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Using statolith elemental signatures to confirm ontogenetic migrations of the squid *Doryteuthis gahi* around the Falkland Islands (Southwest Atlantic)

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ABSTRACT

The Patagonian long-finned squid *Doryteuthis gahi* is an abundant commercial species within Falkland Island waters. The population consists of two temporally distinct spawning cohorts, inferred to have markedly different patterns of migration and timings of ontogenetic events. Ontogenetic migrations of each cohort were confirmed by analysis of the chemical composition of statoliths collected from both cohorts in two consecutive years. Trace element concentrations were quantified using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), to determine temporal and cohort-specific variation. Individual ablation craters, ablated in a transect from the nucleus to the rostrum edge, were aged to produce high-resolution elemental chronologies. Generalized additive mixed models (GAMM) indicated that cohort and life history stage had a significant effect on Sr/Ca and Ba/Ca ratios. Sr/Ca and Ba/Ca ratios were both negatively correlated with near-bottom water temperature, with Ba/Ca also potentially correlated to depth. Statolith elemental chronologies have useful applications as natural tags, discriminating between spawning cohorts.

1. Introduction

Cephalopods have become an increasingly important fisheries resource over the last few decades, as evidenced by the rapid increase in global landings (Arkhipkin et al., 2015; Doubleday et al., 2016; Hunsicker et al., 2010; Pierce and Portela, 2014). They have an unusual life history characterised by; short lifespan, complex population structure and for many species extensive ontogenetic migrations. Understanding the degree of migration, connectivity and structure of a population is fundamental to the design of effective conservation and management strategies (Gillanders, 2005). Traditional techniques such as tagging allow for insights into an individual's movement and behaviour throughout ontogeny (Gilly et al., 2006; Thorrold et al., 2002). However, these techniques are difficult to implement on small species such as coastal loliginid squid, which are too fragile for an external tag and are lacking a suitable attachment site that does not inhibit their behaviour (Arkhipkin, 2005). An alternative method that requires no prior handling is the geochemical analysis of calcified structures in marine organisms. This method has been shown to have applications in determining population structure (Arbuckle and Wormuth, 2014), migration patterns (Ikeda et al., 2003), assigning natal origin (Pecl et al., 2011) and as a proxy for environmental parameters (Beck et al., 1992). Analysis of elemental signatures has been applied to a wide range of taxa such as; scleractinian corals (Beck et al., 1992), teleost fish (Campana, 1999), gastropods (Zacherl et al., 2003), medusae (Mooney and Kingsford, 2012), bivalves (Gillikin et al., 2008) and cephalopods (Arbuckle and Wormuth, 2014; Warner et al., 2009).

Statoliths are paired calcareous concretions found within the statocysts, responsible for the detection of linear and angular acceleration in cephalopods (Arkhipkin and Bizikov, 2000; Clarke, 1978). Analogous to fish otoliths, these hard structures grow continually throughout life and are formed by the deposition of calcium carbonate crystals, primarily in aragonite form, within a protein matrix (Radtke, 1983). Throughout the accretion process, trace elements are incorporated into this matrix (Arkhipkin, 2005; Bettencourt and Guerra, 2000). Uptake of these elements into the statolith microstructure is considered to reflect the ambient environmental conditions at the time of incorporation. For example, Sr/Ca ratios have been suggested to have a negative relationship with temperature in many biogenic calcified structures in a wide range of taxa (Beck et al., 1992; Campana, 1999; Galante-Oliveira et al., 2015; Zacherl et al., 2003). Statoliths are appropriate for use as a natural tag on account of their metabolic inertness after deposition and

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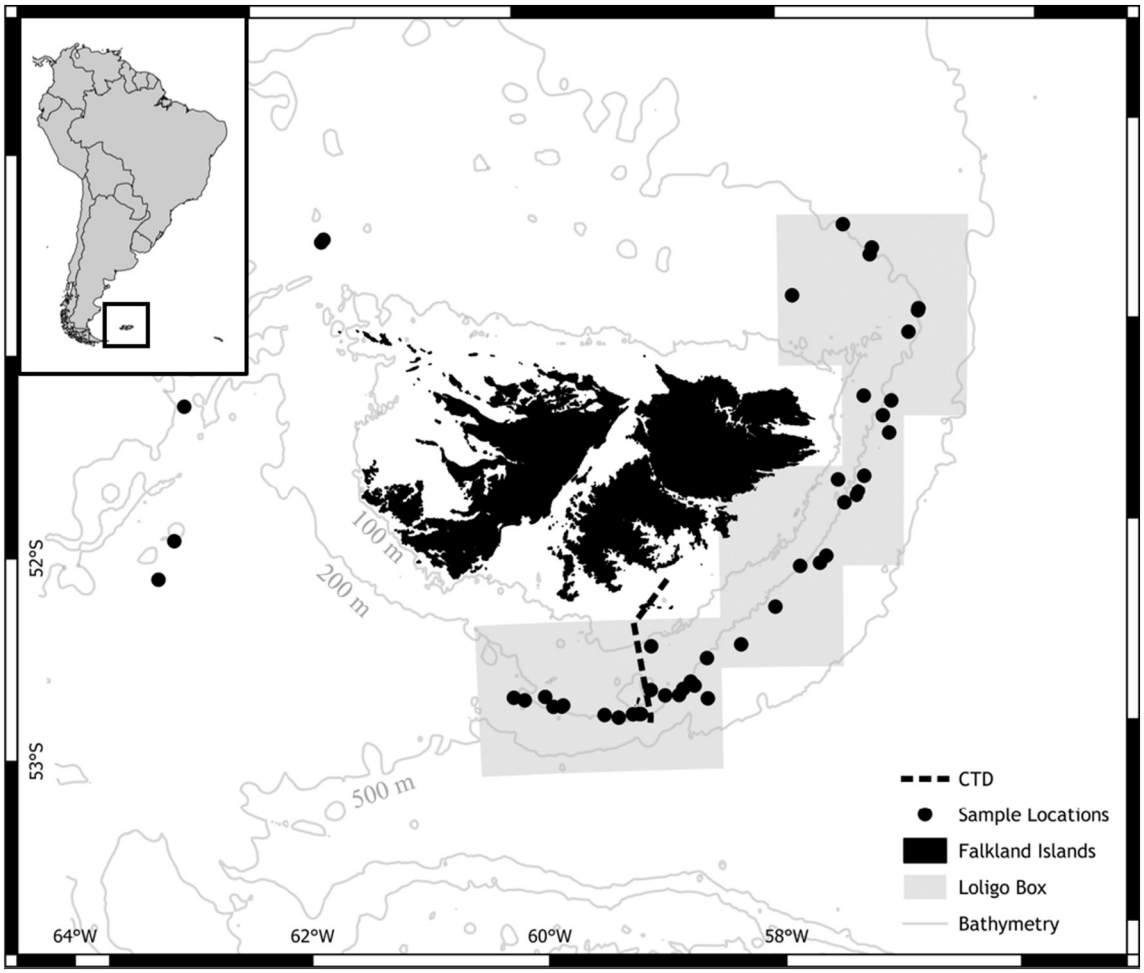

Fig. 1. Sample locations within the Falkland Interim Management and Conservation Zone (FICZ). The Loligo box denotes the fishing area. Monthly oceanographic data were collected along the CTD transect (dotted line). The inset map indicates the position of the Falkland Islands in relation to mainland South America.

the incorporation of continuous growth increments, which give a temporal scale for analysis (Wang et al., 2012).

The Patagonian long-finned squid *Doryteuthis gahi* (D'Orbigny, 1835) is a cold water loliginid most abundant in Falkland Islands waters, where it is subject to an important and economically valuable commercial fishery. It is a small species, typically attaining an adult size of 13–17 cm mantle length (Arkhipkin et al., 2013). As well as being a key fisheries resource, *D. gahi* is involved in the transfer of organic and inorganic material across various parts of the shelf ecosystem and has an important role both as predator and prey (Arkhipkin, 2013). It is an important food source for marine mammals (Arkhipkin, 2013), commercially important finfish (Laptikhovsky et al., 2010) and seabirds (Piatkowski et al., 2001).

These squid undergo horizontal ontogenetic migrations from shallow inshore spawning and nursery grounds to feeding aggregations on the shelf edge and continental slope, where they are targeted by the fishery (Arkhipkin et al., 2004a; Hatfield et al., 1990). The fishery operates within two seasons corresponding to two temporally distinct cohorts (Patterson, 1988), the autumn spawning cohort (ASC) and spring spawning cohort (SSC), both of which have an annual life cycle. The duration of embryogenesis, extent of offshore migration and time of spawning differ between cohorts (Arkhipkin et al., 2013).

An initial study which determined the elemental composition of *D. gahi* statoliths using solution-based inductively coupled plasma mass spectrometry (ICP-MS) found significantly different elemental signatures between cohorts and geographic regions (Arkhipkin et al., 2004a). As the study dissolved the entire statolith and quantified its elemental composition, it was unable to determine how the elemental signal changed throughout ontogeny. Alternative analytical techniques such as ion-probe or laser ablation analysis are able to target specific regions of the statolith microstructure to gather stage-specific information on life history and migration patterns.

A good understanding of migration patterns is of particular importance in short-lived species such as *D. gahi*, which show a strong inter-annual variability and are more sensitive to factors such as increased fishing pressure and environmental change (Doubleday et al., 2016). Therefore, the aims of this study were to generate temporally resolved elemental chronologies for each individual by quantifying trace elements in statoliths, to compare the elemental chronologies generated for each spawning cohort and to explore possible relationships between environmental factors and the element/Ca ratio at the corresponding time of incorporation.

2. Materials and methods

2.1. Statolith collection and preparation

Squid were collected and frozen by scientific observers on board commercial trawling vessels within the Falkland Islands Interim Conservation and Management Zone (FICZ). Data collection took place during both fishing seasons (Season 1: March–May, Season 2: July–October) of both 2014 and 2015 within the designated fishing zone, the “Loligo box” and to the west of the Falkland Islands (Fig. 1). Mature individuals of both sexes were selected to ensure that each