Phylogeny and Taxonomy of Flatheads, Scorpionfishes, Sea Robins, and Stonefishes (Percomorpha: Scorpaeniformes) and the Evolution of the Lachrymal Saber

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We report on the discovery of a remarkable defensive specialization in stonefishes that was identified during a phylogenetic study of scorpionfishes and their relatives. This newly described innovation, the lachrymal saber, involves modifications to the circumorbitals, maxilla, adductor mandibulae, and associated tendons. At its core, the lachrymal saber is an elongation of an anterior spine (or spines) on the ventral surface of the lachrymal that stonefishes are capable of rotating from the standard ventral position to a locked lateral position. The locking mechanism minimally includes a bony spur on the inner surface of the lachrymal and a ridged bony protuberance on the anterolateral end of the maxilla. A modified and highly subdivided adductor mandibulae appears to control the movement of the lachrymal saber by rotating the maxilla while it is engaged with the spur on the medial side of the lachrymal. This maxillary rotation results in a subsequent rotation of the lachrymal that we hypothesize reduces predation on stonefishes. This specialization was included in our phylogenetic analysis of scorpionoid fishes. This study expands upon the previous higher-level taxonomic sampling reported in earlier evolutionary studies of scorpionoid fishes and, unlike previous analyses, explicitly combines molecular and morphological data with an expanded taxonomic sampling to mitigate the conflict between these competing datasets. The resulting phylogeny based on a combination of 113 morphological and 5,280 molecular characters for 63 species is used to produce a revised taxonomy of flatheads, scorpionfishes, sea robins, and stonefishes. Our results do not support the monophyly of the traditional Scorpaeniformes, Scorpaenoidei, Scorpaeonoidea, Platychelys, Bembridae, Scorpaeidae, Sebastidae, Serranidae, Tetrarogidae, or Triglidae. Our monophyletic taxonomy recognizes nine monophyletic families: Bembridae, Congiopodidae, Hoplichthyidae, Neosebataeidae, Platychelysidae, Plectrogeniidae, Scorpaeidae, Synanceidae, and Triglidae. The taxonomic composition of the Congiopodidae, Hoplichthyidae, Neosebataeidae, and Platychelysidae are unchanged. The Bembridae is expanded to include the recently described Parabembra, while Bembradina is moved to the Plectrogeniidae. The Scorpaeidae is expanded to include the traditional Sebastidae and Setarchidae. The Triglidae is expanded to include the Peristidiidae. Finally, a revised Synanceidae, diagnosed by the lachrymal saber, is expanded to include the Apistidae, Aploactinidae, Eschmeieridae, Gnathanaeidae, Pataecidae, Perryidae, and Tetrarogidae. Based on these results, we recommend treating all of these traditional scorpaenoid clades as families in an expanded Scorpaeonoidea that includes a restricted Scorpaenoidei that includes all traditional scorpaenoid families except the Congiopodidae. The resulting phylogeny is then used to explore aspects of scorpaenoid evolution.

DEFENSIVE specializations have altered the evolution of major radiations of organisms because of their role in competition and species survival (Vamosi, 2005; Bosher et al., 2006). In fishes, these innovations range from the evolution of poisons or venoms (Randall et al., 1971; Smith et al., 2016) and related Batesian mimicry (Casewell et al., 2016) to the repeated evolution of armor (Yang et al., 2013) and spines (Moser, 1981; Price et al., 2015). Anti-predator defenses obviously benefit the species that possess them, and these innovations have been implicated as causative agents in the diversification of some groups (Vamosi, 2005; Nagy et al., 2012). Herein, we report on a novel specialization in stonefishes that has a presumed defensive role. This feature, which we call the lachrymal saber, involves modifications to the circumorbitals, maxilla, adductor mandibulae, and associated tendons. This complex defensive morphological innovation was discovered during a study exploring the phylogeny and morphology of flatheads, scorpionfishes, sea robins, and stonefishes (Scorpaeonoidea sensu Imamura, 2004) and has implications for the evolution of the Scorpaeonoidei and the monophyly of the Synanceidae.

The Scorpaeonoidea represents a tremendous assemblage of mail-cheeked fishes with approximately 818 species (Eschmeyer et al., 2017) that has been classified in 6–20 families (e.g., Matsubara, 1943; Washington et al., 1984; Imamura and Shinohara, 1998; Mandyntza, 2000; Shinohara and Imamura, 2005; Eschmeyer et al., 2017). Over the last 30 years, there have been multiple attempts to resolve the phylogenetic relationships of the scorpionoids and the placement of its included fishes among the mail-cheeked fishes using explicit morphological data (e.g., Washington et al., 1984; Ishida, 1994; Imamura, 1996, 2004; Mandyntza, 2001; Richards and Jones, 2002; Shinohara and Imamura, 2005; Ishii and Imamura, 2008; Kawai, 2008; Honma et al., 2013; Fig. 1). These morphological studies have provided phylogenies that are both iterative improvements building upon previous work as well as evolutionary hypotheses that are incongruent with preceding studies. In addition to these morphological phylogenies, there have been DNA-sequence-based explorations of the Scorpaeonoidei or major groups within it (e.g., Smith and Wheeler, 2004, 2006; Hyde and Vetter, 2007; Smith and Craig, 2007; Lautredou et al., 2013; Portnoy et al., 2017; Fig. 2). These studies have not focused on the limits and relationships of Scorpaeonoidei as a whole. However, they have supported some previous morphological hypotheses (e.g., placement of Caracanthus among scorpae- nids; Shinohara and Imamura, 2005; Smith and Craig, 2007; Lautredou et al., 2013) and refuted others (e.g., placement of...
Fig. 1. Morphological hypotheses of inter- and intrafamilial relationships of the scorpaenoid lineage and allies: (A) traditional scorpaeniforms (Matsubara, 1943); (B) scorpionfishes and allies (Matsubara, 1943); (C) Scorpaenoidea (Imamura, 2004); (D) Scorpaenoidei (Ishida, 1994).
Congiopodidae among the stonefishes [Ishida, 1994; Imamura, 2004] vs. outside of the stonefishes [Smith and Craig, 2007; Lautredou et al., 2013]. Differences between the results of morphological and molecular phylogenetic analyses are common (Smith, 2010; Wiley et al., 2011; Grande et al., 2013), but comparing differences among studies or datasets can often enable researchers to recognize or hypothesize previously undetected patterns of convergence and character loss (e.g., Wainwright et al., 2012; Stewart et al., 2014; Davis et al., 2016). These convergences are best explored in combined analyses, so we followed the lead of the morphological studies (Matsubara, 1943; Ishida, 1994; Imamura, 1996, 2004; Shinohara and Imamura, 2005; Honma et al., 2013; Fig. 1) and iteratively improved upon prior work by building on existing morphological data and adding species and new character data. We combined this expanded morphological dataset with a largely complementary molecular dataset to resolve conflict among the varied molecular and morphological phylogenies and generated a comprehensive family-level hypothesis of scorpaenoid relationships and corresponding monophyletic taxonomy.

**MATERIALS AND METHODS**

**Taxon sampling.**—Sixty-three taxa were analyzed in the current phylogenetic study. To provide a test of scorpaenoid monophyly and relationships, 12 outgroups were included: Anthiadiidae, Bathymasteridae, Bembropidae, Bovichtidae, Cirrhitidae, Epinephelidae, Niphonidae, Percidae, Psychrolutidae, Serranidae, and Trachinidae. The topology was rooted with *Cirrhitus* (Centrarchiformes), which has long been closely allied with, but excluded from, the mail-cheeked fishes (Gill, 1888; Smith and Wheeler, 2004; Near et al., 2013). The 51 traditional scorpaenoid terminals analyzed in this study included all 20 scorpaenoid families (clade sensu Imamura, 2004; classification sensu Eschmeyer et al., 2017).
### Table 1. Primers, PCR conditions, and substitution models for each amplicon analyzed in the current study.

<table>
<thead>
<tr>
<th>Primer name (source)</th>
<th>Primer sequence</th>
<th>Primary annealing temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tRNA-Val-16S (Titus, 1992; Feller and Hedges, 1998)</td>
<td>5'-TTAGAAGGCAAGTCGACATCTGTA-3'</td>
<td>48</td>
</tr>
<tr>
<td>125L13-L</td>
<td>5'-GGTGGCTGTCTTTAGGCC-3'</td>
<td>48</td>
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<tr>
<td>TitusH-H</td>
<td>5'-GCCGTGAACTGATGACCTG-3'</td>
<td>48</td>
</tr>
<tr>
<td>16Sar-br (Kocher et al., 1989; Palumbi, 1996)</td>
<td>5'-CCCTCTTATCGAAAAACAT-3'</td>
<td>48</td>
</tr>
<tr>
<td>ar-L</td>
<td>5'-CCCGTGAACCTAGATAGCTG-3'</td>
<td>48</td>
</tr>
<tr>
<td>16S ar-L</td>
<td>5'-GCCAACAATGATAGATGACCTG-3'</td>
<td>48</td>
</tr>
<tr>
<td>COI (Folmer et al., 1994)</td>
<td>5'-AACATCGAGGTGACCAAAAAATCA-3'</td>
<td>46</td>
</tr>
<tr>
<td>LCO1490</td>
<td>5'-AACATCGAGGTGACCAAAAAATCA-3'</td>
<td>46</td>
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<tr>
<td>HCO2198</td>
<td>5'-AACATCGAGGTGACCAAAAAATCA-3'</td>
<td>46</td>
</tr>
<tr>
<td>28S (Hillis and Dixon, 1991)</td>
<td>5'-AAGATGCGAAATGCTGTCAC-3'</td>
<td>48</td>
</tr>
<tr>
<td>28SV</td>
<td>5'-AAGTTAGTTTACCTACT-3'</td>
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<tr>
<td>28SJJ</td>
<td>5'-ATATCGTGTGTTTTTGTGRATYTT-3'</td>
<td>48</td>
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<tr>
<td>Histone H3 (Colgan et al., 1998)</td>
<td>5'-GGACGCAGGACCGCARTAYC-3'</td>
<td>48</td>
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<tr>
<td>H3a-L</td>
<td>5'-GGACTGTCMAAGATGACCACVGC-3'</td>
<td>48</td>
</tr>
<tr>
<td>H3b-H</td>
<td>5'-ATATCGTGTGTTTTTGTGRATYTT-3'</td>
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<tr>
<td>TMO-4c4 (Steeleman and Karl, 1997)</td>
<td>5'-CGTCAAAATGATAGATGACCTG-3'</td>
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<tr>
<td>TMO-f1</td>
<td>5'-GGACGCAGGACCGCARTAYC-3'</td>
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<td>TMO-r1</td>
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<td>Glyt (Li et al., 2007)</td>
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<td>5'-AGGTTAGTTTACCTACT-3'</td>
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**Character sampling.**—A total of 5,393 morphological and molecular characters were scored. These data included 5,280 aligned nucleotides from five nuclear and three mitochondrial loci. Previous studies have shown the effectiveness of the included molecular loci for resolving relationships among percomorphs generally or mail-cheeked fishes specifically (e.g., Chakrabarty et al., 2011a, 2011b; Li et al., 2011; Near et al., 2012a, 2012b; Girard and Smith, 2016). The molecular terminals analyzed in the present study and GenBank accession numbers corresponding to the gene fragments sequenced are listed in Supplemental Table 1 (see Data Accessibility). For these analyses, the 134 novel DNA sequences were combined with previously published DNA sequences from the following sources: Smith and Wheeler (2004, 2006); Smith and Craig (2007); Smith et al. (2009, 2016); Near et al. (2012a, 2013, 2015); Wainwright et al. (2012). The molecular matrix was 90% complete at the ampiclon level and 82% complete at the cell or individual-base-pair level (Supplemental Table 1; see Data Accessibility). These molecular data were simultaneously analyzed with a morphological dataset (Supplemental Table 2; see Data Accessibility; Appendix 1) composed of 113 characters that was built from multiple sources, but focused on the work of Imamura (2004). Details about additional sources of morphological data are listed along with all character descriptions in Appendix 1. The morphological matrix was 92% complete at the cell or individual character level (Supplemental Table 2; see Data Accessibility).

**Acquisition of nucleotide sequences.**—Fish tissues were preserved in 95% ethanol prior to extraction of DNA. Nuclear and mitochondrial DNA was extracted from muscle using a DNeasy Tissue Extraction Kit (Qiagen). The polymerase chain reaction (PCR) was used to amplify all gene fragments. Double-stranded amplifications were performed in a 25 μL volume containing one Ready-To-Go PCR bead (GE Healthcare), 1.25 μL of each primer (10 pmol), and 2–5 μL of undiluted DNA extract. Primers and primer sources are listed in Table 1. Amplifications for all novel fragments except Glyt and zic1 were carried out using the following temperature profile: initial denaturation for 360 sec at 94°C; 36 cycles of denaturation for 60 sec at 94°C, annealing for 60 sec at 46–51°C (see Table 1 for primary annealing temperature for each locus), and extension for 75 sec at 72°C; with a final terminal extension for 360 sec at 72°C. For Glyt and zic1, the following temperature profile was used: initial denaturation for 180 sec at 94°C; ten cycles of denaturation for 45 sec at 94°C, annealing for 45 sec at 57–58°C (see Table 1 for core annealing temperature for each locus), and extension for 75 sec at 72°C; 30 cycles of denaturation for 45 sec at 94°C, annealing for 30 sec at 55–57°C (see Table 1 for secondary annealing temperature for each locus), and extension for 75 sec at 72°C, with a final terminal extension for 360 sec at 72°C. The double-stranded amplification products were desalted and concentrated using AMPure (Beckman Coulter). Both strands of the purified PCR fragments were used as templates and amplified for sequencing using the amplification primers and a Prism Dye Terminator Reaction Kit v1.1 (Applied Biosystems) with minor modifications to the manufacturer's protocols. The sequencing reactions were cleaned and desalted using cleanSEQ (Beckman Coulter). The nucleotide sequences were sequenced and the base pairs were called on a 3730 automated DNA sequencer (Applied Biosystems) or by Beckman Coulter Genomics (Danvers, MA). Contigs were built in Geneious v8.1.8 (Kease et al., 2012) using DNA sequences from the complementary heavy and light strands. Sequences were edited in Geneious and collated into fasta text files. The novel sequences were submitted to GenBank and assigned accession numbers MF966393–MF966401 and MF991301–MF991425.
**Morphological investigation.**—Ethanol preserved, cleared and stained, and dried skeletal material was examined using several stereomicroscopes with varying magnification and lighting regimes. Photographs documenting the anatomy of specimens were taken under normal visible lighting with either a Nikon D800 with an AF-S VR Micro-NIKKOR 105mm f/2.8G IF-ED lens or a Lumenera INFINITY2-5 digital CCD camera attached to a Nikon SMZ-18 stereomicroscope. Fluorescent images were taken either using the D800 with lighting from two NightSea BlueStar flashlights (Lexington, MA) and filtered through the Nikon light-shading plate from the Nikon SMZ-18 microscope or using the Nikon SMZ-18 stereomicroscope with either a Nikon P2-EFL GFP-B or P2-ELF RFP filter cube. Drawings of specimens were aided with a camera lucida arm attachment.

**Phylogenetic analyses.**—A likelihood analysis was used to analyze the molecular and morphological data. For this purpose, each of the eight amplicons was aligned individually in MAFIT v.7.0.17 (Katoh et al., 2002) using default values. The maximum-likelihood dataset was broken into 18 partitions. Two partitions were designated for the mitochondrial (12S, rRNA-Val-16S, and 16Sar-br) and nuclear (28S) ribosomal fragments. Fifteen partitions covered the three codon positions in each of the five protein-coding genes: mitochondrial (cytochrome oxidase I) and nuclear (Glyt, histone H3, TMO-4c4, and zic1). The 18th partition was the morphological dataset (Supplemental Table 2; see Data Accessibility). The optimal nucleotide substitution model for each molecular partition was determined empirically (Table 1) by comparing different models under an Akaike information criterion as executed in jModelTest v0.1 (Posada, 2001). The optimal model was set to Mkv (Lewis, 2001). The datasets were coded, concatenated, examined, and analyzed (ancestral-state reconstructions) in Mesquite v3.04 (Maddison and Maddison, 2017). Maximum-likelihood analyses were conducted in GARLI v2.01 (Zwickl, 2006). The tree with the best likelihood score from 40 independent analyses was selected as the preferred hypothesis. A non-parametric maximum-likelihood bootstrap analysis was conducted for 200 random pseudoreplicates to assess nodal support. For the support analysis, terminals represented solely by morphological data were excluded (Eschmeyer and Perryena) because they have excessive missing data in the combined analysis; the optimal tree with these terminals excluded was otherwise identical to the complete phylogeny (results not shown). We recognize two levels of nodal support: ≥70% bootstrap support represents a moderately supported node or clade and ≥95% bootstrap support represents a well-supported node or clade.

**RESULTS**

**Phylogenetic analyses.**—The likelihood analysis resulted in a single optimal tree (Fig. 3). Most of the 59 nodes recovered in the bootstrap analysis (analysis excluding Eschmeyer and Perryena) were moderately to well supported with 36 (61%) nodes being moderately supported by a bootstrap value ≥70 and 24 (41%) nodes being well supported by a bootstrap value ≥95. In this analysis, the traditional cottoid and zoarcoid representatives were nested within the Scorpaenidae (sensu Imamura, 2004), sister to the Congiopodidae. This congiodod + zoarcoid + cottoid clade was recovered as the sister group to all non-congiodod scorpoidae fishes. Many traditionally recognized family-level clades (sensu Eschmeyer et al., 2017) that were represented by more than a single terminal were recovered as monophyletic: Congiopodidae, Neosebastidae, Pataceidae, Peristediidae, Platyccephalidae, Setarchidae, and Synanceiidae. In contrast, the Bembridae, Scorpaenidae, Sebastidae, Tetrarogidae, and Triglidae were recovered as para- or polyphyletic. As has been seen in previous morphological and molecular analyses, the core scorpionfishes included *Caranx* (Smith and Wheeler, 2004, 2006; Shinohara and Imamura, 2005; Smith and Craig, 2007; Lautredou et al., 2013) and the traditional Setarchidae (Imamura, 2004; Smith and Wheeler, 2004, 2006; Shinohara and Imamura, 2005). Similarly, hoplichthyids were recovered as more closely related to the Triglidae + Peristediidae than to platycephalids (see also Imamura, 1996, 2004; Lautredou et al., 2013). In contrast to morphological phylogenies (Ishida, 1994; Imamura, 2004) and some molecular phylogenies (Lautredou et al., 2013), but in agreement with other molecular phylogenies (e.g., Smith and Wheeler, 2004, 2006), the live-bearing rockfishes (e.g., Helicolenus, Sebastes) were nested deeply in the scorpionfishes as opposed to a stem grade. Despite these similarities to other studies, the combined analysis of morphological and molecular data is frequently in conflict with the traditional taxonomy and prior phylogenetic work. The traditional Peristediidae was nested within the Triglidae (see also Portnoy et al., 2017, *Bembradium* was allied with *Plectrogninium* (see also Imamura, 1996, 2004), Tetrarogidae was widely polyphyletic within a “stonefish” clade (see also Mandrytza, 2001; Smith and Wheeler, 2004; Honma et al., 2013), and representatives of the Scorpaenidae and Sebastidae were variously distributed within a “scorpionfish” clade. If we compare our results to a recent classification of fishes (Betancur-R. et al., 2017), we note that their Percioidei, Platyccephaloidei, Serranoidei, Scorpaenidae, Serranidae, Tetrarogidae, and Triglidae were recovered as polyphyletic. Their Scorpaenoidae was the only relevant higher-level grouping with multiple families that was recovered as monophyletic in our analysis. The differences between our results and previous hypotheses necessitate the familial taxonomic revisions presented herein (Fig. 3; Appendix 2). All of the remaining results and discussion below will use the revised classification unless noted otherwise.

**Description of the lachrymal saber.**—The lachrymal saber is a complex feature that involves a series of modifications to the circumorbitals, maxilla, *adductor mandibulae*, and associated tendons. Among mail-cheeked fishes, there are some modifications to these lachrymal-saber elements (e.g., *adductor mandibulae* variation as illustrated by Yabe [1985] and Mandrytza [1990]), but we treat this element as a single feature in this study. Future studies looking broadly at the phylogeny of mail-cheeked fishes should consider the historical independence of several aspects of the lachrymal saber to assess their individual phylogenetic significance. For example, many triglids have additional tendinous connections between the *adductor mandibulae* and maxilla that appear anatomically similar and potentially convergent with some synanceiids while lacking the remainder of the lachrymal-saber modifications (Yabe, 1985; Mandrytza, 1990; pers. obs.).

As expected, the circumorbitals of synanceiids lie lateral to the suspensorium (Figs. 4, 5). As with most mail-cheeked fishes, the third circumorbital is firmly attached to the preopercle posteriorly forming the characteristic suborbital stay. The circumorbitals are attached anterodorsally to the...
maxilla and anterodorsally to the lateral ethmoid via the lachrymal. Both anterior lachrymal attachments have substantive soft-connective tissue, which enables the necessary rotation of the lachrymal saber while also holding the bones in close association. The circumorbitals of mail-cheeked fishes frequently have elongations of their lateral-line canal pores that create the group's characteristic bony spines and knobs (Smith, 2005). In all species with a lachrymal saber,
the ventral spines associated with the second pore on the first circumorbital (lachrymal) are enlarged (Figs. 4–7). As noted in revisions and artificial keys separating various mail-cheeked fishes (e.g., Poss, 1999), the lachrymal is highly mobile and hinged to the lateral ethmoid dorsally in synanceiids. As the element is relatively free to rotate, it abuts, but is not as firmly bound to, the second circumorbital as is otherwise common among scorpaenoid fishes. This freedom allows for the rotation of this element such that the typical ventral lachrymal spines, including the larger spine, can be rotated laterally and projected outward making the “saber” (Fig. 5).

The lachrymal saber can be held in an outwardly projected or lateral position by a locking mechanism that functions somewhat like a ratchet and pawl that relies on the friction between highly textured (often ridged) modifications on both the medial surface of the lachrymal and the lateral surface of the maxilla. These modifications include a bony spur that ranges from a peg to a cup on the inner surface of the lachrymal (Fig. 6A) and a ridged bony protuberance on the anterolateral end of the maxilla (Fig. 6B). The lachrymal’s medial projection acts as the pawl when the saber is extended laterally. This lachrymal pawl, when in a locked position, is tightly connected to a highly sculptured protuberance on the anterior end of the maxilla that acts somewhat like a ratchet allowing the lachrymal to be held firmly in place (Fig. 7). While the lachrymal is free to rotate, its motion is highly constrained by a notable amount of soft connective tissue.

Manipulations of ethanol preserved and cleared and stained specimens indicate that the lachrymal saber is likely rotated and controlled by movements of the maxilla. The maxilla can be rotated by contractions of the various subunits of the adductor mandibulae A₁ division that have diversified among synanceiids. These separate muscle subdivisions can facilitate the engagement of the locking mechanism as well as outward rotation of the lachrymal (Figs. 4, 5) and, to a lesser degree, the second circumorbital (Fig. 4B). The number, size, and placement of adductor mandibulae A₁ division subunits and their associated tendinous connections vary tremendously among synanceiids (Fig. 8; Mandrytza, 1990). The traditional adductor mandibulae A₁ division in synanceiids has between two and five discernible subunits that variously originate caudally from the preopercle, the suborbital stay of the third circumorbital, the ventral surface of the third circumorbital, and/or the ventral surface of the second circumorbital. These muscles attach anteriorly to the maxilla via a diversity of tendons (Figs. 7, 8; Yabe, 1985; Mandrytza, 1990; Ishida, 1994). As these tendons can be homologous with ligaments in other fish groups (Johnson and Patterson, 2001; Datovo and Vari, 2013), individual representatives of these elements are often referred to as ligaments. As emphasized in Yabe (1985) and Mandrytza (1990), the proliferation of adductor mandibulae A₁ division subunits and their associated tendons/ligaments in synanceiids requires a more taxonomically comprehensive study across percomorphs generally and scorpaenoids specifically before the specific homology of the elements can be determined.

Many aspects of the lachrymal saber vary: the number of adductor mandibulae A₁ division subunits, the caudal origination locations of the adductor mandibulae A₁ division subunits, the number and placement of tendons inserting on the maxilla, the length of the lachrymal spines, and the shape and size of the lachrymal and maxillary components of the locking mechanisms. Despite this substantial variation, all of the synanceiids have the core modifications to the circumorbitals, maxilla, adductor mandibulae, and associated tendons that constitute this novel defensive mechanism.
In addition to anatomical investigations using typical LED “daylight” lighting, one specimen was examined under fluorescence (Synanceiidae: *Centropogon australis*; Fig. 9). The lachrymal saber in this species biofluoresced in the green spectrum (Fig. 9B), whereas other regions of the head fluoresced red (Fig. 9C). Compared to visible light (Fig. 9A), stereomicroscopic images using fluorescence (Fig. 9B) highlight regions associated with the lachrymal saber that fluoresce in the green spectrum. Additional inspection (Fig. 9C) illuminated with two NightSea BlueStar flashlights and filtered through the Nikon light-shading plate highlights both the green lachrymal saber element and the red fluorescence associated with eye rings in this species of stonefish. Considerably more species need to be examined to assess the diversity of species that have biofluorescent lachrymal sabers or even whether additional species have this visual modification.

**DISCUSSION**

This study was designed to look at the limits and relationships of the Scorpaenoidea (*sensu* Imamura, 2004). In particular, we focused on the interrelationships of genera that were recovered in different phylogenetic positions in earlier studies (i.e., *Bembradium, Congiopodus, Ectreposebastes, Helicolenus, Hoplichthys, Hozukius, Plectrogenium, Sebastes, Sebastiscus, Sebastolobus, Setarches, Trachyscorpia*, and *Zanclorhynchus*; Figs. 1, 2). Beyond scorpionfish generic relationships, our results provide an opportunity to re-examine the limits of the scorpionfishes generally. Imamura and Yabe (2002) grouped their Scorpaenoidea with the Serranidae (*sensu* Nelson, 2006) independent of other traditional perciform or scorpioniform fishes. Our results (Fig. 3) did not recover this hypothesized clade or a monophyletic Serranidae or Scorpaenoidea. We recovered a polyphyletic Serranidae (*sensu* Johnson, 1983), which corroborates the findings of all recent studies that have sampled multiple subfamilies of traditional serranids and/or *Acanthistius* and *Niphon* (e.g., Smith and Craig, 2007; Lautredou et al., 2013; Neal et al., 2013, 2015). Imamura and Yabe (2002) and Imamura (2004) expanded our understanding of the Scorpaenoidea over previous studies (e.g., Matsubara, 1943; Washington et al., 1984; Ishida, 1994) and diagnosed their Scorpaenoidea by a single postocular spine in larvae, an extrinsic gas bladder muscle derived from the *obliquus superioris*, a parietal lateral-line canal with spine, and a suborbital stay. Imamura (2004) and the current study did not broadly examine the larval spine feature across all scorpionoid fishes. The postocular spine was not included in the current analysis because its distribution is insufficiently known across scorpionoids. In

![Fig. 5. Lateral (A), rostral (B), and dorsal (C) views of the lachrymal saber in the Soldierfish (*Gymnapistes marmoratus*, AMNH 31009). Arrow highlights both the resting and locked lachrymal saber in the various angles.](https://bioone.org/journals/Copeia)
our analysis, the most recent common ancestor (MRCA) of all traditional scorpaenoids included the representative cottoid and zoarcoid taxa. This larger MRCA is diagnosed by four unambiguous synapomorphies that include two of the three previously identified scorpaenoid characters: a suborbital stay with a broad distal end that is strongly connected to the preoperculum (character 8, state 3) and an extrinsic muscle that was connected to the neurocranium anteriorly and vertebrate posteriorly (character 101, state 2) and two additional characters: the reduction of supraneurals to zero (character 65, state 3) and the fusion of hypurals one and two (character 68, state 1). A more restricted scorpaenoid MRCA that excludes the congiopodids, cottoids, and zoarcoids is herein recognized as a revised Scorpaenoidei that is diagnosed by the presence of a parietal lateral-line canal with a spine (character 24, state 1).

Congiopodidae.—The Congiopodidae is a small Southern Hemisphere endemic family that has been recovered in a diversity of phylogenetic placements (Ishii and Imamura, 2008). Traditional higher-level phylogenetic studies (e.g., Regan, 1913; Greenwood et al., 1966) placed the congiopodids among the mail-cheeked fishes in their own order or suborder. Using morphological data and explicit phylogenetic analyses (Fig. 1), Ishida (1994) placed congiopodids sister to Synanceiidae (sensu Imamura, 2004) using five shared myological features and Imamura (2004) placed congiopodids sister to a clade composed of Gnathanacanthidae and Pataceidae (both sensu Imamura, 2004) using preopercular spination, the loss of the uroneural, and the separation of the transversus ventralis posterior. In contrast, Mandrytza (2001) recognized a congiopodid clade (composed of a separate Congiopodidae and Zanclorhynchidae equivalent to our Congiopodidae) independent of his Scorpaenoidea. Mandrytza (2001) presented a variety of results, but his various explicit morphological analyses either allied his Congiopodoidei with a restricted Cottoidei (not including or associated with the Anoplopomatoidei, Hexagrammatoidei, and Zoarcoidae) or in a polytomy with Anoplopomatoidei, Cottoidei + Hexagrammatoidei, Hoplichthyoidae, Normanichthyoidae, and Scorpaenoidei (all sensu Mandrytza, 2001). Mandrytza (2001) also provided evidence that *Perryena* was not a congiopodid; instead, he suggested that this genus was a member of the Tetrarogidae (sensu Mandrytza, 2001). This finding was largely corroborated in a morphological analysis of a subset of scorpaenoids by Honma et al. (2013) who created a new family, Perryenidae, for this genus because of the non-monophyly of their two putative tetrarogids (*Perryena* and *Tetraroge*) included in their analysis. Earlier analyses of DNA-sequence data have resulted in even more hypotheses than the diversity of morphological studies. Smith and Wheeler (2004) recovered a separate Congiopodus (sister to Neosebastidae) and Zanclorhynchus (sister to the Notothenioidae). Li et al. (2009) recovered Zanclorhynchus sister to all other scorpaeniform fishes. Smith and Wheeler (2006) recovered Congiopodus sister to Bembridae. Smith and Craig (2007; Fig. 2A) recovered a clade composed of Congiopodus + Zanclorhynchus sister to Neosebastidae. Lautredou et al. (2013; Fig. 2B) recovered Zanclorhynchus sister to a clade composed of Plectrogeniidae + Scorpaenidae + Synanceiidae. Near et al. (2015) recovered a clade composed of Congiopodus + Zanclorhynchus sister to a clade composed of Bembridae,

![Fig. 6. Skeletal images of the key lachrymal saber components. (A) Lateral image of the lachrymal, second circumorbital (CO2), and third circumorbital (CO3) in *Minous quincarinatus*, KUI 41397. Circular inset of upper image shows medial view with medial protuberance (PP). (B) Lateral image of the maxilla in *Apistus carinatus*, KUI 41400. Circular inset of lower image shows closeup of the maxillary protuberance (MP). These two protuberances interact to lock the lachrymal saber.](https://bioone.org/journals/Copeia on 16 Apr 2020 Terms of Use: https://bioone.org/terms-of-use)
Fig. 7. Composite dorsal images of various specimens of *Paracentropogon* highlighting the morphology of the components of the lachrymal saber with the locked position on the left side and the resting position on the right side. Note that the anteriormost component of the palatine has been made largely transparent in the images to allow for a better examination of the maxilla. The upper image (A) represents the anatomy with all elements marked, and the lower image (B) represents the image with the circumorbitals shadowed to visualize underlying muscles. Muscle attachments on removed bones are denoted with pale circles at the interface. Abbreviations: A1 or A2 represent the major subdivisions of the *adductor mandibulae*; CO3–circumorbital 3; CO4–circumorbital 4; LAP–*levator arcus palatini*; MP–maxillary protuberance. Illustration by Clara Richardson.
Bembropidae, and Scorpaenidae. Finally, Smith et al. (2016) recovered a clade composed of *Congiopodus* + *Zanclorhynchus* sister to a clade composed of the Plectrogeniidae + Scorpaenidae + Synanceiidae. We recover (Fig. 3) the Congiopodidae sister to a clade composed of the cottoids + zoarcoids, which is most similar to the findings of Mandrytza (2001). Our results corroborate the findings of Mandrytza (2001) and Honma et al. (2013) that separate *Perryena* from other traditional tetrarogids. Our sister-group relationship between congiopodids and cottoids + zoarcoids is supported by the

![Fig. 8. Lateral view of the non-circumorbital components of the lachrymal saber in composite images of the various specimens of *Paracentropogon* above (A) and the various specimens of *Apistus* below (B). The comparisons are shown to illustrate variation in this system between species (e.g., subdivisions and attachment points of the adductor mandibulae). Muscle attachments on removed bones are denoted with pale circles at the interface. Abbreviations: A1 or A2 represent the major subdivisions of the adductor mandibulae; LAP—levator arcus palatini; MP—maxillary protuberance. Illustration by Clara Richardson.](image-url)
loss of the metapterygoid lamina (character 32, state 1), the loss of one branchiostegal ray (character 37, state 1), the loss of a tooth plate on the third epibranchial (character 40, state 1), the separation of the lateral extrascapular into two elements (character 45, state 1), the fusion of the lower hypural plate and the parhypural (character 71, state 1), the origin of the levator operculi on the pterotic and posttemporal (character 83, state 1), the presence of adductores I–III (character 91, state 1), and the obliquus superioris not extending to the neurocranium (character 103, state 1). The overwhelming majority of explicit analyses and our results recover a monophyletic Congiopodidae that includes Zanclopteron; we recover 12 characters supporting the monophyly of this family (Appendix 2). Further, most recent studies separate the Congiopodidae from the Synanceiidae. The placement of this clade is inconsistently recovered across studies, and it remains difficult to know whether the family is more allied with the cottoid or scorpaenoid components of the scorpaeniform tree. We recommend treating this clade as a separate family within its own suborder Congiopodoidei.

**Bembridae, Hoplichthyidae, Platyecephalidae, and Triglidae.**—Traditionally, the Bembridae, Hoplichthyidae, and Platyecephalidae have been treated as a single evolutionary unit (Matsubara, 1943; Washington et al., 1984; Fig. 1). As first noted by Imamura (1996), explicit analyses of “platyecephaloid” relationships do not recover bembrids in a clade with the hoplichthyids and platyecephalids. Instead, Imamura’s (1996) study demonstrated that Platyecephalidae was sister to a clade of Hoplichthyidae + Triglidae. These three families were then hypothesized to be sister to Bembras, and that clade was subsequently hypothesized to be sister to Parabembras (Imamura, 1996; Fig. 1). Our results support Imamura’s (1996) hypothesis that Platyecephalidae is sister to a clade composed of Hoplichthyidae + Triglidae. However, our results place this Hoplichthyidae + Platyecephalidae + Triglidae clade sister to all other scorpaenoids. This relationship supports the view that the less flattened bembrids are more closely related to scorpaeniforms and stonefishes than to hoplichthyids, platyecephalids, and triglids.

The Bembridae is a small, deep-water Indo-Pacific marine family whose limits have varied across studies. Jordan and Hubbs (1925) first separated the Parabembridae from the Bembridae, but this separation was not followed in most subsequent studies. For example, Washington et al. (1984) and Nelson (2006) included Bambradon, Bembradium, Bembras, Brachybembras (not discussed in Washington et al. [1984]), and Parabembras in their Bembridae. Imamura (1996) not only recognized a separate Bembridae and Parabembridae, but he also classified one traditional bembrid, *Bembradium*, as a member of the Plectrogeniidae. Molecular studies have not sufficiently sampled the Bembridae, and they have recovered their included bembrids sister to Congiopodidae, Hoplichthyidae, Platyecephalidae, Plectrogeniidae, Synanceiidae, or a clade composed of the Bembridae + Scorpaenidae (Smith and Wheeler, 2004, 2006; Smith and Craig, 2007; Lautredou et al., 2013; Near et al., 2013; Smith et al., 2016; Betancur-R. et al., 2017). Molecular studies that have included Bembras and Parabembras have consistently resulted in these genera forming a clade (Near et al., 2013, 2015; Betancur-R. et al., 2017), thus not requiring the recognition of a separate family-level status for Parabembridae. The current study is the first study with molecular data that included Bembradium, Bembras, and Parabembras. Given the alignment of Bembradium with Plectrogenium and the separate grouping of Bembras and Parabembras, we recommend classifying Bambradon, Bembras, Brachybembras, and Parabembras as a revised Bembridae (Appendix 2). Further, and as discussed below, our findings support the results of Imamura (1996) who placed Bembradium and Plectrogenium in the Plectrogeniidae. We recovered the Bembridae sister to a clade composed of Neosebastidae + Plectrogeniidae + Scorpaenidae + Synanceiidae (Fig. 3). This sister group relationship is supported by the loss of the lateral-line canal on the pterotic (character 22, state 0), two spines on the first dorsal-fin pterygiophore (character 56, state 0), and the presence of an adductor dorsalis (character 100, state 0).
The Hoplichthyidae is an Indo-Pacific marine family of 17 species that has been variously classified among mail-cheeked fishes but has been allied generally with the platycephalids. Traditional higher-level phylogenetic studies (e.g., Gill, 1888; Regan, 1913; Matsubara, 1943; Quast, 1965; Washington et al., 1984) placed the hoplichthyids as a separate family, closely related to the platycephalids. Greenwood et al. (1966) had a similar classification, but they treated the hoplichthyids as their own suborder, Hoplichthyoidei. Winterbottom (1993) suggested that the hoplichthyids might even be close relatives to the gobioids, so the family's placement has been historically varied. As noted above, Imamura (1996) first suggested that hoplichthyids are more closely related to the triglids than the platycephalids, and his results suggested that Hoplichthys was sister to a clade composed of Peristedion + Satyrichthys. Molecular data, beginning with Smith and Wheeler (2004), have suggested alternative placements for the hoplichthyids ranging from a close relationship with Ovalentaria to sister to the Bembriidae, Normanchitidae, Synanceiidae, a clade composed of Bembriidae + Platycephalidae, a clade composed of the “cottoids and allies” (Anoplopomatoidei, Cottoidei, Gasterosteioidei, Hexagrammoidei, and Zaniolepidoidei) + Triglidae, a clade composed of Cottoidei + Gasterosteioidei + Hexagrammoidei + Triglidae + Zoarcoidei, and a clade composed of the “cottoids and allies” + Scorpaenidae + Triglidae (Smith, 2005; Smith and Wheeler, 2006; Smith and Craig, 2007; Lautredou et al., 2013; Near et al., 2013, 2015; Smith et al., 2016; Betancur-R. et al., 2017, Fig. 2). Our results (Fig. 3) place the Hoplichthyidae sister to the Triglidae, similar to the findings of Imamura (1996, 2004; Fig. 1). This sister group relationship is supported by the presence of tubercles on the neurocranium (character 13, state 1), the loss of one postcleithrum (character 48, state 1), the increase in the number of free pectoral-fin rays to three or more (character 49, state 3), the fusion of the cartilaginous caps on the anterior portion of the pelvis (character 51, state 1), the presence of a hyohyoides inferioris (character 84, state 1), the attachment of dorsal elements of pelvic-fin muscles to the pectoral girdle (character 97, state 1), and the obliquus superioris bypassing and lying ventrally to Baudelot’s liga-

ment (character 104, state 1). As with the Congiopodidae, the placement of the hoplichthyids is inconsistent across studies. Most studies ally the hoplichthyids more with the Triglidae (often combined with the included “cottoids and allies”). Given the ambiguity, we recommend treating the Hoplichthyidae, diagnosed by 20 morphological synapomorphies (Appendix 2), as a separate scorpaenoid family.

The Platycephalidae is a modestly large family of 84 species that is found in brackish and marine environments in the Indo-Pacific region (Nelson, 2006). As has been found in previous studies, the Hoplichthyidae and Platycephalidae were recovered as independent monophyletic groups with the traditional limits (Keenan, 1991; Imamura, 1996; Appendix 2; Fig. 3). The interrelationships of the family have been discussed above, and our results support the findings of Imamura (1996) that the Triglidae + Hoplichthyidae is recovered as the sister group to the platycephalids. This sister group relationship is supported by the presence of a tooth plate on the second epibranchial (character 39, state 1). Additionally, our limited sampling of platycephalids corroborates the phylogeny and classification presented in Imamura (1996).

The Triglidae is a large family of 171 species that are found in tropical, temperate, and deep-water habitats across all oceans (Nelson, 2006). Traditional classifications (e.g., Gill, 1888; Matsubara, 1943; Washington et al., 1984; Imamura, 1996; Eschmeyer et al., 2017) often treat the Peristediidae and Triglidae as independent, closely related families. Our study corroborates the findings of Smith (2005) and Portnoy et al. (2017) that place the traditional peristediids (our peristediines) within the Triglidae. Other than the placement of peristediines inside the triglids, our hypothesized relationships support the phylogenies of Imamura (1996) and Richards and Jones (2002). Similarly, our phylogeny supports the phylogeny of Portnoy et al. (2017), including the placement of peristediines inside the Triglidae. This placement and resulting expansion (and monophyly) of the Triglidae is supported by both morphological and molecular data, and our study recovers seven characters supporting the monophyly of this expanded family (Appendix 2).

Neosebastidae and Plectrogeniidae.—The placement of Neosebastidae and Plectrogeniidae has been historically problematic; they are often represented as early diverging scorpaenoid lineages or “ancestral” forms (Matsubara, 1943; Imamura, 1996). Although the current study is the first study to unite these two families (Fig. 3), Imamura (2004), Smith and Wheeler (2004, 2006), Smith and Craig (2007), and Smith et al. (2016) have often found them relatively closely related. In this study, this sister-group relationship was supported by the separation of the first and second hypurals (character 68, state 0).

The Neosebastidae is a predominantly anti-tropical Indo-Pacific marine family of 18 species that has been often separated from the core scorpin fishes in a separate family or subfamily in modern phylogenies and classifications (Imamura, 2004; Motomura, 2004; Nelson, 2006). Beginning with Matsubara (1943) and supported by Washington et al. (1984) and Nelson (2006), the Neosebastidae has been treated as a separate subfamily (Neosebastinae) of the Scorpaenidae. Matsubara (1943) hypothesized that the neosebastids were allied with the sebastines, and Ishida (1994; Fig. 1) allied the neosebastids with the setarchines and recognized them as a separate family. Imamura (2004; Fig. 1) also recognized the clade as a separate family and suggested a non-scorpaenid relationship for the neosebastids; he resolved them with the more flattened scorpaenoids in the families Bembridae, Hoplichthyidae, Platycephalidae, Plectrogeniidae, and Triglidae. Molecular studies have grouped the neosebastids with several non-scorpaenid groups (e.g., Acanthistius or bembriopsids; Smith and Wheeler, 2006; Smith et al., 2016) or with congiodiopsids (Smith and Wheeler, 2004; Smith and Craig, 2007). Our finding of a Neosebastidae + Plectrogeniidae clade adds additional complications to the placement of the Neosebastidae, but this result is closer to the findings of Imamura (2004) and several molecular studies (e.g., Smith and Wheeler, 2004, 2006) that have plectrogeniids among the closest relatives of the neosebastids.

Species in the Plectrogeniidae are relatively widespread with collections ranging from the western Indian Ocean to Hawaii despite the family including just four species (Imamura, 1996; Nelson, 2006; Eschmeyer et al., 2017). Fowler (1938) first emphasized the distinctiveness of Plectrogenium. Matsubara (1943) supported Fowler’s (1938) assertion, suggesting that the genus may represent the ancestral condition of some of the deeper water, flattened scorpaenoids. He noted that Plectrogenium shared the loss of the gas bladder and the presence of several rows of prominent head spines and notched pectoral fins with some scorpaenids (e.g., Sebastolobus) while also showing characteristics in common with the bembriids. Washington et al.
(1984) further corroborated this hypothesis by pointing to similarities in the scales and caudal fin between *Parabembina* and *Plectrogenium*. Subsequently, Imamura (1996, 2004) supported a placement of an expanded Plectrogeniidae (including *Bembradius* sister to the clade composed of *Bembridae* + *Hoplochthyidae* + *Platycephalidae* + *Triglidae* that was united by the presence of a posterior pelvic fossa. Molecular studies have not fully supported or refuted these morphological hypotheses. Smith and Wheeler (2004) and Smith and Craig (2007) recovered *Plectrogenium* sister to *Bembridae*, Lautredou et al. (2013) recovered *Bembradius* sister to *Synanceiidae* (their analysis did not include any bembrids), and Smith et al. (2016) recovered *Plectrogenium* sister to the *Scorpaenidae*. This is the first molecular study to include both *Bembradius* and *Plectrogenium*, and we found a unique relationship for plectrogeniids sister to Neosebastidae. The monophyly of the Plectrogeniidae (Appendix 2) is supported by five characters and corroborates Imamura’s (1996) hypothesis and the recognition of this distinct family.

**Scorpaenidae and Synanceiidae.**—The scorpaenids and synanceiids are the most species-rich clades of scorpionfishes, and the species in these families have often been classified together in whole or in part. Gill (1888) grouped these clades together to the exclusion of all other mail-cheeked fishes. Regan (1913) modified Gill’s (1888) arrangement and united scorpaenids, synanceiids, and triglids in his *Scopaeiformes* (their studies did not include any representatives of the Neosebastidae or Plectrogeniidae). Matsubara (1943; Fig. 1B) distributed the core scorpionfishes across his “*Cocotropus*-stem,” “*Scopaea*-stem,” and “*Sebastes*-stem” based primarily on circumorbital differences. His “*Cocotropus*-stem” was composed of the Japanese synanceiids. His “*Scopaea*-stem” was composed of *Plectrogenium* and all non-sebastine scorpaenids. Finally, his “*Sebastes*-stem” was composed of the Neosebastidae and Sebastinae. The classification of Washington et al. (1984) largely followed Matsubara (1943) except that they combined his “*Scopaeana*-stem,” “*Sebastes*-stem,” *Synanceiinae*, *Apistus*, and *Cheroscorpaena* into their more inclusive *Scopaeidae*. They distributed the remaining synanceiids across four additional families (*Aploactinidae*, *Gnathanacanthidae*, *Pataecidae*, and *Tetrarogidae*) and recognized *Caranxthus* as a distinct family from the *Scorpaenidae*. Ishida’s (1994) phylogenetic hypothesis (Fig. 1C) and classification recognized 12 families. As noted above, this phylony included Congiopodidae, Neosebastidae, and *Plectrogenium* nested among the included representatives of the Scorpaenidae and Synanceiidae. Ishida’s (1994) major groupings largely followed Washington et al. (1984) except that Ishida often recognized clades at higher taxonomic levels. Ishida (1994) elevated Washington et al.’s (1984) *Apistinae*, *Neosebastinae*, and *Setarchinae* to the family level. Ishida’s (1994) Sebastidae included Washington et al.’s (1984) *Plectrogeniinae*, *Sebastolobinae*, and *Sebastinae*. Ishida’s (1994) classification included a Synanceiidae that incorporated Washington et al.’s (1984) *Choridactyliinae*, *Minoinae*, and *Synanceiinae*. Finally, his *Scorpaenidae* was restricted to Washington et al.’s (1984) *Pteroinae* and *Scorpaeninae*. As noted by Smith and Wheeler (2004), a computer-aided re-analysis of Ishida’s (1994) matrix recovered many equally optimal trees that were shorter than the tree presented by Ishida (1994). This large assortment of most parsimonious trees resulted in a poorly resolved phylogeny with just three of his families represented by more than one species being recovered as monophyletic: *Aploactinidae*, *Congiopodidae*, and *Pataecidae*. Relative to Ishida (1994), Imamura (2004; Fig. 1D) increased the taxon sampling among closely related groups (e.g., *Platycephalidae*, *Triglidae*) and recovered a largely complementary phylogenetic classification with a few changes. Imamura (2004) recognized a Sebastolobidae at the family level and relegated the Setarchidae of Ishida (1994) to a clade within *Scorpaenidae*. Subsequent work by Shinohara and Imamura (2005) also placed *Caranxthus* into the *Scorpaenidae*. Most recently, Honma et al. (2013) recognized a new family *Perryenidae* for a member of Mandryzta’s (2001) Tetrarogidae. This new family and Mandryzta’s (2001) earlier treatment of *Eschmeyeriidae* as an additional monotypic family based on former waspfishes casts doubt on tetrarogid monophyly. The proliferation of new waspfish families and Smith and Wheeler’s (2004) re-analysis of Ishida’s (1994) dataset that recovers 5–6 distinct clades of tetrarogids (*sensu* Ishida, 1994) highlights that traditional “stonefish” taxonomy is becoming complicated with substantial evidence for tetrarogid polyphyly and a diversity of families with three or fewer species (traditional *Apistidae*, *Eschmeyeriidae*, *Gnathanacanthidae*, *Pataecidae*, and *Perryenidae*).

As seen with the morphological studies, molecular phylogenies that have included representatives of both the *Scorpaenidae* and Synanceiidae have recovered varied phylogenetic results, but the clades themselves have been largely repeated. These studies have also echoed some morphological results. For example, molecular studies, like morphological studies, consistently recover a polyphyletic Tetrarogidae (*sensu* Ishida, 1994) and *Plectrogenium* separate from the seabastines (Smith and Wheeler, 2004, 2006; Smith and Craig, 2007; Smith et al., 2016). The molecular results have also largely recovered reciprocally monophyletic scorpaenid and synanceid clades. Smith and Wheeler (2004) recovered independent clades of the *Scorpaenidae* and Synanceiidae with a diversity of included taxa (including non-scorpaeiforms) in the MRCA. Smith and Wheeler (2006) recovered the scorpaenids sister to epinephelids and synanceiids sister to the triglids with an MRCA that includes the “cottoids and allies” as well as scorpaenoid and serranid fishes. Smith and Craig (2007) recovered relationships similar to Smith and Wheeler (2006) except that the MRCA excluded the Epinephelidae and included the Anthiidae, Niphonidae, Percidae, Serranidae, and Trachinidae. With more families sampled, Lautredou et al. (2013) and Smith et al. (2016) recovered a clade composed of *Plectrogeniidae* + *Scorpaenidae* + *Synanceiidae*. Finally, Betancur-R. et al. (2017) recovered a clade composed of *Scorpaenidae* + *Synanceiidae*, but their analysis only included two synanceiids and did not include any congipodids, neo-sebastids, or plectrogeniids, so their phylogeny is of limited comparative value. Our current analysis is the first to recover a clade composed of Neosebastidae + *Plectrogeniidae* + *Scorpaenidae* + *Synanceiidae*, and this clade was supported by the loss of the fourth circumorbital (character 9, state 1).

Despite continued iterative improvement, the march toward a monophyletic taxonomy based on morphological and molecular data has been incompletely accepted by the major fish classifications (e.g., Nelson, 2006; Nelson et al., 2016; Eschmeyer et al., 2017). For example, Nelson (2006) largely follows the pre-phylogenetic study of Washington et al. (1984) except for the placement of Ishida’s (1994) Tetrarogidae in their *Scorpaenidae*. Nelson et al. (2016) followed Nelson (2006) except they placed *Caranxthus* in the *Scorpaenidae* and recognized *Eschmeyeriidae* as a separate family from their Tetraroginae. Curiously, they left the Tetraroginae within the *Scorpaenidae* and continued to recognize *Perryena* in the Congiopodidae despite the evidence for both tetrarogine changes being presented in the
same study (Mandrytza, 2001). In contrast, Eschmeyer et al. (2017) largely followed Ishida (1994) except for the placement of *Caracanthus* in the Scorpaenidae (presumably following Shinohara and Imamura, 2005) and the recognition of a separate Plectrogeniididae (presumably following Imamura, 1996), Eschmeyeriidae (presumably following Mandrytza, 2001), and Perryenidae (presumably following Honma et al., 2013). Betancur-R. et al. (2017) largely followed Eschmeyer et al. (2017) including the retention of a non-monophyletic (in their study) Scorpaenidae. Presumably, their minimal changes relative to Eschmeyer et al. (2017) are due to limited sampling where only 11 of their 21 platycephaloid, scorpaenoid, or trigloid families were examined. All of these previous studies highlight the need to combine molecular and morphological data to generate a complete and holistic phylogenetic hypothesis that can become stable and more widely accepted.

The Scorpaenidae is a worldwide marine family of 370 species that have been collected in environments ranging from shallow to deep water and from the poles to the tropics (Nelson, 2006; Eschmeyer et al., 2017). This group includes the traditional Caracanthidae, Scorpaenidae, Sebastidae, and Setarchidae (*sensu* Ishida, 1994; Appendix 2) and includes animals with reproductive modes ranging from more traditional broadcast spawning to live birth (Breder and Rosen, 1966; Muñoz, 2010). Most inexplicit and explicit morphological studies and one large-scale molecular study generally have resolved the rockfishes (Sebastidae) as an ancestral or stem grade within the scorpaenoid radiation (Matsumura, 1943; Ishida, 1994; Imamura, 1996, 2004; Lautredou et al., 2013). In contrast, Smith and Wheeler (2004, 2006), Smith and Craig (2007), Smith et al. (2016), and Betancur-R. et al. (2017) have recovered the Sebastinae as a deeply nested lineage. This revised phylogenetic hypothesis implies that the scorpaenoids originated in warmer waters and transitioned to deeper (e.g., Setarchinae) and colder habitats (e.g., Sebastinae) rather than the previous hypotheses that would necessitate transitioning from cooler waters into more temperate and tropical regions. This more traditional hypothesis may have been largely driven by the evolutionary perspective that the colder, overwhelmingly North Pacific cottoinds and allies were the closest allies to a sebastine-stem scorpaenoid radiation (Smith and Busby, 2014). This Sebastinae was resolved as the sister group to a clade composed of *Adelosebastes + Sebastolobus*, which have generally been allied with or nested among the core sebastines in previous morphological and molecular studies (Figs. 1, 2). As might be expected with the revised placement of these core rockfishes, we recover this clade nested within a larger assemblage that includes all other sampled deeper and cooler water genera (i.e., *Ectreposebastes, Pontinus, Setarches*, and *Trachypterus*). In this study, this colder-habitat clade of scorpaenoids was recovered as the sister group to a *Scorpaenodes + Pteroinia* clade. This is in contrast to several previous studies (e.g., Imamura, 2004; Smith and Craig, 2007) that have found multiple clades of deep-water scorpaenoids sister to the pteroinid lionfishes and allies (Figs. 1, 2). One of the most consistent results across scorpaenid studies is the sister-group relationship between *Scorpaenodes* and pteroinid lionfishes (e.g., Ishida, 1994; Imamura, 2004; Lautredou et al., 2013; Smith et al., 2016; Betancur-R. et al., 2017). The final scorpaenid clade recovered in our analysis is a primarily tropical and subtropical clade composed of *Caracanthus, Pteroidichthys, Scorpaena, Scorpaenopsis*, and *Taenionotus*. This clade was sister to the cold-water scorpaenoids + lionfishes and allies and has been consistently recovered in molecular studies (Smith and Craig, 2007; Lautredou et al., 2013; Smith et al., 2016; Betancur-R. et al., 2017). In contrast, morphological studies have typically recovered these fishes as a grade with *Scorpaenodes* and Pteroinae (and potentially other genera) nested within the group (Ishida, 1994; Shinohara and Imamura, 2005). It is clear that the inversion of scorpaenid relationships with sebastines deeply nested with the family that is recovered in this combined study and several other molecular studies (Smith and Wheeler, 2004, 2006; Smith and Craig, 2007; Smith et al., 2016; Betancur-R. et al., 2017) has dramatically altered the polarity of morphological transformations and the impact this has on the evolutionary relationships in this commercially important clade.

The Synanceiidae, a family of 133 species, is primarily a marine clade with a few fresh- or brackish-water representatives (e.g., *Gymnapistes, Neovespicula*), which is distributed from the western Indian Ocean to the South Pacific Ocean (Eschmeyer and Rama-Rao, 1973; Nelson, 2006). The largest taxonomic change we are recommending in this study is the consolidation of the traditional Apistidae, Aploactinidae, Eschmeyeriidae, Gnthanacanthidae, Pataecidae, Peryenidae, Synanceiidae, and Tetrarogidae (*sensu* Eschmeyer et al., 2017) into a monophyletic Synanceiidae. This expanded Synanceiidae is diagnosed by the evolution of the lachrymal saber as well as five additional morphological transformations (Appendix 2). Additionally, Leis and Rennis (2000) provided evidence from larval morphology that separates these fishes from the remainder of the core scorpaenoids. We recommend this higher-level change because of the proliferation of family-level names that are already emanating from the former Tetrarogidae (i.e., Eschmeyeriidae, Peryenidae) and that are likely to continue. Our results, previous molecular studies (Smith and Wheeler, 2004, 2006; Smith and Craig, 2007; Smith et al., 2016, and the computer aided re-analysis of Ishida’s (1994) scorpaenoid study in Smith and Wheeler (2004) that have all sampled multiple species of tetrarogids (*sensu* Eschmeyer et al., 2017) have suggested that towards four or five additional small or monogenic families will likely be needed to generate a monophyletic taxonomy. Instead of describing a diversity of new waspfish families, the alternative strategy is chosen here where the diversity of existing comparatively small families of stonefishes and waspfishes can be consolidated into a single, well supported, consistently supported, and taxonomically stable family with the retention of subfamilies as warranted and needed (e.g., Apistinae, Aploactinidae, Pataecinae, Synanceiinae). Further, our classification largely returns the subfamilial taxonomy to that recommended by Matsubara (1943). Our results recover the typical placement for the Apistinae as the earliest diverging lineage in the Synanceiidae. Regan (1913) included this group among his Scorpaenidae, which was composed of our Scorpaenidae, *Apistus, Erishphex* (an aploactine), and six genera of “tetrarogids” (*sensu* Ishida, 1994). Matsubara (1943), Ishida (1994), and Imamura (2004) all treated *Apistus* as the earliest branching lineage in his clad that is largely equivalent to our Synanceiidae. The placement of Apistinae is one of the most consistently recovered relationships in scorpaenoid phylogenetics, but it is important to note that Washington et al. (1984) highlighted a number of features that potentially group the Apistinae with the Triglidae: a bilobed gas bladder with an intrinsic muscle, elongate pectoral-fin rays (also found in hoplichthydids, *Choridactylus, Inimicus*, and *Minous*), and an expansion of the circumorbitals. Thus, continued work is warranted. Our phylogeny, like previous morphological studies (Ishida, 1994; Imamura, 2004), recovers a monophy-
letic Synanceiinae deeply nested within the Synanceiidae. Our study recovers a clade composed of the Aploactininae and Pataecinae sister to the restricted Synanceiinae. Other than his inclusion of the Congiopodidae in this clade, Ishida (1994) recovered this same relationship. Finally, we have a grade composed of the various “tetrarogid” or formerly “tetrarogid” genera and Gnathanascanthus as a diversity of lineages more closely related to Synanceiinae than to Apistinae.

*Evolution of the Scorpaenoididae.*—The combined morphological and molecular phylogeny presented herein provides an opportunity to reconcile the often conflicting datasets and look at the implications for this updated hypothesis on the evolution of this species-rich clade. One of the major findings in this study was the discovery of the lachrymal saber. As noted above, this specialization is hypothesized to have a primarily defensive role. The maxillary rotation of the lachrymal saber has two major anti-predator impacts. First, it expands the width of the head by projecting the spine(s) outward (Figs. 4–7). This expansion increases the rostral width of the fish by 10–25% and would greatly increase the gape required by a would-be predator (Price et al., 2015). Second, the presence of an outwardly directed and sharp spine should reduce predation because of the potential for the saber to pierce a would-be predator. Cowan (1969) described a similar defensive role for the outward projection of the preopercular spines in the closely allied pschothus that have enlarged antler-like modifications (e.g., *Enophris*, *Icelinus*; Yabe, 1985). In addition to its role in avoiding or reducing predation, it is possible that the lachrymal saber is used for intraspecific competition. The maxillary rotation of the lachrymal saber appears to be playing an ecological and/or evolutionary role. As such, it is possible that the synanceiids could be advertising or highlighting this specialization with this fluorescence in a similar role as the bioluminescence associated with the defensive dorsal spines in etmopterid sharks (Claes et al., 2013) or that the lachrymal saber is involved in intraspecific competition and mate choice where synanceiid species are advertising their sabers to conspecifics.

In addition to exploring the evolution of the lachrymal saber, the revised scorpaenoid hypothesis has implications for the evolution of viviparity in this clade. The deeply nested placement of Sebastinae within the Scorpaenidae corroborates Wourms’ (1991) assertion about the evolution of live birth and corresponding intermediate stages in the transition from an oviparous (classical oviparous) ancestor among the non-scorpaenid scorpaenoids. As noted by Smith and Wheeler (2004), there appears to be an evolutionary transition from a more common oviparous ancestor in the platycephalids, synanceiids, and triglids to an oviparous species that releases fertilized eggs within a gelatinous egg mass in genera such as *Dendrochirus*, *Pterois*, *Scorpaena*, *Scorpaenodes*, *Scorpaenopis*, and *Sebastolobus* (Wourms, 1991; Koya and Muñoz, 2007). This intermediate reproductive mode is further modified in *Heliocolenus* where species in the genus have internal fertilization and zygoparity where fertilized ova are held by the mother before being released into the ocean (Wourms, 1991). The reproductive mode of *Hozukius* is unknown, but it shares a II-3 ovarian type with most scorpaenids (e.g., *Caranxthus*, *Dendrochirus*, *Heliocolenus*, *Scorpaena*; Cole, 2003; Koya and Muñoz, 2007). The more derived viviparous sebastine rockfishes (*Sebastes* and *Sebastesciscus*) have a type II-1 ovarian type (Koya and Muñoz, 2007). This suggests that *Hozukius* is likely to be more similar to *Heliocolenus* or *Scorpaena* and not be live bearing. The evolution of reproductive modes and live birth in scorpaenoids has been discussed in considerably more detail in other studies (Wourms, 1991; Koya and Muñoz, 2007; Muñoz, 2010; Pavlov and Emel’yanova, 2013), but their interpretations have implicitly or explicitly relied on the hypothesized placement of Sebastines at the base of the scorpaenoid tree. The inversion of the phylogeny of scorpaenoids proposed in this study is more consistent with traditional views on the evolution of viviparity where there is a transition from external fertilization to internal fertilization with the retention of either the developing eggs or embryos within the mother (Wourms, 1991; Wourms and Lombardi, 1992). These two examples demonstrating the impact of the proposed phylogeny on the evolution of the scorpaenoid fishes. We hope that this revised hypothesis for the relationships of scorpionfish and allies will allow researchers to test additional evolutionary hypotheses for this important percomorph clade.

**MATERIAL EXAMINED**

*Ablabys taenianotus:* KUI 41345  
*Adelosebastes latens:* KUI 28431  
*Aetapicus maculatus:* NMV A 11847  
*Apistus carinatus:* CAS 15975, FMNH 55557, FMNH 119634, KUI 41400  
*Bathymaster signatus:* SIO 93-174  
*Bellator militaris:* AMNH 084578  
*Bembradium roseum:* CAS (SU_ICH) 8653  
*Bembras japonicus:* CAS 67504  
*Bembrops macronema:* AMNH 49698SW  
*Bovichtus chilensis:* AMNH 49664SW  
*Caracanthus unipinnus:* AMNH 18105  
*Centropogon australis:* KUI 41409  
*Chelidonichthys kumu:* AMNH 91672SD  
*Choridactylus multibarbus:* CAS 15071  
*Cirrhitus rivulatus:* SIO 59-225  
*Congiopodus leucopaealis:* AMNH 222767  
*Dendrochirus brachypterus:* AMNH 41595SW  
*Diplectrum formosum:* AMNH 76688  
*Diploprion bifasciatum:* AMNH 97446SW  
*Ectreposebastes imus:* AMNH 27991SW  
*Elates ransonnetii:* FMNH 63930
Erisphex potti: CAS 30316
Erosa erosa: FMNH 121063
Eschmeyer nexus: USNM 233855
Gnathanacanthus goetzeei: AMNH 223040, USNM 47852
Gymnapistes maculatus: AMNH 31009
Hoplichthys citrinus: AMNH 89898
Hozukius embrearius: SIO 75-497
Icelinus quadriseriatus: SIO 84-91
Inimicus didactylus: KUI 41391
Inimicus japonicus: AMNH 38131SW
Lepidotrigla multispinosa: SAIAB 035527
Liocranium praepositum: KUI 41399
Maxillicosta scabriceps: CAS 33304
Minous quincarinatus: FMNH 121037, KUI 41397
Minous trachycephalus: AMNH 098704SD
Neosebastes thetidis: CAS 31111
Niphon spinosus: FMNH 57109, USNM 57737
Parabembras curtus: CAS 49456
Paracentropogon sp.: CAS_SU 68769
Paracentropogon longispinis: KUI 41398
Paracentropogon rubripinnis: FMNH 89090
Pataecus fronto: CAS 67408
Perca flavescens: AMNH 43887SW
Peristethion miniatum: AMNH 75393
Platycephalus indicus: AMNH 88066
Plectrogenium nanum: CAS 70174
Pontinus longispinis: AMNH 83416
Prionotus evolans: AMNH 41773SW
Pseudanthias pleurotaenia: AMNH 38119SW
Pterodichthys amboensis: AMNH uncat.
Pterois volitans: AMNH 38132SW
Pterygotrigla hemisticta: FMNH 120607
Satyrichthys welchi: AMNH 98721
Scorpaena guttata: SIO 52-214
Scorpaenodes guanensis: AMNH 213867
Scorpaenopsis diabolus: FMNH 121052
Sebastes ruberrimus: AMNH 37946SD
Sebastolobus altivelis: KUI 28282
Sebastes marmoratus: AMNH 97547SW
Setarches guentheri: AMNH 64334
Synanceia horrida: AMNH 213070
Taeniandrus trianquillus: FMNH 63586
Thysanophrys celebensis: CAS 80464
Trachinus draco: AMNH 36487
Trachyscorpia eschmeyeri: AMNH 098598SD
Zalanthias kelloggi azumanus: FMNH 57230
Zanclorhynchus spinifer: MNHN 2003-0266

DATA ACCESSIBILITY
Supplemental material is available at http://www.copeiajournal.org/cg-17-669.

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LITERATURE CITED


APPENDIX 1

Characters examined in the phylogenetic analyses

Character descriptions for characters 1–111 from Imamura (2004), 112 from Shinohara and Imamura (2005), and character 113 is new in this study. Data for characters 1–111 for Adelosebastes, Apistus, Bellator, Bembradium, Bembros, Chelidochthys, Choridactylus, Congiopodus, Dendrochirus, Dipsopion, Ectreposebastes, Elates, Erisphex, Erosa, Gnathanacanthus, Helicolemus, Hoplichthys, Hozukius, Inimicus, Lepidotrigla, Max-
illicosta, Minous, Neosebastes, Niphon, Parabembras, Pataecus, Peristedion, Platyccephalus, Plectrogenium, Pontinus, Pronicotus, Pterygotrigla, Satyrichthys, Scorpaena, Scorpaenodes, Scorpaenopsis, Sebastes, Sebastiscus, Sebastolobus, Setarches, Synanceia, Taenionotus, Thysanophrys, Trachyscorpia, and Zalanthias are from Imamura (2004). Data for character 112 for above genera and characters 1–112 for Caracanthus and Pteriodichthys are from Shinohara and Imamura (2005). Data for Eschmeyer, in part, are from Poss and Springer (1983). Data for Perryena are from Honma et al. (2013). Myological data (characters 79–106) come from many sources: Ablabys, Aetapacus, and Gymnapistes (Ishida, 1994); Bathymaster (Imamura and Yabe, 2002); Icelinus (Yabe, 1985); and Zanclopterus (Ishii and Imamura, 2008). All remaining character codings are new in this study (see Material Examined). Characters 2, 5, 18, 43, 45, 48, 49, 50, 52, 54 were modified from Imamura (2004) because of variation in the species added to the analysis.

1. First through third circumorbitals:
   (100) = elements closely associated with each other
   (101) = elements separated from each other

2. First and third circumorbitals (modified from Imamura, 2004):
   (200) = separated by second circumorbital
   (201) = attached
   (202) = separated by second circumorbital and ectopterygoid
   (203) = loss of second circumorbital

3. Middle portion of second circumorbital sensory canal:
   (300) = bridge absent
   (301) = bridge present with no sensory openings
   (302) = bridge present with a single sensory opening
   (303) = bridge present with more than two sensory openings

4. Third circumorbital and lateral ethmoid:
   (400) = separated
   (401) = attached

5. Third and fifth circumorbitals (modified from Imamura, 2004):
   (500) = separated by fourth circumorbital
   (501) = attached
   (502) = loss of fourth or fifth circumorbital

6. Direction of posterior opening of third circumorbital, continuous with sensory canal of fourth to sixth circumorbitals:
   (600) = upward
   (601) = backward

7. Position of upward (or backward) opening of third circumorbital:
   (700) = on dorsal (or posterior) margin of element
   (701) = below (or anterior to) margin

8. Suborbital stay on third circumorbital (ordered via additive binary coding):
   (800) = absent
   (801) = present with distal end not strongly connected with preopercle
   (802) = present with distal end narrowly truncated and strongly connected with preopercle
   (803) = present with distal end broad and strongly connected with preopercle

9. Fourth and fifth circumorbitals (ordered via additive binary coding):
   (900) = both present
   (901) = fourth circumorbital absent
   (902) = fourth and fifth circumorbital absent

10. Sixth circumorbital:
   (1000) = attached to sphenotic
   (1001) = fused to sphenotic
   (1002) = absent

11. Sensory canal of third circumorbital:
   (1100) = canal continuous into fourth or fifth circumorbitals
   (1101) = canal separate/not continuous with fourth or fifth circumorbital

12. Postotic sensory canal:
   (1200) = canal continuous with circumorbital series
   (1201) = canal separate/not continuous with circumorbital series

13. Tubercles on neurocranium:
   (1300) = absent
   (1301) = present

14. Nasal and neurocranium:
   (1400) = loosely attached
   (1401) = sutured

15. Nasals:
   (1500) = separated
   (1501) = nasals sutured together medially

16. Number of vomerine tooth plates:
   (1600) = one
   (1601) = two
   (1602) = none

17. Lateral ethmoids:
   (1700) = separated
   (1701) = meeting in midline

18. Paraphenoid and pterosphenoid:
   (1800) = separated
   (1801) = connected

19. Basiphenoid:
   (1900) = present, posterior margin connected directly with neurocranium
   (1901) = present, posterior margin free from neurocranium
   (1902) = absent

20. Prootic and intercalar:
   (2000) = in contact
   (2001) = separated

21. Intercalar and posttemporal:
   (2100) = with ligamentous articulation
   (2101) = sutured

22. Lateral lateral-line canal pore on pterotic:
   (2200) = absent
   (2201) = present

23. Skinny lateral-line sensory canal between pterotic and preopercle:
   (2300) = present
   (2301) = absent

24. Spines associated with lateral-line sensory canal on parietal:
   (2400) = absent
   (2401) = present

25. Baudelot’s ligament:
   (2500) = originating from basioccipital
   (2501) = originating from basioccipital and first vertebra
   (2502) = originating from first vertebra
   (2503) = absent

26. Ascending process of premaxilla:
   (2600) = continuous with remaining part of premaxilla
   (2601) = separated from the remaining part of premaxilla

27. Notch between ascending process and cranial condyle:
   (2700) = present
   (2701) = absent
28. Teeth on oral jaws: 
   \( (28_o) = \text{present} \)  
   \( (28_i) = \text{absent} \)

29. Palatine and ectopterygoid: 
   \( (29_o) = \text{connected} \)  
   \( (29_i) = \text{separated} \)

30. Teeth on palatine: 
   \( (30_o) = \text{present} \)  
   \( (30_i) = \text{absent} \)

31. Ectopterygoid and metapterygoid: 
   \( (31_o) = \text{separated} \)  
   \( (31_i) = \text{meeting medially} \)

32. Metapterygoid lamina: 
   \( (32_o) = \text{present} \)  
   \( (32_i) = \text{absent} \)

33. Space between metapterygoid and hyomandibula: 
   \( (33_o) = \text{prominent} \)  
   \( (33_i) = \text{rudimentary to absent} \)

34. Preopercular margin: 
   \( (34_o) = \text{with serrations} \)  
   \( (34_i) = \text{without serrations or prominent spines} \)

35. Backwardly directed opercular spine: 
   \( (35_o) = \text{present} \)  
   \( (35_i) = \text{absent} \)

36. Backwardly directed opercular spine: 
   \( (36_o) = \text{ossified} \)  
   \( (36_i) = \text{cartilaginous} \)  
   \( (36_p) = \text{absent} \)

37. Number of branchiostegal rays: 
   \( (37_o) = \text{seven} \)  
   \( (37_i) = \text{six} \)  
   \( (37_p) = \text{five} \)

38. Interarcual cartilage: 
   \( (38_o) = \text{present} \)  
   \( (38_i) = \text{absent} \)

39. Tooth plate on second epibranchial: 
   \( (39_o) = \text{absent} \)  
   \( (39_i) = \text{present} \)

40. Tooth plate on third epibranchial: 
   \( (40_o) = \text{present} \)  
   \( (40_i) = \text{absent} \)

41. First pharyngobranchial: 
   \( (41_o) = \text{present and ossified} \)  
   \( (41_i) = \text{present and cartilaginous} \)  
   \( (41_p) = \text{absent} \)

42. Tooth plate on second pharyngobranchial: 
   \( (42_o) = \text{present} \)  
   \( (42_i) = \text{absent} \)

43. Second through fourth pharyngobranchials (modified from Imamura, 2004): 
   \( (43_o) = \text{separated} \)  
   \( (43_i) = \text{third and fourth continuous} \)  
   \( (43_p) = \text{second to fourth continuous} \)  
   \( (43_p) = \text{only third pharyngobranchial present} \)

44. Medial extrascapular: 
   \( (44_a) = \text{present} \)  
   \( (44_i) = \text{absent} \)

45. Lateral extrascapular (modified from Imamura, 2004): 
   \( (45_o) = \text{single element with three sensory openings} \)  
   \( (45_i) = \text{two elements (horizontal and longitudinal tubes) with two sensory openings} \)  
   \( (45_p) = \text{single element (longitudinal tube) with two sensory openings} \)

46. Cleithrum and coracoid (ordered via additive binary coding): 
   \( (46_o) = \text{without ventromedial connection} \)  
   \( (46_i) = \text{with partial ventromedial connection} \)  
   \( (46_p) = \text{with complete ventromedial connection} \)

47. Dorsalmost actinost and scapula: 
   \( (47_o) = \text{separated} \)  
   \( (47_i) = \text{fused} \)

48. Number of postcleithra (ordered via additive binary coding): 
   \( (48_o) = \text{two} \)  
   \( (48_i) = \text{one} \)  
   \( (48_p) = \text{zero} \)

49. Number of free lower pectoral-fin rays (ordered via additive binary coding): 
   \( (49_o) = \text{zero} \)  
   \( (49_i) = \text{one} \)  
   \( (49_p) = \text{two} \)  
   \( (49_p) = \text{three or more} \)

50. Branched pectoral-fin rays: 
   \( (50_o) = \text{present} \)  
   \( (50_i) = \text{absent} \)

51. Cartilaginous caps on anterior portion of pelvis: 
   \( (51_o) = \text{separated} \)  
   \( (51_i) = \text{fused} \)

52. Posterior pelvic fossa: 
   \( (52_o) = \text{absent} \)  
   \( (52_i) = \text{present, opposing fossae meeting} \)  
   \( (52_p) = \text{present, opposing fossae separated} \)

53. Opposing posteromedial parts of pelvis: 
   \( (53_o) = \text{sutured} \)  
   \( (53_i) = \text{separated} \)

54. Number of pelvic-fin spines and rays (ordered via additive binary coding; modified from Imamura, 2004): 
   \( (54_o) = \text{six} \)  
   \( (54_i) = \text{five} \)  
   \( (54_p) = \text{four} \)  
   \( (54_p) = \text{three} \)  
   \( (54_p) = \text{zero} \)

55. Branched pelvic-fin rays: 
   \( (55_o) = \text{present} \)  
   \( (55_i) = \text{absent} \)

56. Number of spines on first dorsal-fin proximal pterygiophore: 
   \( (56_o) = \text{two} \)  
   \( (56_i) = \text{one} \)

57. Dorsal spines: 
   \( (57_o) = \text{stout} \)  
   \( (57_p) = \text{slender} \)

58. First spine on first anal-fin proximal pterygiophore: 
   \( (58_o) = \text{present} \)  
   \( (58_i) = \text{absent} \)

59. Second element on first anal-fin proximal pterygiophore: 
   \( (59_o) = \text{spine} \)  
   \( (59_i) = \text{soft ray} \)  
   \( (59_p) = \text{absent} \)

60. Element on second anal-fin proximal pterygiophore: 
   \( (60_o) = \text{spine} \)  
   \( (60_i) = \text{soft ray} \)

61. Branched dorsal- and anal-fin rays: 
   \( (61_o) = \text{present} \)  
   \( (61_i) = \text{absent} \)
62. Number of rays supported by posteriormost proximal dorsal- and anal-fin pterygiophores:
   \((62_0) = \text{two}\)
   \((62_1) = \text{one}\)

63. Anterior dorsal-fin pterygiophores:
   \((63_0) = \text{separated from neurocranium}\)
   \((63_1) = \text{sutured to neurocranium}\)

64. Dorsal-fin proximal pterygiophores:
   \((64_0) = \text{not exposed}\)
   \((64_1) = \text{laterally exposed along first dorsal fin}\)
   \((64_2) = \text{laterally exposed along first and second dorsal fins}\)

65. Number of supraneurals (ordered via additive binary coding):
   \((65_0) = \text{three}\)
   \((65_1) = \text{two}\)
   \((65_2) = \text{one}\)
   \((65_3) = \text{zero}\)

66. Dorsal-fin stay:
   \((66_0) = \text{present (separate and ossified)}\)
   \((66_1) = \text{present (fused with proximal pterygiophore and ossified)}\)
   \((66_2) = \text{present (cartilage)}\)
   \((66_3) = \text{absent}\)

67. Anal-fin stay:
   \((67_0) = \text{present (separate and ossified)}\)
   \((67_1) = \text{present (fused with proximal pterygiophore and ossified)}\)
   \((67_2) = \text{present (cartilage)}\)
   \((67_3) = \text{absent}\)

68. First and second hypurals:
   \((68_0) = \text{separated}\)
   \((68_1) = \text{continuous}\)

69. Third and fourth hypurals:
   \((69_0) = \text{separated}\)
   \((69_1) = \text{continuous}\)

70. Fifth hypural:
   \((70_0) = \text{present}\)
   \((70_1) = \text{absent}\)

71. Lower hypural plate and parhypural:
   \((71_0) = \text{separated}\)
   \((71_1) = \text{fused}\)

72. Hemal spine and third preural centrum:
   \((72_0) = \text{separated}\)
   \((72_1) = \text{fused}\)

73. Hemal spine and second preural centrum:
   \((73_0) = \text{separated}\)
   \((73_1) = \text{fused}\)

74. Urostyle and upper hypural plate:
   \((74_0) = \text{separated}\)
   \((74_1) = \text{fused}\)

75. Urostyle and lower hypural plate:
   \((75_0) = \text{separated}\)
   \((75_1) = \text{fused}\)

76. Uroneural:
   \((76_0) = \text{present}\)
   \((76_1) = \text{absent}\)

77. Number of epurals:
   \((77_0) = \text{three}\)
   \((77_1) = \text{two}\)
   \((77_2) = \text{one}\)

78. Branched caudal-fin rays:
   \((78_0) = \text{present}\)
   \((78_1) = \text{absent}\)

79. Posterior end of adductor mandibulae section one:
   \((79_0) = \text{connected to preopercle (and hyomandibula)}\)
   \((79_1) = \text{connected only to hyomandibula}\)
   \((79_2) = \text{free from posterior bony element(s)}\)

80. Adductor mandibulae section one:
   \((80_0) = \text{absent}\)
   \((80_1) = \text{present}\)

81. Origin of adductor mandibulae section two-three:
   \((81_0) = \text{laterally to levator arcus palatini}\)
   \((81_1) = \text{medial margin to levator arcus palatini}\)
   \((81_2) = \text{completely medial to levator arcus palatini}\)
   \((81_3) = \text{not closely associated with levator arcus palatini}\)

82. Position of levator arcus palatini (ordered via additive binary coding):
   \((82_0) = \text{dorsal surface of entopterygoid}\)
   \((82_1) = \text{medial margin of entopterygoid}\)
   \((82_2) = \text{ventral surface of entopterygoid}\)

83. Origin of levator operculi (ordered via additive binary coding):
   \((83_0) = \text{on pterotic}\)
   \((83_1) = \text{on pterotic and posttemporal}\)
   \((83_2) = \text{on posttemporal}\)

84. Hyohyoides inferioris:
   \((84_0) = \text{absent}\)
   \((84_1) = \text{present}\)

85. Anterior portion of transversus dorsalis anterior:
   \((85_0) = \text{branched}\)
   \((85_1) = \text{unbranched}\)

86. Posterior portion of transversus dorsalis anterior (ordered via additive binary coding; modified from Imamura, 2004):
   \((86_0) = \text{branched}\)
   \((86_1) = \text{branched, not continuous with anterior branch of same muscle}\)
   \((86_2) = \text{branched, continuous with anterior branch of same muscle, comprising circular muscle elements}\)

87. Obliquus dorsalis II:
   \((87_0) = \text{absent}\)
   \((87_1) = \text{present}\)

88. Posterior levator internus:
   \((88_0) = \text{laterally to obliquus dorsalis}\)
   \((88_1) = \text{sandwiched by obliquus dorsalis}\)

89. Levator externus III:
   \((89_0) = \text{present}\)
   \((89_1) = \text{absent}\)

90. Levator posterior:
   \((90_0) = \text{present}\)
   \((90_1) = \text{absent}\)

91. Adductores I–III:
   \((91_0) = \text{absent}\)
   \((91_1) = \text{present}\)

92. Transversus ventralis anterior and posterior:
   \((92_0) = \text{overlapping}\)
   \((92_1) = \text{separated}\)

93. Transversus ventralis posterior:
   \((93_0) = \text{without a tendon anteriorly}\)
   \((93_1) = \text{with a tendon anteriorly}\)

94. Protractor pectoralis:
   \((94_0) = \text{sheet-like muscle only}\)
   \((94_1) = \text{composed of sheet-like anterior and robust posterior elements}\)

95. Division of bundles of adductor superficialis serving free pectoral-fin rays:
   \((95_0) = \text{absent}\)
   \((95_1) = \text{present}\)
96. **Origin of coracoradialis:**
   - (96₁₀) = posteromedial face of posterior process of coracoid
   - (96₁₁) = posteromedial face of posterior process of coracoid and posterolateral face of posteroventral process of cleithrum

97. **Dorsal elements of pelvic-fin muscles:**
   - (97₀₀) = not attached to pectoral girdle
   - (97₀₁) = attached to pectoral girdle

98. **Extensor proprius:**
   - (98₀₀) = present
   - (98₁₁) = absent

99. **Flexor ventralis externus:**
   - (99₀₀) = present
   - (99₁₁) = absent

100. **Adductor dorsalis:**
     - (100₀₀) = present
     - (100₁₁) = absent

101. **Extrinsic muscle:**
     - (101₀₀) = absent
     - (101₁₁) = present, connected to neurocranium anteriorly and gas bladder posteriorly
     - (101₂₀) = present, connected to neurocranium anteriorly and vertebrae posteriorly
     - (101₃₀) = present, free from neurocranium anteriorly and connected to vertebrae posteriorly

102. **Intrinsic muscle:**
     - (102₀₀) = absent
     - (102₁₁) = present

103. **Obliquus superioris:**
     - (103₀₀) = extending to neurocranium
     - (103₁₁) = not extending to neurocranium

104. **Obliquus superioris** and Baudelot’s ligament:
     - (104₀₀) = *obliquus superioris* penetrated by Baudelot’s ligament
     - (104₁₁) = *obliquus superioris* bypassing and lying ventrally to Baudelot’s ligament

105. **Supracarinalis** anterior:
     - (105₀₀) = present
     - (105₁₁) = absent

106. **Inclinator dorsalis** associated with first dorsal spine:
     - (106₀₀) = present
     - (106₁₁) = absent

107. **Gill membranes** (ordered via additive binary coding; modified from Imamura, 2004):
     - (107₀₀) = free from isthmus
     - (107₁₀) = gill opening wide
     - (107₂₀) = broadly fused with isthmus, gill opening narrow

108. **Sensory ducts in lateral line:**
     - (108₀₀) = simple
     - (108₁₀) = with two or more branches

109. **Body lateral line:**
     - (109₀₀) = with scales
     - (109₁₀) = with tube-like bones
     - (109₂₀) = with bony plates

110. **Spines on lateral-line scales:**
     - (110₀₀) = absent
     - (110₁₁) = present

111. **Body scales:**
     - (111₀₀) = present
     - (111₁₀) = absent except in dorsal region
     - (111₂₀) = entirely absent
     - (111₃₀) = present as bony plates

112. **Caudal peduncle:**
     - (112₀₀) = straight
     - (112₁₁) = bent dorsally

113. **Lachrymal saber:**
     - (113₀₀) = absent
     - (113₁₁) = present

### APPENDIX 2

**Proposed subordinal, familial, and subfamilial classification, morphological diagnoses, support, and composition of the flatheads, scorpionfishes, sea robins, and stonefishes**

#### CONGIOPODOIDEI

**Congiopodidae Gill, 1889**
- **Type genus:** *Congiopus* Perry, 1811
- **Sister taxon:** Cottoidei + Zoarcoidei

**Concept and content:** Eight species classified in three genera: *Alertichthys*, *Congiopus*, and *Zanclorhynchus*

**Phenotypic diagnosis:** Loss of fourth or fifth circumorbital (character 5, state 2); loss of fourth circumorbital (character 9, state 1); intercalar and posttemporal sutured together (character 21, state 1); lateral lateral-line canal pore on pterotic absent (character 22, state 0); Baudelot’s ligament absent (character 25, state 3); palatine and ectopterygoid separated (character 29, state 1); teeth on palatine absent (character 30, state 1); uroneural absent (character 76, state 1); two epurals (character 77, state 1); levator posterior absent (character 90, state 1); gill membranes broadly fused with isthmus, gill opening narrow (character 107, state 2); body lateral line with tube-like bones (character 109, state 1).

**Support statistics:** The bootstrap support for this clade was 1.00.

**Systematic comment:** Familial and generic composition and species recognition follow Eschmeyer et al. (2017).

#### SCORPAENOIDEI

**Bembridae Kaup, 1873**
- **Type genus:** *Bembrus* Cuvier in Cuvier and Valenciennes, 1829
- **Sister taxon:** Neosebatiidae + Plectrognathiidae + Scorpaenidae + Synanceiidae

**Concept and content:** Nine species classified in four genera: *Bambradon*, *Bembras*, *Brachybembras*, and *Parabembras*

**Phenotypic diagnosis:** First and second hypurals are separated (character 68, state 0).

**Support statistics:** The bootstrap support for this clade was 0.70.

**Systematic comment:** This revised Bembridae includes the recently recognized Parabembridae because our phylogeny and previous work (e.g., Near et al., 2013) have resolved these two families as a single clade. We retain *Bambradon* and *Brachybembras* in Bembridae following Eschmeyer et al. (2017). Additional work on their placement is warranted. Generic composition and species recognition follow Eschmeyer et al. (2017).

**Hoplichthyidae Kaup, 1873**
- **Type genus:** *Hoplichthys* Cuvier in Cuvier and Valenciennes, 1829
- **Sister taxon:** Triglidae

**Concept and content:** 17 species classified in one genus: *Hoplichthys*

**Phenotypic diagnosis:** Middle portion of second circumorbital sensory canal bridge present with more than two
sensory openings (character 3, state 3); basiphenoid absent (character 19, state 2); prootic and intercalar in contact (character 20, state 1); lateral lateral-line canal pore on pterotic absent (character 22, state 0); skinny lateral-line sensory canal between pterotic and preopercle present (character 23, state 1); Baudelot’s ligament absent (character 25, state 3); metapterygoid lamina absent (character 32, state 1); rudimentary to no space between metapterygoid and hyomandibula (character 33, state 1); first pharyngobranchial cartilaginous (character 41, state 1); tooth plate on second pharyngobranchial absent (character 42, state 1); dorsal spines slender (character 57, state 1); first pharyngobranchial cartilaginous (character 66, state 1); posterior pelvic fossa present, fossae meeting (character 52, state 1); dorsal-fin stay cartilaginous (character 66, state 2); anal-fin stay cartilaginous (character 67, state 2); hyohyoides inferioris present (character 84, state 1).

**Support statistics:** The bootstrap support for this clade was 0.34.


**Scorpaenidae Risso, 1827**

**Type genus:** Scorpaena Linnaeus, 1758

**Sister taxon:** Neosebastidae + Plectrognidiidae

**Concept and content:** 371 species classified in four superfamilies and 34 genera: Pteroinae: Brachypterois, Dendrochirus, Ebonpa, Parapleris, and Pterois; Scorpaeninae: Caracanthus, Iricundus, Parasauruspaena, Pteroichthys, Scorpaena, Scorpaenopsis, Sebastapistes, and Tualanotus; Sebastinae: Helicolenus, Hozuki, Sebastes, and Sebastiscus; Setarchinae: Ectreposebastes, Liocorpius, and Setarches; incertae sedis: Adelosebastes, Hidropompaena, Hoplosebastes, Idiastion, Neomerinthe, Neoscorpaena, Phoscoescopris, Pogonoscorpius, Pontinus, Rhinopias, Scorpaeodnies, Sebastolobus, Trachyscorpia, and Ursinoscorpaenopsis

**Phenotypic diagnosis:** Posterior opening of third circumsoridibl posteriorly directed (character 6, state 1); sensory canal of third circumsoridibl separate/not continuous with fourth or fifth circumsoridibl (character 11, state 1); transversus ventralis posterior with a tendon anteriorly (character 93, state 1).

**Support statistics:** The bootstrap support for this clade was 1.00.

**Systematic comment:** Familial and subfamilial classification based on the resulting phylogeny in this study. Iricundus included in Scorpaeninae following Smith and Craig (2007), and Parasauruspaena and Sebastapistes included in Scorpaeninae following Lautredou et al. (2013). Generic composition and species recognition follow Eschmeyer et al. (2017).

**Synanceiidae Swainson, 1839**

**Type genus:** Synanceia Bloch and Schneider, 1801

**Sister taxon:** Neosebastidiae + Plectrognidiidae + Scorpaenidae

**Concept and content:** 134 species classified in seven superfamilies and 53 genera: Apistinae: Apistops, Apistus, and Cheroscorpaena; Aploactininae: Acanthosphe, Adventor, Aploactis, Aploactisoma, Bathypalectis, Cocotreps, Erisplex, Kanekonia, Matsubarichthys, Neoaploactis, Paraploactis, Peristominus, Prosproctus, Pseudopatae, Ptarmus, Stemonus, and Xenopatae; Eschmeyerinae: Eschmeyer; Gnathanacanthinae: Gnathaniacanthus; Pataeinae: Acteopus, Neopataeus, and Pataeac; Parryenia: Parryenia; Synanceiinae: Choridanctus, Dampiera, Erosa, Inimicus, Leptosynanceia, Minous, Pseudosynanceia, Synanceia, and Trachiphalus; incertae sedis: Ablabys, Centropogon, Coclipomphii, Cottapistris, Gympactis, Gymnaptus, Liocanthium, Neocentropogon, Neovespicula, Notesthes, Ocosia, Paracentropogon, Pseudovespicula, Richardsonicthys, Snyderina, Tetroneco, Trichosomus, and Vespicta

**Phenotypic diagnosis:** Sixth circumsoridibl fused to sphenotic (character 10, state 1); metapterygoid lamina absent (character 32, state 1); lower hypural plate and parhypural fused (character 71, state 1); origin of adductor
mandibulae section two-three partially medial to levator arcus palatini (character 81, state 1); origin of levator operculi on pterotic and posttemporal (character 83, state 1); lachrymal saber present (character 113, state 1).

**Support statistics:** The bootstrap support for this clade was 1.00.

**Systematic comment:** Familial and subfamilial classification based on the resulting phylogeny in this study. Subfamilial composition follows familial composition of Eschmeyer et al. (2017) except for their Tetrarogidae. Generic composition and species recognition follow Eschmeyer et al. (2017).

**Triglidae Rafinesque, 1815**

**Type genus:** Trigla Linnaeus, 1758

**Sister taxon:** Hoplichthyidae

**Concept and content:** 173 species classified in four subfamilies and 15 genera: Peristediinae: Gargariscus, Heminodus, Paraheminodus, Peristedion, Satyrichthys, and Scalicus; Prionotinae: Bellator and Prionotus; Pterygotriglinae: Bovitrigla and Pterygotrigla; Triglinae: Chelidonichthys, Eutrigla, Lepidotrigla, Trigla, and Trigloporus

**Phenotypic diagnosis:** First and third circumorbitals attached (character 2, state 1); third circumorbital and lateral ethmoid attached (character 4, state 1); nasal and neurocranium sutured (character 14, state 1); notch between ascending process and cranial condyle absent (character 27, state 1); transversus ventralis anterior and posterior separated (character 92, state 1); transversus ventralis posterior with a tendon anteriorly (character 93, state 1); division of bundles of adductor superficialis serving free pectoral-fin rays present (character 95, state 1).

**Support statistics:** The bootstrap support for this clade was 1.00.

**Systematic comment:** Familial classification and treatment of Peristediinae as a triglid subfamily follows our phylogeny and the phylogeny from Portnoy et al. (2017). The remaining triglid subfamilies follow the tribes from Richards and Jones (2002). Generic composition and species recognition follow Kawai (2008) and Eschmeyer et al. (2017).