

1
201

This is to certify that the
thesis entitled

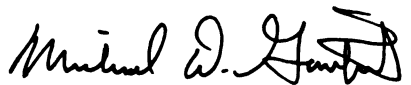
Morphometric Analysis of Extant and
Fossil Mako Sharks (*Isurus*, Lamnidae)

presented by

Lisa Beth Whitenack

has been accepted towards fulfillment
of the requirements for

Masters degree in Geological Sciences



Major professor

Date 5/5/01



PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.
MAY BE RECALLED with earlier due date if requested.

DATE DUE	DATE DUE	DATE DUE
OCT 25 2003		
061002		
JUL 28 2006		

**MORPHOMETRIC ANALYSIS OF EXTANT AND FOSSIL MAKO SHARKS
(*ISURUS*, LAMNIDAE)**

By

Lisa Beth Whitenack

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

MASTER OF SCIENCE

Department of Geological Sciences

2001

Assistant Professor Michael D. Gottfried

ABSTRACT

MORPHOMETRIC ANALYSIS OF EXTANT AND FOSSIL MAKO SHARKS

(*ISURUS*; LAMNIDAE)

By

Lisa Beth Whitenack

Studies of fossil neoselachian sharks have largely relied on qualitative data from isolated teeth, which are abundant but problematic due to various forms of heterodonty. This issue is addressed here by using geometric morphometrics to analyze shape variation in teeth of the two extant Mako shark species, *Isurus oxyrinchus* and *I. paucus*. The teeth and their relative jaw were characterized using Procrustes superposition and principle components analysis, which does distinguish between teeth of the two species and also identified characteristics of the genus. Only the third tooth (from the symphysis) displayed asymmetry between the left and right sides. Teeth of the fossil Mako *I. hastalis* were then subjected to similar analysis. The results do distinguish between the extant and fossil species, indicating that these morphometric techniques are and more objective than qualitative approaches. Geometric morphometric techniques can be more broadly applied in future systematic studies on other groups of sharks.

ACKNOWLEDGEMENTS

I owe everyone who was involved in this project a huge amount of gratitude. Thank you to Drs. Michael Gottfried, Robert Anstey, and Danita Brandt for all of their help with every aspect of this, as well as their encouragement. I am indebted to Dr. Miriam Zelditch (University of Michigan) for much last minute advice and tutoring. Also, a big thanks to Jeremy Cliff (Kwa Zulu – Natal Sharks Board), Robert Purdy (National Museum of Natural History), Gordon Hubbell, Mary Anne Rogers (Field Museum of Natural History), and David Catania (California Academy of Science) for the specimen loans. Last, but not least, my husband and family gave me enough support and love for two theses.

TABLE OF CONTENTS

List of Tables	v
List of Figures	vi
Introduction	1
Materials and Methods	10
Results and Discussion	16
Conclusions	52
Appendix	54
References	73

LIST OF TABLES

List of Materials Examined	11
Results of Clustering Analysis	47

LIST OF FIGURES

(a) Distribution of <i>Isurus oxyrinchus</i> (b) Distribution of <i>Isurus paucus</i> . Shaded areas represent known distributions of the species. Areas bounded by dashed lines represent areas the species is thought to inhabit (Holthe, 1998; Stevens and Scott, 1995; Gillespie and Saunders, 1995; Killam and Parsons, 1986; Munoz, 1985; Compagno, 1984).....	2
(a) <i>Isurus oxyrinchus</i> , x0.03 (b) <i>Isurus paucus</i> , x0.06. Arrows indicate the pectoral fin, the external feature most commonly used to identify extant Mako species. After Compagno, 1984.....	3
(a) <i>Isurus oxyrinchus</i> (b) <i>Isurus paucus</i> . Tooth series from the upper and lower jaws, left side, labial view (x0.5). After Compagno, 1984.....	4
Distribution of <i>Isurus</i> species through the Cenozoic and representative lower anterior tooth of each species depicted. Compiled from: Cione and Reguero, 1995; Kent, 1994; Uyeno et al, 1990; Karasawa, 1989; Cappetta, 1987; Case, 1980; Casier, 1943; Leriche, 1905.....	6
<i>Isurus oxyrinchus</i> tooth series from the upper and lower jaws, left side, labial view. Numbers indicate tooth positions assigned for data acquisition. After Compagno, 1984.....	12
Location of landmarks shown on an <i>Isurus oxyrinchus</i> tooth, upper jaw, left side, second tooth from the symphysis, labial view.....	13
Procrustes shape coordinates for <i>I. oxyrinchus</i> , lower jaw, position 1.....	17
Procrustes shape coordinates for <i>I. oxyrinchus</i> , lower jaw, position 3.....	18
Procrustes shape coordinates for <i>I. oxyrinchus</i> , lower jaw, positions 1, 2, and 3.....	19
Procrustes shape coordinates for <i>I. oxyrinchus</i> , lower jaw, positions 4, 5, 6, and 7.....	20
Procrustes shape coordinates for <i>I. oxyrinchus</i> , upper jaw, positions 1, 2, and 3.....	21

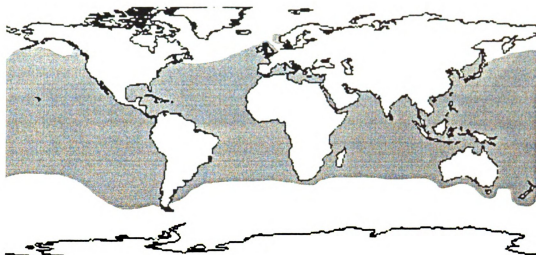
Procrustes shape coordinates for <i>I. oxyrinchus</i> , upper jaw, positions 4, 5, 6, and 7.....	22
Procrustes shape coordinates for <i>I. paucus</i> , lower jaw, positions 1, 2, and 3.....	23
Procrustes shape coordinates for <i>I. paucus</i> , lower jaw, positions 4, 5, 6, and 7.....	24
Procrustes shape coordinates for <i>I. paucus</i> , upper jaw, positions 1, 2 and 3.....	25
Procrustes shape coordinates for <i>I. paucus</i> , upper jaw, positions 4, 5, 6, and 7.....	26
Principle components for <i>I. oxyrinchus</i> , positions 1, 2, and 3, lower jaw.....	28
Principle components for <i>I. oxyrinchus</i> , positions 4, 5, 6, and 7, lower jaw.....	29
Principle components for <i>I. oxyrinchus</i> , positions 1, 2, and 3, upper jaw.....	30
Principle components for <i>I. oxyrinchus</i> , positions 4, 5, 6, and 7, upper jaw.....	31
Principle components for <i>I. paucus</i> , positions 1, 2, and 3, lower jaw.....	32
Principle components for <i>I. paucus</i> , positions 4, 5, 6, and 7, lower jaw.....	33
Principle components for <i>I. paucus</i> , positions 1, 2, and 3, upper jaw.....	34
Principle components for <i>I. paucus</i> , positions 4, 5, 6, and 7, upper jaw.....	35
Procrustes shape coordinates for <i>I. oxyrinchus</i> , lower jaw.....	36
Procrustes shape coordinates for <i>I. oxyrinchus</i> , upper jaw.....	37
Procrustes shape coordinates for <i>I. paucus</i> , lower jaw.....	38
Procrustes shape coordinates for <i>I. paucus</i> , upper jaw.....	39
Deformations shown as vectors on landmarks that represent principle components 1 (a) and 2 (b) for <i>I. oxyrinchus</i> , lower jaw. See Figure 3 for landmark identities.....	40

Deformations shown as vectors on landmarks that represent principle components 1 (a) and 2 (b) for <i>I. oxyrinchus</i> , upper jaw.....	41
Deformations shown as vectors on landmarks that represent principle components 1 (a) and 2 (b) for <i>I. paucus</i> , lower jaw.....	42
Deformations shown as vectors on landmarks that represent principle components 1 (a) and 2 (b) for <i>I. paucus</i> , upper jaw.....	43
Procrustes shape coordinates for <i>I. oxyrinchus</i> (black circle) and <i>Isurus paucus</i> (gray X), lower jaw.....	45
Principle components for <i>I. hastalis</i> , <i>I. oxyrinchus</i> , and <i>I. paucus</i> (mean values).....	49
Procrustes shape coordinates for <i>I. hastalis</i>	51

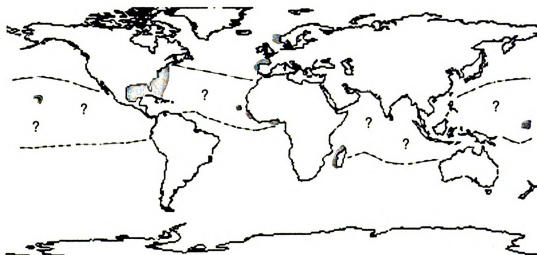
INTRODUCTION

The Mako sharks (*Isurus*; Family Lamnidae) include two extant species: the Shortfin mako (*Isurus oxyrinchus*) and the Longfin mako (*I. paucus*). *I. oxyrinchus* is typically found offshore in tropical waters worldwide (warmer than 16 degrees Celsius), from the surface to a depth of ca.152 meters. *I. paucus* is less common than *I. oxyrinchus*, and therefore its distribution is not as well known; it has been hypothesized that the two species occupy similar ranges (Figure 1) (Compagno, 1984). Makos are active predators, feeding primarily on teleost fishes, including bluefish and scombrids, and small elasmobranchs up to 1 meter in total length, along with occasional squid and cetaceans (Cliff, et al., 1990; Compagno, 1984; Stillwell and Kohler, 1982).

The two extant Mako species are very similar in external appearance (Figure 2). Both species display sexual dimorphism, with the female larger than the male. Male Shortfins reach 284 cm in total length (TL), while females reach 394 cm TL. Male Longfins reach 245 cm TL; females reach 245–417 cm TL (Compagno, 1984; Pratt and Casey, 1983). The two species can be distinguished externally by the relative lengths of their pectoral fins. Shortfins have long and broad pectoral fins that are shorter than their heads; Longfins have pectoral fins that are shaped similarly to those of Shortfins, but the fins are longer than their heads and more narrowly proportioned. The two species can also be distinguished based on their teeth (Figure 3). Both species have unserrated, unicuspid teeth,



(a)



(b)

Figure 1 (a) Distribution of *Isurus oxyrinchus* (b) Distribution of *Isurus paucus*. Shaded areas represent known distributions of the species. Areas bounded by dashed lines represent areas the species is thought to inhabit (Holthe, 1998; Stevens and Scott, 1995; Gillespie and Saunders, 1995; Killam and Parsons, 1986; Munoz, 1985; Compagno, 1984).

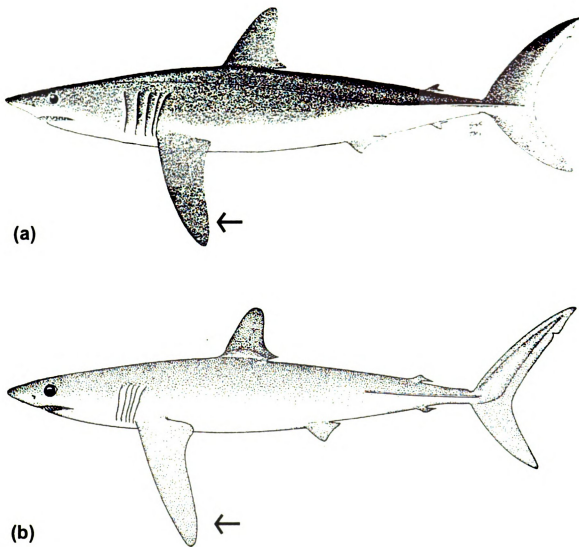
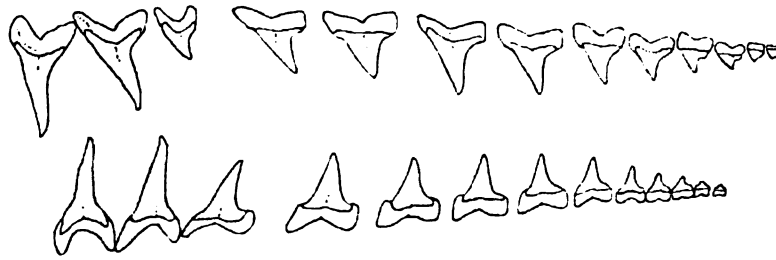
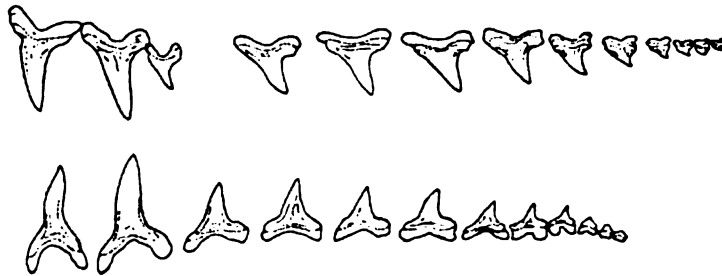


Figure 2 (a) *Isurus oxyrinchus*, x0.03 (b) *Isurus paucus*, x0.06.
Arrows indicate the pectoral fin, the external feature most commonly used to identify extant Mako species. After Compagno, 1984.



(a)



(b)

Figure 3 (a) *Isurus oxyrinchus* (b) *Isurus paucus*
Tooth series from the upper and lower jaws, left side,
labial view (x0.5). After Compagno, 1984.

but the teeth of *I. oxyrinchus* have narrow cusps with reversed and labially recurved tips, whereas *I. paucus* teeth have broad cusps that are not recurved (Compagno, 1984).

Seven extinct species of *Isurus* are presently recognized (Figure 4) (Cappetta, 1987). Additional fossil species of *Isurus* have been named, but, as is the case with a number of other fossil shark taxa based on isolated teeth, many of these assignments are dubious or represent junior synonyms. The fossil sharks that can confidently be assigned to *Isurus* are widely distributed and range back to the Paleocene. The earliest record of *Isurus* is *I. winkleri*, from Paleocene strata of Belgium (Cappetta, 1987; Casier, 1943). *I. praecursor* has been recorded from Eocene sediments of Africa, Europe, Antarctica, Syria, and the southeast United States (Cione and Reguero, 1995; Kent, 1994; Cappetta, 1987). *I. desori* appears in the Oligocene and continues into the Pliocene. This species occurs in Europe, Africa, Japan, and the United States (Kent, 1994; Karasawa, 1989; Cappetta, 1987). Additional species join *I. desori* in the Miocene: *I. escheri*, *I. hastalis*, *I. planus*, and *I. retroflexus*. *I. escheri* occurs in Europe (Cappetta, 1987; Leriche, 1905). *I. retroflexus* has been recorded in Europe, Australia, and the United States (Kent, 1994; Cappetta, 1987). *I. planus* occurs in Antarctica, Japan, and the United States (Karasawa, 1989; Cappetta, 1987). *I. hastalis* is the most widespread of the Miocene species, occurring in Europe, Africa, Antarctica, South America, Australia, the United States, and Japan (Kent, 1994; Uyeno et al, 1990; Karasawa, 1989; Cappetta, 1987).

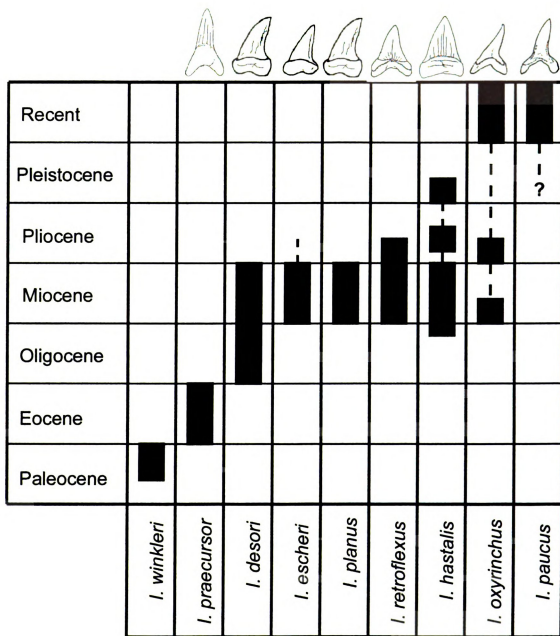


Figure 4 Distribution of *Isurus* species through the Cenozoic and representative lower anterior tooth of each species depicted. Compiled from: Cione and Reguero, 1995; Kent, 1994; Uyeno et al, 1990; Karasawa, 1989; Cappetta, 1987; Case, 1980; Casier, 1943; Leriche, 1905.

The Miocene also marks the first appearance of the extant species *I. oxyrinchus*, which is found in the United States and Japan (Case, 1980; Uyeno et al., 1980).

Like the extant Makos, fossil forms of *Isurus* are also identified on the basis of qualitative descriptions of tooth morphology. As with many neoselachians, teeth are often the only parts of Mako sharks preserved in the fossil record. The crowns of chondrichthyan teeth are composed of apatite, $\text{Ca}(\text{PO}_4)_3\text{F}$, which is insoluble and very durable. Additionally, a single shark can produce thousands of teeth in its lifetime (Correia, 1998). For these reasons, shark teeth are the most common vertebrate fossils.

Despite the abundance of fossil shark teeth, studies that rely solely on isolated teeth have inherent problems. Sharks exhibit various and sometimes complicated forms of heterodonty within a given jaw (monognathic heterodonty) or between the upper and lower jaws of the same species (dignathic heterodonty) (Figure 3) (Compagno, 1988). For example, not only may the third tooth from the symphysis in the upper jaw be different in shape from the adjacent teeth in the same jaw, but it may also differ in shape from the corresponding tooth in the lower jaw. Complete shark dentitions are extremely rare in the fossil record, which means that the degree of heterodonty within fossil species is typically not well known. Tooth morphology is also affected by ontogeny. A free-swimming juvenile may have teeth that exhibit a far different morphology from those of an adult of the same species (Compagno, 1988). Some neoselachians,

e.g. *Carcharhinus dussumieri*, exhibit sexual heterodonty, which involves differences between the males and females in the arrangement of the teeth within the jaw and/or tooth morphology (Compagno, 1988; Peyer, 1968). Tooth shape can also be convergent between closely or distantly related species.

Taxonomic practice has begun to better reflect some of the challenges involved in working with isolated fossil shark teeth. In the case of *Isurus*, a number of species (*Cretoxyrhina mantelli*, *Anomotodon sheppeyensis*, *Paranomotodon angustidens*, *Sphenodus lundgreni*, and *Parotodus benedeni*) that were initially placed in *Isurus* based on tooth morphology are now considered to belong to different genera (Cappetta, 1987). Currently, two fossil species of *Isurus*, *I. desori* and *I. retroflexus*, are considered questionable and are being investigated. *I. desori* has a very similar tooth morphology to *I. oxyrinchus*, and *I. retroflexus* is similar to *I. paucus*. It is possible that the two fossil species are synonymous with the two extant Mako species (Purdy, in press).

The problems caused by heterodonty and convergence have cast doubt on qualitative studies of isolated fossil shark teeth. A more quantitative approach, using modern morphometric techniques, is employed here to establish objective criteria for distinguishing between the two extant species, *I. oxyrinchus* and *I. paucus*, and the common fossil form *I. hastalis*. Morphometric techniques have been applied to a wide variety of organisms, from studying birds by analyzing ratios of linear parameters of humeri (Warheit, 1992), to applying triangulation

techniques to brachiopod cardinal processes (Leighton and Maples, 2000). For chondrichthyans, discriminant function analysis and quadratic discriminant analysis of linear measurements were used by Naylor and Marcus (1994) to characterize modern *Carcharhinus* teeth for the purpose of identifying isolated fossil teeth of the same genus; however fossil carcharhinid teeth have never been analyzed using morphometric techniques. Quantitatively studying extant and fossil Mako shark teeth by applying the morphometric techniques of triangulation (baseline coordinates) and Procrustes superposition, as well as statistical techniques, such as principle components analysis, provide a more objective basis for taxonomic assignment than do traditional qualitative morphological descriptions. This approach may also prove appropriate for other lamnids and other groups of sharks with both extant and extinct members.

MATERIALS AND METHODS

Teeth of the two extant Mako species, *Isurus oxyrinchus* and *Isurus paucus*, were characterized morphometrically in order to identify criteria that differentiated between the two species. For this portion of the study, tooth sets and jaws of adult *I. oxyrinchus* and *I. paucus* were obtained from the collections of the National Museum of Natural History (NMNH), the Field Museum of Natural History (FMNH), the Kwa Zulu – Natal Sharks Board, and the private collection of Gordon Hubbell (Table 1). Each jaw and each of the first seven teeth posterior to the symphysis within each jaw were photographed individually using an Olympus C3000 digital camera, then digitized using Adobe Photoshop 5.0 and Adobe Illustrator 9.0. Tooth position was recorded in order to account for heterodonty (Figure 5). If the tooth was taken from either the upper left or lower right jaw, the image of the tooth was reflected about a vertical axis so that all teeth curved to the viewer's right for ease of comparison. Seven landmarks were chosen from the labial side of each tooth to reflect the shape of the crown and of the entire tooth (Figure 6). Those teeth that were missing landmarks (e.g. the apex of the crown was broken off) were discarded. The raw coordinate data taken from the digitization process was then run through CoordGen6 (morphometric software by David Sheets, 2001) to calculate the Bookstein shape coordinates, using the baseline coordinates (triangulation) method (Bookstein, 1991). One landmark is designated (0,0), and a second is designated (1,0), creating the baseline. The positions of the remaining landmarks are plotted relative to the baseline. This method corrects for size differences (Leighton and Maples, 2000) that may be

Table 1

List of Materials Examined

Institution	Specimen Number	Species	Specimen Description
Field Museum of Natural History	FMNH 83731	<i>I. oxyrinchus</i>	Upper and lower jaws
Kwa Zulu – Natal Sharks Board	SUL 92014	<i>I. oxyrinchus</i>	Upper and lower jaws
	UMH 9202	<i>I. oxyrinchus</i>	Upper and lower jaws
	UMH STRANDING	<i>I. oxyrinchus</i>	Upper and lower jaws
	WIN 93001	<i>I. oxyrinchus</i>	Upper and lower jaws
National Museum of Natural History	USNM 110881	<i>I. oxyrinchus</i>	Upper and lower jaws (test specimen)
	USNM 110948	<i>I. oxyrinchus</i>	Lower jaw
	USNM 263282	<i>I. oxyrinchus</i>	Upper and lower jaws
	USNM Teaching Collection	<i>I. paucus</i>	Associated teeth (n=28)
Gordon Hubbell (private collection)	CASTRO	<i>I. paucus</i>	Upper and lower jaws
	ISUR-2-13	<i>I. paucus</i>	Upper and lower jaws
	LONG 1786	<i>I. paucus</i>	Associated teeth (n=28)
	LONG 5599	<i>I. paucus</i>	Associated teeth (n=28) (test specimen)
	OXY CASTS	<i>I. oxyrinchus</i>	Casts of associated teeth (n=28)
	PAUC COMP	<i>I. paucus</i>	Associated teeth (n=28)
	SHTFIN 11191	<i>I. oxyrinchus</i>	Associated teeth (n=28)
Michigan State University Museum	VPTC	<i>I. hastalis</i>	Individual teeth (n=27)

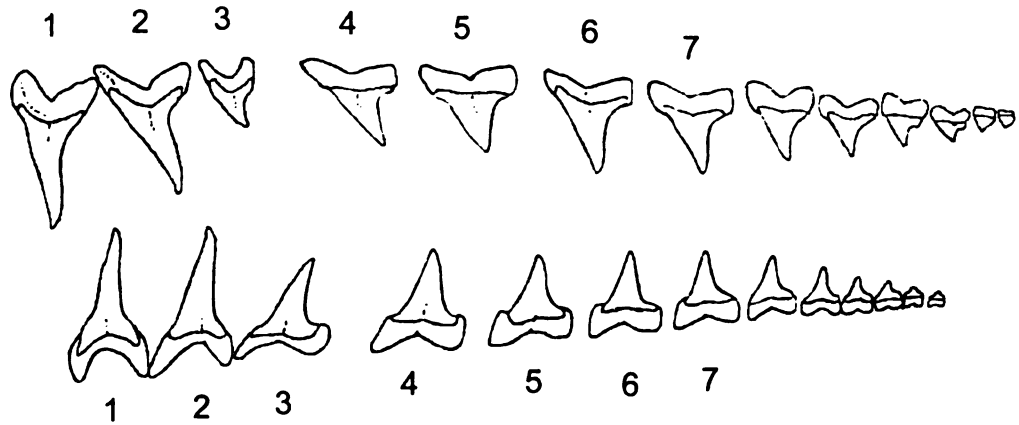


Figure 5 *Isurus oxyrinchus* tooth series from the upper and lower jaws, left side, labial view. Numbers indicate tooth positions assigned for data acquisition. After Compagno, 1984.

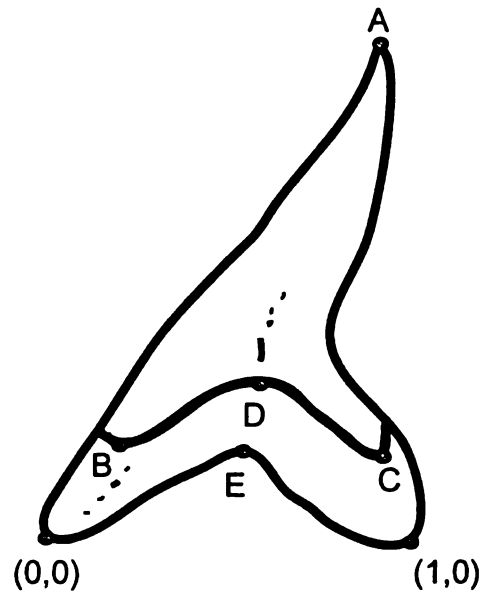


Figure 6 Location of landmarks shown on an *Isurus oxyrinchus* tooth, upper jaw, left side, second tooth from the symphysis, labial view.

present due to jaw position or age differences between free-swimming sharks. This was necessary because the ages of the sharks that the fossil teeth came from are not known. The teeth were analyzed in PCAGen6 (Sheets, 2000) to determine if any errors were made during the digitizing process.

The Bookstein shape coordinates were then transformed using Procrustes superposition, which minimizes the variance between two specimens through rotation and resizing. The Procrustes coordinate data were evaluated using TwoGroup6 (Sheets, 2001) to determine if teeth from the right and left sides of the jaw display fluctuating asymmetry or antisymmetry (Palmer, 1986). If any asymmetry is present, it is necessary to keep the data from each side separate. The Procrustes shape coordinate data were then run through PCAGen 6 to perform principle components analyses in order to characterize differences in tooth morphology, both within the same species and between *I. oxyrinchus* and *I. paucus*. F-tests were also used to determine if the two species were statistically different from each other.

The next step involved blind-testing of the morphometric criteria found in the first part of the study. One set of jaws for each extant species was utilized for this purpose. The designated test specimens were not used in the initial analysis. From each test specimen, a random set of teeth was chosen. The test specimens were digitized and Procrustes shape coordinates were obtained. This data was then tested against the Procrustes shape coordinates of the initial set of

specimens using clustering analysis to determine if they fall within the parameters established in the initial analysis.

The Miocene Mako *Isurus hastalis* was then added to the study to determine if its teeth could be distinguished morphometrically from the extant species, and whether the jaw position of individual teeth could be assigned. Twenty-seven individual teeth of *I. hastalis* were obtained from the Michigan State University Museum Vertebrate Paleontology Teaching Collection. The fossil teeth were subjected to analysis similar to the first set of specimens. Promising results in this part of the study would support the use of similar morphometric techniques in studies of other groups of fossil sharks.

RESULTS AND DISCUSSION

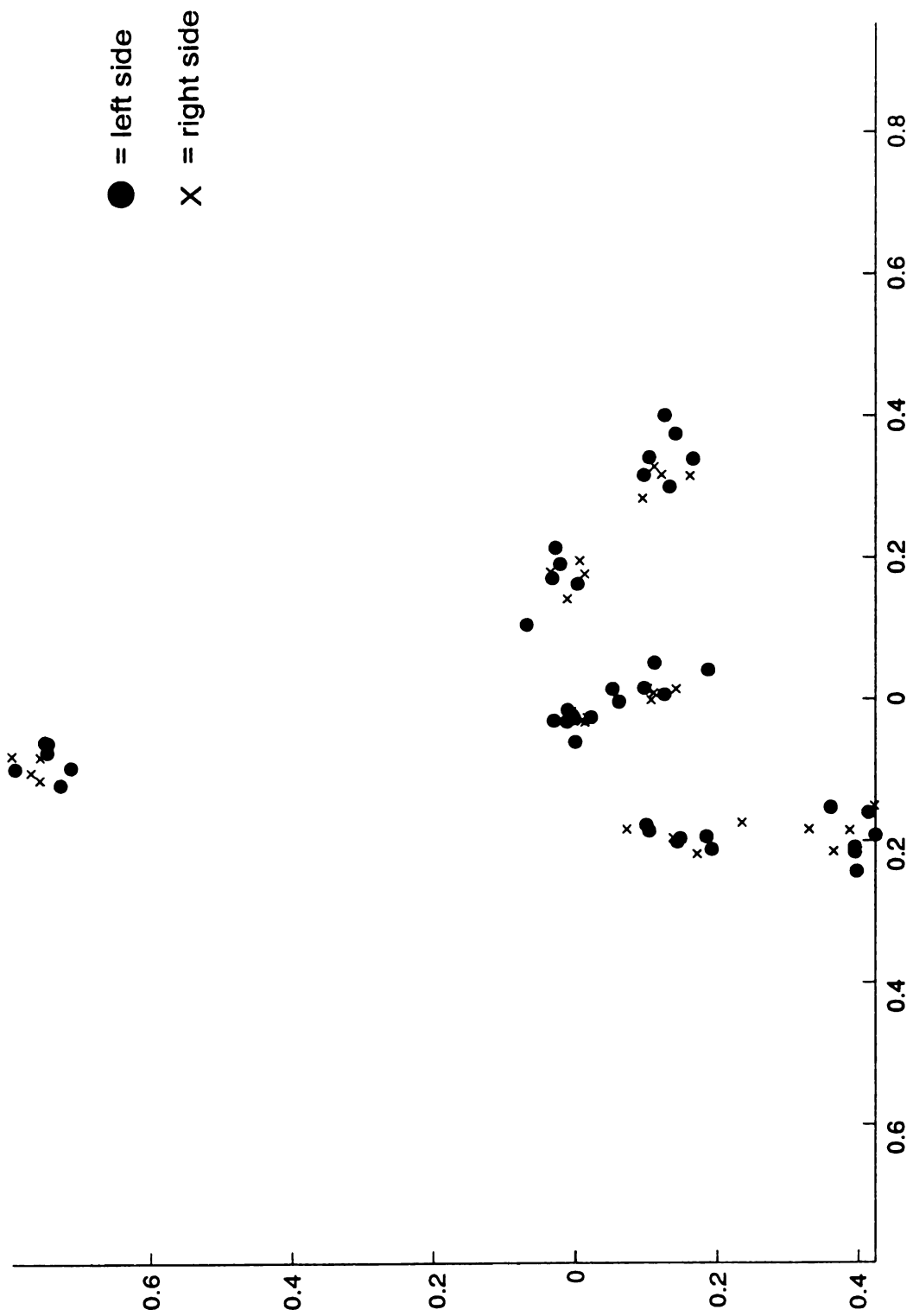
Testing for asymmetry

Procrustes shape coordinate data were tested for statistical significance using an F-test, a resampling test which calculates the likelihood that similar data could be obtained randomly. The Procrustes shape coordinates were also graphed and visually analyzed (Figures 7 and 8). In both extant species, only jaw position 3, in both the upper and lower jaws, displayed asymmetry (antisymmetry); the other positions were generally symmetrical. Thus for each jaw position except 3, shape coordinates of the teeth from the right and left sides of the jaw were combined into one data set.

The cause of this asymmetry is not known. One possibility is “handedness” in feeding. Just as humans tend to favor their right or left hand, perhaps some sharks favor feeding from the right or left side. No studies have been performed on shark handedness, so it cannot be said whether this occurs or not. A second possibility is that it is not functional. In humans, there are small differences between the right and left sides of the face that are not correlated with function. The slight asymmetry in Makos may be similar.

Characterizing the extant species

For each species, the Procrustes shape coordinates for positions 1 through 7 were plotted, keeping data from the upper jaw and lower jaw separate (Figures 9



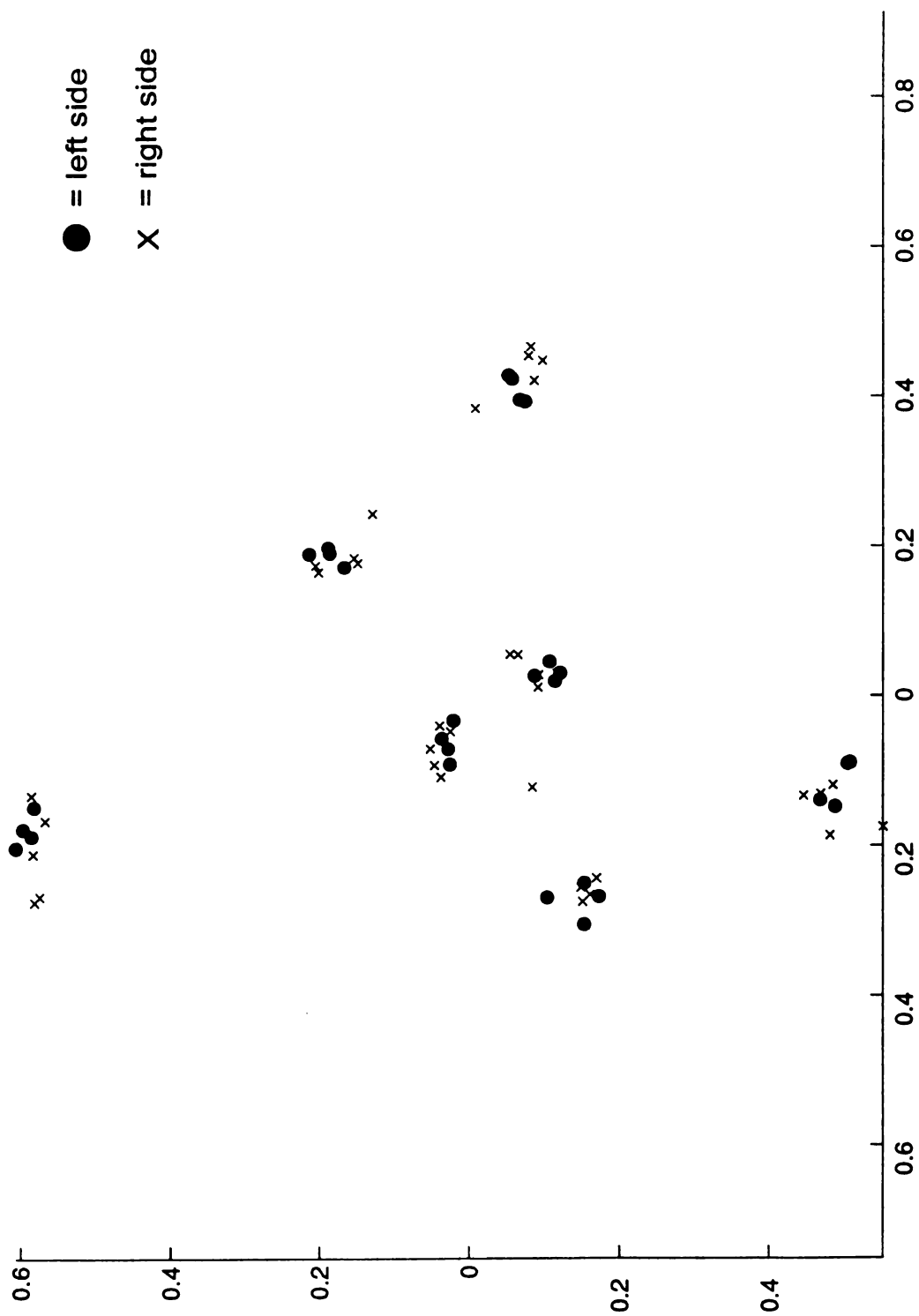


Figure 8 - Procrustes shape coordinates for *I. oxyrinchus*, upper jaw, position 3.

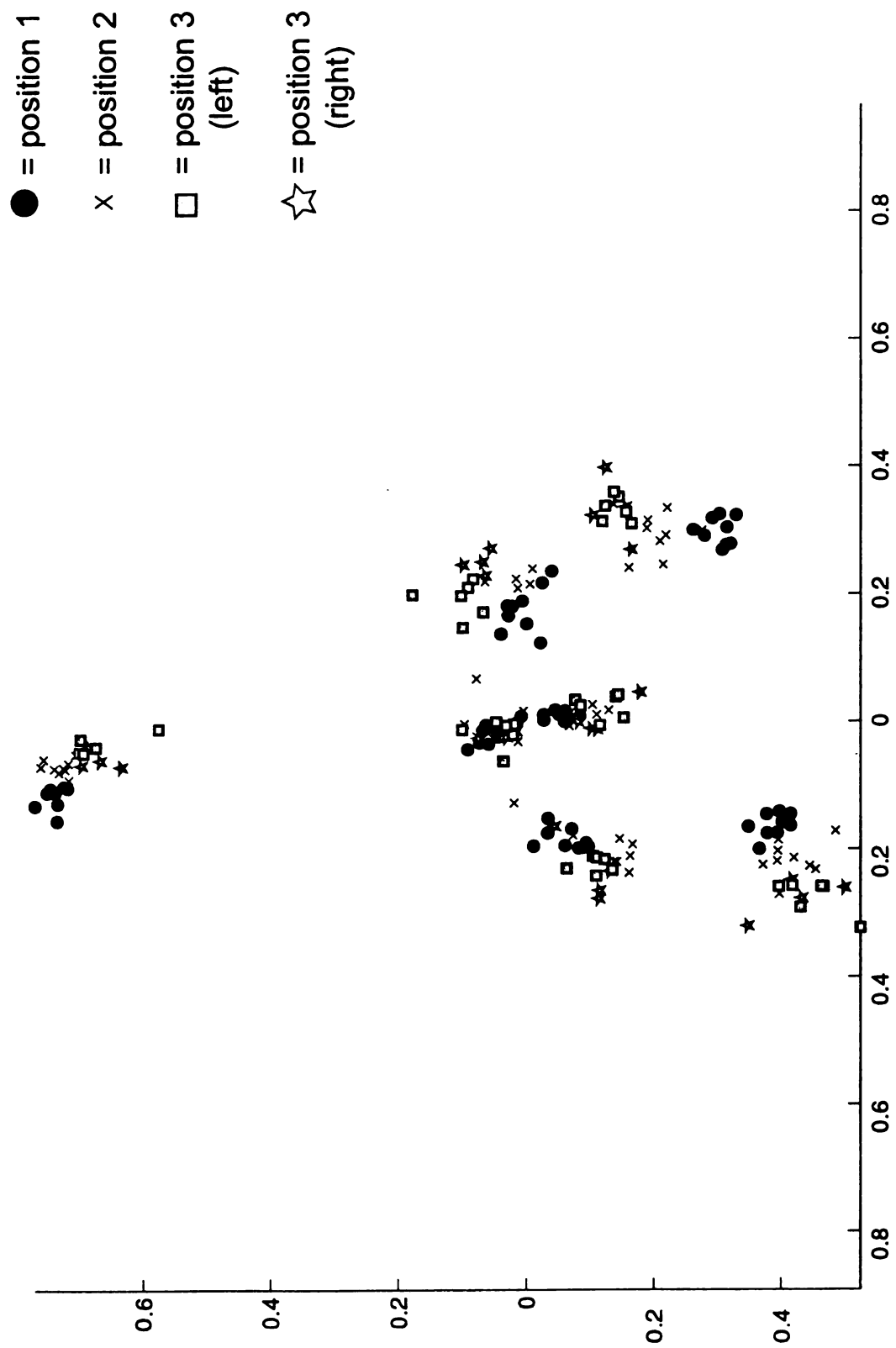


Figure 9 - Procrustes shape coordinates for *I. oxyrinchus*, lower jaw, positions 1, 2, and 3.

- = position 4
- x = position 5
- = position 6
- ☆ = position 7

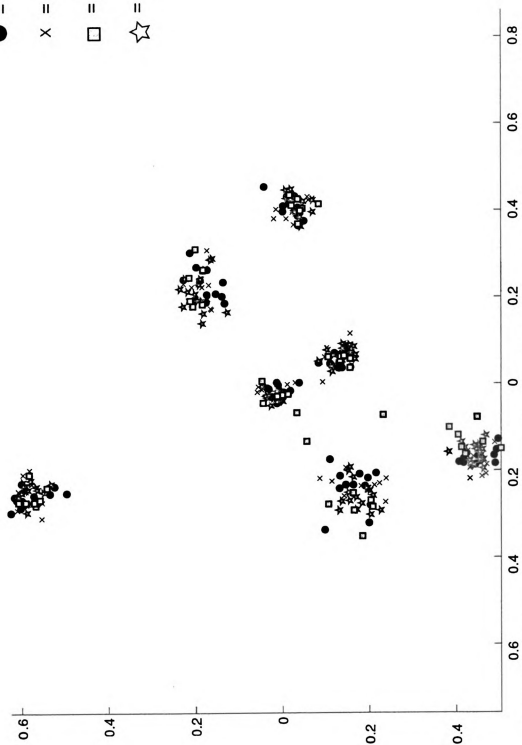


Figure 10 - Procrustes shape coordinates for *I. oxyrinchus*, lower jaw, positions 4, 5, 6, and 7.

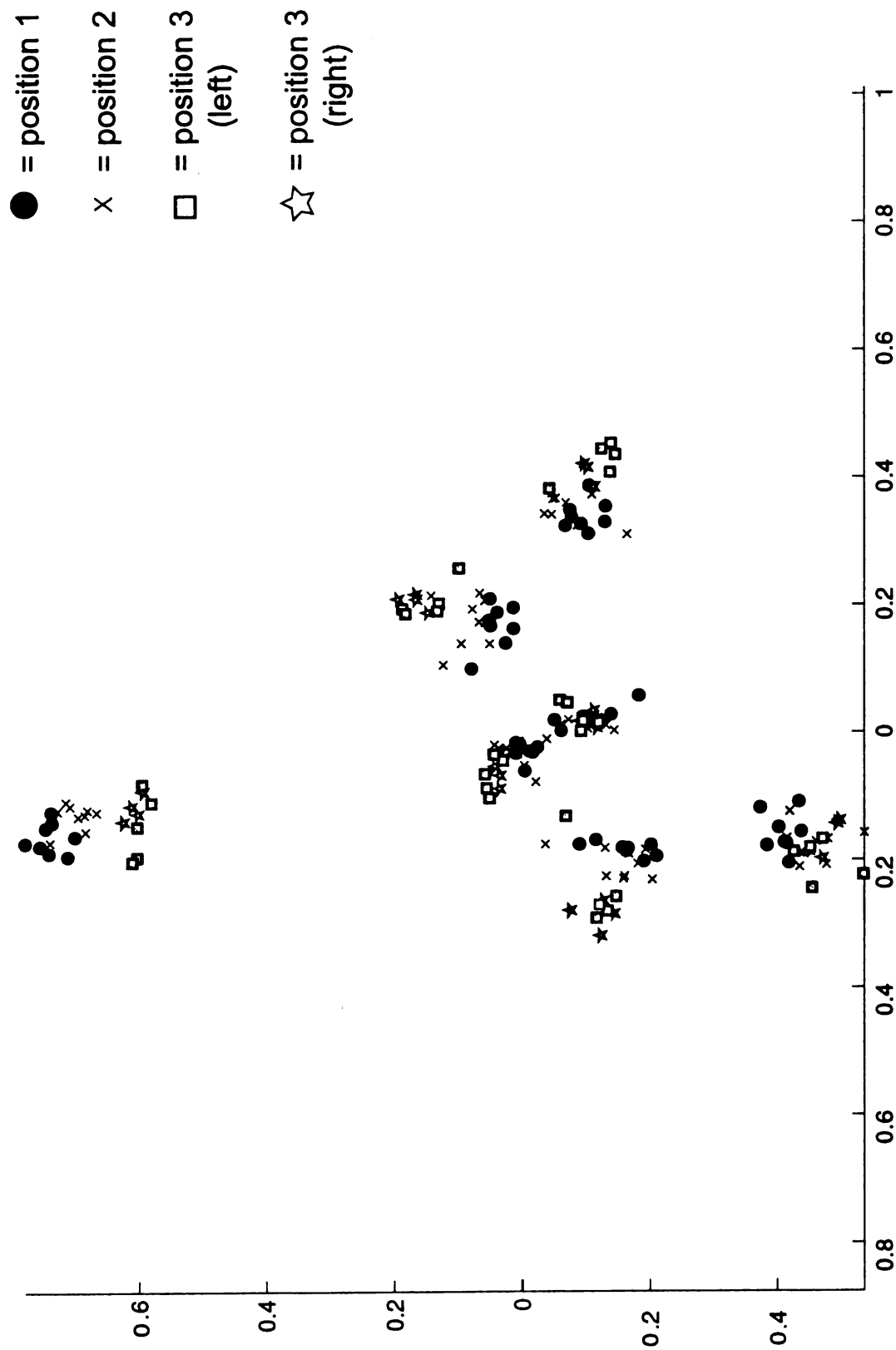


Figure 11 - Procrustes shape coordinates for *I. oxyrinchus*, upper jaw, positions 1, 2, and 3.

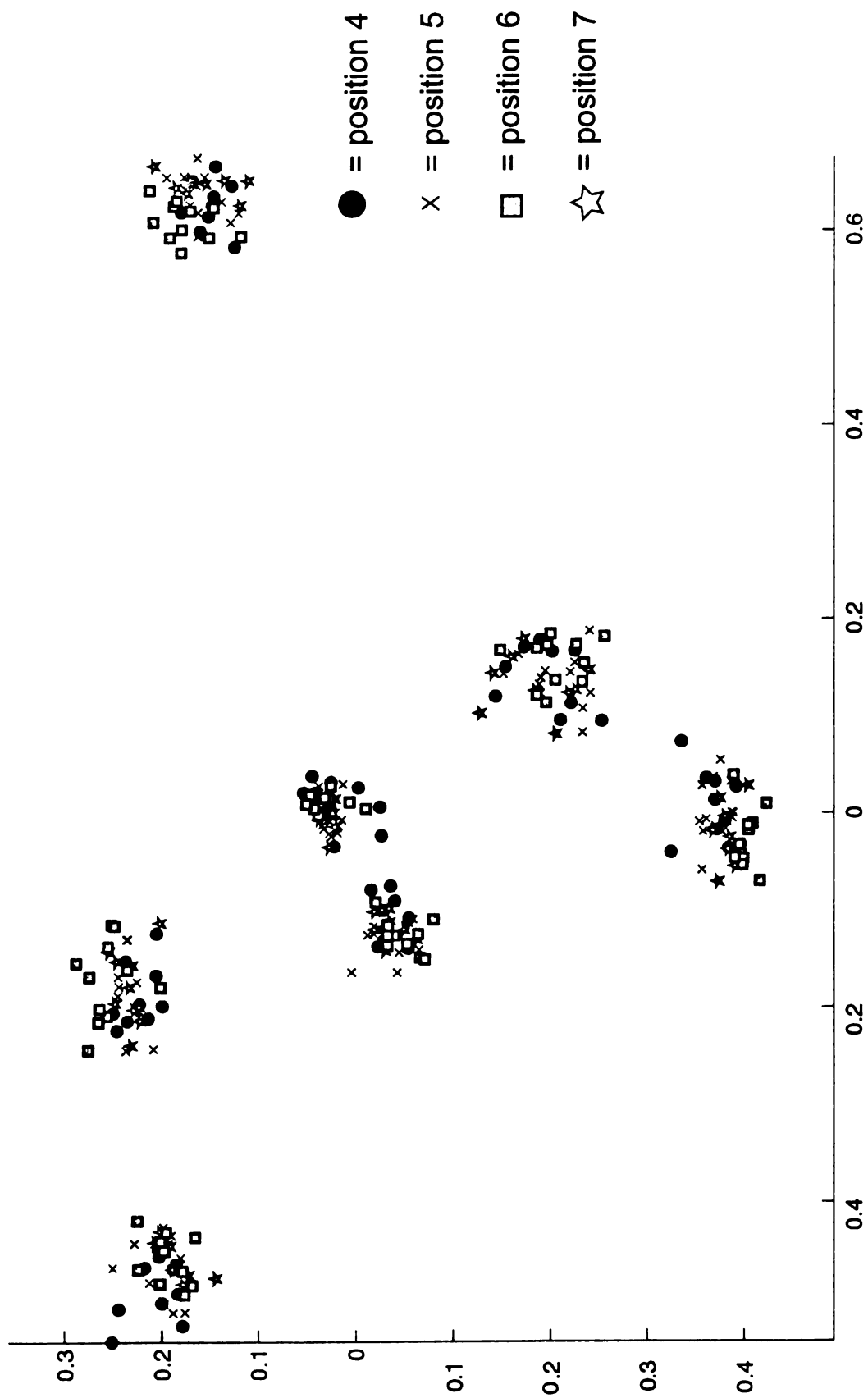


Figure 12 - Procrustes shape coordinates for *I. oxyrinchus*, upper jaw, positions 4, 5, 6, and 7.

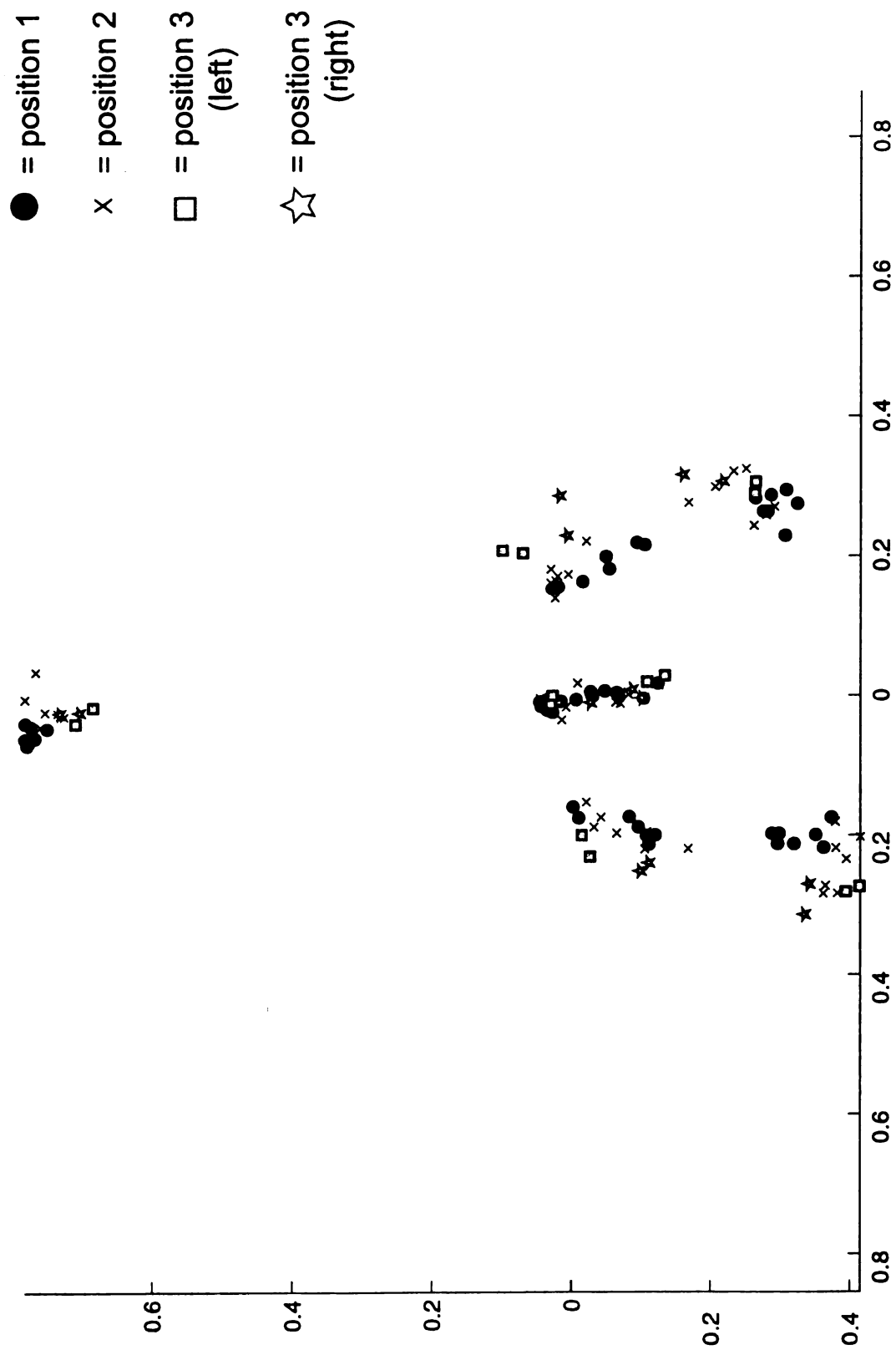


Figure 13 - Procrustes shape coordinates for *I. paucus*, positions 1, 2, and 3, lower jaw.

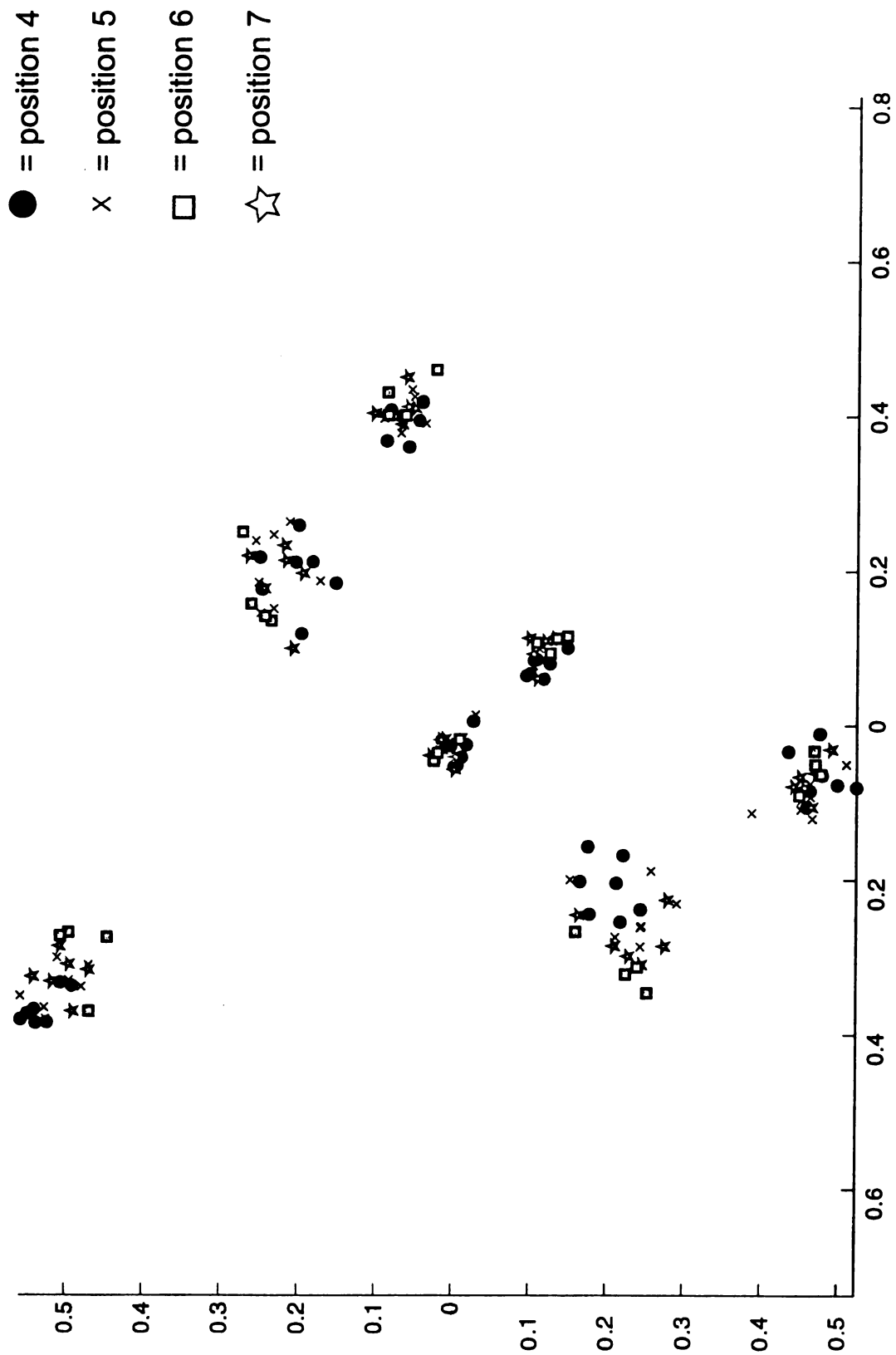


Figure 14 - Procrustes shape coordinates for *I. paucus*, positions 4, 5, 6, and 7, lower jaw.

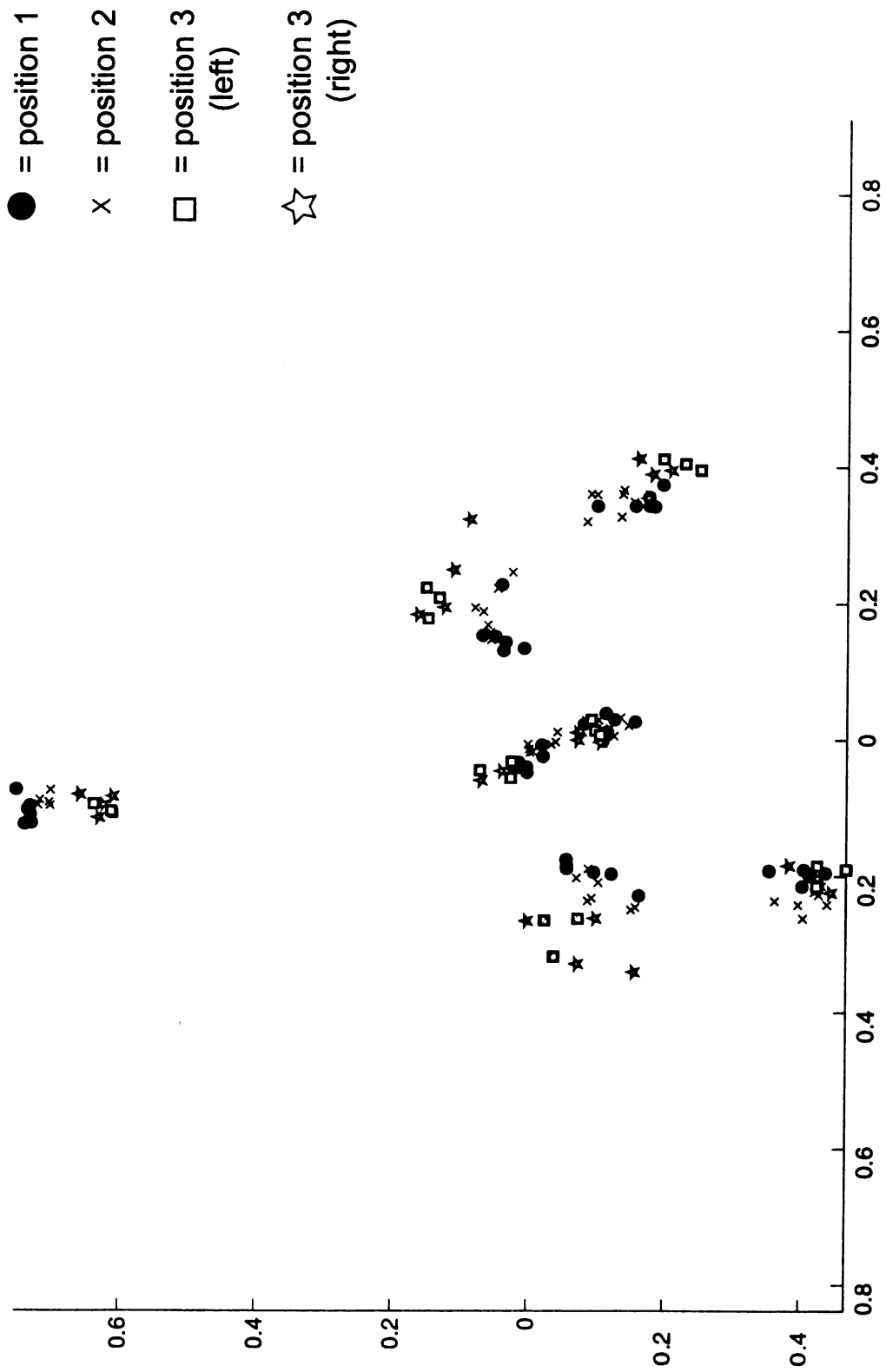


Figure 15 - Procrustes shape coordinates for *I. paucus*, positions 1, 2, and 3, upper jaw.

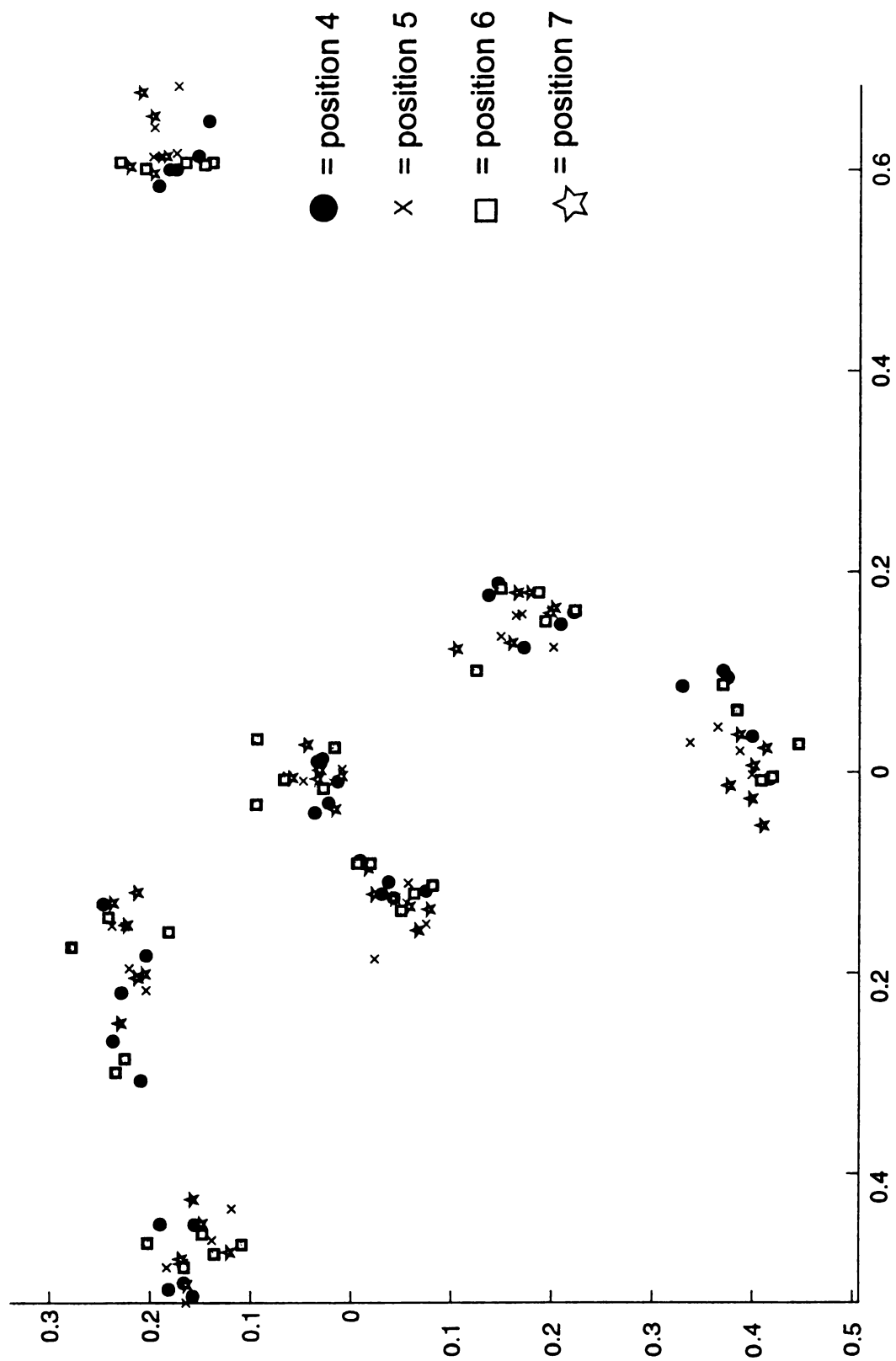


Figure 16 - Procrustes shape coordinates for *I. paucus*, positions 4, 5, 6, and 7, upper jaw.

through 16). These data were also analyzed using principle components analysis (Figures 17 through 24). On both the principle components plot and the graphs of the Procrustes shape coordinates, tooth positions 1, 2, and 3 fall into distinct clusters, while positions 4, 5, 6, and 7 fall into one cluster. This holds true for the upper and lower jaws, and for both species. Thus, for each jaw (upper and lower) and species, the jaw positions can be sorted into five groups: jaw position 1, jaw position 2, jaw position 3 (left side), jaw position 3 (right side), and jaw positions 4 through 7. This part of the analysis strongly supports the presence of monognathic heterodonty in Mako sharks. The Procrustes shape coordinate data for the teeth in the upper jaw were then tested against the data for the lower jaw using an F-test. For both extant species, the differences were statistically significant ($p=0.01$), indicating that Mako sharks also have strong dignathic heterodonty.

The plots of the Procrustes shape coordinates can be used to describe the change in shape between tooth positions (Figure 25 through 28). In the lower jaws of both *I. oxyrinchus* and *I. paucus*, tooth position 1 has a long, narrow cusp and base. As the teeth are tracked to tooth position 4, the cusp becomes shorter, and the base becomes wider. The upper jaw of *I. oxyrinchus* and *I. paucus* display a similar pattern, with the exception of tooth position 3, which has a base that is as wide or wider than as the base in position 4, and a shorter cusp than position 4. These observations are supported in the principle components analysis (29 through 32). Principle component 1, which accounts for

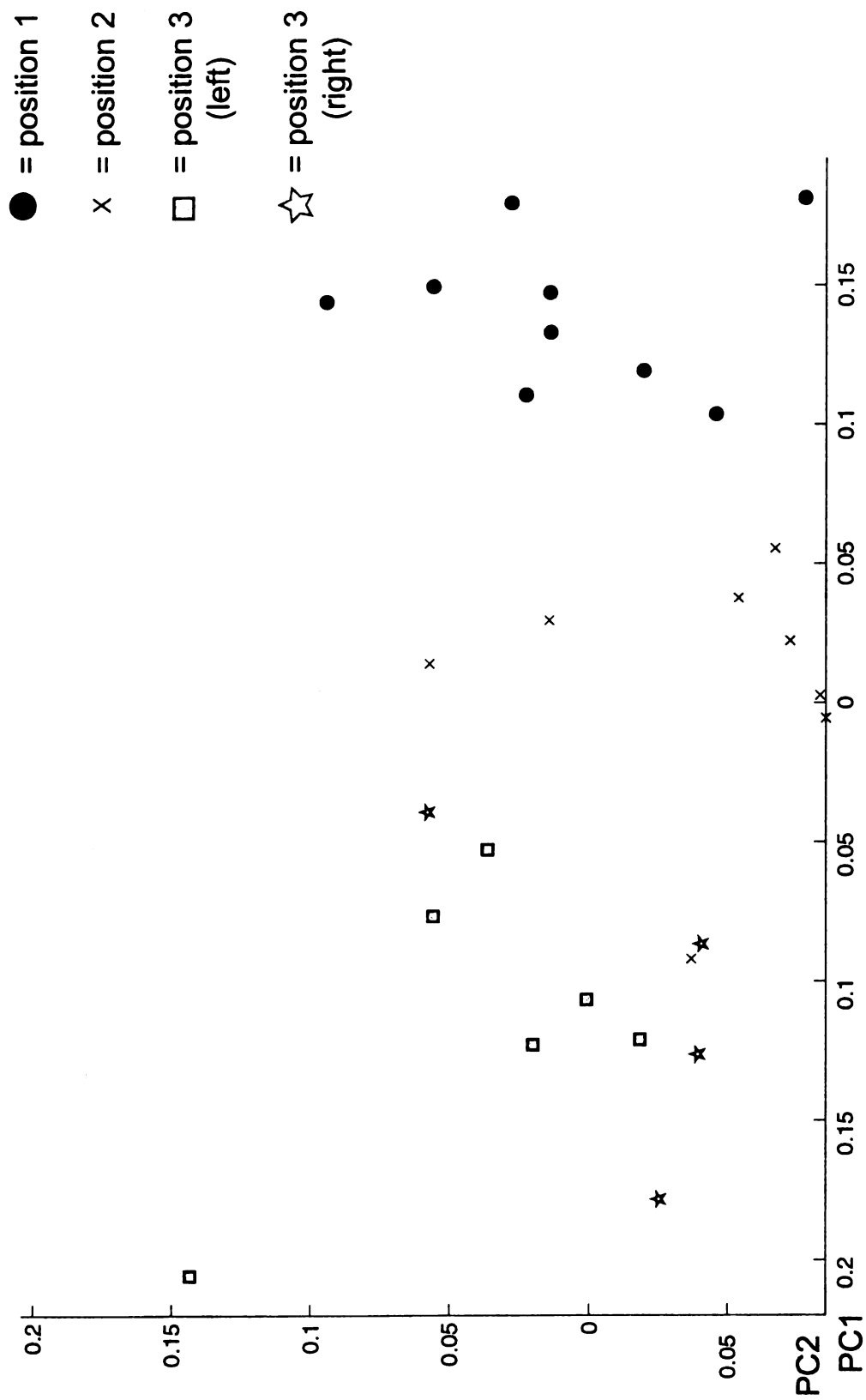
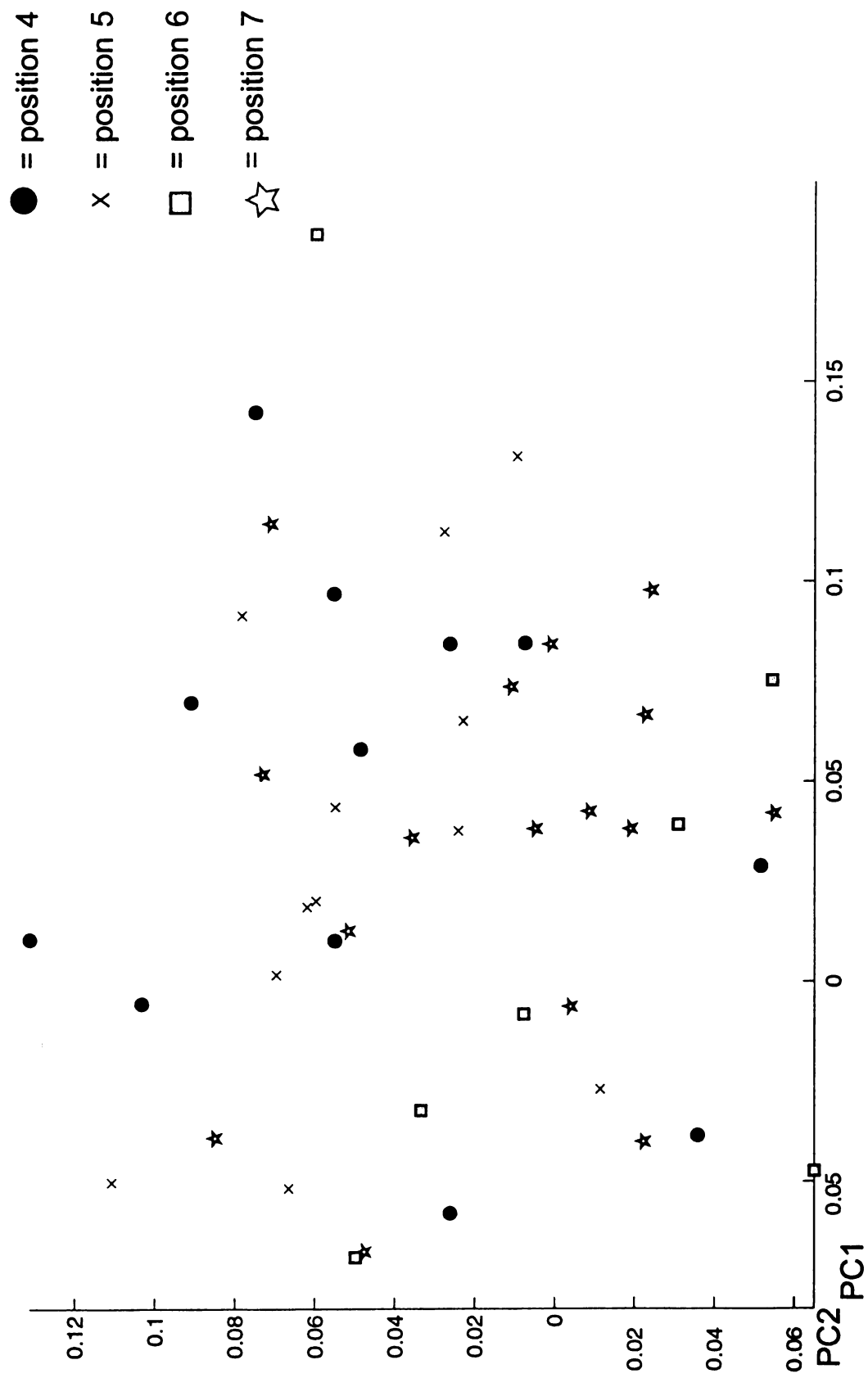


Figure 17 - Principle components for *I. oxyrinchus*, positions 1, 2, and 3, lower jaw.



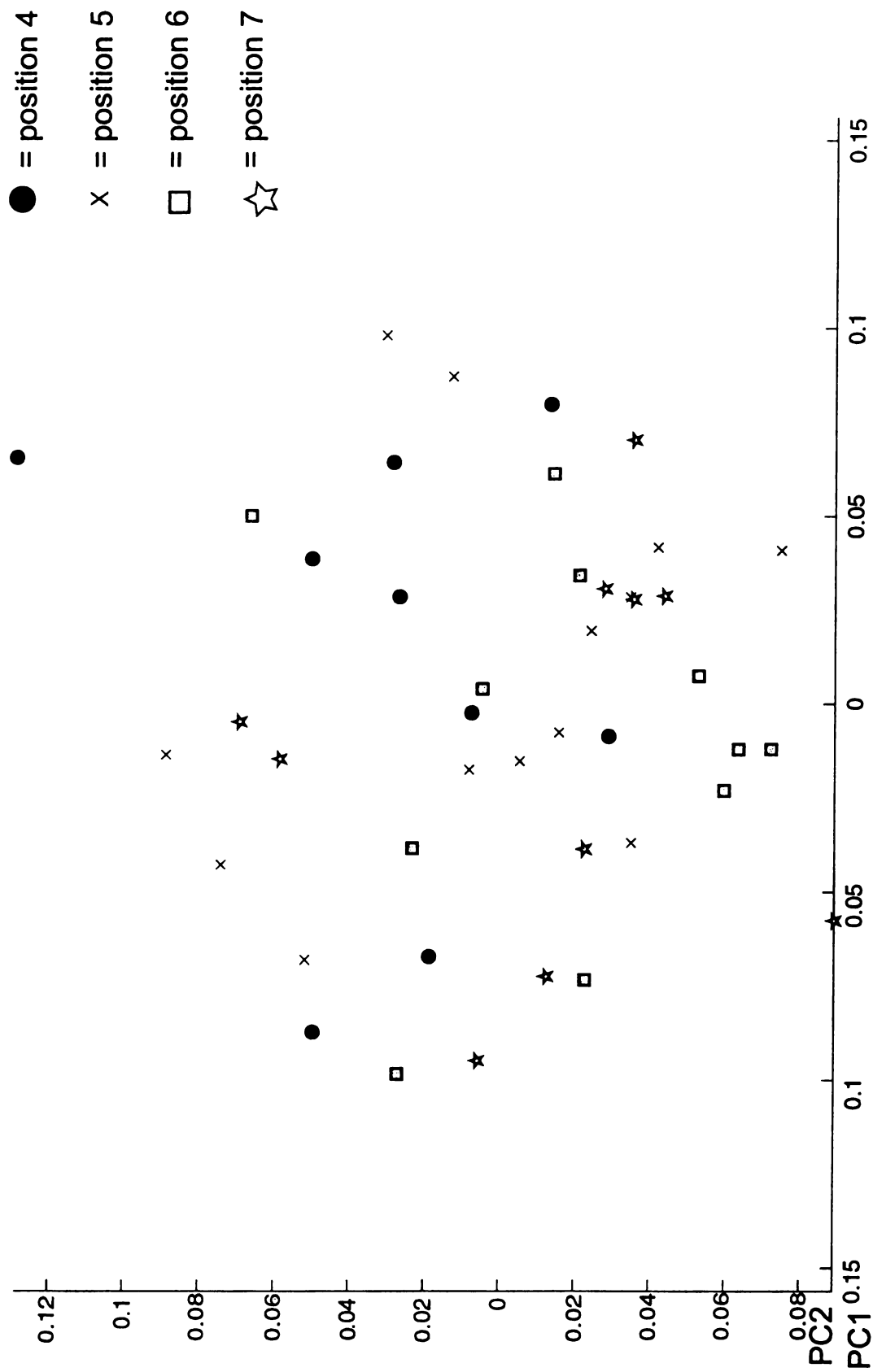


Figure 20 - Principle components for *I. oxyrinchus*, positions 4, 5, 6, and 7 upper jaw.

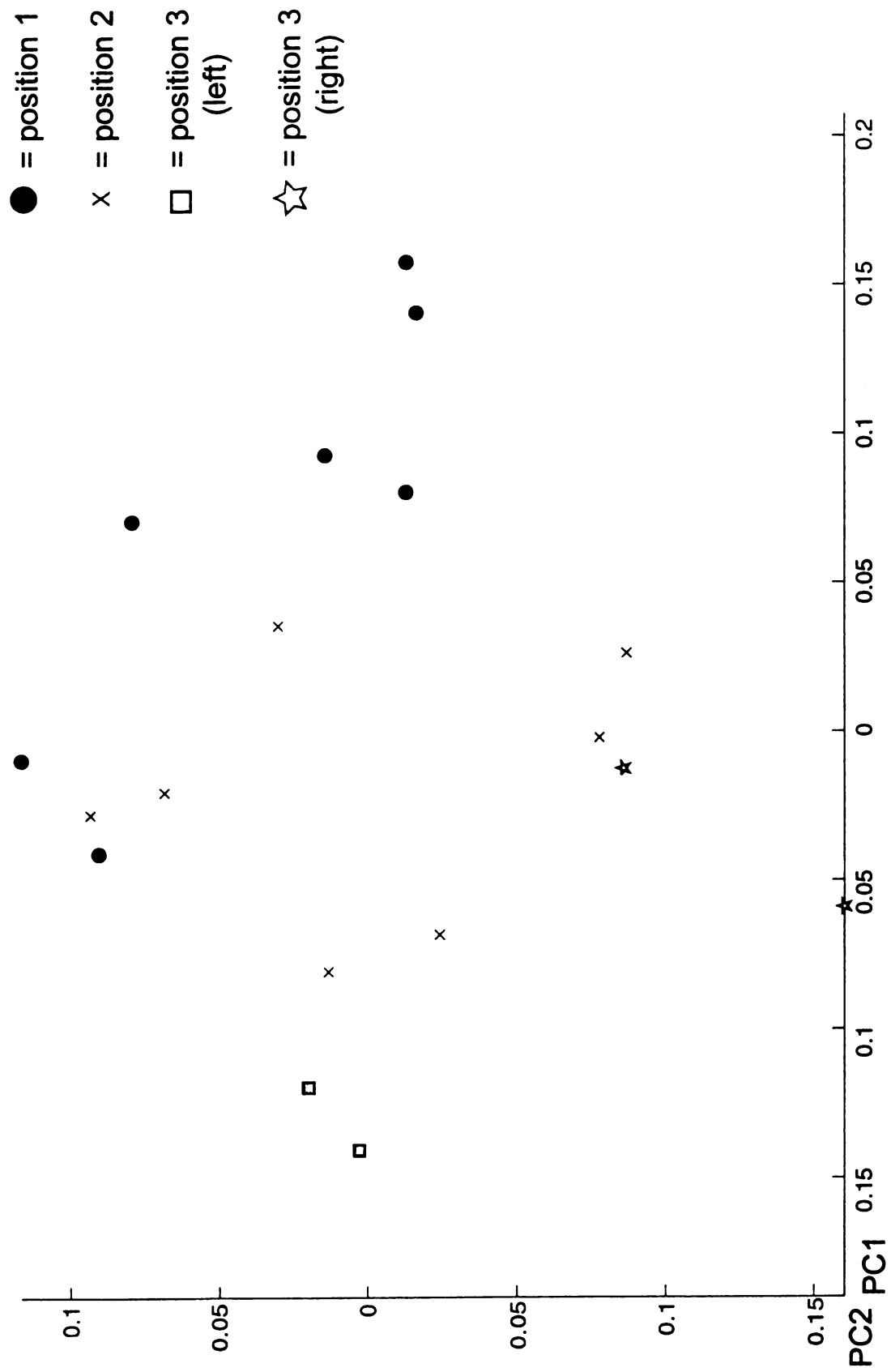


Figure 21 - Principle components for *I. paucus*, positions 1, 2, and 3, lower jaw.

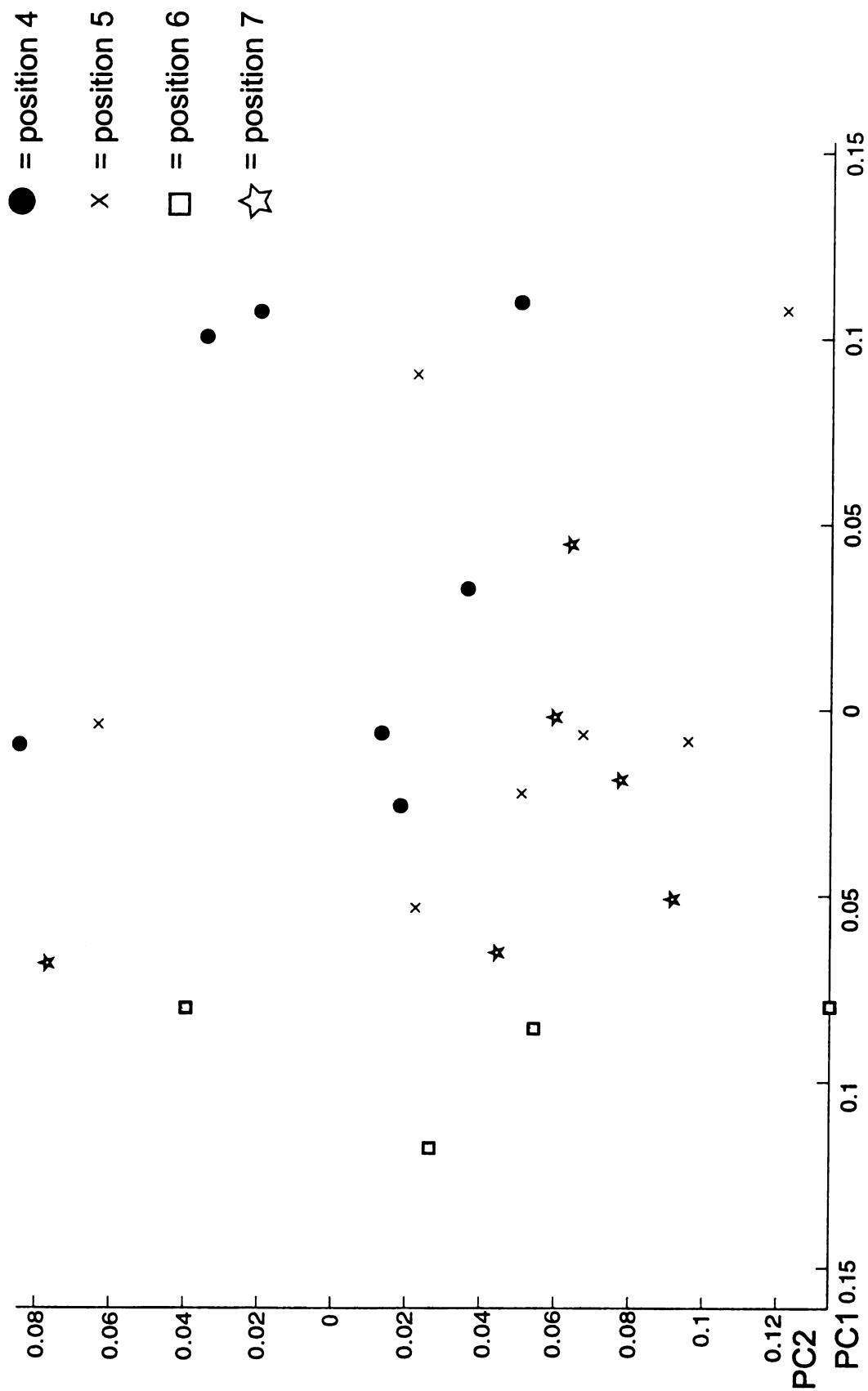


Figure 22 - Principle components for *I. paucus*, positions 4, 5, 6, and 7, lower jaw.

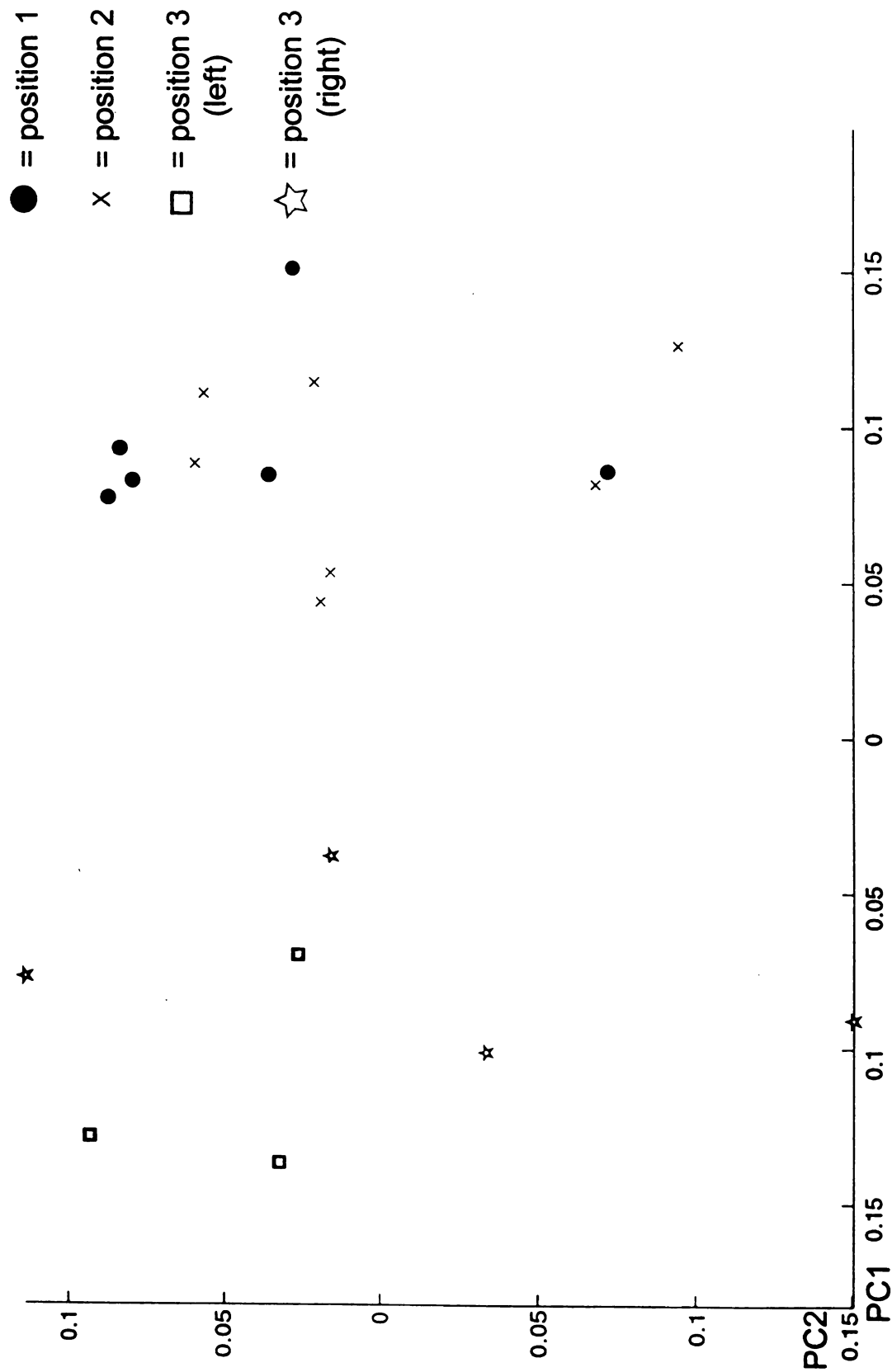


Figure 23 - Principle components for *I. paucus*, positions 1, 2, and 3, upper jaw.

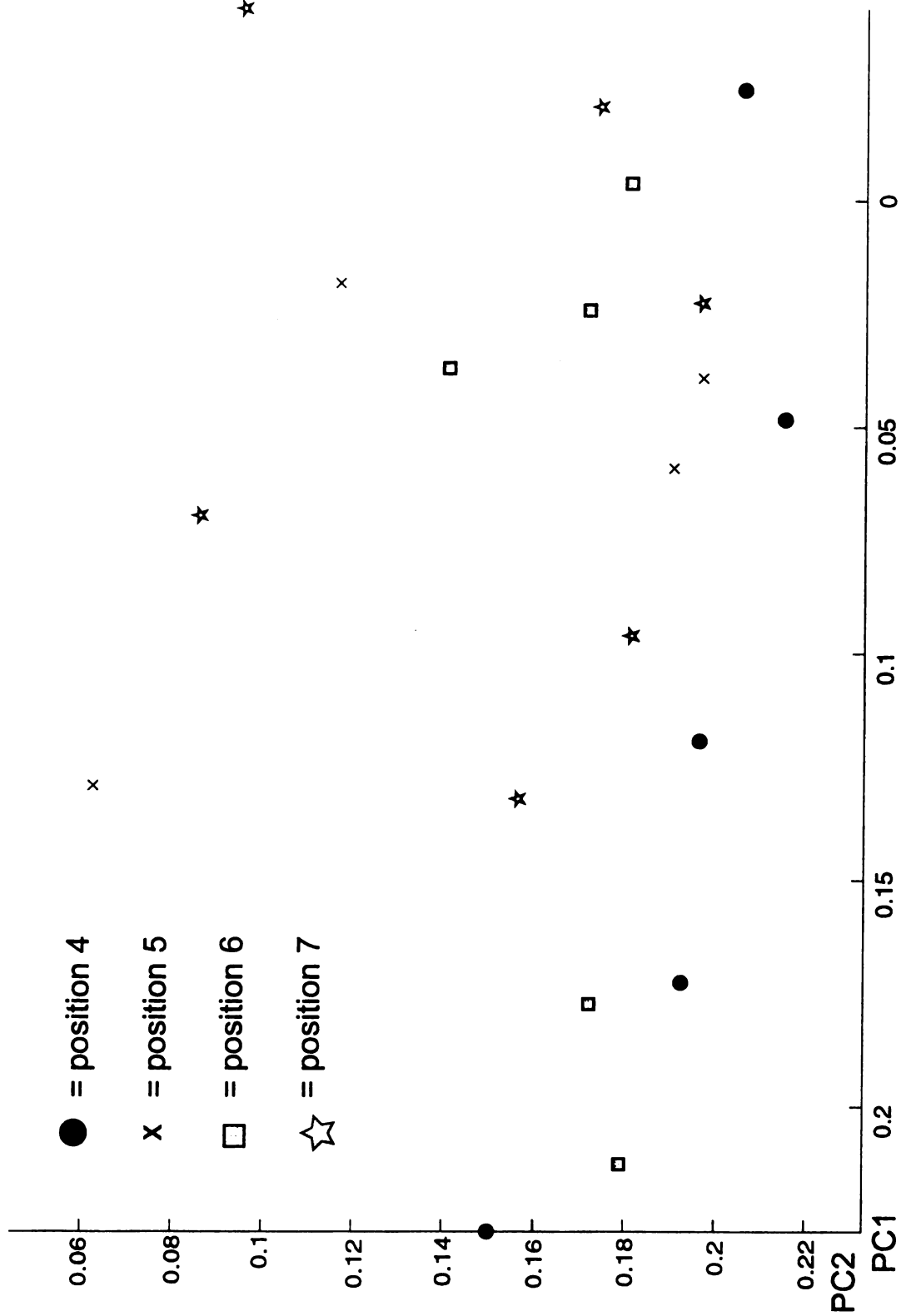


Figure 24 - Principle components for *I. paucus*, positions 4, 5, 6, and 7, upper jaw.

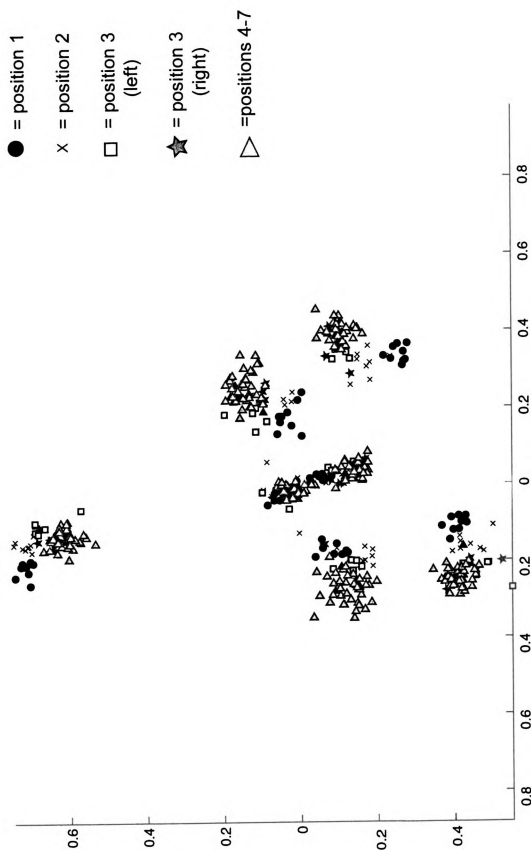


Figure 25 - Procrustes shape coordinates for *I. oxyrinchus*, lower jaw

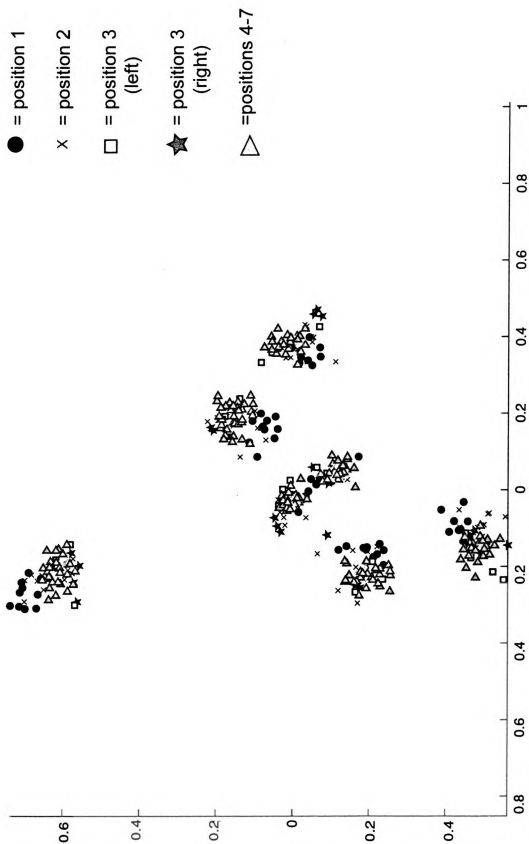


Figure 26 - Procrustes shape coordinates for *I. oxyrinchus*, upper jaw

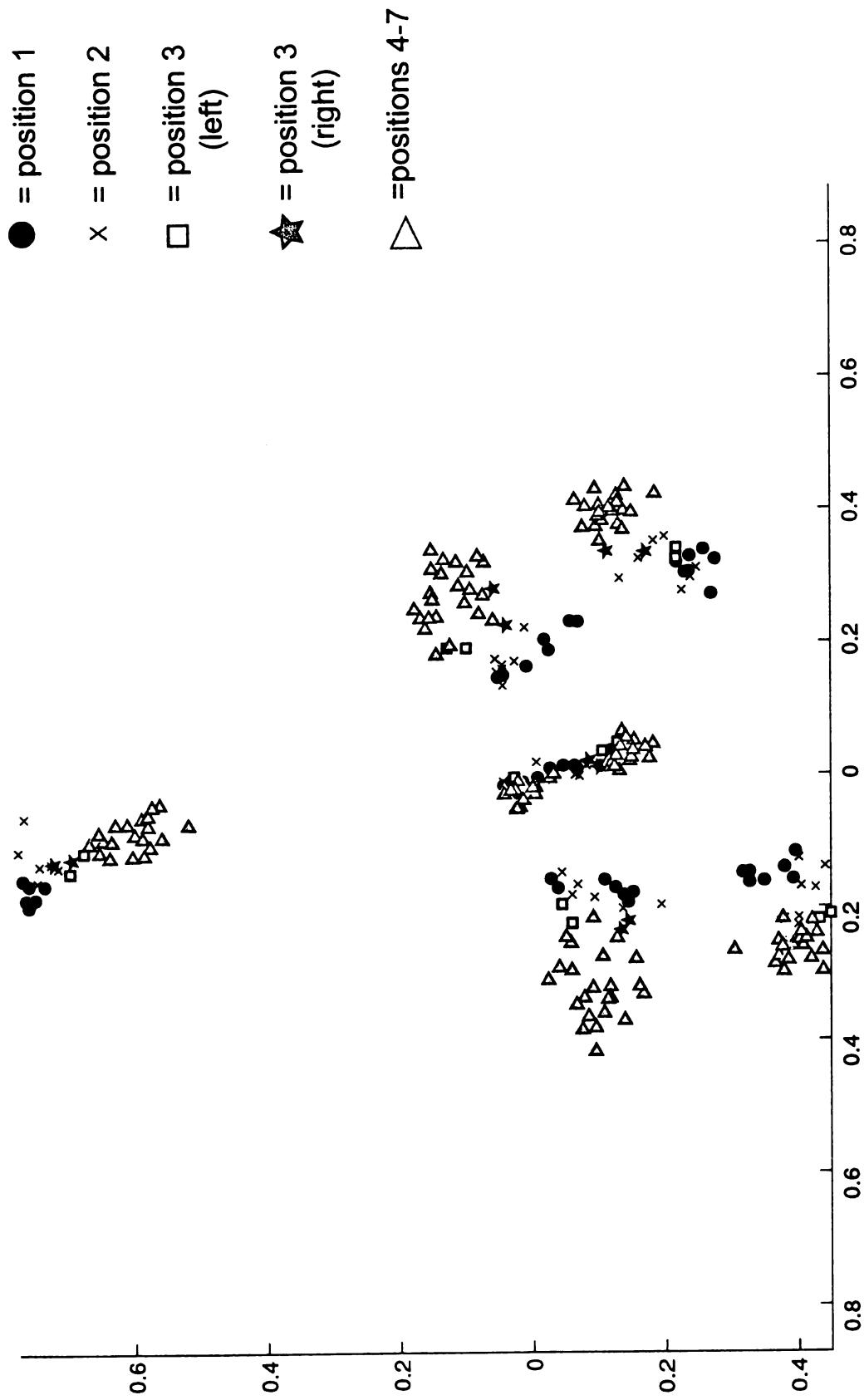
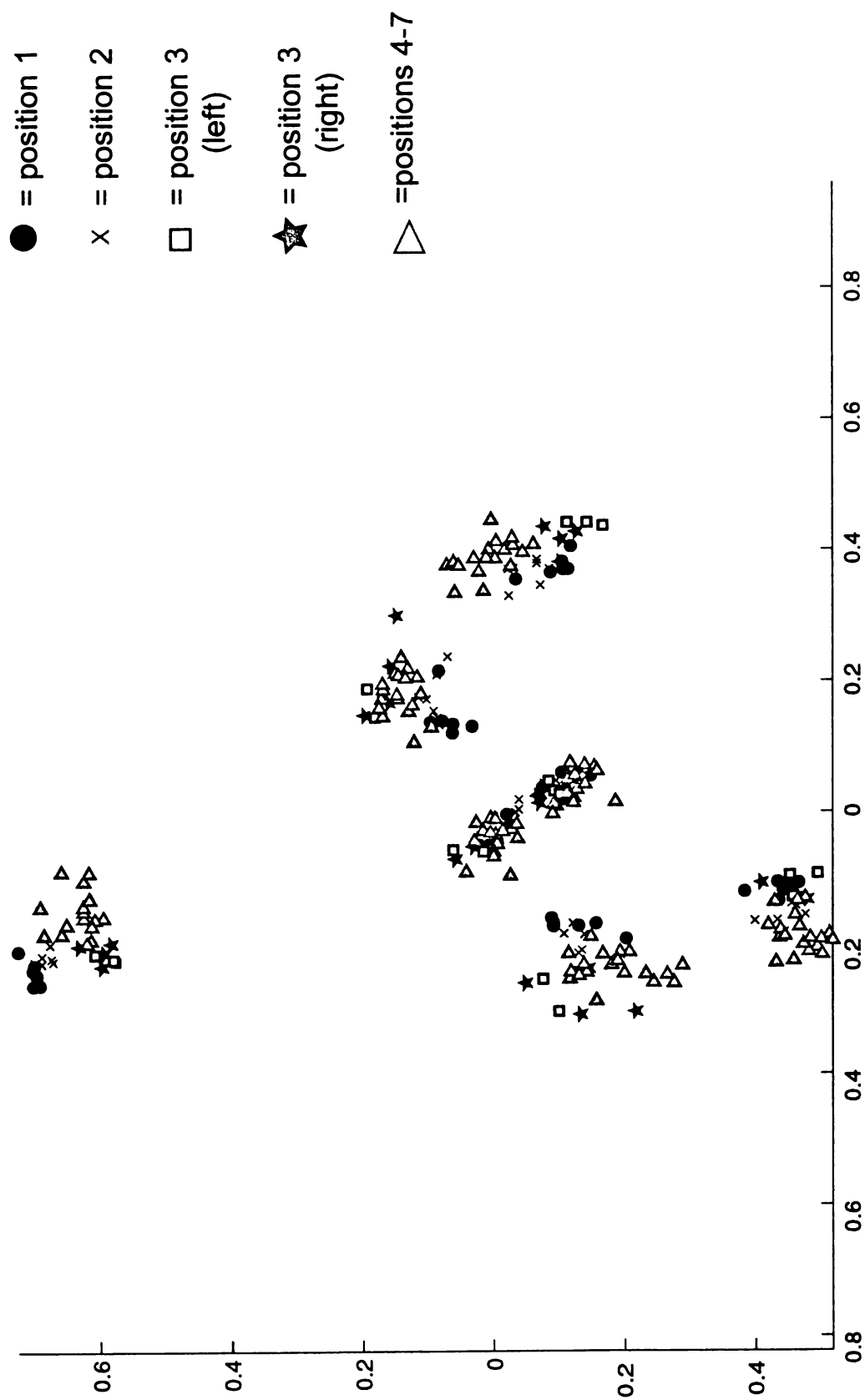


Figure 27 - Procrustes shape coordinates for *I. paucus*, lower jaw



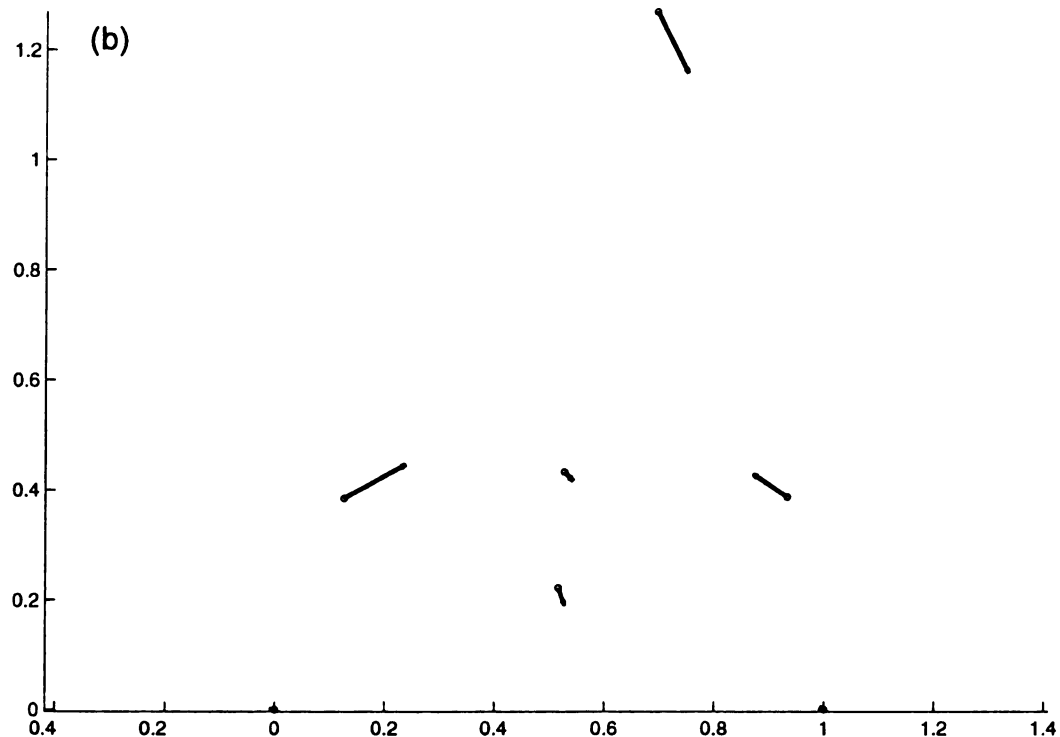
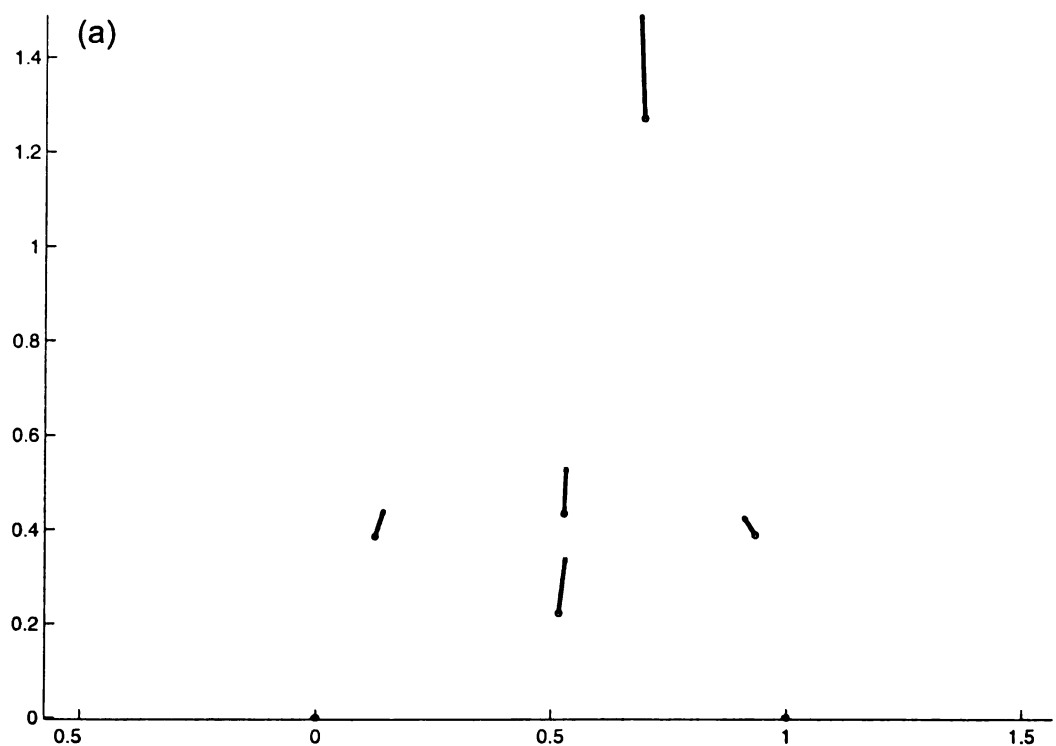


Figure 29 - Deformations shown as vectors on landmarks that represent principle components 1 (a) and 2 (b) for *I. oxyrinchus*, lower jaw. See Figure 3 for landmark identities.

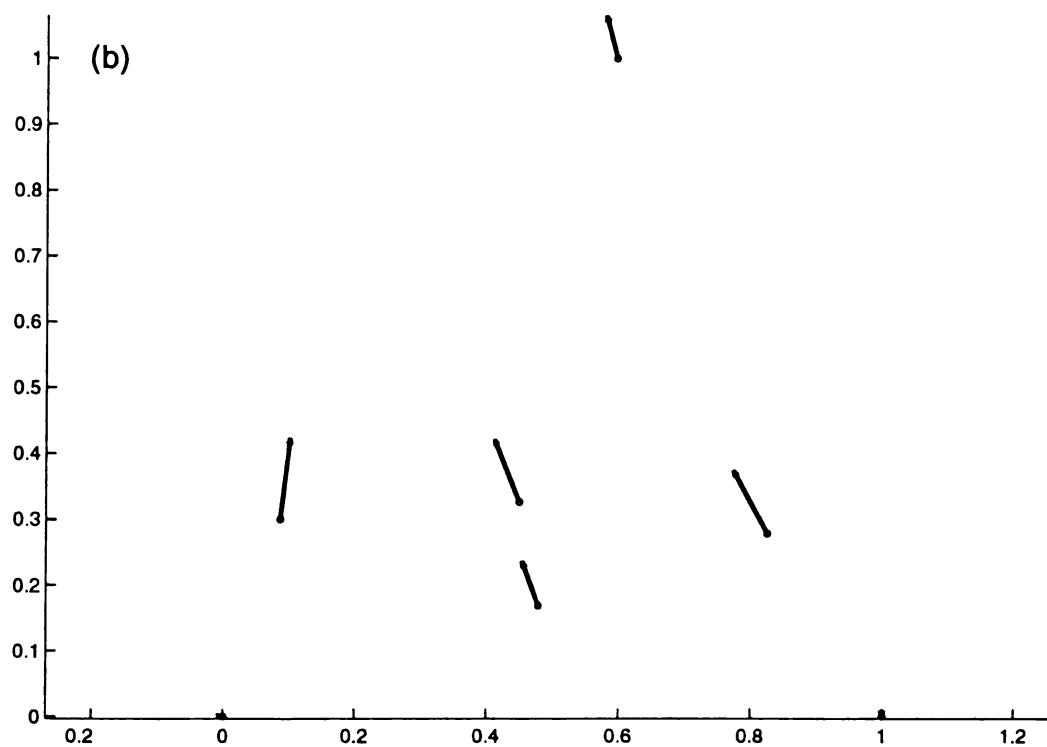
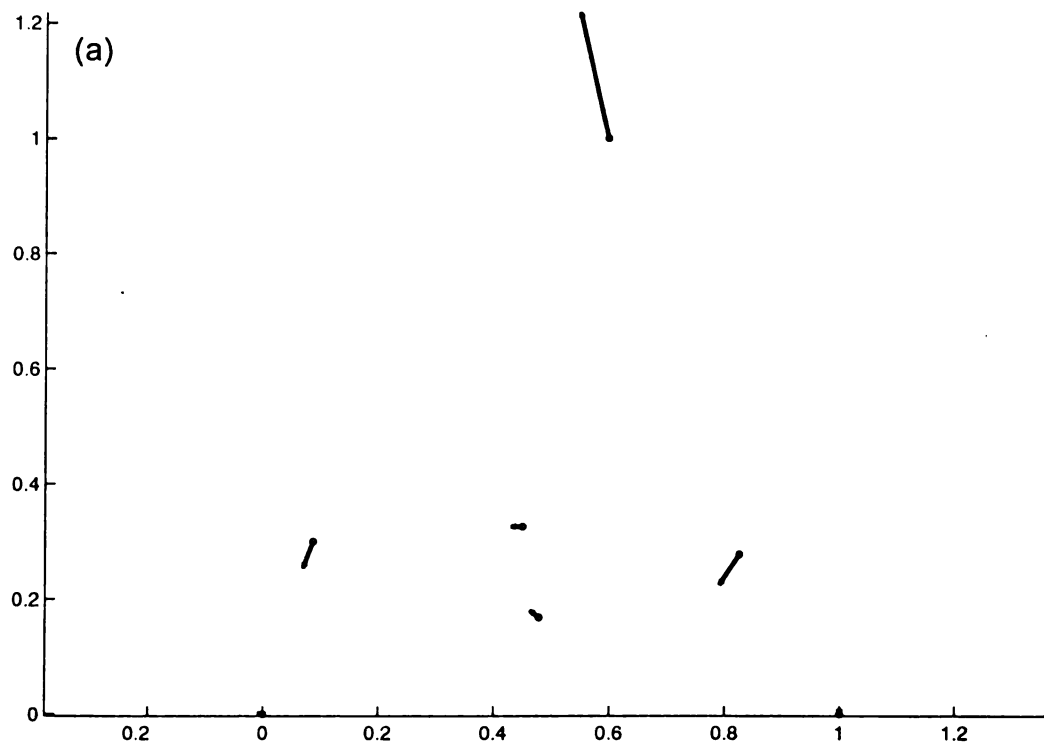


Figure 30 - Deformations shown as vectors on landmarks that represent principle components 1 (a) and 2 (b) for *I. oxyrinchus*, upper jaw.

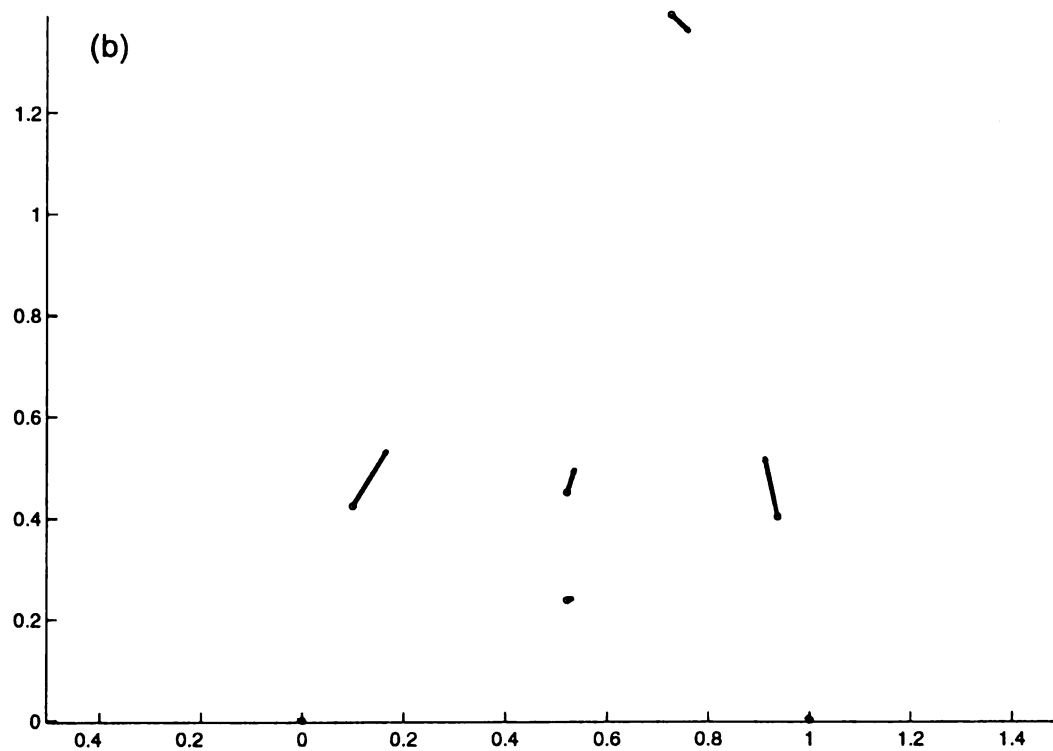
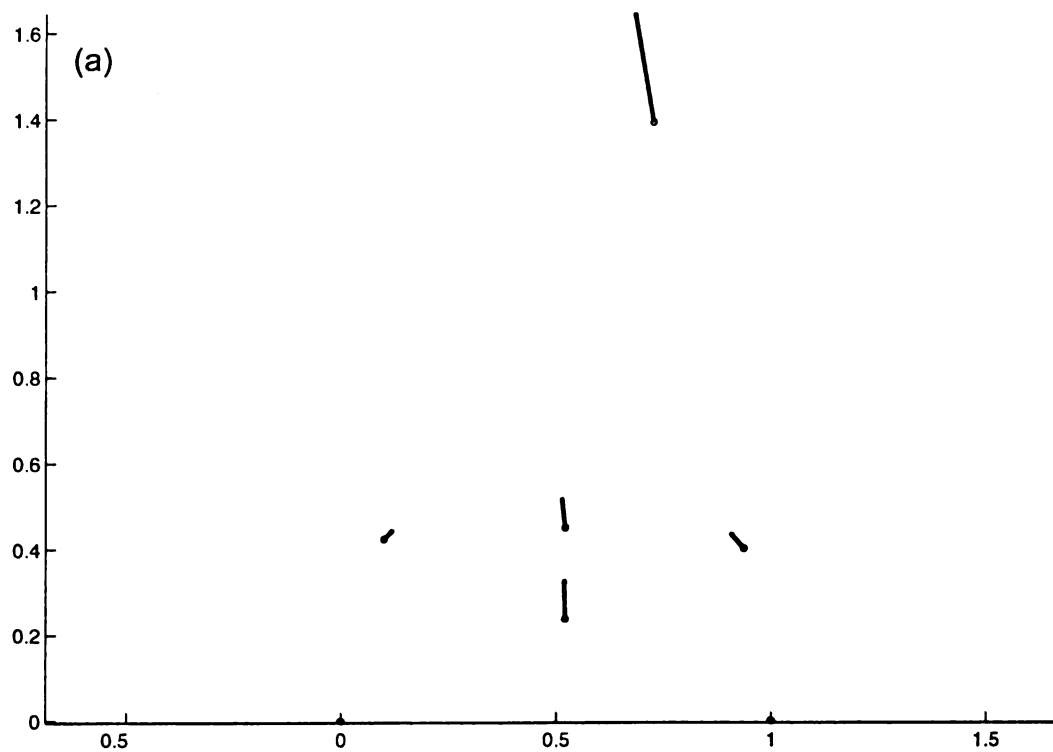


Figure 31 - Deformations shown as vectors on landmarks that represent principle components 1 (a) and 2 (b) for *I. paucus*, lower jaw.

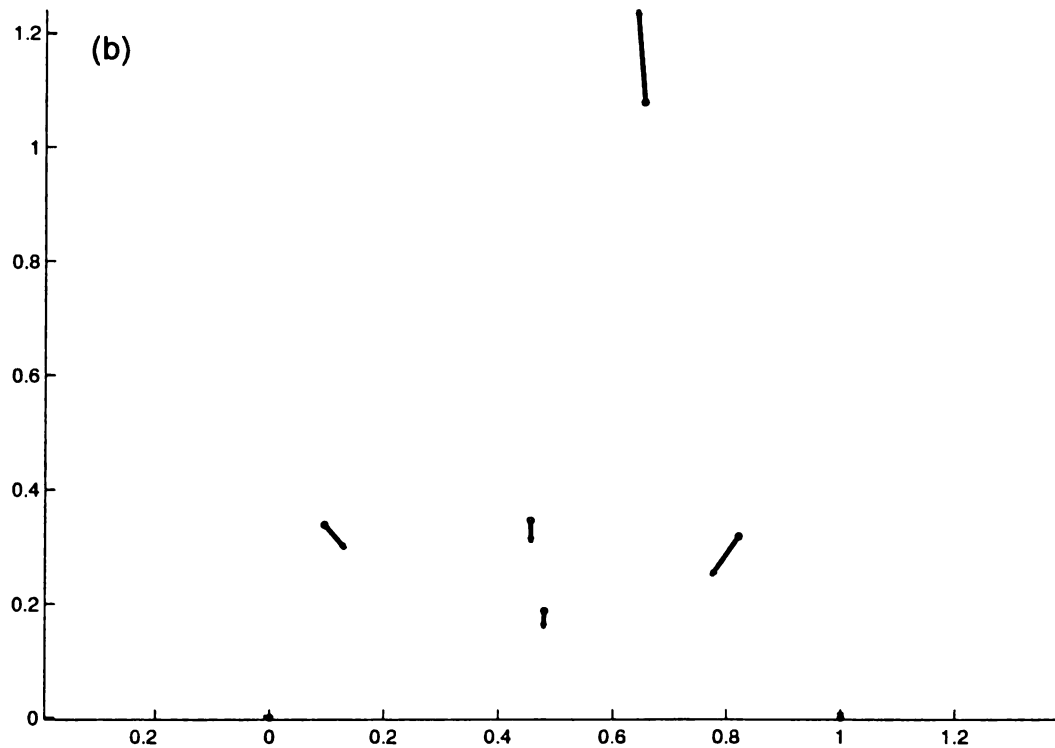
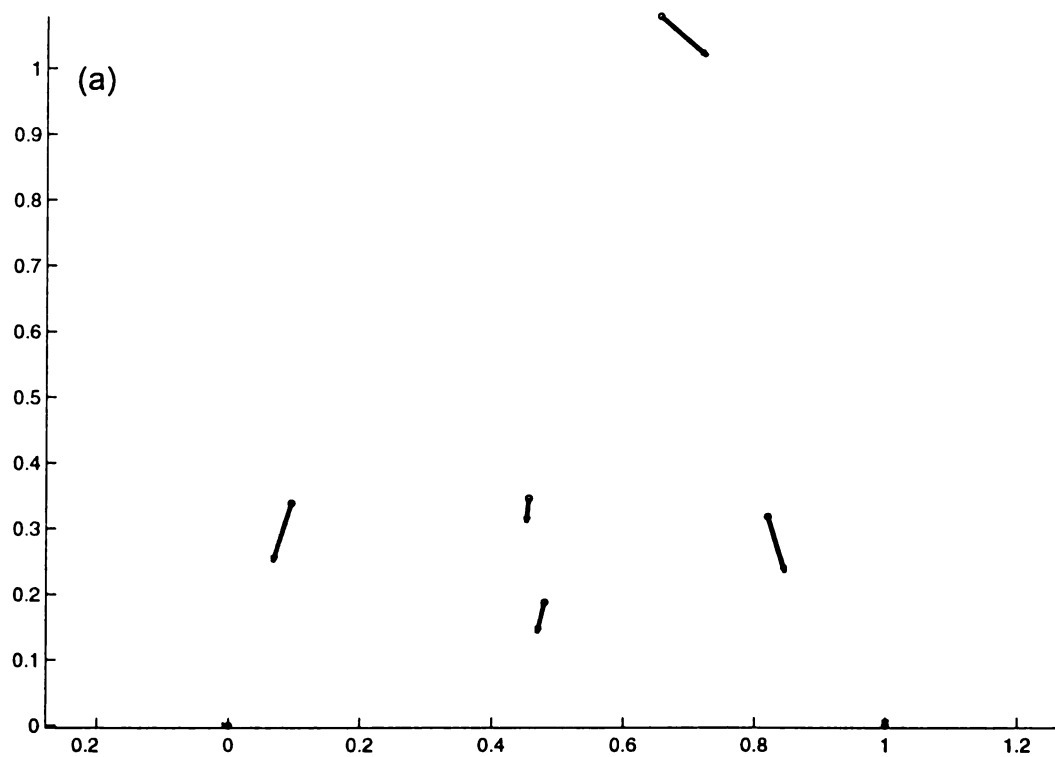


Figure 32 - Deformations shown as vectors on landmarks that represent principle components 1 (a) and 2 (b) for *I. paucus*, upper jaw.

the majority of variation between specimens, is the length of the cusp. Principle component 2 is the size of the tooth base.

Comparing extant species

Procrustes shape coordinates for corresponding tooth positions (e.g. tooth position 1, upper jaw) of the two extant species were plotted and tested using an F-test. The graph of the shape coordinates showed considerable overlap of the two species (Figure 33). This was confirmed with the F-test; p-values ranged from 0.0575 to 0.49. In order to be statistically significant, p-values must be equal to or lower than 0.05. Thus, teeth of *I. oxyrinchus* and *I. paucus* are not significantly different. However, it should be noted that the sample size for this study is fairly small (10 *I. oxyrinchus* jaws, 5 *I. paucus* jaws), which may account for the high p-values. If the teeth of the two species are visually compared, there are obvious differences in morphology (Figure 3). The teeth of *I. oxyrinchus* are more curved than those of *I. paucus*, and also have longer, thinner cusps. Additional specimens would add data that may lead to better resolution in this portion of the study.

Testing the methods

The Procrustes shape coordinate data for the 14 test teeth were clustered with the Procrustes shape coordinate data for the teeth analyzed. The unknown tooth was given the designation of the tooth that it was paired with (species, tooth position, upper/lower jaw) (Table 2). If the unknown tooth was added to a cluster

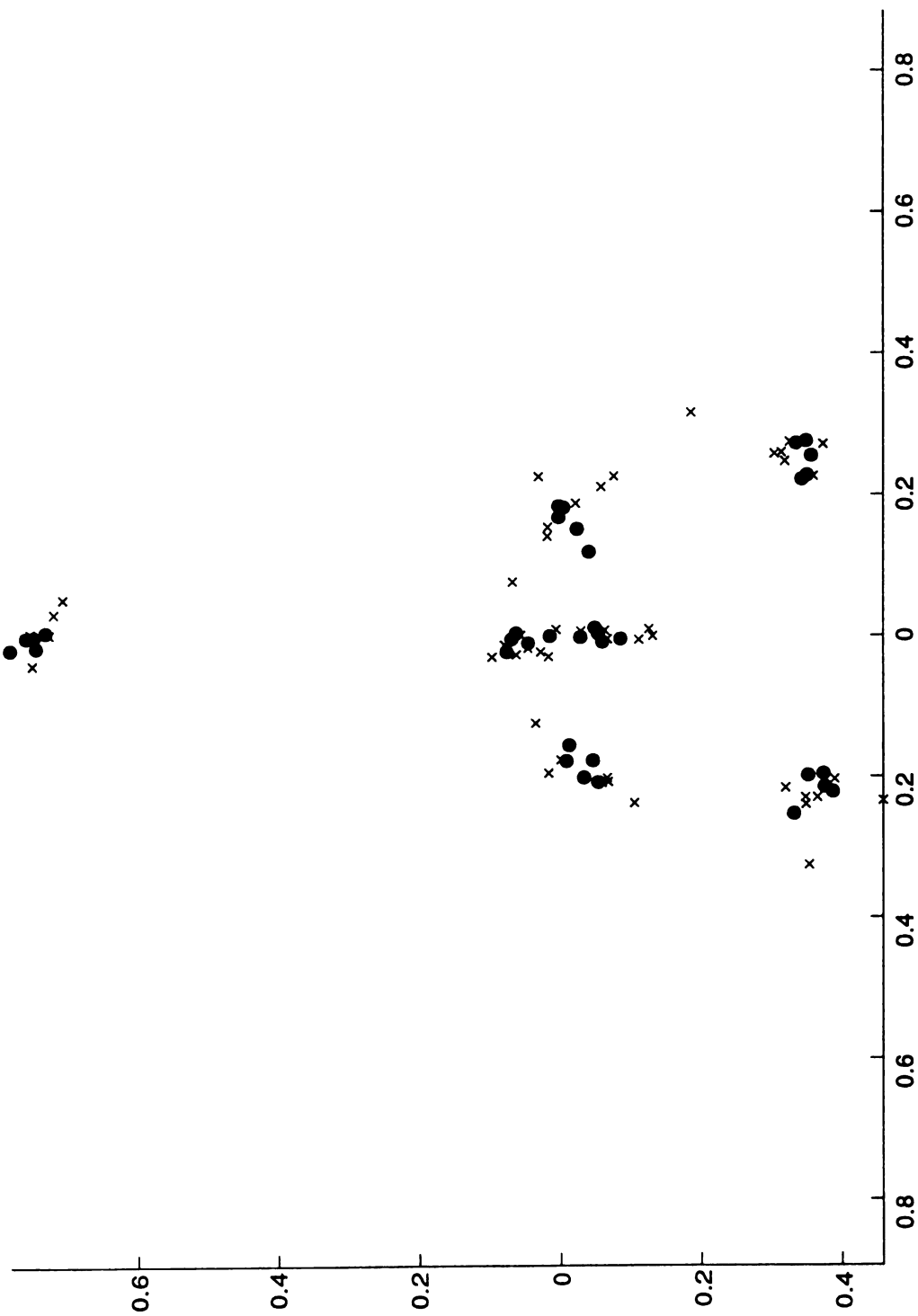


Figure 33 - Procrustes shape coordinates for *I. oxyrinchus* (black circle) and *I. paucus* (gray X), lower jaw, position 1.

Table 2

Results of the Clustering Analysis

The identification of the test specimens is based on which specimens (with known assignments) were clustered with the test specimens. The test specimen number is based on the order of specimens in the data matrix used in the clustering analysis.

Table 2
Results of the Clustering Analysis

Test Specimen	Clustered With	Assigned Identity	Actual Identity
222	76 and 154	<i>I. oxyrinchus</i> , upper jaw, position 1 or <i>I. paucus</i> , lower jaw, left side, position 3	<i>I. oxyrinchus</i> , upper jaw, position 2
223	99	<i>I. oxyrinchus</i> , upper jaw, right side, position 3	<i>I. oxyrinchus</i> , upper jaw, position 4
224	48 and 178	<i>I. oxyrinchus</i> , lower jaw, position 4 through 7 or <i>I. paucus</i> , lower jaw, position 4 through 7	<i>I. oxyrinchus</i> , upper jaw, position 6
225	146 and 150	<i>I. paucus</i> , lower jaw, position 1 or 2	<i>I. oxyrinchus</i> , lower jaw, position 1
226	81	<i>I. oxyrinchus</i> , upper jaw, position 2	<i>I. oxyrinchus</i> , lower jaw, right side, position 3
227	164 and 174	<i>I. paucus</i> , lower jaw, position 4 through 7	<i>I. oxyrinchus</i> , lower jaw, position 5
228	78	<i>I. oxyrinchus</i> , upper jaw, position 1	<i>I. oxyrinchus</i> , upper jaw, position 1
229	199	<i>I. paucus</i> , upper jaw, right side, position 3	<i>I. oxyrinchus</i> , upper jaw, right side, position 3
230	144	<i>I. paucus</i> , upper jaw, position 1	<i>I. paucus</i> , lower jaw, position 5
231	45 and 217	<i>I. oxyrinchus</i> , lower jaw, position 4 through 7 or <i>I. paucus</i> , upper jaw, position 4 through 7	<i>I. paucus</i> , lower jaw, position 6
232	11	<i>I. oxyrinchus</i> , lower jaw, position 2	<i>I. paucus</i> , upper jaw, position 2
233	107 and 209	<i>I. oxyrinchus</i> , upper jaw, position 4 through 7 or <i>I. paucus</i> , upper jaw, position 4 through 7	<i>I. paucus</i> , upper jaw, position 4
234	106	<i>I. oxyrinchus</i> , upper jaw, positions 4 through 7	<i>I. paucus</i> , upper jaw, position 6
235	72	<i>I. oxyrinchus</i> , upper jaw, position 1	<i>I. paucus</i> , upper jaw, position 1

composed of a pair of known teeth, it was assigned the identity of both known specimens. If the known specimens belonged to different species, tooth position, or jaw, the unknown tooth was still given the identity "A or B" (e.g. "*I. paucus*, upper jaw, position 1 or 2"). Species was correctly assigned 39.2% of the time, tooth position was assigned correctly 68% of the time, and assignment to the upper or lower jaw was correct 64.3% of the time. Overall, positions 4 through 7 were assigned correctly to all categories more often than 1 through 3. This may be due to the fact that there were more data for this group than for the others. *I. oxyrinchus* was correctly assigned to species and upper or lower jaw more often than *I. paucus*. Again, this may be due to the fact that there are more *I. oxyrinchus* specimens than *I. paucus*. However, *I. paucus* was more often assigned to the correct tooth position than *I. oxyrinchus*. If the graphs of the Procrustes shape coordinates are compared, the data points of *I. oxyrinchus* are clustered more tightly than those of *I. paucus* (Figures 25 through 28). This implies that the differences in morphology for *I. paucus* are more pronounced than *I. oxyrinchus*, increasing the chance that a tooth of known species and tooth position will have a shape similar to another tooth of the same species and position.

Analysis of I. hastalis

Procrustes shape coordinates of 27 *I. hastalis* teeth were compared to the means of the Procrustes shape coordinates of the extant species and analyzed using principle components analysis (Figure 34). The principle components graph

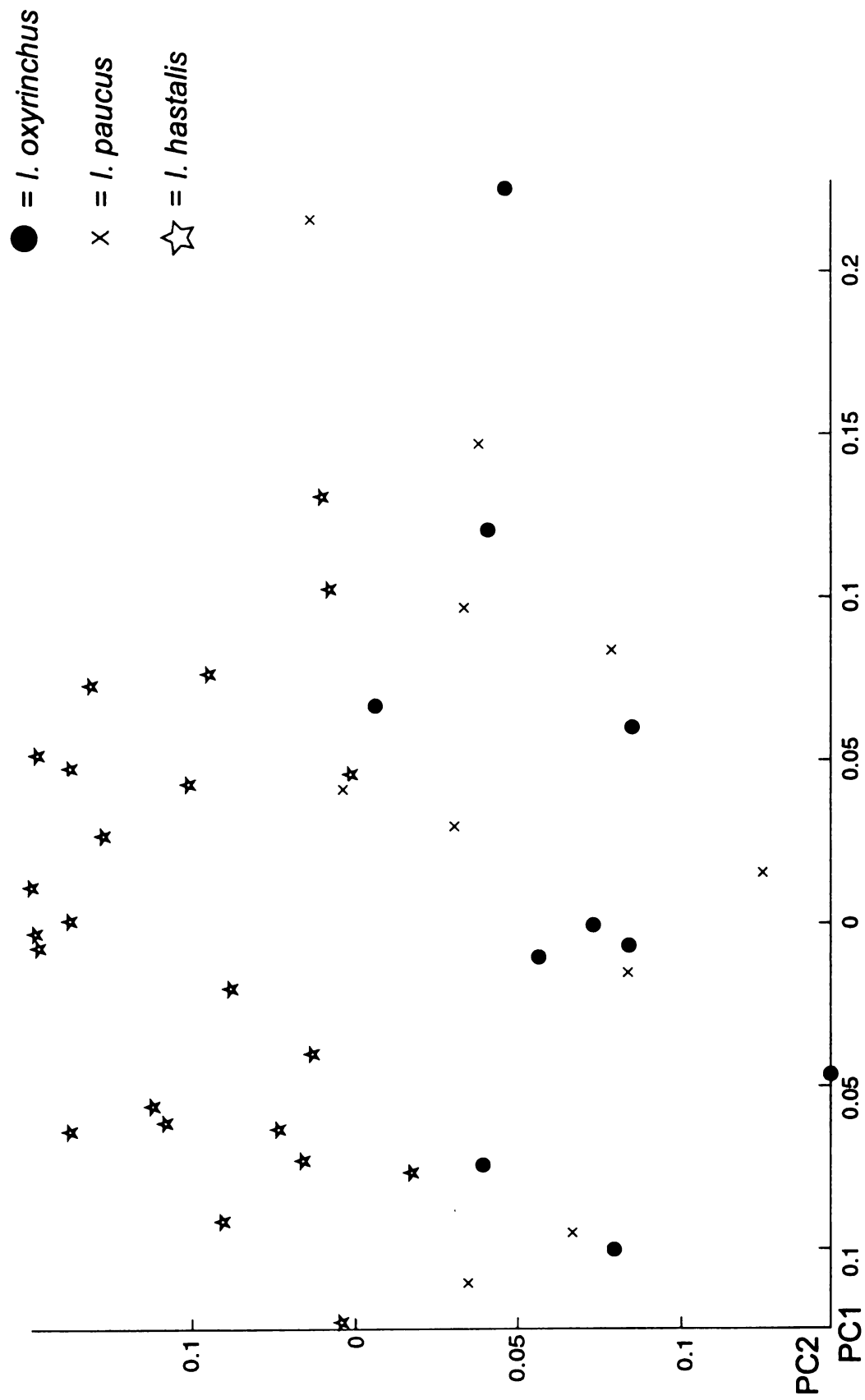


Figure 34 - Principle components for *I. hastalis*, *I. oxyrinchus* (mean values), and *I. paucus* (mean values).

shows that the data points for *I. hastalis* cluster separately from the two extant species, indicating that it is a separate species. When comparing the Procrustes shape coordinate graph of *I. hastalis* to that of the extant species, the shapes of the clusters are different (Figures 25 through 28, 35). For example, when looking at the cluster for landmark A (the apex of the cusp), the clusters for the extant species are elongate and curved, whereas the cluster for *I. hastalis* is not. The tooth positions for the extant species form a distinct pattern, while *I. hastalis* does not show the same pattern. Therefore, the pattern of the data points cannot be used to assign tooth position to *I. hastalis*.

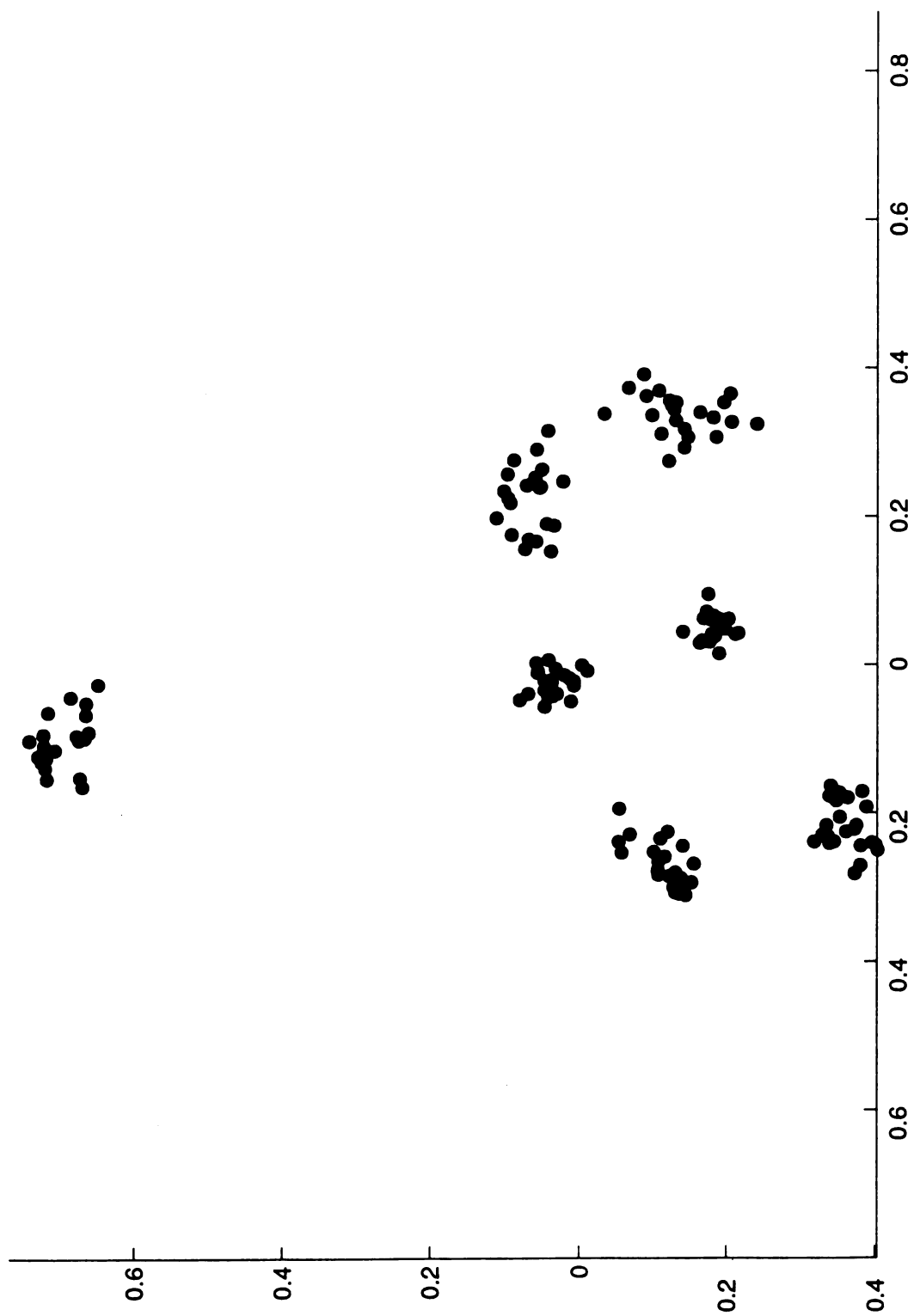


Figure 35 - Procrustes shape coordinates for *I. hastalis*.

CONCLUSIONS

The use of geometric morphometrics was successful for analyzing some aspects of tooth morphology of the extant Mako species. While tooth positions one through three have the most distinct morphology, positions 4 through 7 were correctly identified more often. As mentioned previously, this is likely due to the number of specimens in each group of jaw positions. If every tooth photographed was used, the group composed of positions 4, 5, 6, and 7 ideally would have four times as many specimens as the group that is only composed of position 1. The addition of more specimens may even the gap out and result in more correct assignments. A greater number of unbroken teeth could be added to the analysis.

The methods used were also fairly successful in differentiating between the extant species and *I. hastalis*. This has implications for future studies of fossil Makos and other fossil sharks. As mentioned in the Introduction, some current fossil species of *Isurus* are questionable (*I. retroflexus* and *I. deson*). It is not clear if these species are junior synonyms of the extant taxa, or are separate species. This method may be appropriate for comparing the fossil species to the two extant species to determine if there is enough morphological difference to warrant separate designations.

The morphometric analyses used in this study did have one shortcoming: they were not able to distinguish *I. paucus* and *I. oxyrinchus*. The addition of more specimens, especially to the *I. paucus* data set, may remedy this. It is possible that some specimens sampled may actually display abnormal morphologies, which would appear as outliers in a graph that included more specimens. However, it is also possible that none of the specimens represent outliers, and that the extant Makos cannot be distinguished based on tooth morphology alone. The addition of more specimens would likely resolve this issue.

In addition to answering some questions, this study has prompted new ones. Examining the tooth morphology of these sharks begs the question “why?” What about the function of these teeth causes asymmetry in the third tooth position, the similarity of teeth in jaw positions 4 through 7, and the distinct morphologies of positions 1, 2, and 3? Work has not been done on the feeding mechanics of Makos. A detailed analysis of feeding mechanics may not only answer the questions stated above, but may also give insight to tooth function of fossil Makos.

APPENDIX

**Bookstein Coordinates for
FMNH 83731**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	4	0.8219	1.1712	0.2192	0.2945	0.911	0.2877	0.589	0.3219	0.5274	0.1301
Lower left	5	0.8014	1.0274	0.2123	0.274	0.9521	0.2877	0.5685	0.2877	0.5548	0.089
Lower left	6	0.8014	1.3356	0.1301	0.3767	0.9726	0.4589	0.5753	0.4726	0.589	0.2123
Lower right	2	1.0822	1.9658	0.1438	0.4178	0.9863	0.4863	0.6507	0.6507	0.6027	0.4452
Lower right	3	0.9589	1.2192	0.2877	0.3219	0.9315	0.3699	0.637	0.3973	0.5548	0.2123
Lower right	4	0.8425	1.1575	0.3288	0.363	0.8904	0.3014	0.5753	0.363	0.5	0.137
Lower right	5	0.8904	1.0069	0.2055	0.2534	0.9932	0.274	0.589	0.3219	0.5616	0.089
Lower right	6	0.726	1.1438	0.226	0.3014	0.8082	0.3288	0.5068	0.363	0.5	0.1438
Upper left	1	1.1233	1.4795	0.1781	0.2671	0.9178	0.2466	0.5959	0.411	0.5753	0.2192
Upper left	4	0.9726	0.9384	0.3082	0.2329	0.9658	0.2534	0.6712	0.2808	0.5959	0.1438
Upper left	5	1	1.1301	0.226	0.3219	0.911	0.2808	0.5616	0.3288	0.5342	0.1644
Upper left	6	0.9726	1.1781	0.1849	0.2808	0.9658	0.2603	0.5616	0.3356	0.5548	0.1575
Upper left	7	0.8356	1.0959	0.137	0.274	0.9521	0.3219	0.5548	0.3425	0.5137	0.1438
Upper right	3	0.6712	1.3699	0.0822	0.4589	0.9521	0.3904	0.5274	0.5068	0.5616	0.3014
Upper right	5	0.9795	1.137	0.1986	0.2945	0.9863	0.2603	0.6027	0.2945	0.5753	0.0822
Upper right	6	0.8904	1.1644	0.1918	0.2603	0.9315	0.274	0.5616	0.3151	0.5548	0.1712
Upper right	7	0.8493	1.2123	0.1164	0.3014	0.9247	0.3356	0.5548	0.3767	0.589	0.1438

**Bookstein Coordinates for
SUL 92014**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.6712	2.5822	0.0685	0.774	0.9658	0.774	0.5274	0.9247	0.5411	0.6918
Lower left	2	1.137	1.9863	0.4863	0.8219	0.8699	0.774	0.7123	0.8425	0.6233	0.4521
Lower left	4	0.7192	1.274	0.1301	0.3014	1.0069	0.3699	0.5411	0.3767	0.5479	0.089
Lower left	5	0.7123	1.2192	0.2397	0.3014	0.9178	0.3562	0.5479	0.2808	0.5342	0.0959
Lower right	1	0.5274	2.0343	0.1507	0.8904	0.7329	0.8219	0.4384	0.8425	0.4521	0.4658
Lower right	2	1.0069	1.774	0.1644	0.411	0.9795	0.3425	0.637	0.6096	0.5685	0.3904
Lower right	3	0.9247	1.3562	0.2055	0.363	0.9384	0.3836	0.5822	0.4178	0.5205	0.1644
Lower right	5	0.637	1.1918	0.2671	0.4247	0.8767	0.411	0.6027	0.4247	0.5822	0.1027
Lower right	6	0.726	1.2466	0.2397	0.3219	1.0206	0.3562	0.5822	0.363	0.5479	0.0959
Upper left	1	1.1438	1.4521	0.3014	0.4041	0.8219	0.4041	0.5411	0.4452	0.5274	0.1096
Upper left	2	1.1301	1.3493	0.2192	0.3082	0.9178	0.2192	0.4932	0.3836	0.4795	0.1575
Upper left	3	0.9658	1.2534	0.2055	0.5822	0.9384	0.4589	0.5205	0.5548	0.5137	0.2808
Upper left	5	0.8904	1.2055	0.1644	0.2466	0.9178	0.2123	0.5959	0.3493	0.5137	0.1575
Upper left	6	0.863	1.2808	0.2671	0.3699	0.8904	0.2808	0.5616	0.363	0.5137	0.1575
Upper right	1	1.1438	1.774	0.1164	0.1301	0.8904	0.2055	0.5479	0.3699	0.5137	0.1986
Upper right	4	0.9521	1	0.2123	0.2397	0.9384	0.137	0.5959	0.2808	0.589	0.1507
Upper right	7	0.7877	1.1781	0.1918	0.2808	0.8767	0.2877	0.589	0.2945	0.5479	0.0753

**Bookstein Coordinates for
UMH 9202**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.6918	2.1575	0.1849	0.7123	0.7603	0.589	0.5	0.8288	0.5479	0.5959
Lower left	6	0.8288	1.3014	0.1164	0.3562	1.1027	0.2877	0.6	0.4315	0.5959	0.2192
Lower right	1	0.1986	2.363	-0.014	0.5548	0.9452	0.6027	0.4	0.8493	0.4521	0.7397
Lower right	2	0.863	1.6986	0.1164	0.3288	0.9384	0.3699	0.6	0.5411	0.5753	0.3425
Lower right	4	0.6507	0.9384	0.1301	0.4247	0.911	0.2466	0.5	0.2671	0.4863	0.0753
Lower right	5	0.6986	1.1438	0.1438	0.2397	1.0548	0.2671	0.6	0.3767	0.5068	0.2055
Lower right	6	0.6301	1.2945	-0.027	0.3767	1	0.4932	0.5	0.4726	0.5068	0.1986
Upper left	1	1.1164	1.9178	0.1301	0.3836	0.8767	0.3219	0.5	0.4521	0.5	0.2466
Upper left	2	1.0685	1.274	0.2123	0.2945	0.8493	0.3356	0.6	0.3014	0.5274	0.2123
Upper left	7	0.8562	1.2466	0.1096	0.3836	0.9521	0.3288	0.5	0.411	0.5137	0.1781
Upper right	4	1.0616	0.7671	0.3288	0.2123	0.9726	0.1849	0.7	0.1849	0.6301	0.0959
Upper right	5	0.9452	0.9384	0.2397	0.1644	1.0137	0.226	0.6	0.2671	0.5959	0.0822

**Bookstein Coordinates for
UMH STRANDING**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.3973	1.9863	0.1438	0.5137	0.7808	0.6233	0.4726	0.726	0.4658	0.4521
Lower left	3	0.9589	1.3767	0.1849	0.411	1.0411	0.3151	0.637	0.5274	0.5411	0.2603
Lower left	4	0.7671	1.089	0.2671	0.3562	0.9041	0.3151	0.5685	0.3699	0.5342	0.1781
Lower left	5	0.7603	1.3014	0.2329	0.4726	0.911	0.4521	0.5685	0.4315	0.5616	0.274
Lower left	6	0.7466	1.1849	0.1301	0.3836	0.8219	0.4452	0.4795	0.3836	0.4658	0.1164
Lower left	7	0.6096	1.3151	0.0205	0.3836	0.9521	0.3767	0.5205	0.4247	0.1849	0.1438
Lower right	2	0.9041	1.7055	0.2329	0.4863	0.8904	0.4726	0.5822	0.6027	0.5616	0.4178
Lower right	4	0.8767	1.1849	0.2397	0.411	0.9589	0.3767	0.6301	0.4041	0.5411	0.1781
Upper left	1	0.8425	1.3973	0.2055	0.2397	0.8219	0.3288	0.5479	0.4384	0.5616	0.3014
Upper left	2	1.048	1.1918	0.3288	0.3356	0.8219	0.274	0.6233	0.3767	0.5685	0.1849
Upper left	3	0.8562	1.1712	0.1849	0.4247	0.9384	0.4315	0.5479	0.4726	0.5068	0.2466
Upper left	5	1.0411	1.2877	0.2534	0.3493	0.9726	0.3493	0.6096	0.3836	0.5616	0.1918
Upper left	6	0.9658	1.1849	0.2329	0.3562	0.9178	0.3219	0.5822	0.363	0.5685	0.1644
Upper left	7	0.8219	1.1507	0.2397	0.4178	0.9247	0.411	0.589	0.411	0.5753	0.1781
Upper right	2	1.1438	1.2945	0.4521	0.5548	0.911	0.4795	0.6644	0.5	0.5753	0.2808
Upper right	3	1.0548	0.9658	0.2945	0.3836	0.9521	0.3014	0.6438	0.4315	0.6644	0.226
Upper right	4	1.0959	1.0411	0.3493	0.3836	0.8904	0.3082	0.6301	0.3767	0.5616	0.1712

**Bookstein Coordinates for
WIN 93001**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.5822	2.1096	0.089	0.363	0.9452	0.3288	0.5068	0.6575	0.5137	0.5
Lower left	3	1.089	1.2192	0.2808	0.3288	1.0274	0.2466	0.6575	0.363	0.5822	0.2123
Lower left	6	0.7329	1.1575	0.1233	0.2877	0.9521	0.3562	0.5137	0.3219	0.5068	0.1644
Lower right	1	0.1986	2.363	-0.014	0.5548	0.9452	0.6027	0.4247	0.8493	0.4521	0.7397
Lower right	2	0.863	1.6986	0.1164	0.3288	0.9384	0.3699	0.6164	0.5411	0.5753	0.3425
Lower right	4	0.6507	0.9384	0.1301	0.4247	0.911	0.2466	0.5	0.2671	0.4863	0.0753
Lower right	6	0.6096	1.3151	0.0205	0.3836	0.9521	0.3767	0.5205	0.4247	0.1849	0.1438
Upper left	1	1.1164	1.9178	0.1301	0.3836	0.8767	0.3219	0.5342	0.4521	0.5	0.2466
Upper left	2	1.0685	1.274	0.2123	0.2945	0.8493	0.3356	0.5616	0.3014	0.5274	0.2123
Upper left	3	0.8904	1.2945	0.1301	0.4384	0.9932	0.4521	0.5753	0.4589	0.5548	0.2397
Upper left	4	1.0069	1	0.1781	0.2466	0.9795	0.226	0.5616	0.2397	0.5411	0.1096
Upper left	5	0.9315	1.1301	0.1712	0.3014	0.911	0.2945	0.5342	0.2945	0.4932	0.0822
Upper left	6	0.9247	1.1575	0.1438	0.2192	0.9863	0.2671	0.5616	0.3151	0.5479	0.1644
Upper left	7	0.8151	1.1986	0.1918	0.3836	0.9726	0.3425	0.589	0.363	0.5205	0.1644
Upper right	1	1.1027	1.637	0.1438	0.3356	0.9178	0.3288	0.5616	0.4315	0.5548	0.2534
Upper right	2	1.1986	1.1781	0.226	0.2808	0.3082	0.274	0.6644	0.363	0.6027	0.1096
Upper right	4	1.137	1.226	0.1918	0.3356	1.0274	0.363	0.6781	0.2808	0.6301	0.1575
Upper right	5	0.9384	0.9863	0.1712	0.1849	0.9521	0.2123	0.5753	0.2397	0.5616	0.0822
Upper right	6	0.911	1.1096	0.2055	0.2877	0.9726	0.2534	0.5411	0.274	0.5342	0.137
Upper right	7	0.8288	1.0548	0.1301	0.2808	0.9863	0.3014	0.5342	0.3425	0.5274	0.1918

**Bookstein Coordinates for
USNM 110881**

Specimen number	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
222	1.1329	1.4476	0.0629	0.2308	0.9441	0.2867	0.5804	0.4266	0.5524	0.1958
223	1.0909	1.0699	0.3077	0.3357	1.035	0.2238	0.6923	0.3217	0.5874	0.1538
224	0.8112	1.2448	0.1049	0.2727	0.972	0.3147	0.5315	0.4056	0.5035	0.1888
225	0.5734	2.3776	0.0699	0.5175	0.9091	0.5035	0.5035	0.7762	0.4965	0.6084
226	1.2448	1.3706	0.3147	0.5105	1.0909	0.3916	0.7133	0.4825	0.6224	0.2657
227	0.7483	1.2587	0.0839	0.4126	1.007	0.3776	0.5105	0.3846	0.4755	0.1538
228	0.9091	1.6713	0.1469	0.2727	0.9371	0.2448	0.5245	0.4196	0.5315	0.2657
229	0.8881	1.5385	0.0629	0.6923	0.972	0.6084	0.5175	0.5594	0.5175	0.3846

**Bookstein Coordinates for
USNM 110948**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	5	0.8425	1.205	0.1438	0.3151	0.9863	0.3082	0.5616	0.3356	0.5548	0.1164
Lower left	6	0.7534	1.199	0.1575	0.3836	0.8767	0.4247	0.5342	0.3699	0.5342	0.137
Lower left	7	0.7603	1.5	0.089	0.6096	0.9726	0.5753	0.5137	0.5068	0.4726	0.226
Lower right	3	1.1164	1.322	0.2534	0.3425	1.0206	0.3151	0.6027	0.4521	0.6164	0.137
Lower right	4	0.7534	1.295	0.1644	0.274	1.0822	0.3425	0.5616	0.2808	0.5548	0.1575
Lower right	5	0.774	1.055	0.1644	0.1849	0.9658	0.3356	0.5616	0.3288	0.5274	0.089
Lower right	6	0.7329	1.075	0.1507	0.4178	0.9795	0.411	0.5274	0.363	0.5274	0.089
Lower right	7	0.6644	1.247	-0.082	0.4452	0.9863	0.4384	0.4795	0.4178	0.4658	0.1507

**Bookstein Coordinates for
USNM 263282**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.5753	2.2671	0.0616	0.6507	0.8836	0.7329	0.4589	0.9041	0.4932	0.6849
Lower left	4	0.637	1.0959	0.0137	0.3288	0.9658	0.411	0.5342	0.3699	0.5068	0.1164
Lower left	5	0.6301	1.1918	0.0411	0.3219	0.9795	0.4658	0.5548	0.4452	0.5205	0.1507
Lower left	6	0.6849	1.274	0.0548	0.3973	1	0.3904	0.5411	0.4247	0.5274	0.1027
Lower right	1	0.6781	2.1164	0.1164	0.5342	0.9521	0.4795	0.5	0.8288	0.5205	0.5
Lower right	2	1.2671	1.8082	0.2603	0.3425	1.1233	0.2945	0.7534	0.5548	0.6849	0.2603
Lower right	3	1.0822	0.9658	0.4247	0.4178	1.048	0.3973	0.7671	0.4521	0.6644	0.1575
Lower right	6	0.726	1.137	0.2192	0.3219	0.9384	0.4589	0.6027	0.3973	0.5137	0.1164
Lower right	7	0.6712	1.2945	0.0411	0.3356	1.0137	0.3767	0.5205	0.4589	0.5068	0.1507
Upper left	2	0.9384	1.3767	0.1507	0.226	0.9247	0.226	0.5548	0.3288	1.1781	0.1918
Upper left	4	1.0137	1.1301	0.2534	0.3836	0.9178	0.3699	0.6301	0.3973	0.5685	0.1507
Upper left	5	0.9795	1.1575	0.1986	0.2534	0.9589	0.2123	0.6027	0.3288	0.5274	0.1438
Upper left	7	0.863	1.0069	0.2534	0.2466	0.8493	0.2603	0.5411	0.3151	0.5274	0.1438
Upper right	1	0.9452	1.5685	0.2055	0.3014	0.8767	0.226	0.5685	0.3904	0.5137	0.1507
Upper right	2	0.9932	1.3219	0.2055	0.3562	0.9384	0.2603	0.6164	0.4247	0.5411	0.2055
Upper right	3	0.637	1.1849	0.3562	0.3699	0.8493	0.4247	0.4521	0.4932	0.5	0.2329
Upper right	4	1	1.1507	0.2603	0.3151	0.9521	0.2466	0.5822	0.3836	0.5274	0.1507
Upper right	5	1.0206	1.1781	0.1986	0.3014	1	0.2397	0.6096	0.3836	0.5274	0.1712

**Bookstein Coordinates for
USNM Teaching Collection**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.5685	2.0548	0.1712	0.637	0.8014	0.6438	0.4658	0.6781	0.5137	0.3836
Lower left	2	0.7808	1.6027	0.3014	0.4658	0.8425	0.4658	0.5753	0.5411	0.5685	0.2808
Lower left	3	0.8562	1.363	0.2055	0.2945	1.0274	0.2466	0.5822	0.3014	0.5616	0.1918
Lower left	4	0.7534	1.1507	0.1781	0.3014	1.0137	0.2123	0.5548	0.2603	0.5137	0.1233
Lower left	5	0.6164	1.2329	-0.014	0.1986	1.0137	0.2671	0.5068	0.2466	0.4932	0.1164
Lower right	1	0.4384	2.2671	0.1438	0.6918	0.7945	0.6986	0.4589	0.6644	0.4521	0.4658
Lower right	2	0.7808	1.589	0.2534	0.411	0.8699	0.4315	0.5753	0.4863	0.5616	0.2466
Upper left	1	0.8151	1.7534	0.0685	0.2329	0.9658	0.2192	0.4726	0.3904	0.4863	0.2466
Upper left	2	0.9863	1.4178	0.1507	0.274	0.9726	0.1849	0.5753	0.2808	0.5479	0.1438
Upper left	3	0.8288	1.411	0.1438	0.4658	0.9041	0.5137	0.5205	0.5137	0.5205	0.3014
Upper left	6	0.9384	1.2945	0.1644	0.2808	0.8767	0.3356	0.5274	0.3014	0.5274	0.1233
Upper right	2	0.9384	1.2945	0.274	0.3288	0.8562	0.3014	0.5753	0.2808	0.5616	0.137
Upper right	4	0.9384	0.9178	0.137	0.1849	0.9178	0.1712	0.5342	0.2123	0.5205	0.089

**Bookstein Coordinates for
CASTRO**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.3562	2.089	0.0753	0.3699	0.8014	0.4384	0.4315	0.5822	0.4521	0.4247
Lower left	2	1.2671	1.7192	0.1712	0.3356	0.9521	0.3425	0.6096	0.5068	0.589	0.3493
Lower left	4	0.7397	1.1986	0.1781	0.2808	0.863	0.2808	0.5068	0.3288	0.5137	0.1712
Lower left	5	0.7534	1.137	0.1301	0.2329	0.8836	0.274	0.5205	0.2945	0.5205	0.1233
Lower left	6	0.774	1.1918	0.0411	0.2877	0.9726	0.3288	0.5	0.3699	0.4932	0.1644
Lower right	1	0.589	2.0822	0.089	0.3904	0.8836	0.4178	0.4726	0.6301	0.4863	0.4247
Lower right	2	0.9041	1.6233	0.2192	0.3699	0.9589	0.3082	0.6301	0.5137	0.5822	0.3082
Lower right	3	0.8014	1.3767	0.2192	0.3014	1.0274	0.5548	0.6233	0.411	0.5753	0.2877
Lower right	4	0.8836	1.1849	0.3219	0.3493	1.0069	0.2603	0.637	0.363	0.589	0.1781
Upper left	1	1.1027	1.4589	0.274	0.4041	0.8014	0.2877	0.5616	0.4178	0.5274	0.1507
Upper left	2	1.0548	1.4384	0.3425	0.411	0.911	0.3562	0.6438	0.3288	0.637	0.2603
Upper left	5	1.1644	1.2192	0.1644	0.3014	0.9589	0.226	0.5411	0.3767	0.4384	0.089
Upper left	6	0.9658	1.0274	0.226	0.2808	0.9384	0.2603	0.5685	0.3082	0.5205	0.1507
Upper left	7	1.0411	0.9658	0.1233	0.2397	0.911	0.2397	0.5411	0.4041	0.5274	0.1849
Upper right	1	0.8151	1.6781	0.0753	0.3082	0.9315	0.363	0.4658	0.4658	0.4726	0.2603
Upper right	2	0.9589	1.2877	0.1712	0.3014	0.911	0.2466	0.5685	0.3425	0.5205	0.1918
Upper right	4	1.137	0.9658	0.1164	0.1644	0.9521	0.1575	0.5411	0.2329	0.5342	0.1438
Upper right	6	0.8973	1.0959	0.1096	0.2534	0.8973	0.3014	0.4932	0.3562	0.4932	0.1986
Upper right	7	1.0274	0.9315	0.0959	0.2055	0.9384	0.1849	0.5205	0.3082	0.5068	0.1644

**Bookstein Coordinates for
ISUR-2-13**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.7945	2.6575	0.137	0.6644	0.9589	0.6918	0.5753	0.9041	0.5753	0.6781
Lower left	4	0.7397	1.1918	0.0959	0.4178	0.9726	0.4384	0.5342	0.4041	0.5342	0.1918
Lower left	5	0.6575	1.1301	0.0479	0.3356	0.9452	0.4178	0.5137	0.363	0.5274	0.137
Lower left	6	0.6918	1.1233	0	0.411	1.0206	0.3973	0.5411	0.3836	0.5342	0.1575
Lower left	7	0.8356	1.0959	0.0342	0.4521	0.9795	0.4315	0.5411	0.363	0.5548	0.1438
Lower right	2	1.0411	2.1644	0.2671	0.7192	1	0.6164	0.6301	0.7329	0.6233	0.5342
Lower right	5	0.7055	0.9863	0.0753	0.3288	0.9863	0.2671	0.5411	0.3288	0.5411	0.1027
Lower right	6	0.774	1	0.0411	0.3151	0.9041	0.274	0.5411	0.3493	0.5548	0.0959
Upper left	1	0.9795	1.637	0.3014	0.5342	0.8562	0.4315	0.5822	0.5274	0.5959	0.2877
Upper left	3	0.7808	1.3014	0.0548	0.5274	0.9384	0.4384	0.5	0.5137	0.4726	0.2945
Upper left	4	1.048	0.863	0.2329	0.2671	0.6164	0.1781	0.5959	0.274	0.5342	0.0959
Upper left	5	1.0685	0.9658	0.3151	0.3562	0.9315	0.2603	0.6233	0.2877	0.5753	0.1164
Upper left	6	0.863	1.0753	0.2534	0.3493	0.9452	0.2534	0.5959	0.3356	0.5548	0.1438
Upper right	3	0.7192	1.3836	0.1301	0.4863	0.8836	0.5342	0.4658	0.5205	0.4863	0.3082
Upper right	4	0.9315	0.9384	0.2329	0.2671	0.7877	0.2603	0.5753	0.274	0.5342	0.1507
Upper right	5	0.9795	1.048	0.2945	0.274	0.8836	0.2603	0.5753	0.2808	0.5548	0.1027

**Bookstein Coordinates for
LONG 1786**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.411	2.2466	0.0068	0.3767	0.9247	0.3699	0.4658	0.6575	0.4658	0.5274
Lower left	3	0.7945	1.637	0.1507	0.3425	0.9521	0.3699	0.5685	0.4726	0.5616	0.2945
Lower left	4	0.7603	1.363	0.0205	0.4041	0.9863	0.3699	0.4795	0.4452	0.5068	0.1849
Lower left	6	0.7466	1.1849	0.1507	0.4863	0.8288	0.4795	0.4795	0.4452	0.5	0.1575
Lower left	7	0.589	1.2603	0.0822	0.5205	0.8904	0.5342	0.4863	0.4932	0.4932	0.1781
Lower right	1	0.3219	2.2466	0.0205	0.3356	0.9041	0.3562	0.4178	0.6781	0.4589	0.5274
Lower right	2	0.8151	2.0616	0.3151	0.6438	0.8767	0.6164	0.637	0.6027	0.589	0.5
Lower right	3	0.8288	1.6918	0.2945	0.5685	0.9863	0.5548	0.637	0.5616	0.6233	0.2877
Lower right	4	0.8014	1.3562	0.1781	0.4863	0.8836	0.4795	0.5	0.4795	0.4863	0.1712
Lower right	5	0.8425	1.2466	0.2671	0.4589	0.9932	0.4315	0.5685	0.4247	0.5685	0.1438
Upper left	1	0.7671	1.6712	0.226	0.5068	0.7603	0.4726	0.4863	0.5342	0.5137	0.2808
Upper left	3	0.7397	1.4041	0.1986	0.6164	0.9041	0.6027	0.5411	0.3699	0.5411	0.363
Upper left	4	0.9247	1.0548	0.2671	0.4247	0.8904	0.3904	0.5959	0.3767	0.5822	0.1644
Upper right	2	0.9315	1.4384	0.274	0.4384	0.8288	0.3836	0.5753	0.411	0.5274	0.1918
Upper right	3	0.7329	1.5206	0.1507	0.6712	0.8973	0.6849	0.5274	0.6918	0.5479	0.411
Upper right	5	0.9589	1.1918	0.1986	0.3973	0.863	0.3493	0.5274	0.3767	0.5274	0.1164
Upper right	6	0.9521	1.3219	0.2397	0.4658	0.8151	0.4521	0.5616	0.4795	0.5205	0.1712
Upper right	7	0.9521	1.1575	0.1164	0.4452	0.8904	0.4247	0.4384	0.4247	0.5479	0.1781

**Bookstein Coordinates for
Long 5599**

Specimen number	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
229	0.8881	1.5385	0.0629	0.6923	0.972	0.6084	0.5175	0.5594	0.5175	0.3846
230	0.7832	1.1818	0.9441	0.3916	0.9091	0.3986	0.5664	0.3706	0.5315	0.1469
231	0.7063	1.1818	0.2308	0.3986	0.9161	0.3706	0.4895	0.3636	0.4615	0.1259
232	1.1539	2.3846	0.4266	0.6923	0.8741	0.6993	0.6504	0.8042	0.6224	0.5315
233	1.028	1.1049	0.2308	0.3357	0.9371	0.2937	0.5944	0.3147	0.5594	0.1259
234	0.9091	1.1958	0.1748	0.3217	0.9091	0.3077	0.5524	0.3217	0.5175	0.1119
235	1.1259	2.028	0.1748	0.4755	0.9161	0.3986	0.5455	0.5804	0.5035	0.3357

**Bookstein Coordinates for
OXY CASTS**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	1	0.4452	2.5822	0.1233	0.7603	0.8288	0.7329	0.4795	0.8219	0.4589	0.6507
Lower left	3	1.274	1.3973	0.5274	0.5	1.137	0.3151	0.7945	0.4658	0.7123	0.3151
Lower left	4	0.7603	1.2397	0.1781	0.3562	0.9452	0.3767	0.5479	0.363	0.5548	0.1575
Lower left	5	0.7397	1.2534	0.1644	0.4178	0.9384	0.4041	0.5616	0.3562	0.5822	0.1849
Lower left	6	0.8014	1.1438	0.1712	0.3904	1	0.3973	0.5685	0.3562	0.5685	0.1096
Lower left	7	0.7808	1.137	0.1164	0.411	0.3493	0.3425	0.5479	0.4041	0.5068	0.1507
Lower right	1	0.5274	2.2603	0.0685	0.8151	0.7603	0.7945	0.4178	0.8973	0.4795	0.637
Lower right	2	1.089	1.6986	0.3699	0.5342	1.0069	0.5068	0.7192	0.5959	0.6849	0.3767
Lower right	4	0.7534	1.3836	0.1438	0.274	0.9863	0.3288	0.5959	0.3767	0.5685	0.2192
Lower right	5	0.8425	1.2603	0.0548	0.3082	1.0685	0.3082	0.5753	0.3904	0.5753	0.1712
Lower right	6	0.8219	1.2123	0.1164	0.3973	0.9589	0.4521	0.5822	0.4384	0.5685	0.137
Lower right	7	0.7534	1.2534	0.0616	0.3425	1.137	0.3151	0.5616	0.3904	0.5685	0.1644
Upper left	1	0.9863	1.5137	0.2055	0.4247	0.5	0.4589	0.5068	0.4589	0.5274	0.2466
Upper left	2	1.2055	1.3425	0.2877	0.4589	1.089	0.363	0.6233	0.4452	0.6027	0.2329
Upper left	3	1.0548	1.2603	0.137	0.5959	1.0616	0.5068	0.5822	0.5616	0.5753	0.3356
Upper left	4	1.0343	0.9658	0.3836	0.3904	0.9315	0.9795	0.6438	0.3014	0.5959	0.1301
Upper left	5	0.9452	1.0548	0.2603	0.3288	0.9178	0.2808	0.5822	0.2877	0.589	0.137
Upper left	6	1.0069	1.2671	0.2123	0.4178	0.9521	0.4315	0.6164	0.4178	0.589	0.1781
Upper left	7	0.9863	1.1164	0.2603	0.4384	0.911	0.3973	0.5753	0.3767	0.5616	0.137
Upper right	1	1.1644	1.8425	0.2808	0.5685	0.8767	0.411	0.5753	0.5274	0.5548	0.3356
Upper right	2	1.1781	1.274	0.2397	0.3767	0.911	0.2671	0.6164	0.3904	0.5753	0.1986
Upper right	3	0.8151	1.2123	0.1164	0.4658	0.911	0.5274	0.4795	0.5616	0.4863	0.3219
Upper right	4	0.9863	0.9658	0.2534	0.2808	0.8904	0.1918	0.6096	0.3493	0.5685	0.1918

Coordinates for OXY CASTS continued

Upper right	5	1.0343	1.0206	0.3014	0.3836	0.8973	0.3151	0.6027	0.3219	0.5685	0.1507
Upper right	6	1.0206	1.2329	0.1918	0.4521	0.8836	0.4247	0.5616	0.4247	0.5205	0.2123

**Bookstein Coordinates for
PAUC COMP**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	3	1.0548	1.548	0.0068	0.6438	1.1233	0.5822	0.6781	0.6027	0.6164	0.3562
Lower left	4	0.774	1.1027	0.1918	0.4247	1.0206	0.3425	0.5342	0.3699	0.5274	0.1507
Lower left	5	0.7192	1.1301	0.0479	0.363	0.9041	0.4589	0.5137	0.4041	0.4932	0.1507
Lower left	6	0.7123	1.1986	0.0616	0.4384	1.0069	0.3082	0.5479	0.3699	0.5274	0.0959
Lower left	7	0.7808	1.0548	0.0205	0.4658	0.8836	0.4247	0.5137	0.411	0.4863	0.1027
Lower right	2	1.089	2.3699	0.1507	0.5685	1	0.637	0.6027	0.7123	0.5753	0.5548
Lower right	3	0.8767	1.6164	0.2466	0.5753	0.9932	0.5959	0.6164	0.5753	0.6096	0.3425
Lower right	5	0.7055	1.0959	0.0959	0.3904	1.0274	0.3288	0.5274	0.3356	0.5137	0.1233
Lower right	6	0.7603	1.137	0.0411	0.4452	0.9658	0.411	0.5342	0.4041	0.5342	0.137
Lower right	7	0.7192	0.9932	-0.027	0.411	1.0411	0.3219	0.5274	0.363	0.5068	0.1027
Upper left	1	0.863	1.589	0.2123	0.3836	0.8425	0.4589	0.5274	0.4315	0.5616	0.3151
Upper left	2	0.9452	1.4589	0.2329	0.4452	0.9384	0.4041	0.589	0.4247	0.589	0.2603
Upper left	3	0.774	1.5137	-0.089	0.4315	1.1096	0.411	0.4932	0.6164	0.5	0.3562
Upper left	6	0.8904	1.1575	0.2534	0.411	0.9315	0.3904	0.5959	0.3493	0.5753	0.137
Upper left	7	0.8219	1.1027	0.2808	0.2808	0.9178	0.3425	0.5479	0.3082	0.5342	0.1233
Upper right	1	0.8973	1.6918	0.2945	0.5137	0.863	0.4589	0.5753	0.4589	0.5411	0.3014
Upper right	2	0.9521	1.4178	0.226	0.4452	0.9041	0.3699	0.5959	0.411	0.5274	0.2329
Upper right	3	0.6507	1.4863	0.0137	0.6233	0.9178	0.637	0.4726	0.5753	0.4795	0.3699
Upper right	4	0.9658	0.9658	0.2808	0.2945	0.9041	0.3288	0.5959	0.2877	0.5411	0.1507
Upper right	5	0.9521	1.0411	0.2397	0.2945	0.911	0.2945	0.6096	0.3014	0.5753	0.137
Upper right	6	0.9452	1.0548	0.274	0.3699	0.9384	0.3356	0.589	0.3493	0.5479	0.1644
Upper right	7	0.8493	1.0274	0.226	0.363	0.7603	0.3014	0.5685	0.3425	0.5274	0.1438

**Bookstein Coordinates for
SHTFIN 11191**

Jaw	Position	A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
Lower left	6	0.863	1.2397	0.1575	0.4795	0.9658	0.4178	0.5548	0.4041	0.4795	0.1712
Lower left	7	0.8562	1.1781	0.1096	0.4384	0.9658	0.4247	0.5342	0.3699	0.5137	0.1712
Lower right	3	1.1233	1.3425	0.3219	0.411	0.9384	0.4384	0.6849	0.4384	0.6507	0.2808
Lower right	4	0.9521	1.2329	0.2466	0.4726	1.0206	0.411	0.5959	0.3973	0.5411	0.2123
Lower right	5	0.863	1.1712	0.1575	0.3288	0.9795	0.4178	0.5616	0.3699	0.5274	0.1644
Lower right	6	0.8493	1.2397	0.137	0.4041	0.9932	0.4041	0.5479	0.3904	0.5205	0.1438
Lower right	7	0.8699	1.2466	0.4315	0.4315	0.9726	0.4041	0.5205	0.3973	0.5205	0.1781
Upper left	5	1.0411	0.9452	0.3014	0.3767	0.9521	0.2808	0.5822	0.3014	0.4795	0.1438
Upper left	6	1.0685	1	0.2192	0.3288	0.9521	0.3151	0.5959	0.3014	0.5411	0.1644
Upper right	3	0.7329	1.3014	0.1164	0.4589	0.8904	0.5548	0.5	0.5068	0.5	0.3082
Upper right	5	1.048	0.8973	0.2671	0.3151	0.911	0.2534	0.5822	0.2534	0.5411	0.089
Upper right	6	1.0343	1	0.2055	0.274	0.8014	0.2808	0.5685	0.3356	0.5274	0.1781
Upper right	7	0.9932	0.9452	0.1233	0.2808	0.9452	0.2808	0.5548	0.3288	0.5274	0.137

**Bookstein Coordinates for
VPTC**

A(x)	A(y)	B(x)	B(y)	C(x)	C(y)	D(x)	D(y)	E(x)	E(y)
0.6504	1.8741	0.021	0.4406	0.958	0.4126	0.4615	0.6783	0.4266	0.1608
0.7902	1.6643	-0.021	0.3706	0.986	0.3706	0.5944	0.4895	0.5594	0.0839
0.7413	2.007	-0.049	0.5105	1.035	0.5105	0.4965	0.7063	0.4755	0.1189
0.7552	1.4336	0.014	0.3566	0.979	0.3916	0.5315	0.4545	0.5175	0.0699
0.8741	1.3147	0.0769	0.3776	0.9161	0.3636	0.5315	0.4476	0.5385	0.0909
1.2168	1.8462	0.0909	0.4406	0.979	0.4056	0.6154	0.4476	0.5734	0.0769
0.6154	1.8252	0.0559	0.5035	0.8112	0.5455	0.4615	0.5874	0.4545	0.1189
0.8392	1.4126	0.035	0.3077	1.028	0.2587	0.5245	0.4406	0.5175	0.049
0.8252	1.3287	0.1329	0.3357	0.972	0.3776	0.5874	0.4406	0.6294	0.0699
1.007	1.8532	-0.035	0.4825	1.0909	0.3916	0.5455	0.5874	0.5385	0.1119
0.986	1.1678	0.0979	0.3776	0.9021	0.3427	0.5385	0.4336	0.5175	0.042
0.9091	1.2168	0.1399	0.3916	0.8392	0.3566	0.5315	0.4126	0.5175	0.0839
0.7902	1.8322	0.3287	0.7552	0.8671	0.7133	0.6014	0.7762	0.5664	0.3566
0.8951	1.6154	0.1538	0.3706	0.8881	0.3427	0.5385	0.4406	0.5664	0.1119
0.5455	1.5594	0.028	0.3566	1.049	0.3427	0.5315	0.5035	0.4965	0.1119
0.7902	1.8741	0.1958	0.5734	0.8741	0.5804	0.5315	0.6504	0.5455	0.1748
0.6224	2.042	0.049	0.6504	0.9021	0.6014	0.5594	0.7273	0.5315	0.3357
1.0839	1.1888	0.1399	0.3566	0.9441	0.1818	0.5524	0.3566	0.5175	0.049
0.7622	1.4615	-0.014	0.3357	1.007	0.3636	0.5175	0.4126	0.4965	0.1119
0.8252	1.3427	0.1818	0.3706	0.9441	0.3706	0.5944	0.4126	0.5385	0.0699
0.8741	1.7483	0.0699	0.4336	1.042	0.3846	0.5734	0.4965	0.5245	0.1189
0.8671	1.5944	0.049	0.3007	1.028	0.2867	0.5734	0.3706	0.5175	0.0839
0.5804	1.6154	0.0909	0.5105	0.9301	0.4895	0.5245	0.5804	0.4895	0.2168
0.958	1.4126	0.0769	0.3986	0.7972	0.3217	0.5315	0.3986	0.5385	0.0839

REFERENCES

REFERENCES

- Becker, M.A.; Chamberlain, J.A.; Stoffer, P.W., 2000. Pathologic tooth deformities in modern and fossil chondrichthyans: a consequence of feeding-related injury. *Lethaia*, 133 (2): 103-118.
- Bookstein, F.L., 1991. *Morphometric Tools for Landmark Data*. Cambridge University Press, New York. 435 pp.
- Cappetta, H., 1987. *Chondrichthyes II, Mesozoic and Cenozoic Elasmobranchi*. Gustav Fisher Verlag, New York. 193 pp.
- Case, G.R., 1980. Selachian fauna from the Trent Formation, Lower Miocene (Aquitania) of eastern North Carolina, U.S.A. *Palaeontographica Abteilung A Palaeozoologie-Stratigraphie*, 171 (1-3): 75-103.
- Casier, E. 1943. Contributions à l'étude des poissons fossiles de la Belgique; IV, Observations sur la faune ichthyologique du landénien. *Bulletin du Musée royal d'histoire naturelle de Belgique*, 19 (36): 1-16.
- Cione, A.L. and Reguero, M., 1995. Extension of the range of hexanchid and isurid sharks in the Eocene of Antarctica and comments on the occurrence of hexanchids in recent waters of Argentina. *Ameghiniana*, 32 (2): 151-157.
- Cliff, G.; Dudley, S.F.J.; Davis, B., 1990. Sharks caught in the protective gill nets off Natal, South Africa, 3: the Shortfin Mako shark *Isurus oxyrinchus* (Rafinesque). *South African Journal of Marine Science*, 9: 115-126.
- Compagno, L.J.V., 1984. *Sharks of the World, FAO Fisheries Synopsis*, 125 (4) vol. 1: 249 pp.
- Compagno, L.J.V., 1988. *Sharks of the Order Carcharhiniformes*. Princeton University Press, Princeton. 486 pp.

- Correia, J.P., 1998. Tooth loss rate from two captive Sandtiger sharks (*Carcharias taurus*). *Zoo Biology*, 18 (4): 313-317.
- Gillespie, G.E. and Saunders, M.W., 1995. First verified record of the shortfin mako shark, *Isurus oxyrinchus*, and second records or range extensions for three additional species, from British Columbia waters. *Canadian Field Naturalist*, 108 (3): 347-350.
- Holthe, T., 1998. Shortfin Mako *Isurus oxyrinchus* caught in Northern Norway. *Fauna (Oslo)* 51 (3): 102.
- Karasawa, H., 1989. Late Cenozoic elasmobranchs from the Hokuriku District, central Japan. *Science Reports of Kanazawa University*, 34 (1): 1-57.
- Kent, B.W., 1994. *Fossil Sharks of the Chesapeake Bay Region*. Egan Rees & Boyer, Inc., Columbia. 146 pp.
- Killam, K. and Parsons, G., 1986. First record of the longfin mako, *Isurus paucus*, in the Gulf of Mexico. *United States Fish and Wildlife Service Fishery Bulletin*, 84 (3): 748-749.
- Leighton, L.R., and Maples, C.G., 2000. Determining utility of morphologically variable characters with an example from the strophomenide cardinal process. *The Geological Society of America Abstracts with Programs*. 32, 4: A-23.
- Leriche, M., 1905. Les poissons éocènes de la Belgique. *Mémoires du Musée royal d'histoire naturelle de Belgique*, 3: 49-228.
- Munoz, C.R., 1985. An analysis of pelagic shark catches in the northeastern Atlantic (15-40 degrees north). *Investigacion Pesquera*. 49 (1): 67-80.
- Naylor, G.P., and Marcus, L.F., 1994. Identifying isolated shark teeth of the genus *Carcharhinus* to species: relevance for tracking change through the fossil record. *American Museum Novitates*. 3109: 53 pp.

- Palmer, A.R., 1986. Inferring relative levels of genetic variability in fossils: the link between heterozygosity and fluctuating asymmetry. *Paleobiology*, 12, 1: 1-5.
- Peyer, B., 1968. *Comparative Odontology*. The University of Chicago Press, Chicago. 347 pp.
- Pratt, H.L. and Casey, J.G., 1983. Age and growth of the shortfin mako, *Isurus oxyrinchus*, using four methods. *Canadian Journal of Fisheries and Aquatic Sciences*, 40 (11): 1944-1957.
- Purdy, R., et al, in press. The Neogene sharks, rays, and bony fishes from Lee Creek Mine, Aurora, North Carolina. *Smithsonian Contributions to Paleobiology*.
- Sheets, D., 2001. CoordGen 6. Coordinate generating utility; also file translator to/from X1Y1, TPS file formats.
- Sheets, D., 2001. TwoGroup 6. Comparison of statistically significant differences in shape between two groups.
- Sheets, D., 2000. PCAGen 6. Principle components analysis based on partial warp scores; outputs partial warps scores and principle axis scores.
- Stevens, J.D. and Scott, M., 1995. First record of the longfin Mako (*Isurus paucus*) from Australian waters. *Memoirs of the Queensland Museum*, 38 (2): 670.
- Stillwell, C.E. and Kohler, N.E., 1982. Food, feeding habits, and estimates of daily ration of the shortfin mako (*Isurus oxyrinchus*) in the northwest Atlantic. *Canadian Journal of Fisheries and Aquatic Sciences*, 39 (3): 407-414.
- Uyneno, T.; Kondo, Y; Inoue, K., 1990. A nearly complete tooth set and several vertebrae of the lamnid shark *Isurus hastalis* from the Pliocene of Chiba, Japan. *Journal of the Natural History Museum and Institute Chiba*, 1: 15-20.

Uyeno, T.; Haswgawa, Y.; Kakuta, T., 1980. Some shark teeth from Miocene Ichishi Formation in Mie Prefecture, Japan. *Bulletin of the National Science Museum Series C (Geology and Paleontology)*: 6 (4): 125-128.

Warheit, K.I., 1992. The role of morphometrics and cladistics in the taxonomy of fossils: a paleornithological example. *Sytematic Biology*. 41, 3: 345-369.

MICHIGAN STATE UNIVERSITY LIBRARIES



3 1293 02112 3462