Varying frequency of vateritic otoliths in the Baltic herring
*Clupea harengus membras*

Katja Mäkinen\(^1\) ♦ | Marjut Rajasilta\(^1\) | Ermei Mäkilä\(^2\) | Sami Jokinen\(^3,4\) | Jari Hänninen\(^1\)

1Archipelago Research Institute, Biodiversity Unit, University of Turku, Turku, Finland
2Laboratory of Industrial Physics, Department of Physics and Astronomy, University of Turku, Turku, Finland
3Department of Geography and Geology, University of Turku, Turku, Finland
4Marine Geology, Geological Survey of Finland (GTK), Espoo, Finland

Correspondence
Katja Mäkinen, Archipelago Research Institute, Biodiversity Unit, University of Turku, FI-20014 Turku, Finland.
Email: katja.makinen@utu.fi

Funding information
Sakari Alhopuro Foundation, Grant/Award Number: 20200084

Abstract
We report observations of vateritic crystallization in the sagittal otoliths of the Baltic herring *Clupea harengus membras* in the northern Baltic Sea. While the existence of vaterite in the calcium carbonate matrix of sagittal otoliths has been observed in various species globally, reports from the brackish Baltic Sea are few in number. Large variation in the frequency of vaterite in 1984, 1988, 1997, 2010 and 2017 was observed, suggesting that the phenomenon is not static and more long-term studies should be conducted in search of the ultimate causing factors.

**KEYWORDS**
aragonite, Baltic herring, mineral composition, otoliths, vaterite, XRD

The calcium carbonate (CaCO\(_3\)) matrix of sagittal otoliths is, in most cases, composed of aragonite, whereas the two other polymorphs, calcite and vaterite, are used relatively infrequently (Carlström, 1963; Gauldie, 1986; Reimer et al., 2016; Strong et al., 1986). Each of these polymorphs have their characteristic crystal structure, and a ‘switch’ from aragonite to either calcite or vaterite results in the formation or co-precipitation of a translucent or ‘glass-like’ crystalline matrix, which often also causes considerable distortion to the shape, density, brittleness, and size of the otolith (e.g., Gauldie, 1986; Tomás & Geffen, 2003). This non-aragonite crystallization, also referred to in the literature as ‘aberrant’ crystallization, has been documented in the otoliths of several fish species in various environments (e.g., Budnik et al., 2020; Loeppky et al., 2021; Melancon et al., 2005; Reimer et al., 2016; Tzeng et al., 2007), including juvenile Atlantic herring *Clupea harengus* L. in the Celtic and Clyde Seas (Tomas and Geffen, 2003; Tomas et al., 2004). Yet, the ultimate factors determining which CaCO\(_3\) polyform is produced are still not completely understood (Thomas & Swearer, 2019).

Based on current knowledge, vaterite crystallization is associated with changes in the internal physiology of the fish and is possibly protein-mediated (as reviewed in Thomas & Swearer, 2019). For instance, Reimer et al. (2017) showed that fast-growing Atlantic salmon *Salmo salar* L. were three times more likely to have vaterite otoliths than slow-growing individuals were. The authors speculated that the difference could be caused, for example, by the greater energy content of fast-growing fish, which may lead to greater transport of bicarbonate ions (HCO\(_3^-\)) relative to Ca\(^{2+}\) into the endolymph and result in a lower (Ca\(^{2+}\))/(CO\(_3\)^{2-}\) ratio conducive for vaterite formation. Studies have also shown that the environment (temperature, pH) can impact otolith mineralization (Coll-Lladó, 2021; Loeppky et al., 2021). In connection with this, physiological or environmental stress has been suggested to explain the occurrence of vaterite crystallization in some wild fish (Melancon et al., 2005; Tzeng et al., 2007; Yedier & Bostanci, 2019).

In the Baltic Sea, the existence of crystallized otoliths has long been recognized (e.g., ICES, 2008), yet only few studies on the topic exist (e.g., Lill et al., 2020; Tzeng et al., 2007). In these studies, the occurrence of vaterite was reported with respect to otolith microchemistry due to vaterite’s capability to confound studies using

---

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

© 2022 The Authors. *Journal of Fish Biology* published by John Wiley & Sons Ltd on behalf of Fisheries Society of the British Isles.
otolith elemental signatures as biological tracers (Tzeng et al., 2007). Nevertheless, the semi-enclosed, brackish-water ecosystem of the Baltic Sea could also provide a unique model system to study causing environmental and physiological factors as its organisms are subjected to pronounced latitudinal and vertical temperature and salinity gradients, which directly and indirectly dominate their physiological ecology. In addition, climate change is affecting the ecosystem of the Baltic Sea in ways that most coastal areas will experience only in the future (Reusch et al., 2018). To date, climate-induced hydrological changes have caused several changes in the ecosystem and food web that, for instance, have affected the growth rate and condition of the Baltic herring Clupea harengus membras L. (Casini et al., 2011; Möllmann et al., 2005; Rajasila et al., 2019, 2021; Rönkkönen et al., 2004).

Here, we report observations of ‘abnormal’ or ‘vateritic’ crystallization in the sagittal otoliths of adult C. harengus membras from selected years, over the period 1984–2017. The mineral composition was studied from archival otoliths, collected in 1984, 1988, 1997, 2010, and 2017 as part of an annual monitoring program of the species spawning population in the northern Baltic Archipelago Sea (60°23’N, 22°05’E). The area encompasses one of the main spawning areas for the species in the northern Baltic Sea (Rajasila et al., 1993). In the Baltic Sea, C. harengus membras is a dominant, shoaling fish species that lives and reproduces throughout the brackish-water basin and exhibits large variation in its characteristics. Sagittal otoliths were removed from the fish during the standard sample treatment for age determination (Eklund et al., 2001) and visually analysed as a whole under a stereomicroscope at 40× magnification. According to standard classification, described, for example, by Gauldie (1986) and Sweeting et al. (2004), the otolith was classified as ‘vateritic’ if any translucent and ‘glass-like’ crystals were clearly identifiable in either otolith, or as ‘aragonitic’ if the studied otoliths were opaque and no crystalline structure was evident (Fig. 1). The frequency of vaterite crystallization was defined as the percentage (%) of vateritic otoliths in fish in each study year (Table 1). In total 7792 fish were studied. Variation in the number of vaterite otoliths in each fish was not recorded during the monitoring.

The mineral composition and validity of the visual inspection was verified using powder X-ray diffraction (XRD), a common technique for characterizing crystalline materials (e.g., Dinnebier and Billinge, 2008; Fawcett et al., 2019). Six otolith samples (three ‘aragonitic’ and three ‘vateritic’), taken from fish that were collected by commercial trawling in the Archipelago sea (AS) during May–July 1984 were ground as a whole and analysed individually to assess if any changes had occurred in the mineralogy of otoliths that would be visible to the eye. The powder XRD measurements were performed with an Empyrean diffractometer (Malvern Panalytical Ltd, The Netherlands) in Bragg–Brentano configuration using Cu Kα radiation (λ = 1.5418 Å) and a PilXcel4D detector. The mineralogical compositions of the otoliths were estimated from the diffractograms with Highscore Plus v4.9. software (Malvern Panalytical Ltd).

Vaterite crystallization was found in all study years with varying frequency. In 1984, the occurrence of vaterite was most frequent, with 48% of all studied fish having vaterite crystallization. The frequency varied also in the later study years, indicating a decline in frequency in 1997 and an increase in 2010 and 2017 (Table 1). The extent of vaterite replacement in each otolith as well as the number of vateritic otoliths in each fish was also observed to vary but was not quantitatively recorded during the monitoring. However, adding this information to future studies could be useful as it may have implications on how the otolith data should be analysed and interpreted (Vignon, 2020). The XRD analysis concurred that the studied otoliths from 1984 were composed of aragonite and/or vaterite as indicated by the visual inspection, while no calcite peaks were identified in the diffraction patterns. The otoliths that had been visually categorized as ‘aragonitic’ were determined to be composed only of aragonite as no vaterite peaks were identified in the patterns. In contrast, the otoliths categorized as ‘vateritic’ contained distinguishable vaterite peaks in addition to aragonite.

Recently, vaterite crystallization in sagittal otoliths has received attention as the polymorph-related changes in the otolith’s mass symmetry have been suspected to negatively affect the auditory capacity and directionality, and thereby affect fish survival, growth and even stock replenishment (Reimer et al., 2016; Oxman et al., 2007; Vignon & Aymes, 2020). Nevertheless, the impact of the phenomenon...
on the survival of fish in the wild is inadequately understood, as most studies focusing on the ecological impact of the phenomenon have been conducted with farmed fish or in experimental conditions. In the wild, the occurrence of vaterite might not have any impact on individual fitness, or the fish might rely on other sensory organs or school behaviour to avoid danger and access food (Tómas & Geffen, 2003; Vignon & Aymes, 2020). The aim of this study was to provide important primary information on the inter-annual occurrence of vateritic otoliths in a C. harengus membras population due to its importance for fisheries and in the ecosystem. In the Baltic Sea, the occurrence of aberrant otoliths in C. harengus membras has been acknowledged in reports (e.g., ICES, 2005, 2008) as well as recorded, to variable degree, in international and national databases, as it is generally agreed and recommended that the occurrence of vaterite otoliths is recorded but not used for age reading (e.g., ICES, 2008). As vaterite replacement might have potential impact on the fish itself as well as to fish stock management practices, it is our belief that more studies using inter-annual otolith data are called for to aid in understanding the implications of the phenomenon.

ACKNOWLEDGEMENTS

The authors owe thanks to Jan Eklund, who compiled the first version of the used otolith data. We also wish to thank local professional fisheremen for providing us with the fish samples. We also thank Arto Petotola (Department of Geography and Geology, University of Turku) for his initial help with the XRD analyses. In addition, we would like thank the two anonymous reviewers of this journal for their valuable comments and suggestions. The study has received financial support from the Sakari Alhopuro Foundation (Project Ref. No.: 20200084). This study also utilized research infrastructure facilities provided by the Finnish Marine Research Infrastructure network and Materials Analysis Research Infrastructure at the Department of Physics and Astronomy, University of Turku.

CONTRIBUTIONS

K.M. analysed the otolith data, wrote the first draft and finished the final version, and designed the study together with M.R., who also participated in writing the text. E.M. conducted the XRD analyses and wrote the respective text in the materials and methods section, and participated in revising the text. S.J. and J.H. participated in drafting and revising the text. All authors contributed to the article and approved the submitted version.

ORCID

Katja Mäkinen https://orcid.org/0000-0002-3668-1528

REFERENCES

Budnik, R. R., Farver, J. R., Gagnon, J. E., & Miner, J. G. (2020). Trash or treasure? Use of sagittal otoliths partially composed of vaterite for hatchery stock discrimination in steelhead. Canadian Journal of Fisheries and Aquatic Sciences, 77(2), 276–284.

Casini, M., Kornilovs, G., Cardinale, M., Möllmann, C., Grygiel, W., Jonsson, P., … Feldman, V. (2011). Spatial and temporal density dependence regulates the condition of Central Baltic Sea clupeids: Compelling evidence using an extensive international acoustic survey. Population Ecology, 53(4), 511–523.

Carlström, D. (1963). A crystallographic study of vertebrate otoliths. Biology Bulletin, 125(3), 441–463. https://doi.org/10.2307/1539358.

Coli-Llado, C., Mittermayer, F., Webb, P. B., Allison, N., Clemmesen, C., Stiasny, M., … Garcia de la serrana, D. (2021). Pilot study to investigate the effect of long-term exposure to high pCO2 on adult cod (Gadus morhua) otolith morphology and calcium carbonate deposition. Fish Physiology and Biochemistry, 47(6), 1879–1891.

Dinnebier, R. E., & Billinge, S. J. L. (2008). Overview and principles of powder diffraction. In R. E. Dinnebier & S. J. L. Billinge (Eds.), Powder Diffraction: Theory and Practice (pp. 1–19), Cambridge: RSC Publishing.

Eklund, J., Rajsilta, M., & Laine, P. (2001). Baltic herring growth pattern in relation to spawning time. In F. Funk, J. Blackburn, D. Hay, A. J. Paul, R. Stephenson, R. Toresen, & D. Whitherell (Eds.), Proceedings of the Symposium Herring 2000: Expectations for a new millennium (pp. 185–191). AK-SG-01-04, Fairbanks: University of Alaska Sea Grant.

Fawcett, T. G., Gates-Rector, S., Gindhart, A. M., Rost, M., Kabekkodu, S. N., Blanton, J. R., & Blanton, T. N. (2019). A practical guide to pharmaceutical analyses using X-ray powder diffraction. Powder Diffraction, 34(2), 164–183.

Gauldie, R. W. (1986). Vaterite otoliths from Chinook salmon (Oncorhynchus tshawytscha). N. Z. J. Marine and Freshwater Research, 20(2), 209–217. https://doi.org/10.1080/00288330.1986.9516145.

ICES. 2005. Report from The Herring Age Reading Workshop, 6–9 June 2005, island of Seili, Finland. Available at: https://www.ices.dk/community/Documents/PGCDBS/her.agewk2005.pdf (last accessed May 16, 2022).

ICES. 2008. Report of the workshop on age Reading of Baltic herring (WKARBH), 9–13 June 2008, Riga, Latvia. ICES CM 2008/ACOM:36. 37 pp. Available at: https://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2008/WKARBH/WKARBH08.pdf (last accessed May 16, 2022).

Lill, J. O., Finnäs, V., Heinbrand, Y., Blas, M., Föjdö, S., Lahaye, Y., … Hägerstrand, H. (2020). Information depths of analytical techniques assessing whitefish otolith chemistry. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 477, 104–108.

Loeppky, A. R., Belding, L. D., Quijada-Rodriguez, A. R., Morgan, J. D., Pracheil, B. M., Chakoumakos, B. C., & Anderson, W. G. (2021). Influence of ontogenetic development, temperature, and pCO2 on otolith calcium carbonate polymorph composition in sturgeons. Scientific Reports, 11(1), 1–10.

Melancon, S., Fryer, B. J., Ludsí, S. A., Gagnon, J. E., & Yang, Z. (2005). Effects of crystal structure on the uptake of metals by lake trout (Salvelinus namaycush) otoliths. Canadian Journal of Fisheries and Aquatic Sciences, 62(11), 2609–2619.

Möllmann, C., Kornilovs, G., Fetter, M., & Köster, F. W. (2005). Climate, zooplankton, and pelagic fish growth in the Central Baltic Sea. ICES Journal of Marine Science, 62(7), 1270–1280. https://doi.org/10.1016/j.jmarsci.2005.04.021.

Oxman, D. S., Barnett-Johnson, R., Smith, M. E., Coffin, A., Miller, D. L., Josephson, R., & Popper, A. N. (2007). The effect of vaterite deposition on sound reception, otolith morphology, and inner ear sensory epithelia in hatchery-reared Chinook salmon (Oncorhynchus tshawytscha). Canadian Journal of Fisheries and Aquatic Sciences, 64(11), 1469–1478. https://doi.org/10.1139/f07-106.

Rajasilta, M., Eklund, J., Hänninen, J., Kurislähti, M., Kääriä, J., Rannikko, P., & Soikkeli, M. (1993). Spawning of herring (Clupea harengus membras L) in the Archipelago Sea. ICES Journal of Marine Science, 50, 233–246.

Rajasilta, M., Hänninen, J., Laaksenon, L., Laine, P., Suomela, J. P., Vuorinen, I., & Mäkinen, K. (2019). Influence of environmental conditions, population density, and prey type on the lipid content in Baltic herring (Clupea harengus membras) from the northern Baltic Sea.
Rajasilta, M., Mäkinen, K., Ruuskanen, S., Hänninen, J., & Laine, P. (2021). Long-term data reveal the associations of the egg quality with abiotic factors and female traits in the Baltic herring under variable environmental conditions. *Frontiers in Marine Science*, 1528. https://doi.org/10.3389/fmars.2021.698480.

Reimer, T., Dempster, T., Wargelius, A., Fjelldal, P. G., Hansen, T., Glover, K. A., … Swearer, S. E. (2017). Rapid growth causes abnormal vaterite formation in farmed fish otoliths. *Journal of Experimental Biology*, 220(16), 2965–2969. https://doi.org/10.1242/jeb.148056.

Reimer, T., Dempster, T., Warren-Myers, F., Jensen, A. J., & Swearer, S. E. (2016). High prevalence of vaterite in sagittal otoliths causes hearing impairment in farmed fish. *Scientific Reports*, 6(1), 25,249. https://doi.org/10.1038/srep25249.

Reusch, T. B., Dierking, J., Andersson, H. C., Bonsdorff, E., Carstensen, J., Casini, M., … Zandersen, M. (2018). The Baltic Sea as a time machine for the future coastal ocean. *Science Advances*, 4(5), eaar8195.

Rönkkönen, S., Ojaveer, E., Raid, T., & Viitasalo, M. (2004). Long-term changes in Baltic herring (*Clupea harengus membras*) growth in the Gulf of Finland. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(2), 219–229. https://doi.org/10.1139/f03-167.

Strong, M. B., Neilson, J. D., & Hunt, J. J. (1986). Aberrant crystallization of pollock (*Pollachius virens*) otoliths. *Canadian Journal of Fisheries and Aquatic Sciences*, 43(7), 1457–1463. https://doi.org/10.1139/f86-180.

Sweeting, R. M., Beamish, R. J., & Neville, C. M. (2004). Crystalline otoliths in teleosts: Comparisons between hatchery and wild coho salmon (*Oncorhynchus kisutch*) in the strait of Georgia. *Reviews in Fish Biology and Fisheries*, 14(3), 361–369.

Thomas, O. R. B., & Swearer, S. E. (2019). Otolith biochemistry—A review. *Reviews in Fisheries Science & Aquaculture*, 27(4), 458–489. https://doi.org/10.1080/23308249.2019.1627285.

Tomáš, J., & Geffen, A. J. (2003). Morphometry and composition of aragonite and vaterite otoliths of deformed laboratory reared juvenile herring from two populations. *Journal of Fish Biology*, 63(6), 1383–1401. https://doi.org/10.1046/j.1095-8649.2003.00245.x.

Tomáš, J., Geffen, A. J., Allen, I. S., & Berges, J. (2004). Analysis of the soluble matrix of vaterite otoliths of juvenile herring (*Clupea harengus*): Do crystalline otoliths have less protein? *Comparative Biochemistry & Physiology Part A: Molecular & Integrative Physiology*, 139(3), 301–308.

Tzeng, W., Chang, C., Wang, C., Shiao, J., Iizuka, Y., Yang, Y., … Ložys, L. (2007). Misidentification of the migratory history of anguillid eels by Sr/ca ratios of vaterite otoliths. *Marine Ecology Progress Series*, 348, 285–295. https://doi.org/10.3354/meps07022.

Vignon, M. (2020). When the presence of a vateritic otolith has morphological effect on its aragonitic partner: Trans-lateral compensation induces bias in microecological patterns in one-side-only vateritic otolith. *Canadian Journal of Fisheries and Aquatic Sciences*, 77(2), 285–294. https://doi.org/10.1139/cjfas-2019-0066.

Vignon, M., & Aymes, J. C. (2020). Functional effect of vaterite – The presence of an alternative crystalline structure in otoliths alters escape kinematics of the brown trout. *Journal of Experimental Biology*, 223(12), jeb222034. https://doi.org/10.1242/jeb.222034.

Yedier, S., & Bostanci, D. (2019). Aberrant crystallization of blackbelled angler *Lophius budegassa* Spinola, 1807 otoliths. *Cahiers de Biologie Marine*, 60, 527–533.

How to cite this article: Mäkinen, K., Rajasilta, M., Mäkilä, E., Jokinen, S., & Hänninen, J. (2022). Varying frequency of vateritic otoliths in the Baltic herring *Clupea harengus membras*. *Journal of Fish Biology*, 101(3), 741–744. https://doi.org/10.1111/jfb.15127

APPENDIX A

The study area in the northern Baltic Sea. Baltic herring samples were collected from the inner region of the Archipelago Sea (AS) from trap-nets situated near known spawning sites.