Analyzing the Impact of Increased Species Diversity on Machine Learning-Based Image Classification within the Megatoothed Sharks

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1 Introduction

Originating in the Late Cretaceous[17], **otodontids** were a lineage of large predatory sharks that survived the Cretaceous-Paleogene mass extinction and persisted into the Neogene. Across the probable chronospecific lineage from ***Cretalamna*** to ***Otodus***[1,11,15,17,20], body size increased[13,20] as **dentition** shifted from narrow, cuspleted crowns to enlarged crowns with reduced or absent cusplets[11,19]. Early forms are interpreted as piscivores[7], whereas later species, including ***O. megalodon***, occupied high trophic levels and fed on other large marine vertebrates[7].

Fossilized otodontid teeth are abundant across the Atlantic Coastal Plain (ACP), but many specimens are reworked or isolated, complicating species-level identification due to lost stratigraphic context and morphological overlap. **Deep-learning convolutional neural networks** (CNNs) provide a potential solution by automating image classification. When trained on robust datasets, these machine learning models may aid fossil identification[19], though broader adoption in paleontology remains limited despite success with theropod dinosaur teeth[2,5], fossil footprints[6], and even fossils found in carbonate rock[18].

Figure I: ACP sites in New Jersey known to have produced multiple otodontid taxa at a single geographic location, complicating identification where they might co-occur.

Study objectives: Assuming *Cretalamna* and *Otodus* indeed form a chronospecific lineage, this study sought to:

- Evaluate how well an optimized deep-learning classifier resolves taxa across a morphologically transitional fossil lineage.
- Evaluate model performance when separating otodontids from a broader diversity of shark taxa in a mixed training set without any geotemporal information.
- Assess the continued utility of machine learning in paleontology.

2 Methods

Multiple **DenseNet-121** CNN models[14] were trained to test how increasing morphological diversity affects classification of isolated otodontid shark teeth. Performance was assessed using confusion matrices and summary accuracy, precision, and recall metrics.

- **Phase 1:** Models were trained on the *Cretalamna-Otodus* lineage using 50 base images per taxon (N); 70% of images were augmented sevenfold for training (≈5.6N), and 30% were kept for validation (≈0.3N). Models were trained for 15 epochs (batch size = 8) and tested on ten static images per taxon; the initial run included only *C. appendiculata* and *O. megalodon*, with additional otodontids added stepwise until the full lineage was represented.
- **Phase 2:** Additional non-otodontid lamniform and carcharhiniform taxa were added incrementally while maintaining parameters from the final Phase 1 run and the full otodontid prediction set; a final run incorporated a non-galeomorph shark to maximize training diversity using all available images.

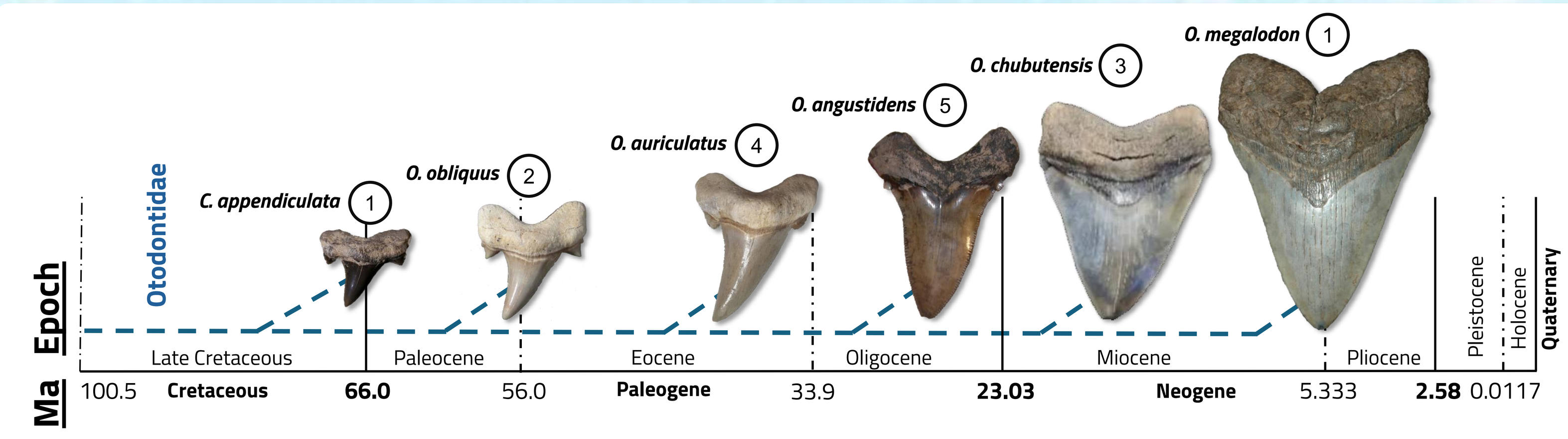
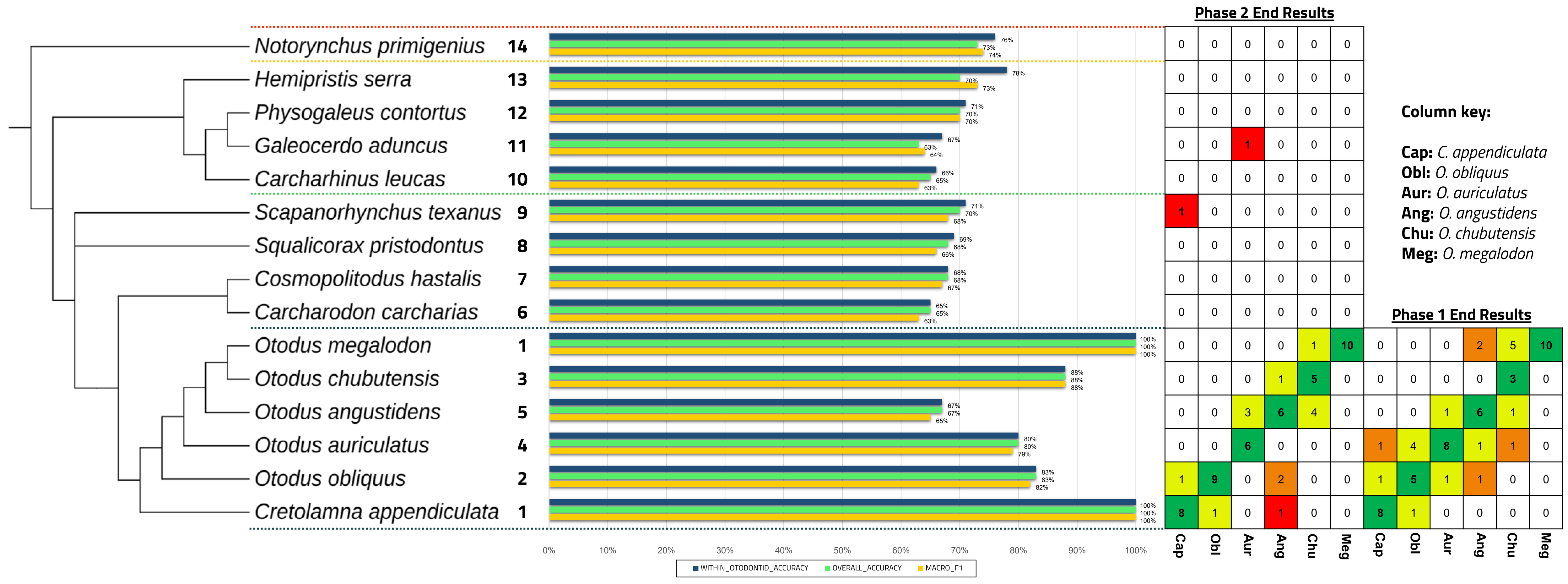


Figure II: Transition from *Cretalamna* to *Otodus*. Species listed according to their temporal range (not to scale). Numbers indicate the order in which a species was added to the training, validation, and prediction set.

3 Results

Performance was assessed using **within-otodontid accuracy** (correct classifications among otodontids), **overall accuracy** (correct predictions across all classes), and **Macro F1** (the unweighted mean of per-class F1 scores, precision and recall).

- **Phase 1:** Within-otodontid and overall accuracy were identical. Accuracy and Macro F1 peaked at 100% in the initial two-taxon run, then declined to 67% and 65% as additional taxa were introduced.
- **Phase 2:** Adding the first shark from a new major outgroup temporarily reduced performance. For example, inclusion of *Carcharhinus leucas* (first carcharhiniform) lowered within-otodontid accuracy, overall accuracy, and Macro F1 to about 66%, 65%, and 63%, compared with roughly 71%, 70%, and 68% in the previous run (*Scapanorhynchus texanus*, the last lamniform added).
- Performance peaked at **run 13** (*Hemipristis serra*) and remained comparatively high after inclusion of the non-galeomorph *Notorhynchus primigenius*, with the final run reaching 76% within-otodontid accuracy, 73% overall accuracy, and 74% Macro F1.



Phase 2 End Results

	Cap	Obl	Aur	Ang	Chu	Meg
Notorynchus primigenius	0	0	0	0	0	0
Hemipristis serra	0	0	0	0	0	0
Physogaleus contortus	0	0	0	0	0	0
Galeocerdo aduncus	0	0	1	0	0	0
Carcharhinus leucas	0	0	0	0	0	0
Scapanorhynchus texanus	1	0	0	0	0	0
Squalicorax pristodontus	0	0	0	0	0	0
Cosmopolitodus hastalis	0	0	0	0	0	0
Carcharodon carcharias	0	0	0	0	0	0
Otodus megalodon	0	0	0	0	1	10
Otodus chubutensis	0	0	0	1	5	0
Otodus angustidens	0	0	3	6	4	0
Otodus auriculatus	0	0	6	0	0	0
Otodus obliquus	1	9	0	2	0	0
Cretalamna appendiculata	8	1	0	1	0	0

Phase 1 End Results

	Cap	Obl	Aur	Ang	Chu	Meg
Otodus megalodon	0	0	0	2	5	10
Otodus chubutensis	0	0	0	0	3	0
Otodus angustidens	0	0	1	6	1	0
Otodus auriculatus	1	4	8	1	1	0
Otodus obliquus	1	5	1	1	0	0
Cretalamna appendiculata	8	1	0	0	0	0

Figure III: Model performance before and after inclusion of non-otodontid taxa. A simplified phylogeny at left, synthesized from published shark relationships[1,3,4,8,10,11,15,16,17,20] (branch lengths not to scale), shows the order in which taxa were added to each model run. Per-class **within-otodontid accuracy**, **Macro F1**, and **overall accuracy,** are shown at center. Confusion matrices at right summarize prediction outcomes for the final Phase 2 run and the final Phase 1 run, respectively.

4 Discussion & Conclusion

Figure V: The morphological gradient in this study demonstrated using sample fossil shark teeth from each taxon. Teeth not to scale.

Phase 1 results show errors clustering among visually similar taxa added to the model's training set, indicating that poor performance likely tracks morphological overlap rather than random noise. **Phase 2** suggests that adding broader diversity outside Otodontidae stabilizes predictions within the clade, implying increased taxonomic and morphological variation can improve classification performance. Together, **these patterns suggest that a deep-learning image classifier, when provided a diverse enough dataset, can be tuned to resolve fossil identity even among closely related species with fine morphological distinctions.**

Comparable deep-learning studies report similar performance ranges: PCA, K-means, and *Keras* CNN workflows using *Pectinodon bakkeri* teeth achieved about 71% accuracy and 70.5% F1[2], while CNN analyses of planktonic foraminifera species reached about 81% F1, exceeding expert (about 63%) and novice (about 53%) performance[9]. Results from this study fall within that range.

Broader sampling and taxonomic coverage are still needed to validate these results and test how well they generalize across fossil datasets. **Future work** could include:

- **Observer benchmarking:** Compare model predictions against observers with varying levels of expertise.
- **Dataset expansion:** Increase training imagery, particularly underrepresented non-galeomorph taxa.
- **Model comparison:** Evaluate additional deep-learning architectures and identify lighter CNNs that maintain comparable performance.

Figure IV: Reconstruction of 3m female *Cretalamna sp.* compared to 20m *O. megalodon* based on Perez et al. (2021).

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