P. armeniacus*. The males produced series with a quite variable duration of 20.0±22.5 s (n=11; range 2.4–75 s) at intervals of 12.2±6.3 (n=3) s. A series contained on average 200 syllables (SRR 12.6 Hz; T=25–29ºC; Fig. 6). The syllables had a duration of 51.6±3 ms (n=7) and contained 5.6±0.7 (n=7) impulses, resulting in a mean interval of 10.4 ms between the impulses (Fig. 7).

The spectrum of the song had its peak between 30 and 40 kHz (Fig. 9; high pass filter 12 kHz)

For details of the stridulatory file see Table 2, Fig. 5.

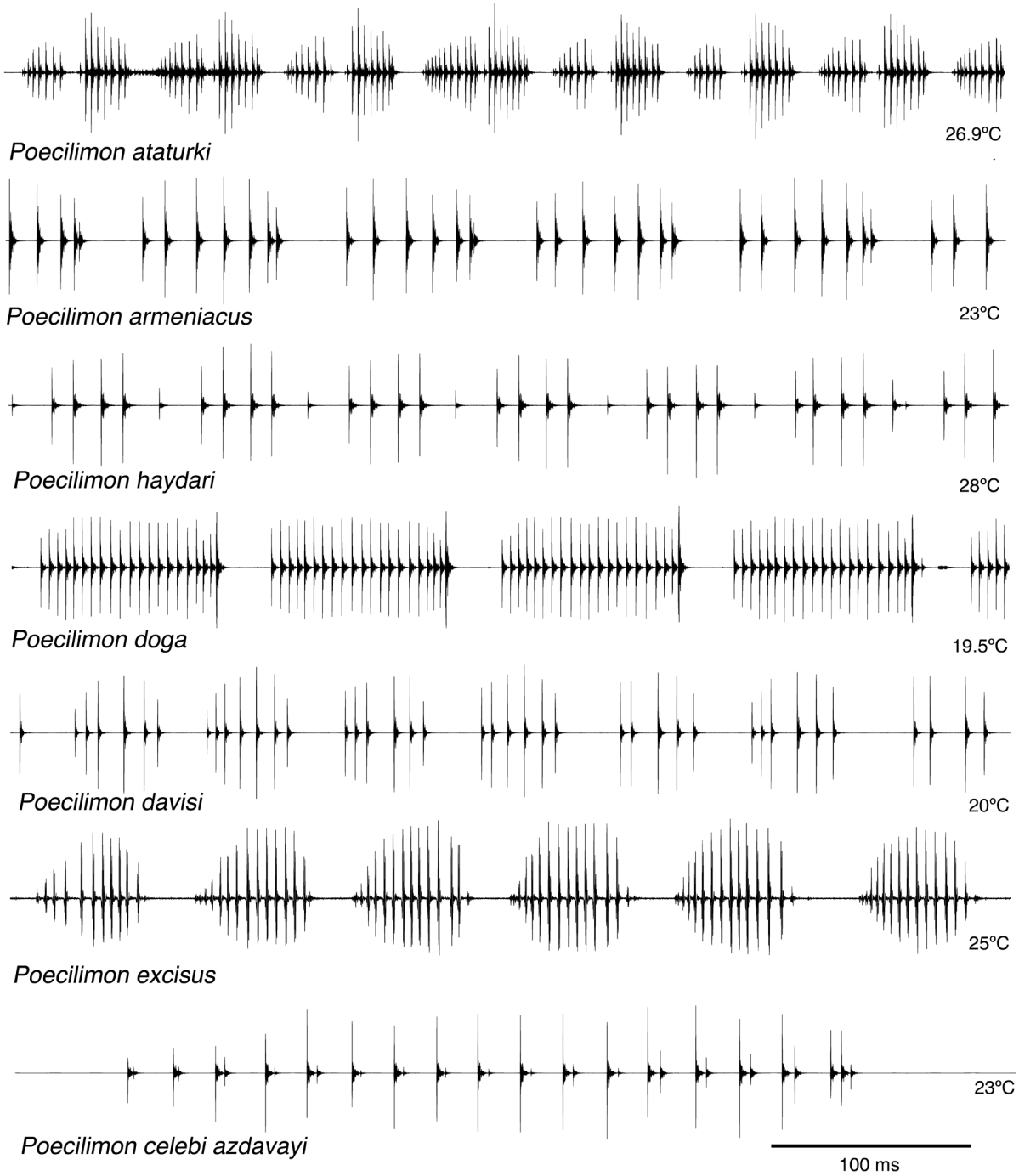

FIGURE 7. Oscillograms of male calling songs of *Poecilimon* species, details. Name of taxa and air temperature during recording provided below each oscillogram. Time scale in the lower right corner.

Poecilimon doga Ünal, 2004 (*minutus*-group)

TURKEY: Isparta, Davras Gebirge above Savköy, near ski lift (37.7667°N, 30.7167°E), 27.06.2002, leg. K.-G.

Heller; 2 males recorded (Fig. 6); Afyonkarahisar province, E of Başören (Suhut – Sandıkli road), pasture, keeps on *Urtica*, common, 1900 m (38.46630ºN, 30.38322ºE), 26.06.2014, leg. D. Chobanov, 1 male recorded (Fig. 7), stridulatory file studied.

In structure, the song is quite similar to that of *P. armeniacus*. The males produced series with a quite variable duration of 7.7±8.3 s (n=13; range 0.5–25 s) at intervals of 21.1±11.7 (n=4) s. A series contained on average about 100 syllables (SRR 12.5 Hz; T=27–28ºC; Fig. 6). The syllables had a duration of 54.6±1.8 ms (n=5), but contained with 22±0.8 (n=7) much more impulses than that of the previous species, resulting in a mean interval of 2.6 ms between the impulses. At 19–20ºC the SRR was only 8.3 Hz and the syllables had a duration of about 93 ms (Fig. 7).

For details of the stridulatory file see Table 2, Fig. 5.

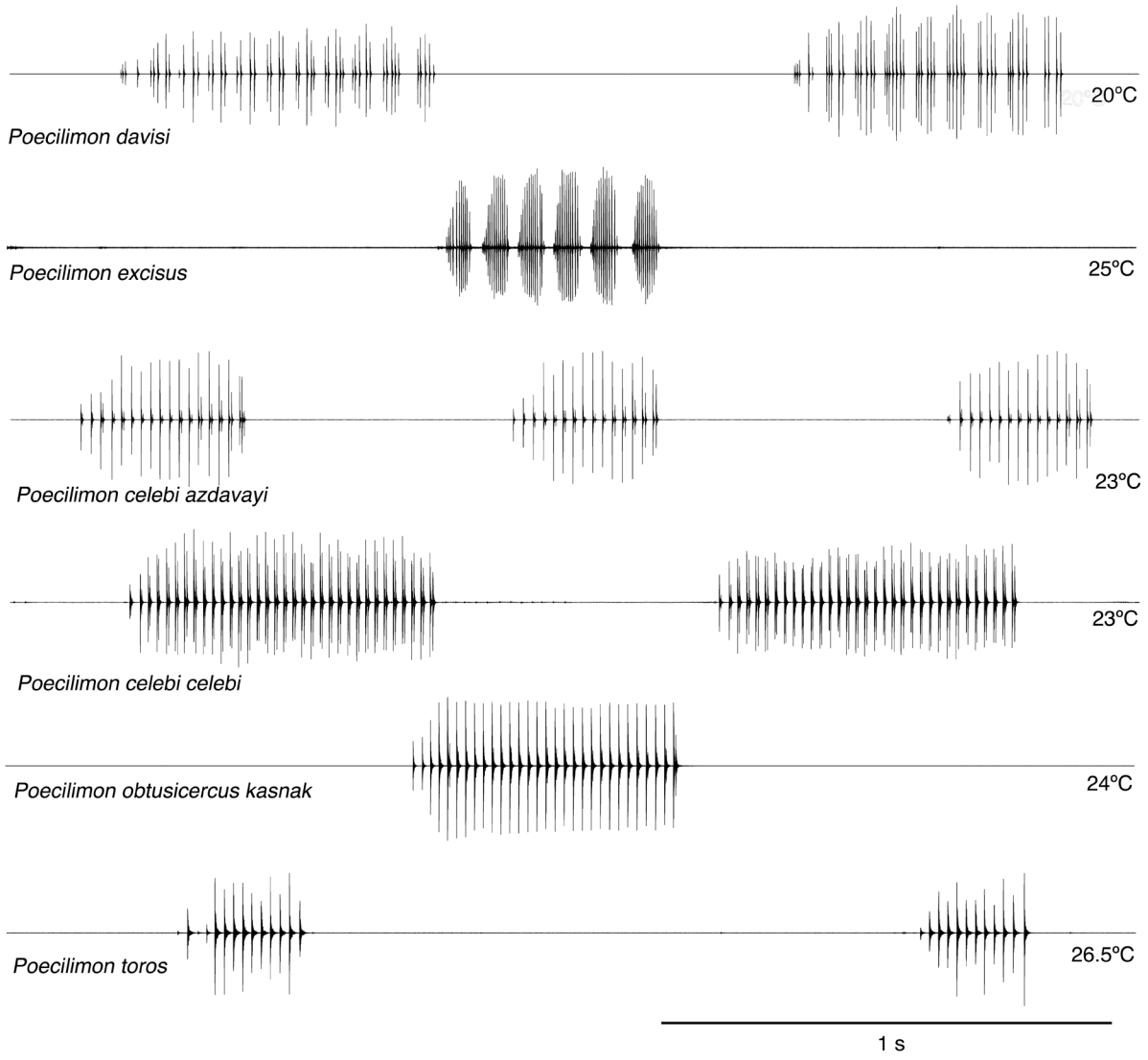

FIGURE 8. Oscillograms of male calling songs of *Poecilimon* species, an overview. Name of taxa and air temperature during recording provided below each oscillogram. Time scale in the lower right corner.

A3) Song consisting of polysyllabic echemes (5–12 syllables) with syllable repetition rates of about 20 Hz

Poecilimon davisi Karabag, 1953 (*davisi*-group)

TURKEY: Isparta, Dedegöl Mt., 1700–1800 m (37.69437ºN, 31.29401ºE), 14.06.2014, nymphs last instar and imago, leg. D. Chobanov & S. Kaya, several males recorded (Fig. 7, 8), stridulatory file studied; Adana, Madenli vill., 1700 m (37. 32325ºN, 31. 83269ºE), 15.06.214, nymphs, leg. D. Chobanov & S. Kaya; Isparta, Sultan Dagh near Aksehir, 1900 m (38.2833°'N, 31.3167°E), 28.06.2002, leg. K.-G. Heller, 2 males recorded; Isparta, Yalvaç

(38.2667°N, 31.1667°E), 28.06.2002, leg. K.-G. Heller, 2 males recorded.

The males were active at night and produced short echemes with a duration of 0.4±0.1 s (n=54; range 0.25–0.63 s; Fig. 8). During the recording sessions always at least two males were in acoustical contact. In this situation the echemes were often arranged in groups with two or more males alternating. However, occasionally also isolated echemes were heard (duration of intervals 3.9±8.1s, range 0.2–47s, n=45). An echeme contained on average 9 syllables (SRR 20.2 Hz; T=25–26ºC). The syllables had a duration of 30.6±3.8 ms (n=13) and contained 5.1±1.1 (n=13) impulses (Fig. 7) resulting in a mean interval of 7.8 ms between the impulses. Sometimes intrasyllable gaps were as large as the gaps between the syllables. At 20ºC the SRR was only 15.3 Hz and the syllables had a duration of about 40.6±3.9 ms (n=9).

The spectrum of the song had its peak near 30 kHz (Fig. 9).

For details of the stridulatory file see Table 2, Fig. 5.

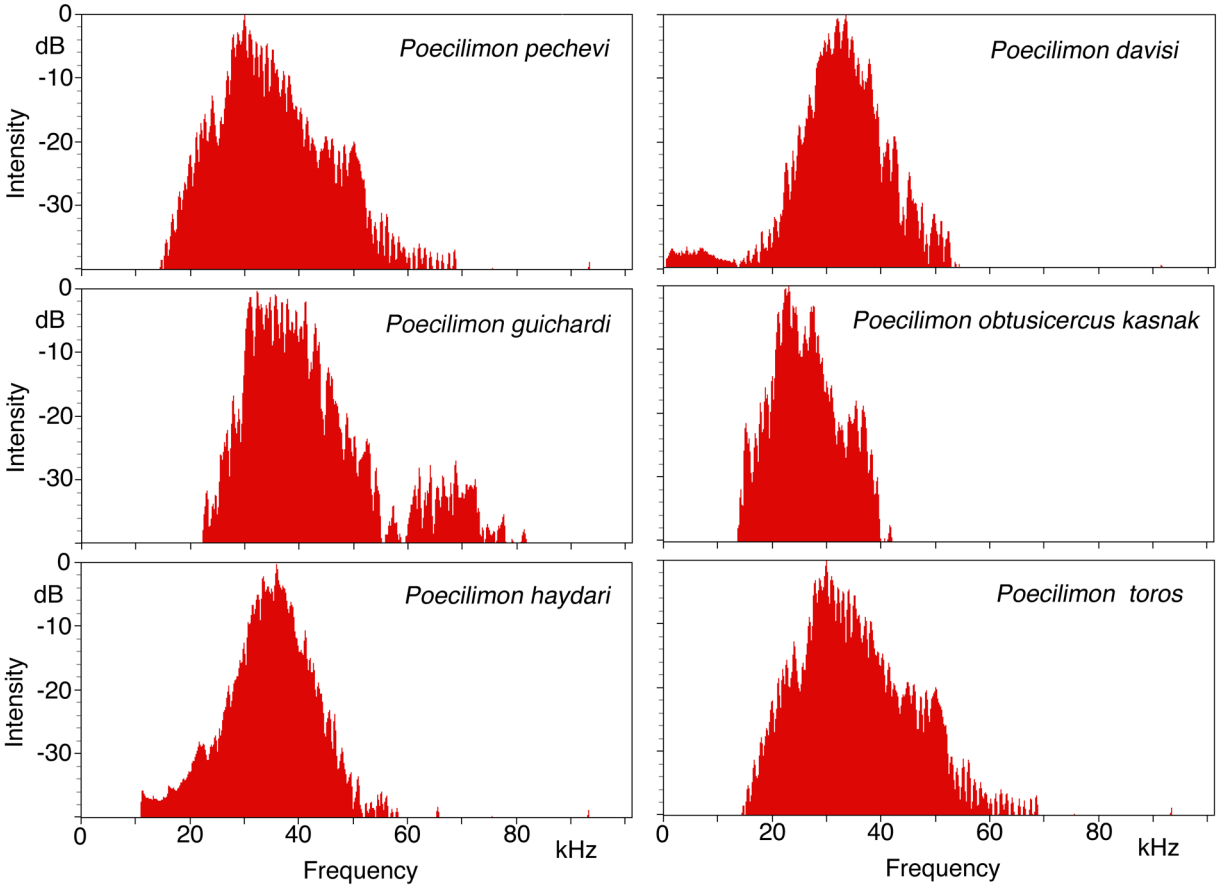

FIGURE 9. Spectral composition of male calling songs.

Poecilimon excisus Karabag, 1950 (*armeniacus*-group)

TURKEY: Eskisehir, Sivrihisar, 06.07.2003, leg. H. Sevgili; Isparta, Sultan Dagh near Aksehir, 1900 m (38.2833°N, 31.3167°E), 28.06.2002, leg. K.-G. Heller, 2 males recorded (Fig. 7, 8), stridulatory file studied; Konya, Aksehir (38.35°N, 31.4833°E), 29.06.2002, leg. K.-G. Heller, 2 males recorded.

The males produced short echemes with a duration of 0.44±0.14 s (n=56; range 0.2–0.79 s; Fig. 8). During the recording sessions the singing males were usually in acoustical contact. The intervals between the echemes had a duration of 2.9±2.0 s (range 0.9–9.8 s, n=51). An echeme contained on average 6 syllables (SRR 12.6 Hz; T=25–30ºC). The syllables had a duration of 56.5±4.1 ms and contained 14.3±1.8 (n=12) impulses (Fig. 7) resulting in a mean interval of 4.4 ms between the impulses.

For details of the stridulatory file see Table 2, Fig. 5.

B) Song consisting of short polysyllabic echemes (14–40 syllables) with syllable repetition rates between 40–50 Hz

This song type was described as typical for the *P. syriacus* group (Heller *et al.* 2008)

***Poecilimon celebi azdavayi* Ünal, 2003 (*celebi*-group)**

TURKEY: Karabük province, Ağaçkesen vill., 990 m (41.35238ºN, 32.74289ºE), 09.07.2011, leg. B. Çıplak, S. Kaya & D. Chobanov, 1 male recorded.

The male produced short echemes with a duration of 0.38±0.04 s (n=11; range 0.33–0.45 s; Fig. 8). The intervals between the echemes had a duration of 0.8±0.2 s (range 0.5–1.0 s, n=10). An echeme contained on average 18 syllables (SRR 45.5 Hz; T=23ºC). The syllables had a mean duration of 6 ms and contained 1–3 impulses (Fig. 7).

***Poecilimon celebi celebi* Karabag, 1953 (*celebi*-group)**

TURKEY: Devrekani–Bozkurt, 09.07.2011, 1200 m (41.70733ºN, 33.97399ºE), leg. B. Çıplak, S. Kaya & D. Chobanov, 2 males recorded.

The males produced short echemes with a duration of 0.72±0.1 s (n=24; range 0.6–1.0 s; Fig. 8). The intervals between the echemes had a duration of 2.5±3.6 s (range 0.8–14.6 s, n=11). An echeme contained on average 36 syllables (SRR 50.4 Hz; T=23ºC). The syllables had a mean duration of 4.8 ms and contained 2 impulses.

***Poecilimon obtusicercus kasnak* Ünal, 2010 (*syriacus*-group)**

TURKEY: Antalya province, Ibradi–Derebucak, 1330 m (37.13384ºN, 31.5604ºE), mesophyte meadow and oak scrub, 14.06.2014, leg. D. Chobanov & S. Kaya, 1 male recorded.

The male produced short echemes with a duration of 0.54±0.1 s (n=12; range 0.4–0.6 s; Fig. 8). The intervals between the echemes had a duration of 3.7±2.5 s (range 1.8–9.5 s, n=11). An echeme contained on average 27 syllables (SRR 50.6 Hz; T=24ºC). The syllables had a mean duration of 2.5 ms and contained 1–2 impulses.

The spectrum of the song had its peak between 20 and 30 kHz (Fig. 9).

***Poecilimon toros* Ünal, 2003 (*syriacus*-group)**

TURKEY: Antalya, road Elmali–Korkuteli, near branching off to Avdan (36.9345°N, 30.0942°E), 21.05.2009, leg. D. Chobanov, H. Braun, K.-G. Heller, 2 males recorded.

The males produced short echemes with a duration of 0.34±0.1 s (n=21; range 0.23–0.45 s; Fig. 8). The intervals between the echemes had a duration of 4.2±4.2 s (range 0.7–14.4 s, n=18). An echeme contained on average 14 syllables (SRR 40.8 Hz; T=24ºC). The syllables had a mean duration of 3.2 ms and contained 1–3 impulses.

The spectrum of the song had its peak near 30 kHz (Fig. 9).

C) Species with unknown song

***Poecilimon stschelkanovzevi* Tarbinsky, 1932**

TURKMENISTAN: Ahal Province, Dushak Mt., Erekdag Observatory, 2470 m (37.95611°N, 57.90556°E), 30.06.1992 [labelled "Obszervutor / Tn / 1992.VI.30"], 1 male, 1 female, Hungarian Natural History Museum (Budapest).

Redescription. Average sized animal, stockyly built, with moderately shiny integument. Measurements according to Bey-Bienko (1954) in mm—body length male 18.5–22, female 24–25; pronotum male 4.9–5.3, female

5.3–5.5; tegmina (visible part) male 1.6, female 0.7; hind femur male 16, female 16.5–18.4; ovipositor 6.5. Own measurements in mm—pronotum male 5.2, female 6.2; tegmina (visible part) male 1.7, female 0.8; (whole tegmen of the female 3.0 mm); hind femur male 18.2, female 18.4; cercus 2.9; ovipositor 7.5.

Male (Fig. 4a–c, f, i). The fastigium verticis is short, tapering to the tip, half the width of the scapus. Antennal joints dark in their base, thus antennae look with dark and light rings. The pronotum is constricted in the middle, pro- and metazone widening fore- and backeards, respectively, hind margin of metazone concave. The mid sulcus passes before the middle of pronotum. The lateral plates of pronotum have rounded corners. The acoustic stigma has large aperture. Half of tegmina are covered by pronotum, comparatively small, with slight excision at the medial (anal) edge. The stridulatory area is bulged over the costal area and has pronounced strongly chitinized venation. The stridulatory vein is covered by the pronotum, massive and long. The stridulatory file (Fig. 4i) measures 2.56 mm in length (shortest distance between ends) and 0.12 mm in its widest point. The file bears 132 teeth, clearly separated to a basal part of 1.34 mm with 45 wide, sparse teeth, enlarging towards the middle, and an apical part of 1.34 mm with 87 finer dense teeth. Both parts are separated by a step-like descent from the basal to the apical part.

Legs quite long, fore and mid femora much longer than pronotum (ca. 7.7–8 mm). Hind femora lack spines on their ventral keels. Hind margins of the abdominal tergites are not protruded. The epiproct is broader than long. The cerci (Fig. 4f) are comparatively long, slightly incurved, tapering almost to the tip, when they are strongly incurved and widened. Their apical part ends with a short, wide, decurved spine spine. The subgenital plate is short, slightly tapering to the tip, where it has a shallow rectangular incision.

Coloration. The body of the dried specimens is pale, yellowish, though living animals are possibly fresh green or yellowish-green with large rusty-brown speckles. A thin whitish band passes along the middle of the vertex, occiput and the distal part of tergites. The sides of metazone are bordered by a reddish band. Pale light bands pass over the sides of the reddish band of pronotum and continues on the abdominal tergites, where it is much sharper and bordered by black on both sides. The tegmina are yellowish with dark stridulatory area on which yellow veins are sharply visible. All femora with dark colored ventral keels.

Female (Fig. 4d, e, g, h, j). The fastigium is wider than in the male – almost as wide as scapus. The pronotum is almost cylindrical, longer then in male, with a long metazone, almost entirely covering the large tegmina. The tegmina (Fig. 4e, j) are roundish, the left tegmen bearing a well-developed stridulatory apparatus with at least four proximal rows of parallel spines and a large distal area of circular spines. The epiproct is broader than long. The cerci are conical, in- and decurved, slightly longer than the epiproct. The subgenital plate (Fig. 4g) is half as long as wide, widely rounded, with a small triangular projection at the apex. Ovipositor short with the basal fold of the upper edge of lower ovipositor valve (lamella) forming typical roundish projection (Fig. 4h).

Coloration. Similar to the male.

Diagnosis. Bey-Bienko (1954) compares this species with *P. thoracicus* (Fieber, 1853), rejecting close relationships between both due to the difference in the coloration of male tegmina. On the other hand, the shape of male pronotum and cerci, the long legs, the structure of male tegmina and especially of the stridulatory file suggest closer relationships with *P. schmidtii* (Fieber, 1853) and partly with some members of the *Poecilimon heroicus* Stshelkanovtzev, 1911 species group (Heller *et al.* 2006). The area of distribution of the latter taxa opposite to that of *P. stschelkanovzevi* at the western side of the Caspian Sea and the close relationships between *P. schmidtii* and the *Poecilimon heroicus* group (Ullrich *et al.* 2010) may further support that hypothesis.

Discussion

According to their song, the studied species fall into two large groups (Tab. 1). *P. celebi, obtusicercus* and *toros* show the typical characteristics of the *P. syriacus* group: very short syllables and an unusually high syllable repetition rate. We consider them as members of one group and include the *P. celebi* group within the *P. syriacus* group. Unpublished DNA data support this view (Chobanov *et al.* in prep). The other song group is more heterogeneous. The majority of the species (*P. pechevi*, *P. armeniacus*, *P. harveyi*, *P. guichardi, P. haydari*, *P. doga*) present a song pattern very similar to that of *P. ampliatus*. The close relationships of at least some species to this group is supported by morphology (e.g., *pechevi*; see above) and molecular data (e.g., *armeniacus, haydari, doga*; Ullrich *et al.* 2010). The two species *P. davisi* and *P. excisus* have also similar syllables and SRRs, but short echemes contrasting to the long sequences of the others. Molecular data suggest that they also belong to this group (Ullrich *et al.* 2010). *P.*

ataturki finally is also quite similar in basic song structure and is considered to belong to the *P. ampliatus* group by Ünal (2010), but has some unusual peculiarities. Its syllables are bi-partite and the stridulatory file has a distinct step in the middle not found in any other species of the group, but observed in several species with acoustically responding females (see e.g., Heller 1988, *P. stschelkanovzevi* above). For the moment we refrain to place it (together with its sister species *P. glandifer* Karaman, 1950) in any existing species group until new genetic data on their relationships (in prep.) will be available.

The species of the *ampliatus*-group as given in Ullrich *et al.* 2010 (including *armeniacus* group and *luschani/orbelicus* group) are bioacoustically interesting because on the one hand their syllables differ in number of impulses, on the other hand the stridulatory files differ in number of teeth. From a comparison of both characteristics some rules can be recognized (Fig. 10). Numbers of impulses and of teeth are highly correlated (r^2=0.95). Obviously and perhaps as expected, the animals do not use all teeth for sound production. The regression line cuts the x-axis at 36 teeth, indicating that the file must have at least this number of teeth (Fig. 10 a). Possibly about half of this number is reserved for the mute beginning and half for the mute end of the stridulatory movement, perhaps for accelerating the tegmina and slowing down them respectively. The teeth in these areas are usually distinctly smaller than in the central part of the file. Surprisingly, however, even besides this 'mute' parts there is no 1:1-relation between tooth and impulse number. The regression line runs parallel to a "2 teeth:1 impulse" relation. Either the males use only part of the file for sound production or they use non-neighbouring teeth omitting some situated in between. At present it is unclear if the reasons for this behaviour have to be searched for in sound production or on the receiver side. The male may try to produce louder songs or the female may prefer longer and more "gappy" syllables. Impulse periods and inter-tooth distances are not significantly correlated (Fig. 10 b).

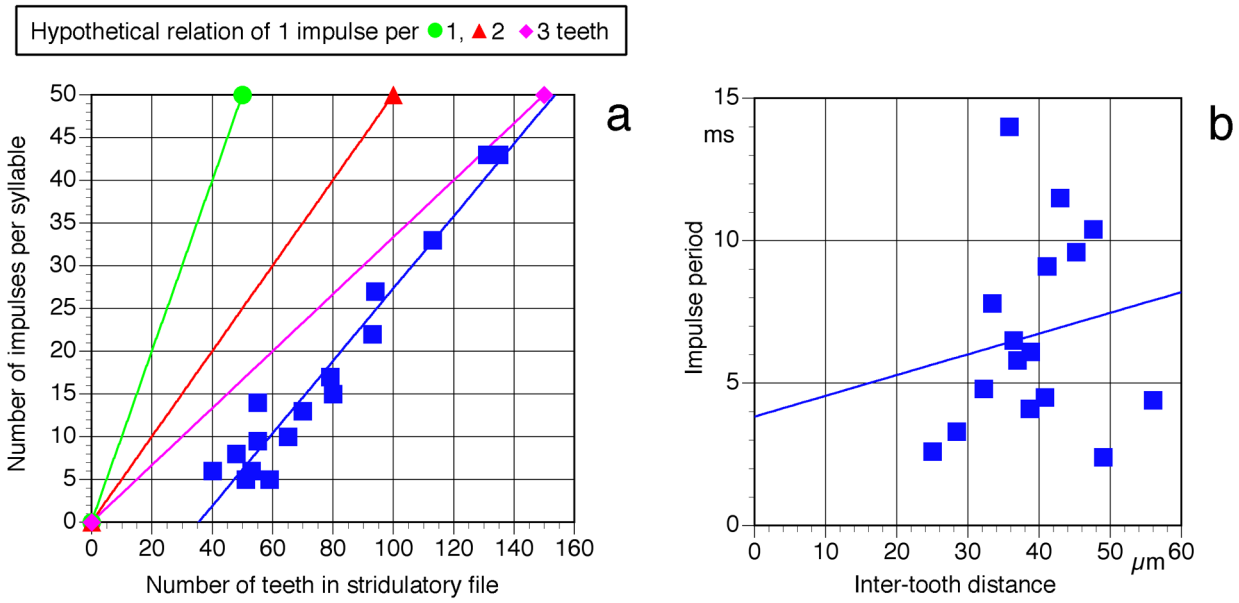

FIGURE 10. Relationships between stridulatory file and syllable structure in species of the *P. ampliatus*-group s.l. (see Table 2); **a** impulse number depending on file length (tooth number; r^2=0.95; p<0.001), coloured lines indicate hypothetical relations of one impulse per 1,2,3 teeth; **b** impulse period depending on inter-tooth distance (in middle of file; r^2=0.03, n.s.).

The present study provides hints for solving some disagreement between recent revisions, especially concerning the groups *ampliatus, armeniacus, celebi, davisi, luschani, syriacus* (mostly after Ünal 2010), as well as for clarifying the position of the poorly known species *P. guichardi, P. pechevi* and *P. stschelkanovzevi*. This may be an initial step towards a needed complete review of the systematics of *Poecilimon*. The acoustic peculiarities of the *ampliatus*-group as descibed here and their evolutionary basis provide ground for future experimental research and may help understanding the acoustic evolution of this hyper-diverse group of bush-crickets.

Acknowledgements

This study was supported by the National Science Fund (MES) of Bulgaria – project DN11/14–18.12.2017 to DPC.

DPC is indebted to Battal Çıplak and Sarp Kaya for the joint studies during his postdoctoral research at the Akdeniz University (Antalya) via The Scientific and Technological Research Council of Turkey (TÜBITAK). We thank Simeon Borissov for mapping localities for Figure 1. Part of the material was collected with the support by joint project 'Phylogenetic relationships in the group Barbitistini (Orthoptera, Tettigoniidae, Phaneropterinae) based on genetic studies' carried in collaboration with Battal Çıplak. Specimens of *Poecilimon stschenkanovzevi* have been studied and most SEM images used have been taken with the support of SYNTHESYS (European Commission's Research Infrastructures Network funded under FP7) grant HU-TAF-2202 to D. Chobanov.

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Appendix

Locality data of specimens used in Table 2.

Poecilimon amissus Brunner v. Wattenwyl, 1878; CH2975; Greece: Lesbos/Mytilini, Umg. Vrissa, Burgruine sö, 39° 2' N, 26° 11' E, 23 May 1993 , coll. K.-G. Heller. *Poecilimon ampliatus* Brunner v. Wattenwyl, 1878; CH0062; Slowenia: Grize, 15 km nordöstl. Triest, 45° 45' N, 13° 56' E, 1-31 May 1986 , coll. E. Blümm. *Poecilimon armeniacus* Uvarov, 1921; CH7577; Turkey: Agri, Balik Gölü, elev. 2200 m, 16 July 2011 , coll. Dragan Chobanov. *Poecilimon ebneri* Ramme, 1933; CH0006; Greece: Kastoria, oberhalb Klissoura, elev. 1220 m, 40° 34' N, 21° 27' E, 28 June 1986 , coll. Heller. *Poecilimon helleri* Boztepe, Kaya & Çiplak, 2013; CC; Turkey: E of Basoren (Suhut - Sandıkli), 26.06.2014, N 38.46630, E 30.38322, 1900 m, coll. Dragan Chobanov. *Poecilimon luschani birandi* Karabag, 1950; CC; Turkey: Bakirli Dag, near Festikan Yayla, 24.07.2011, coll. Dragan Chobanov. *Poecilimon marmaraensis marmaraensis* Naskrecki, 1991; CH4581; Turkey: Kirklareli, 10 km westl. Lüleburgaz (Abzweigung nach Saricaali), 41° 25' N, 27° 15' E, 1-31 May 1996 , coll. Holger Braun. *Poecilimon orbelicus* Pancic, 1883; CH0381; Greece: Drama, Kato Vrondou nordöstl. Serrai, 41° 16' N, 23° 44' E, 26 May 1983 , coll. v. Helversen. *Poecilimon tuncayi* Karabag, 1953; CH0262; Turkey: Mugla, Labranda, 37° 24' N, 27° 42' E, 2 May 1985, coll. Heller.