



An exploration for deep-sea fish sounds off Vancouver Island from the NEPTUNE Canada ocean observing system



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ABSTRACT

Our understanding of the significance of sound production to the ecology of deep-sea fish communities has improved little since anatomical surveys in the 1950s first suggested that sound production is widespread among slope-water fishes. The recent implementation of cabled ocean observatory networks around the world that include passive acoustic recording instruments provides scientists an opportunity to search for evidence of deep-sea fish sounds. We examined deep-sea acoustic recordings made at the NEPTUNE Canada Barkley Canyon Axis Pod (985 m) located off the west coast of Vancouver Island in the Northeast Pacific between June 2010 and May 2011 to determine the presence of fish sounds. A subset of over 300 5-min files was examined by selecting one day each month and analyzing one file for each hour over the 24 h day. Despite the frequent occurrence of marine mammal sounds, no examples of fish sounds were identified. However, we report examples of isolated unknown sounds that might be produced by fish, invertebrates, or more likely marine mammals. This finding is in direct contrast to recent smaller studies in the Atlantic where potential fish sounds appear to be more common. A review of the literature indicates 32 species found off British Columbia that potentially produce sound could occur in depths greater than 700 m but of these only *Anoplopoma fimbria* and *Coryphaenoides* spp. have been previously reported at the site. The lack of fish sounds observed here may be directly related to the low diversity and abundance of fishes present at the Barkley Canyon site. Other contributing factors include possible masking of low amplitude biological signals by self-generated noise from the platform instrumentation and ship noise. We suggest that examination of data both from noise-reduced ocean observatories around the world and from dedicated instrument surveys designed to search for deep-sea fish sounds to provide a larger-scale, more conclusive investigation into the role, or potential lack thereof, of sound production.

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1. Introduction

Marine organisms inhabiting the deep-sea are subjected to a number of physical and biological factors (e.g., intense pressure, little to no light, limited food sources, and dispersed conspecifics) that make survival, not to mention reproduction, challenging (Herring, 2002). There are varying modalities of sensory organs employed by marine organisms throughout the oceanic depth layers and as depth increases and light vanishes a shift in behavior (and energy) away from sight and towards other sensory systems is common. This is particularly true for fish. For some species, one of those alternate sensory systems

may be hearing (Fine et al., 1987; Buran et al., 2005; Deng et al., 2011), and with improved or at least adequate hearing abilities follows the potential for sound communication. There is good evidence that the soundscape may be important to deep-sea fishes, those inhabiting the continental slope, abyssal plain, canyons and trenches. Over 50 years ago Marshall (1954, 1967) used anatomical studies to determine the possibility of widespread biological sound production by fishes in the deep-sea. He further hypothesized that sound production should be common in bottom fishes on the continental slope (bathyal zone), but rare in pelagic fishes over the slope and abyssal plain (meso and bathypelagic zones) and absent in benthic fishes below the slope (abyssal and hadal zones). These conclusions were based on the presence of swim bladders and sonic muscles in many of the bathyal species and their absence in other groups (Marshall, 1954, 1967). Since that time few studies have reported observations, in large part anecdotal, of possible deep-sea fishes sound production using passive acoustic recordings (Marshall, 1954; Griffin, 1955; Cato, 1978; Kelly et al., 1985; Mann and Jarvis, 2004; McDonald et al.,

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2006; Rountree et al., 2012), although anatomical studies continue to report apparent sound producing organs in deep-sea fishes (Fine et al., 2007; Nguyen et al., 2008).

Marshall (1954) cites Bonaparte (1832) as the only person to report direct evidence of sound production of a deep-sea fish when he reported that the deep-sea rattail or grenadier (*Coelorhynchus coelorhynchus*) often croaked like a gurnard when caught. In no other case have scientists been able to positively validate that observed deep-sea sound are in fact produced by fish. Griffin (1955) reported recording a possible deep-sea fish sound that his calculations showed might have been swimming in the water column at a maximum depth of 3500 m over a 5000 m bottom. Kelly et al. (1985) reported night time biological choruses at three sites located 250–900 km off the coast of Northwest Australia in depths of 1500–5500 m, but seemed to dismiss the possibility of deep-sea fish sounds and suggest these sounds were produced by coastal sciaenids. However, since they were able to clearly discern individual calls and the study site is located far offshore, it is more likely that the source was much closer to the deep water study sites. Cato (1978) attributed sounds from 1000 m depths in Australia to be from sea urchins. Mann and Jarvis (2004) used the US Navy AUTECH range to track the location of a highly probable fish sound in 550–700 m (over a 1600 m bottom depth) off the Bahamas. McDonald et al. (2006) suggested that more recent US Navy monitoring in deep-sea areas provide no evidence of deep-sea sound production by fishes. However, they go on to report possible fish sounds in deep water off the coast of California. Rountree et al. (2012) conducted the first pilot study specifically designed to look for deep-sea fish sound production using baited bottom-mounted recorders. Deep-water autonomous underwater listening system (DAULS) recorders were deployed by commercial fishermen on the seafloor in submarine canyons on the southern flank of Georges Bank in the Northwest Atlantic in locations where deep-sea fish were known to occur. A 24 h recording from Welkers Canyon (682 m depth) contained numerous examples of possible fish sounds (Rountree et al., 2012).³ More recently, Širović et al. (2012) presented sounds they suggested were from sablefish, *Anoplopoma fimbria*, based on a comparison of video and audio data recorded at the NETPUNE Canada Ocean observatory.

Advances in passive acoustic technology and the implementation of large-scale, long-term stationary and autonomous recording platforms (Au et al., 2006; Gannon, 2008; Rountree and Juanes, 2010; Wall et al., 2012, 2013), have enabled scientist to examine diel, seasonal and spatial patterns of behavior associated with sound production in numerous soniferous species (Rountree et al., 2006; Locascio and Mann, 2011) as well as elucidate phylogenetic relationships among fishes (Kaatz and Stewart, 2012). However, these efforts have focused primarily on coastal waters for reasons driven mainly by accessibility. In comparison, sounds produced by deep-sea fish remain largely a mystery. Complications due to increased depth (and thus pressure) and the vastness of the global open ocean (and thus potential sparseness of individuals) has limited acoustic research on these species. The implementation of cabled ocean observatory systems such as NEPTUNE Canada (described in more detail below) is beginning to facilitate the study of deep-sea ecology (Favali and Beranzoli, 2009; Barnes et al., 2011) potentially making it an ideal platform to conduct long-term passive acoustic research on the sound production of deep-sea fish.

The waters off British Columbia are home to over 400 known marine fish species, but sound production has been studied in only a few species (Table 1). However, many more species are suspected of sound production based on anatomical and/or sound

production studies in related species in other parts of the world. Here we provide a brief synopsis of those species (or Families) that are present and likely to produce sound, especially in deep water. Many gadids (Gadidae) have been documented to produce sounds in the Atlantic (Hawkins and Rasmussen, 1978; Hawkins, 1986); however, only walleye pollock (*Theragra chalcogramma*) are reported to produce sounds in the Pacific (Park et al., 1994). Although the closely related Atlantic cod, *Gadus morhua*, has been the subject of many studies in the Atlantic (see review in Rountree et al., 2006), the Pacific cod, *G. macrocephalus*, was found to be silent during courtship and spawning (Sakurai and Hattori, 1996). The related Morids (Moridae) and rattails (Macouridae) are deep water fishes present off British Columbia and are thought to be probable sound producers due to the presence of large sonic muscles and swim bladders in many species (Marshall, 1954, 1967, and citations therein). However, Bonaparte's (1832) anecdotal observations of *C. coelorhynchus* remains the only direct evidence of sound production for either family. Two other important deep water families are the cusk-eels (Ophidiidae) and closely related Brotulids (Bythitidae=Brotulidae), which Marshall (1954, 1967) also reported as typically possessing large sonic muscles and swim bladders. To date, sound production has only been reported for two shallow water cusk-eels in the Atlantic, *Ophidion marginatum* (Mann et al., 1997; Rountree and Bowers-Altman, 2002; Mann and Grothues, 2008) and in the Mediterranean *Ophidion rochei* (Parmentier et al., 2010), and one cave dwelling brotulid from Cuba, *Lucifuga subterranean* (Bridges, 1904; Fish, 1948). Plainfin midshipman (*Porichthys notatus*) produce sound (Brantley and Bass, 1994) but are a mainly intertidal species present off British Columbia with migrations to waters up to 360 m deep (Love et al., 2002). Over 35 species of rockfish (Scorpaenidae) are present in the Northeast Pacific (Love et al., 2002). Sound production in at least six *Sebastes* species has been previously documented (Nichols, 2005; Širović and Demer, 2009; Širović et al., 2009).

Based on studies in other regions, several other Families with potential soniferous species in British Columbia include Cottidae (Fish, 1954; Fish and Mowbray, 1970), Acipenseridae (Tolstoganova, 2000; Bruch and Binkowski, 2002; Sulak et al., 2002; Johnston and Phillips, 2003), Salmonidae, Clupeidae, Carangidae (e.g., Fish, 1954; Fish and Mowbray, 1970), Sciaenidae, Embiotocidae, Gobiidae (Amorim, 2006; Kasumyan, 2008), Gasterosteidae (Fish and Mowbray, 1970; Amorim, 2006; Kasumyan, 2008), and Molidae. Altogether, our review of the literature suggests that at least 32 species of fish from known sound producing Families present off British Columbia have depth ranges greater than 700 m (Table 2). While it is possible that pelagic fishes occurring in the water column above the observatory might also be detected (e.g., *Mola mola* and *Clupea pallasii*), little is known about sound production in epipelagic, mesopelagic and benthopelagic taxa. Finally, although research has been limited, many marine invertebrates are capable of both incidental and communicative sound production (Fish, 1964; Popper et al., 2001; Rountree et al., 2006).

The primary goal of this study was to determine if there is evidence for deep-sea fish sounds in support of Marshall's hypothesis using a long-term passive acoustic dataset recorded at the NEPTUNE Canada ocean observing system off Vancouver Island. It is also our intent to provide a review of literature on sound production in the Northeast Pacific with specific inclusion of deep-sea species. To our knowledge, such an effort has not been made since Fish (1948).

2. Materials and methods

The NorthEast Pacific Time-Series Undersea Networked Experiments project (NEPTUNE) Canada, part of the Ocean Networks Canada Observatory, is located off the west coast of Vancouver

³ Sample sound clips from this study can be downloaded at <http://www.fishecology.org>

Table 1
Summary of marine and anadromous fishes of British Columbia that have been reported to produce sound.

Family	Species	Common name	Depth range (m)	Sound production source
Anoplopomatidae	<i>Anoplopoma fimbria</i>	Sablefish	305–2740 ^a	Meldrim (1965), Širović et al. (2012)
Batrachoididae	<i>Porichthys notatus</i>	Plainfin midshipmen	0–366 ^b	Fish (1948), Ibara et al. (1983); Bass (1990); Brantley and Bass (1994)
Carangidae	<i>Naucrates ductor</i>	Pilotfish	0–30 ^b	Fish (1954), Fish and Mowbray (1970)
Clupeidae	<i>Clupea pallasii</i>	Pacific herring	0–475 ^c	Fish (1948, 1954); Schwarz and Greer, 1984; Wilson et al. (2004), Kuznetsov (2009)
Cottidae	<i>Sardinops sagax</i>	Pacific sardine	0–200 ^d	Kuznetsov (2009)
	<i>Enophrys bison</i>	Buffalo sculpin	0–20 ^b	Fish (1948); Fish and Mowbray (1970); Meldrim (1965)
	<i>Enophrys dicerca</i> (<i>E. lucasi</i>)	Antlered sculpin	0–380 ^e	Fish (1948) (as <i>E. claviger</i>)
Embiotocidae	<i>Leptocottus armatus</i>	Staghorn sculpin	0–156 ^b	Fish (1948)
Gadidae	<i>Rhacochilus vacca</i>	Pile perch	Up to 46 ^b	Meldrim (1965)
Molidae	<i>Theragra chalcogramma</i>	Walleye pollock	0–1280 ^e	Park et al. (1994)
	<i>Mola mola</i>	Ocean sunfish	30–480 ^e	Uchida (1934); Fish (1948), Fish and Mowbray (1970)
Salmonidae	<i>Oncorhynchus gorbuscha</i>	Pink salmon	0–250 ^e	Neproshin and Kulikova (1975), Kuznetsov (2009)
Salmonidae	<i>Oncorhynchus keta</i>	Chum salmon	0–250 ^e	Neproshin and Kulikova (1975); Kuznetsov (2009)
	<i>Oncorhynchus mykiss</i>	Rainbow trout	0–200 ^f	Phillips (1989)
Sciaenidae	<i>Atractoscion nobilis</i>	White seabass	0–122 ^d	Skogsberg (1939), Fish (1948), Aalbers (2008), Aalbers and Drawbridge (2008), Aalbers and Sepulveda (2012)
Scorpaenidae	<i>Genyonemus lineatus</i>	White croaker	Up to 183 ^d	Skogsberg (1939), Fish (1948), Aalbers and Sepulveda (2012)
	<i>Sebastes atrovirens</i>	Kelp rockfish	Up to 46 ^d	Nichols (2005); Širović et al. (2009)
	<i>Sebastes carnatus</i>	Gopher rockfish	Up to 55 ^d	Nichols (2005), Širović et al. (2009)
	<i>Sebastes chrysomelas</i>	Black-and-yellow rockfish	0–37 ^d	Nichols (2005), Širović et al. (2009)
	<i>Sebastes melanops</i>	Black rockfish	0–366 ^e	Nichols (2005), Širović et al. (2009)
	<i>Sebastes nebulosus</i>	China rockfish	3–128 ^b	Nichols (2005); Širović et al. (2009)
	<i>Sebastes paucispinis</i>	Bocaccio	0–476 ^g	Nichols (2005), Širović et al. (2009)

^a Allen and Smith (1988).

^b Eschmeyer and Herald (1999).

^c Coad and Reist (2004).

^d Whitehead et al. (1988).

^e Froese and Pauly (2013).

^f Hart (1973).

^g Kramer and O'Connell (1988).

Island in the Northeast Pacific (<http://www.neptunecanada.ca>; Fig. 1a). This cabled ocean network contains five nodes ranging in depth from 23 m to 2660 m creating highly advanced, multi-parameter platforms for the multidisciplinary study of deep-sea ecosystems (Barnes et al., 2011). The Barkley Canyon node located in Barkley Sound contains several pods that branch off from the main instrument platform (Barkley Upper Slope Instrument Platform) (Fig. 1b). Hydrophones were installed at the Folger Passage Deep, Barkley Upper Slope Instrument Platform, Barkley Axis Pod, Barkley Upper Slope Pod 2 and Barkley Vertical Profiler System. However, only Barkley Axis Pod located in the axis of the Barkley Canyon provided audio data at a depth sufficient to record deep-sea fish over an extended period of time (latitude: 48° 19.0046'N, longitude: 126° 03.0075'W, depth: 985 m). In addition to a passive acoustic system, Barkley Axis Pod contains a rotary sonar (675 kHz; Kongsberg Mesotech Rotary Sonar 1071), a current profiler (2 MHz; Nortek Aquadopp HR-Profiler), and a color video camera with pan/tilt capabilities (Axis network camera). This pod is connected to the Barkley Upper Slope Instrument Platform via a 1430 m extension cable, which is linked to the other nodes by electro-optic cables spanning over 800 km.

The passive acoustic system at Barkley Axis Pod was deployed on September 11, 2009 and has recorded data from November 2, 2009 until July 14, 2011 with little interruption. This system incorporated a Naxys ethernet hydrophone (–179 dB re 1 V/μPA with 20 dB gain, NAXYS Technology) and operated continuously at a 96 kHz sample rate. The hydrophone was only calibrated from 10 to 96 kHz so only relative amplitude measurements can be provided for signals below this frequency range (10 Hz < 10 kHz). Files are stored in 5 min segments, producing 12 files per h.

In order to explore acoustic files for sounds not previously recorded much less without having prior knowledge of diel or seasonal patterns, manual analysis was imperative. However, the large dataset available at this node precluded anyone's ability to scan over 175,000 files in a timely manner. Therefore, a subset of files recorded between June 27, 2010 and May 1, 2011 was examined by selecting one day at the beginning of each month and analyzing one file an hour, recorded at the top of the hour (24 files per month). These sound files were analyzed audibly and visually by examining each file's spectrogram (1024 point Hann-windowed FFTs with 50% overlap). In order to discern low amplitude sounds, 20 dB amplification was added to sound files. The presence, if any, of suspected fish sounds, marine mammals, and abiotic noise were noted.

Additional files recorded within 15 min either before or after suspected fish sounds were examined to determine if the signals in question were repetitive, which would help to resolve their origin. Files containing suspected fish or other sounds of interest were analyzed in depth by three scientists to reduce subjectivity. All files were examined using Raven Pro software (Cornell Lab of Ornithology).

3. Results

Of the 313 sound files analyzed, there was no observation of an unequivocal example of fish sound production. Calls from marine mammal and self-generated instrument noise, however, were recorded frequently. Over 19% of the sound files (58/313) contained marine mammal calls including baleen whales

Table 2
Summary of deep-sea fish species present off British Columbia in depths greater than 700 m that are from known sound producing Families.

Family	Species	Common name	Depth range (m)
Anoplopomatidae	<i>Anoplopoma fimbria</i>	Sablefish	305–2740 ^a
Scorpaenidae	<i>Sebastes aleutianus</i>	Rougheye rockfish	25–900 ^e
	<i>Sebastes alutus</i>	Pacific ocean perch	0–825 ^a
	<i>Sebastes aurora</i>	Aurora rockfish	124–769 ^a
	<i>Sebastes borealis</i>	Shortraker rockfish	0–1200 ^e
	<i>Sebastes diploproa</i>	Splitnose rockfish	0–800 ^e
	<i>Sebastes pinniger</i>	Canary rockfish	0–838 ^c
	<i>Sebastes polyspinis</i>	Northern rockfish	0–740 ^b
	Ophidiidae	<i>Bassozetus zenkevitchi</i>	
<i>Dicrolene filamentosa</i>			935–1867 ^g
<i>Porogadus longiceps</i>			245–3281 ^g
<i>Spectrunculus grandis</i>		Pudgy cuskeel	800–4300 ^e
Macrouridae	<i>Albatrossia pectoralis</i>	Giant grenadier	140–3500 ^e
	<i>Coryphaenoides acrolepis</i>	Pacific grenadier	300–3700 ^e
	<i>Coryphaenoides armatus</i>	Abyssal grenadier	282–5180 ^b
	<i>Coryphaenoides cinereus</i>	Popeye grenadier	150–3500 ^e
	<i>Coryphaenoides leptolepis</i>	Ghostly grenadier	610–4000 ^e
	<i>Coryphaenoides liocephalus</i>	Bearded rattail	Up to 3750 ^e
	<i>Coryphaenoides longifilis</i>	Longfin grenadier	550–3000 ^e
	<i>Coryphaenoides spinulosus</i>		Up to 1248 ^a
	<i>Nezumia stelgidolepis</i>	California grenadier	277–909 ^h
	Moridae	<i>Antimora microlepis</i>	Finescale mora
<i>Antimora rostrata</i>		Blue antimora	350–3000 ^h
<i>Halargyreus johnsonii</i>		Slender codling	450–3000 ^d
Gadidae	<i>Theragra chalcogramma</i>	Walleye pollock	0–1280 ^d
	<i>Gadus macrocephalus</i>	Pacific cod	0–1280 ^d
Cottidae	<i>Hemilepidotus spinosus</i>	Brown Irish lord	0–780 ^e
	<i>Icelinus filamentosus</i>	Threadfin sculpin	18–800 ^f
	<i>Icelus spatula</i>	Spatulate sculpin	12–930 ^b
	<i>Icelus spiniger</i>	Thorny sculpin	25–770 ^f
	<i>Myoxocephalus polyacanthocephalus</i>	Great sculpin	0–775 ^f
	<i>Triglops pingelii</i>	Ribbed sculpin	0–930 ^e
	<i>Zesticelus profundorum</i>	Flabby sculpin	88–2580 ^a

^a Allen and Smith (1988).

^b Eschmeyer and Herald (1999).

^c Coad and Reist (2004).

^d Whitehead et al. (1988).

^e Froese and Pauly (2013).

^f Kramer and O'Connell (1988).

^g Nielsen et al. (1999).

^h Cohen et al. (1990).

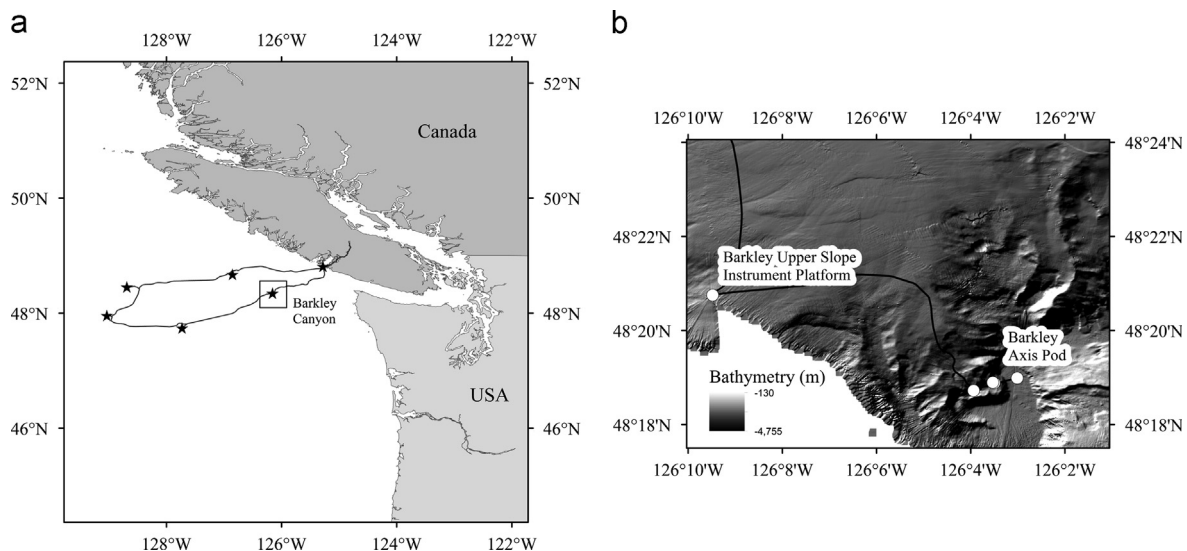


Fig. 1. Study area. (a) Overview of the NEPTUNE Canada cabled ocean network. (b) Detailed view of the Barkley Canyon node. The Barkley Axis Pod is where the passive acoustic data were collected.

(humpback whales, *Megaptera novaeangliae*; blue whales, *Balaenoptera musculus*, and fin whales, *Balaenoptera physalus*), and odontocetes (killer whales, *Orcinus orca* and Pacific white-sided dolphins, *Lagenorhynchus obliquidens*). Broadband pulses (1–48 kHz) were recorded throughout the dataset. The amplitude, number of pulses and inter-pulse intervals of the broadband pulse signal varied (data not shown) as well as its periodicity (mean \pm S.D.; 356 s \pm 168). These broadband pulses were always followed by lower amplitude pulses between 2 and 6 kHz. Timing between the broadband pulses and the 2–6 kHz pulses varied (mean \pm S.D.; duration: 42.5 s \pm 23, $n=51$). These pulse trains are suspected to result from the firing of the rotary sonar. A short duration 900 Hz mechanical tone from the pan or tilt of the video camera located near the hydrophone was also frequently recorded (mean \pm S.D.; duration: 1.8 s \pm 0.2; peak frequency: 909 Hz \pm 45). Frequencies below \sim 100 Hz and at 33 kHz contain noise from the general instrument operation, the latter creating a ubiquitous narrowband (< 50 Hz) tone from the microcontroller's oscillating crystal circuit used to keep time.

In addition to the above identifiable sounds, some sounds of unknown origin were also observed. We have selected a few of particular note due to their low frequency and short duration characteristics.⁴ Fig. 2 illustrates a sound (“Unknown Sound 1”) between 140 and 300 Hz recorded twice in a single file (3 s and 22 s). Another sound (“Unknown Sound 2”) between 160 and 240 Hz was also observed (Fig. 3). Finally two short duration pulses were recorded between 180 and 230 Hz, “Unknown Sound 3” (Fig. 4). Characteristics of each sound are provided in Table 3.

4. Discussion

Passive acoustic data recorded at the NEPTUNE Canada Barkley Canyon Axis Pod were examined for the presence of deep-sea fish sound production. Despite some unknown sounds identified in the files, it is impossible to say with any certainty that any of the sounds outlined here are unequivocally fish. Although the unknown sounds are low frequency and short in duration, which are general characteristics of fish sounds (Fish and Mowbray, 1970; Amorim, 2006; Kasumyan, 2008), the frequent occurrence of marine mammal calls also makes cetaceans a potential source. There was a definite lack of nocturnal chorusing, typical of fish sound production, similar to those observed by Kelly et al. (1985). Although we suspect the unknown sounds reported here are of biological origin based on *a priori* knowledge of fish sound production, none of the sounds presented here are similar to any known fish sounds previously encountered.

Sablefish (*Anoplopoma fimbria*) were observed 76.2% of the time in an analysis of video data recorded at the Barkley Canyon Axis Pod (Doya et al., in press). Sablefish were also frequent within video frames coincident with the time period of this study (data not shown). This species is suspected to produce broadband clicks up to 10 kHz (Meldrim, unpubl. data). However, sablefish sound production remains ambiguous as these recordings have never been replicated. Širović et al. (2012) examined 30 h of concurrent video and acoustic data recorded at the Barkley Canyon Axis Pod between May 2010 and February 2011. Sablefish were again commonly observed in the video data and broadband pulses were recorded while sablefish were in the video frame 1/5 of the time (Širović et al., 2012). While the 1560 h of acoustic data examined in our analysis were recorded over the same time period as Širović et al. (2012), we did not examine files specifically recorded when the video camera was on. The movement and, more likely, lights

associated with the video data may increase the likelihood of sound production by sablefish thereby potentially producing different results between the studies (Doya et al., in press). Further analysis of the NEPTUNE acoustic and video data as well as a high signal to noise recording of captive sablefish would help to determine with greater certainty the contribution of sablefish to the acoustic soundscape.

Doya et al. (in press) also noted the presence of eelpouts (*Lycenchelys* spp.), hagfish (*Eptatretus* spp.), blackfin poachers, (*Bathyagonus nigripinnis*), rattails (*Coryphaenoides* spp.), and rex sole (*Glyptocephalus zachirus*) at the Barkley Canyon Axis site. Of these species, only rattail potentially produce sound (Marshall, 1954, 1967). While at least nine species have depth ranges that overlap with the study site, rattails are most abundant between 2000 and 3000 m (Stein and Percy, 1982). At nearly 1000 m, this observatory site lies at the transition between the photic and aphotic layer, which may contribute to limiting the number of individuals and species present (see Table 2).

Additional potential sound producing species expected to be present at depth in the Northeast Pacific were not observed in our analysis nor within the Doya et al. (in press) survey (see Table 2). One possibility is that sound production may occur in the upper water column rather than on the seafloor since some species have adaptations for increased buoyancy as they mature (Stein and Percy, 1982). A second possibility is the use of lights, a necessity in video analysis in the aphotic layer, which might influence behavior and, potentially, sound production (Stoner et al., 2008; Doya et al., in press; Rountree and Juanes, 2010). A third possibility is the potential for deep-sea fish to only produce low amplitude sound intended for close field communication, e.g., agonistic behavior. Therefore, even in very quiet environments the detection range for deep-sea fish sounds may be limited to several meters. Further, the placement of the NEPTUNE nodes was primarily driven by geophysical research initiatives rather than being deployed in known areas of high fish concentrations (Rountree et al., 2012), which may inherently limit observations of soniferous fishes, especially when the limitations noted above become compounding factors. These factors will similarly impede our detection of invertebrate sound production, which are typically of low amplitude and, based on low diversity at the site, likely infrequent.

Although ocean observatories such as NEPTUNE Canada provide excellent opportunities to conduct long-term deep-sea research, there are limitations to platform-based acoustic analysis. Most importantly is noise generated from instrumentation on the platform itself. The broadband pulses and the video camera have been outlined as consistent noise producers; however, other instruments on this or nearby nodes, in addition to regular maintenance efforts, can contribute to the levels of ambient noise. This noise can be problematic when potentially low amplitude and infrequent biotic sounds are the focus, as in this study. Ambient noise is further increased by the broadband, high amplitude sounds associated with vessel traffic (McDonald et al., 2006; Slabbekoorn et al., 2010). Recent research has outlined areas of excessively high sound exposure levels from vessels in Barkley Sound (Erbe et al., 2012). A catalog of all noises associated with platform instrumentation and operation is suggested for any ocean observing system, and specifically for those containing a passive acoustic recording system, to help differentiate between instrument-, vessel- and other mechanical-based sounds that contribute to the soundscape.

A further challenge in this study is the lack of prior knowledge on the characteristics of deep-sea fish sounds present. While this gap in knowledge is the driving factor for this exploratory research, not having a baseline to start with could cause some sounds to be overlooked or classified improperly (e.g., as marine mammal sounds).

⁴ Copies of these sounds are posted online at <http://www.fishecology.org>

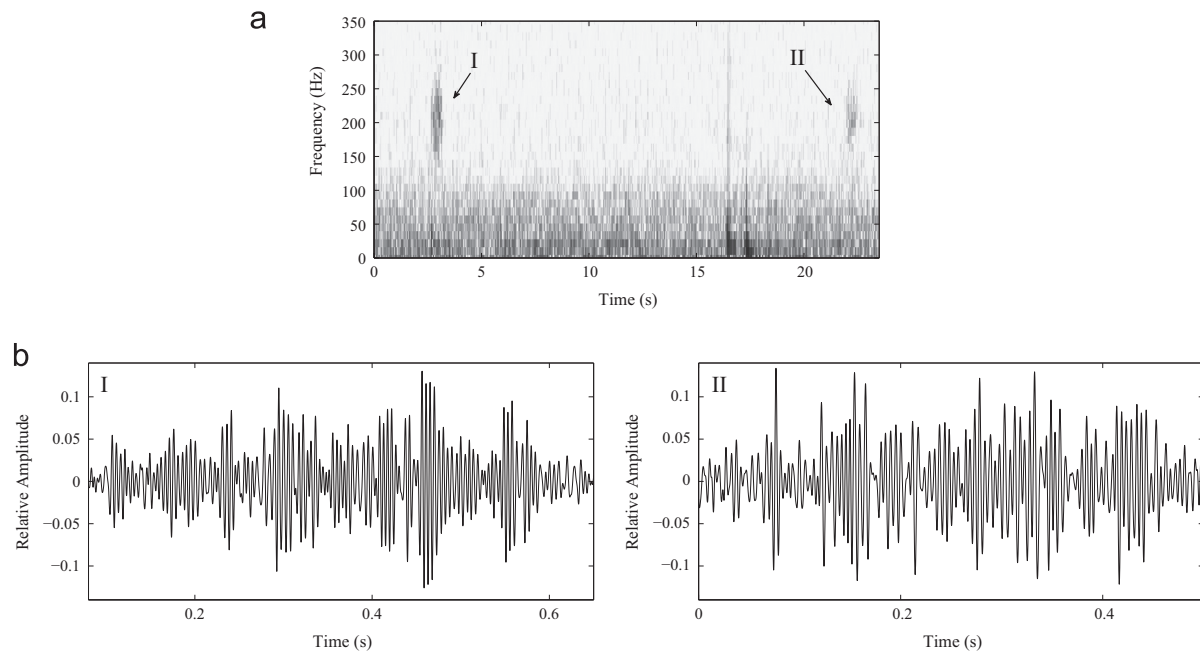


Fig. 2. Example of “Unknown Sound 1”. (a) Spectrogram (1024 point FFT) and (b) waveform. The black arrows point to the sound. Individual sounds are denoted as I and II.

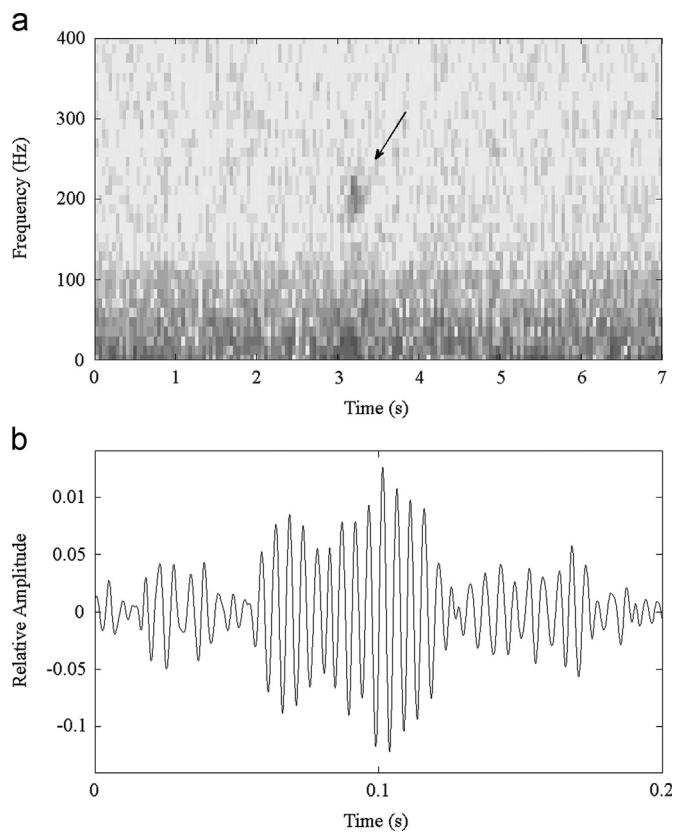


Fig. 3. Example of “Unknown Sound 2”. (a) Spectrogram (1024 point FFT) and (b) waveform. The black arrow points to the sound.

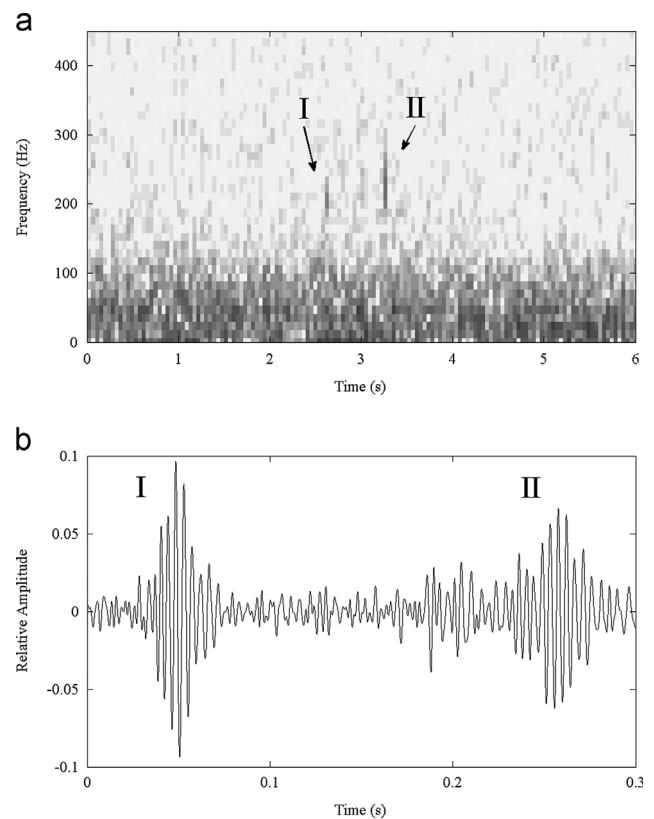


Fig. 4. Example of “Unknown Sound 3”. (a) Spectrogram (1024 point FFT) and (b) waveform. The black arrows point to the sound. Individual sounds are denoted as I and II.

Implementing multiple hydrophones in order to localize sounds will help identify where a sound was made (e.g., in the water column, on the seafloor, or on the platform) and thus greatly aid in determining the source (Mann and Jarvis, 2004; Rountree, 2008).

Animals depend on sound for communication, predator avoidance, prey detection, and/or environmental orientation (Slabbekoorn and Bouton, 2008). Therefore, determining how the marine

soundscape and its function in the marine ecosystem are affected by long-term increases in chronic and acute anthropogenic noise is of increasing importance. Researchers are just beginning to focus on these issues, particularly in studies of marine mammal ecology, however, there is a dearth of information on biological sound production by marine fishes and invertebrates, namely in relation to how the soundscape functions in their ecologies, (Rountree,

Table 3

Characteristics of three unknown sounds recorded at the NEPTUNE Barkley Canyon Axis Pod. Unknown Sounds 1 and 3 contain two occurrences of the sound in each example. Measurements were made for each instance and are denoted by I and II. The lowest frequency (“Low Freq.”), peak frequency (“Peak Freq.”), highest frequency (“High Freq.”), duration, and interpulse duration of each unknown sound as well as the date and local time of the acoustic file (“Recording Date”, “Recording Time”, respectively), and the time within the file the sound starts (“Start Time”) are provided below. The full name of the acoustic file (“File name”) is indicated for each unknown. *Denotes a file altered by the Royal Canadian Navy due to naval activity in the area, which resulted in 11 min files of 12 kHz sample rate. N/A denotes not applicable.

Name	Low frequency (Hz)	Peak frequency (Hz)	High frequency (Hz)	Duration (s)	Interpulse duration (s)	Recording date	Recording time (Local)	Start time
File name: NAXYS_HYD_007_20101114T140903.031Z.WAV*								
Unknown sound 1 I	138.8	210.9	295.6	0.5	N/A	14-Nov-10	6:09	7:03
Unknown sound 1 II	167.5	199.2	267.9	0.6	N/A	14-Nov-10	6:09	7:22
File name: NAXYS_HYD_007_20101114T134630.116Z.WAV								
Unknown sound 2	159.1	210.9	242.8	0.3	N/A	14-Nov-10	5:46	2:28
File name: NAXYS_HYD_007_20101114T152830.455Z.WAV								
Unknown sound 3 I	184.4	368.7	234.4	0.1	0.1	14-Nov-10	7:28	1:16
Unknown sound 3 II	191.9	262.6	222.7	0.1		14-Nov-10	7:28	1:16

2008; Luczkovich et al., 2008; Fay, 2009). The results presented here focus on one specific location of the deep sea. However, studying additional areas using different or at least complementary methods may elucidate a more conclusive, larger scale understanding of the role of the underwater soundscape and the importance of biological sound production to deep-sea ecosystems. The deep-sea soundscape is particularly vulnerable to increasing anthropogenic noise (e.g., McDonald et al., 2006) while at the same time being subjected to increasing pressures from resource users (Koslow et al., 2000). Therefore, we advocate the need for basic research to be conducted before resources are fully exploited. Complementary research that involves passive acoustic data collected at both multi-parameter ocean observatories and individual locations that specifically target concentrations of deep-sea fish would provide valuable “baseline” information on sound source identity, behavior, and habitat characteristics.

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