The Compression Mating Fossil of Sciarid Fly (Diptera: Sciaridae) from Shiobara, Tochigi Prefecture, Japan

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The compression mating fossil of sciarid fly (Diptera: Sciaridae) from Shiobara, Tochigi Prefecture, Japan

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Abstract. Preservations illustrating insect reproductive behaviors are much rarer in compression fossils than in amber. We discovered a copulating compression fossil of the sciarid flies from the Pleistocene Shiobara Group, Tochigi Prefecture, Japan, which is briefly described herein. The specimen represents one of the rare examples of a compression fossil showing mating dipteran insects. This finding implies that the small bodies of sciarid flies which readily fall onto the water surface may have contributed to the preservation of our copulating fossil. Moreover, the depositional environment of the paleo-Shiobara Lake was the main factor that served to preserve this specimen.

Key words: copulating fossils, insect fossil, Pleistocene, Sciaridae, Shiobara

Introduction

Preserved fossils occasionally show not only the remains of an organism but also the past "behavior" of an organism, with this behavior sometimes having evolutionary implications (e.g. Wang *et al*., 2015). Determining the behavior of a fossil animal in comparison with that of modern related taxa is an integral part of paleoethology. The preservation of mating behavior within a fossil is one of the most obvious forms of evidence for direct intraspecific interactions between male and female (Penney and Jepson, 2014). Because of the paucity of examples of mating behavior in insect fossils, studies of their mating behavior are preliminary. At present, examples of fossils showing mating behavior have been reported in four orders of insects, spanning 24 families (Boucot and Poinar, 2011; Li *et al*., 2013). Most of these specimens have been preserved in amber, representing approximately 40 examples; however, examples of preserved compression fossils are dramatically fewer. In fact, Boucot and Poinar (2011) and Li *et al*. (2013) listed only eight compression fossil specimens of insects showing the process of mating, representing four known families and two undetermined families in four orders. In Diptera, fossils representing 11 families showing mating behavior are listed (Boucot and Poinar, 2011), and only five compression specimens are known from the two families, Bibionidae (Fujiyama and Iwao, 1974) and Chironomidae (Heer, 1850; Abel, 1935; Müller, 1957, 1979), among them. However, some examples of chironomid compression specimens showing mating are in fact from amber specimens (Abel, 1935; Müller, 1957, 1979), and no more than two dipteran compression specimens belonging to Bibionidae (Fujiyama and Iwao, 1974) and Chironomidae (Heer, 1850) have ever been recognized. In this study, we report on a new dipteran compression fossil showing mating behavior. We describe this specimen briefly based on a single specimen collected from the quarry of the Konoha Fossil Museum in Nasushiobara City, Tochigi Prefecture, central Japan.

As many as 142 species in 14 genera of the sciarid fossils have been reported globally, spanning the Cretaceous to Quaternary age, with most being found on European continent (Evenhuis, 1994, updated online in 1996). However, there have been few previous reports of sciarid fossils from Japan. Fujiyama and Iwao (1975) described three species of sciarid flies as *Sciara*? sp. A, B, and Sciaridae gen. et sp. indet. from the middle–upper Pliocene or lower Pleistocene Togo Formation, Togo, Kagoshima Prefecture. In addition, *Sciara* sp. has been reported from the lower Miocene Masaragawa Formation, Sado Island, Niigata Prefecture, central Japan. (Fujiyama, 1985). Recently, six species of Sciaridae gen. et sp. A–F from Shiobara have been briefly described by Aiba (2015).

Geological setting

Shiobara Basin is a caldera basin located on the northern slope of the Quaternary Takahara Volcano situated along the Hoki River (Figure 1). The caldera had a lake (paleo-Shiobara Lake in Tsujino and Maeda, 1999), the deposits of which have been assigned to the Middle Pleistocene Shiobara Group. The age of deposits was determined from the correlation of fossil flora (Onoe, 1989) and tephrochronology (Suzuki *et al*., 1998). The group adjoins and unconformably covers the Miocene volcanic and sedimentary rocks on the west, north, and east sides, and the lavas of the Takahara Volcano intercalate on the south side. In some places, the group is overlain by terrace deposits and altered volcanic ash layers. The Shiobara Group includes a series consisting of sandstone, taffaceous mudstone, diatomaceous laminated mudstone, and conglomerate. The group shows lateral lithological variation and is composed of two formations (the Kamishiobara and Miyajima formations), which represent contemporaneous heterotopic facies. The Kamishiobara Formation represents a terrigenous marginal facies and includes coarse sediments. The Miyajima Formation, distributed in the center of the basin, shows profound facies of the paleo-Shiobara Lake and is composed mainly of diatomaceous laminated mudstones. This formation is exposed in the Konoha Fossil Museum, and a number of exceptionally well-preserved fossils, including leaves (e.g. Nathorst, 1883; Endo, 1931; Onoe, 1989), insects (e.g. Fujiyama, 1968, 1969, 1979, 1983; Aiba, 2015), and vertebrates (e.g. Shikama, 1955; Hasegawa and Aoshima, 1988) have been discovered. Because of the remarkable preservation, the locality has recently been described as a conservation Lagerstätten (Allison *et al*., 2008), and new specimens are being obtained from the quarry in the museum. The fossil bearing rock comprises whitish liminite, which consist of rhythmic alternations of gray and white thin parallel laminae. Allison *et al.* (2008) observed that the former gray laminae is clastic layer and the latter is white cemented laminae of porcelaneous opaline silica. These liminae may be regarded as annual rhythmites (Akutsu, 1964; Aiba, 2015). The specimen is occurred at the boundary of these laminae and it was parallel to bedding.

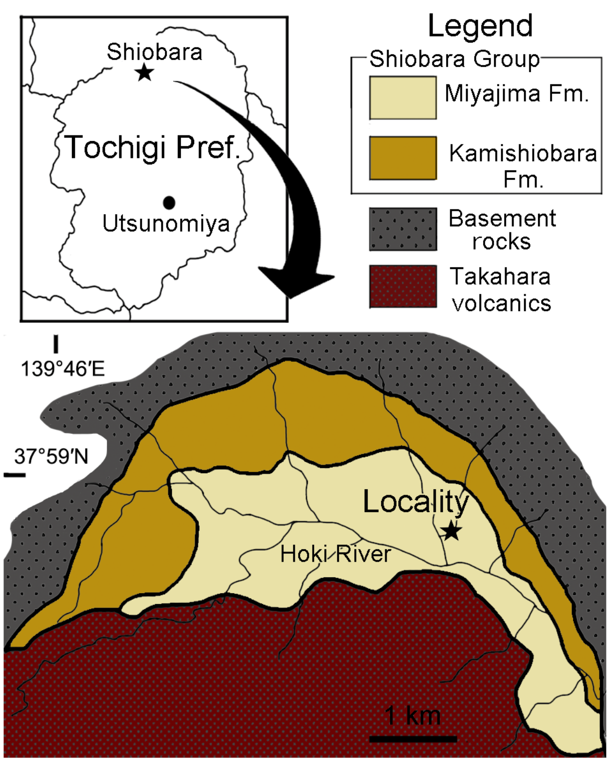

Figure 1. The schematic map at the upper left shows a location of Shiobara, Tochigi Prefecture, Japan (after TuZino *et al.*, 2009). The lower is the simplified local geological map of Shiobara. The star represents the locality, Konoha Fossil Museum, which is located on the Miyajima Formation.

Systematic paleontology

Order Diptera Linnaeus, 1758
Family Sciaridae Billberg, 1820
Sciaridae gen. et sp. indet.

Figure 2A–D

Referred specimen.—EES-ty0001a, b; they are counterparts of one another. They show two individual flies: one male and one female. The studied specimens are deposited at the Graduate School of Life and Environmental Sciences, University of Tsukuba, the Ibaraki Prefecture, Japan. The prefix EES represents the abbreviation of Earth Evolutionary Science, University of Tsukuba.

Remarks.—Two individual flies were identified from the fossil. They were identified as a male and female based on their traced genital organs (Figure 2D-2). In Figure 2A, the abdomen of the left individual is slightly larger than that of the right individual. This difference of abdominal size also suggests that the left individual is female and the right is male. The wing shape and venation of the female individual are partly observed and are traced here (Figure 2C-2). The following wing veins are clearly visible in this

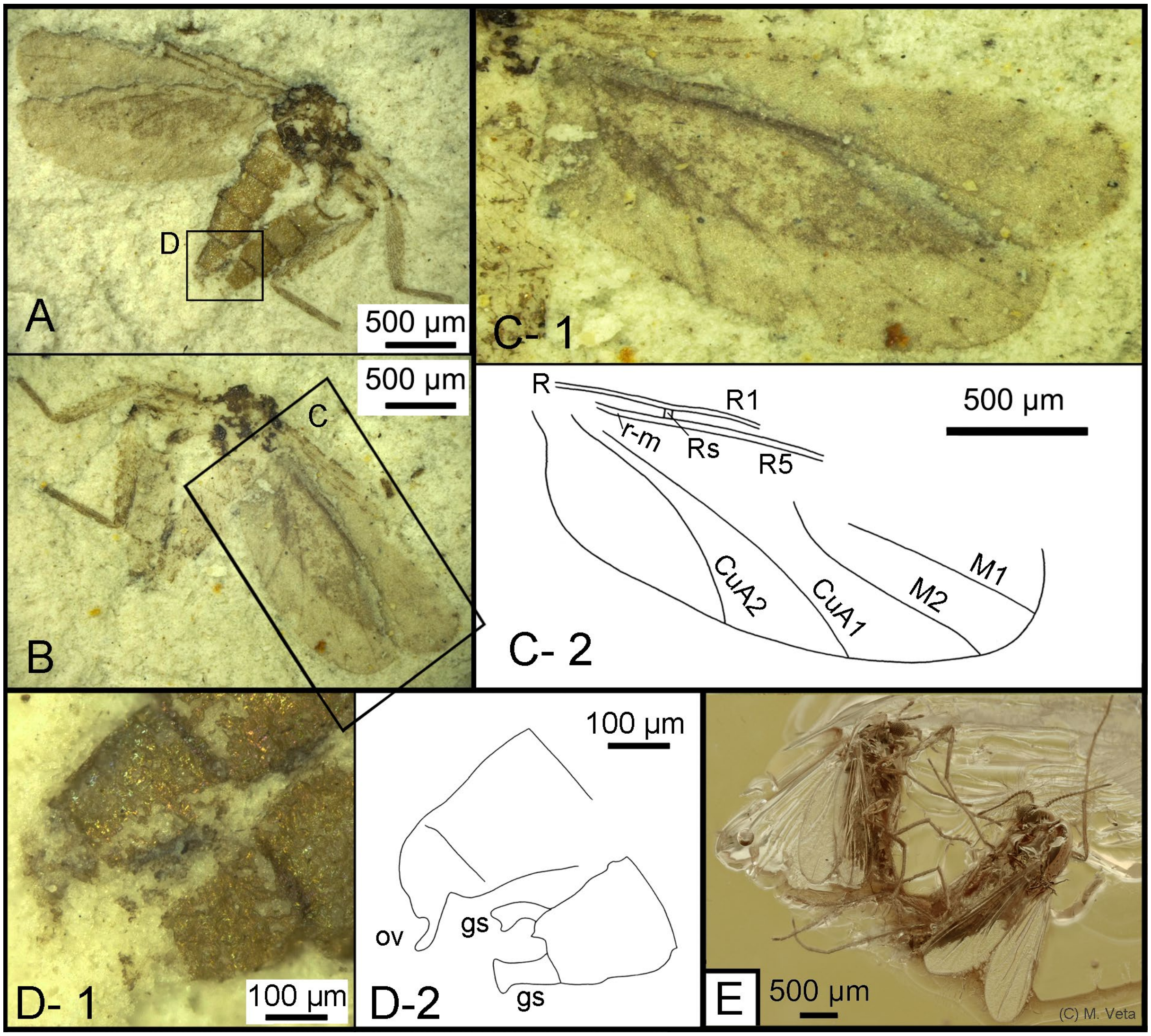

Figure 2. Mating fossils of sciarid and chironomid flies. **A**–**D**, mating pair of sciarid flies from the Pleistocene Shiobara Group; A, EES-ty0001a; B, EES-ty0001b, counter part of A; C-1, wings of the female; C-2, interpretation of C-1; D-1, distal parts of the abdomen; D-2, interpretation of D-1; **E,** mating pair of chironomid flies in Eocene Baltic amber. The right individual represents male and left female. The photo is reprinted by cortesy of M. Veta. Abbreviation: R1 = anterior branch of radius; R5 = posterior branch of radius; Rs = radial sector; r-m = crossvein; M1 = anterior branch of media; M2 = posterior branch of media; CuA1 = first branch of anterior branch of cubitus; CuA2 = second branch of anterior branch of cubitus; Ov = ovipositor of the female; gs = gonostylus of the male genitalia.

example (please see the caption of Figure 2 for abbreviations): R, R1, R5, Rs, r-m, M1, M2, CuA1, and CuA2. Based on the arrangement of these wing veins, this fossil fly can be identified as a member of the family Sciaridae (black fungus gnat). In particular, the branching at the base of the wing veins CuA1 and CuA2 are characteristic of fungus gnats of this family. For the genus- and species-level identification of the sciarid flies, examination of the detailed structures of the antenna, maxillary palpus, inner apex of foretibia, and male genitalia is necessary. Unfortunately, these characteristics are not preserved or clearly visible in the fossil flies reported here. Although examination of the detailed structures of the genitalia of the two flies identified in this fossil is difficult, the outlines of the apices of the abdomens are traceable, and we show the attenuated female terminalia and the claspers of the male genitalia called the gonostylus (Figure 2D-2). Posterior parts of the abdomens of these two flies are closely contiguous with each other; therefore, they could represent a female and a male sciarid fly in the process of copulation. Generally during copulation of sciarid flies, a line forms connecting genitalia of both flies (Mohrig *et al*., 2013, fig. A on page 142). Copulating postures are often disturbed in fossils showing copulating insects. The line connections are preserved in more or less V shape with fulcrums of their connecting points found in both amber and compression fossils (e.g. Penney and Jepson, 2014; Boucot and Poinar, 2011; Fujiyama and Iwao, 1974 and also see Figure 2E). Some line connections have strongly curved postures (see figure 183 on page 157 in Penney and Jepson, 2014 and Figure 2E). Therefore, we interpret that the copulatory position of these two sciarid flies was also probably disturbed during their transportation and deposition probably because of the collision to the water surface and water current, and eventually the connection was loosely broken.

Discussion

Although insect fossils demonstrating mating behavior are rare, these fossils are relatively well recognized in midges (Chironomidae and Ceratopogonidae), scavenger flies (Scatopsidae), and sciarid flies (Sciaridae). These taxa demonstrate comparatively long-lasting copulation times, and their mating pairs are thought to be more easily preserved as fossils than those of other groups of insects (Boucot and Poinar, 2011). Most sciarid flies inhabit forests and water sides, and they fly during the initial stage of their copulation. Their small bodies may be easily blown off on a windy day. These facts indicate that they tend to fall onto the surface of water while remaining in the coupling posture. Experimental verification has shown that soft tissue preservation is closely related to the intensity and duration of the transportation of water current and the degree of decay of the bodies of animals (Spicer, 1981; Allison, 1986). Fossils with well-preserved soft tissue are thought to be deposited in a short period without extensive transportation or decay. Martínez-Delclòs and Martinell (1993) have suggested that small insects can be trapped on the water surface by surface tension for several days; however, physical factors such as weak waves produced by wind and rain readily facilitate their sinking to the bottom. The fact that the two flies of our specimen remained is in a mating posture with little disturbance confirms that the specimen was rapidly buried. Fossil animals are mostly limited in laminite in Shiobara lacustrine deposits and rapid burying and anoxia probably protected them from scavenging (Allison *et al*., 2008; TuZino *et al*., 2009). Soft tissue preservation requires fast diagenesis (Briggs, 2003). Lepispheres of opal-CT derived from diatomaceous opal-A are recognized in this formation and the early diagenetic mineral associated with soft tissue preservation is silica in Shiobara (Allison *et al*., 2008). The phase change of silica may stabilize the biotic remains and contribute to the preservation of soft tissue (TuZino *et al*., 2009). In addition, diatomaceous mud works like a microbial mat, which plays a role in early mineralization and prevention of scavenging (Seilacher *et al*., 1985; Harding and Chant, 2000). Hence, the characteristics of the mating behavior of fungus gnats and the sedimentary environment of the paleo-Shiobara Lake facilitated the preservation of the specimen described here. The Shiobara lacustrine deposits have yielded many macrofossils, and this discovery serves as a reminder of the importance of this deposit. Further discoveries of ethology-indicative insect fossils, such as those that show predatory behaviors (which are more frequently seen than copulation) are prospective.

Conclusion

The specimen described here represents one of the rare examples of dipteran compression fossil showing mating behavior of sciarid flies. The mating behavior of the sciarid fly and the particularly depositional environment of the paleo-Shiobara Lake were factors that facilitated the preservation of this specimen. This discovery reiterates the importance of the Shiobara lacustrine deposit. Further discoveries of fossils indicative of the ethology of insects are expected.

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