Describing morphological shape variations of the shell of *Terebralia sulcata* from Muduing Bay, Zamboanga Peninsula, using landmark-based geometric morphometric analysis

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Abstract. *Terebralia sulcata* is a brackish gastropod commonly collected by coastal people to be sold in the market and cooked as food. In this study, the changes in the morphological shape of *T. sulcata* from six different sampling locations in Muduing were identified using a landmark-based geometric-morphometric analysis. Twenty-three anatomical landmarks were used along the ventral and apertural sections of the shell. The body morphology of *T. sulcata* considerably differs across the six sample villages (Picanan, Boyugan Wests, Gusom, Bualan, Pamintayan, and Latas). A relative warp analysis revealed that the body length, breadth, and aperture of various populations varied. This study has shown how geometric morphometrics' relative warp analysis method can be used to characterize changes in the shell form. Variations in morphometry can result from various causes, such as environmental, ecological, genetic variants, plasticity, and evolutionary change.

Key Words: benthic, phenotypes, plasticity, morphometry.

Introduction. Gastropods are a group of animals that frequently display great morphological diversity (Morton 1963; Salvini-Plawén 1972, 1980, 1984, 1990; Salvini-Plawén & Steiner 1996; Strong et al 2008; Pechenik 2016; Mutlu 2004; Andrade & Solferini 2006; Mutaf & Aksit 2009). They display diverse color morphism (Bond 2007; Gray & McKinnon 2007; McKinnon & Pierotti 2010; Wellenreuther et al 2014; McLean & Stuart-Fox 2014; White & Kemp 2016; Svensson 2017; Cook 2017; Takahashi & Noriyuki 2019; Jamie & Meier 2020). Quantifying phenotypic change is a prerequisite for comprehending species ecology and evolution (Rice & Mack 1991; Hageman & Sawyer 2006; Adams & Collyer 2009). Benthic invertebrates, such as gastropods, are appropriate models to examine regional phenotypical variation since adults are frequently sessile or immobile and exposed to habitat-specific limitations that are comparatively easy to measure. The most common method to investigate phenotypic variability and plasticity is the shell's physical properties, because they react predictably to ecological variables such as wave action, desiccation danger, or predator attack (Vermeij 1973; Trussell 2000). Studies have demonstrated that environmental and ecological factors, genetic differences, plasticity, and evolutionary change influence the variations in morphological traits (Janson 1982; Reid 1993; Makinen et al 2008; Saunders et al 2009; De la Rosa et al 2010; Hollander et al 2010; Patiluna & Demayo 2015).

A wide variety of specialized tools are being created with increasing speed to examine the morphological diversity of organisms. Recent years have seen a rise in the use of geometric morphometrics (GM), a generic analytical framework for assessing patterns of phenotypic development (Rohlf 1993; Rao & Suryawanshi 1996; Rohlf 2001; Adams et al 2004; Slice 2007). Geometric morphometrics provides a means of dividing biological form's shape and size components, making investigations on character evolution trends easier to manage (Dryden & Mardia 1998; Torres et al 2010; Tabugo et al 2010; Ganzon et al 2012; Anies et al 2013; Hermita et al 2013; Pucot et al 2021). Several GM techniques have already been used in research to pinpoint, define, and quantify the extent of spatial and temporal alterations in populations of organisms (Bruner 2004; Matondo & Demayo 2018; Madjos & Demayo 2018; Gelsano & Demayo 2019; Torres et al 2019; Gualberto & Demayo 2018). The GM method depicts the shapes of biological structures as geometric arrangements of a set of landmarks derived from two-dimensional pictures of the form.

Terebralia sulcata is a mollusk that inhabits mangrove forests and depends on them for sustenance. The loss of the mangroves affects many species in the mangrove environment, including mollusks. The species of *T. sulcata* are robust generalists that can endure desiccation, a range of substrate types, and substantial volumes of sand and debris. *T. sulcata* feeds on algae and vascular plants. The local population harvests *T.sulcata* from the mangroves. Nevertheless, despite their ecological significance, widespread distribution, and abundance, there have been relatively few studies of their general biology, including their feeding biology (Soemodihardjo & Kastoro 1977; Shokita et al 1984; Barnes 2009), early growth (Rao 1938) and historical population declines (Ohgaki & Kurozumi 2000). This study aimed to define and explain the morphological variety within *T. sulcata* using the geometric morphometric technique based on landmarks.

Material and Method

Description of the study sites. The study site was determined to be Muduing Bay, a section of the Dumanquillas Bay Protected Landscape and Seascape that comprises the three municipalities of Zamboanga del Sur and Zamboanga Sibugay. Four coastal villages in the Municipality of Kumalarang, Zamboanga del Sur, with coordinates of 7.7703° N and 123.1464° E, were sampled: Village Boyugan West, Bualan, Gusom, and Picanan. Two coastal villages, Village Latas of the Municipality of Lapuyan and Village Pamintayan of the Municipality of Buug, Zamboanga Sibugay, with coordinates of 7.7407° N and 123.0564° E, respectively (Figure 1, Figure 2).

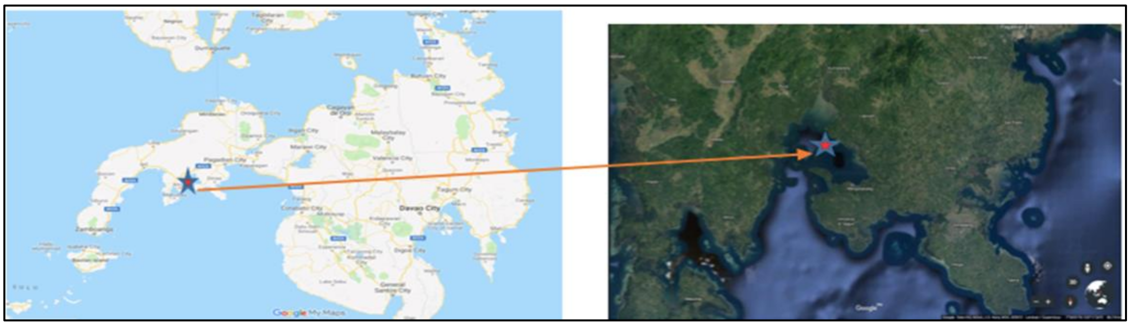

Figure 1. Map of Mindanao (left) and satellite image (Right) of the Muduing Bay.

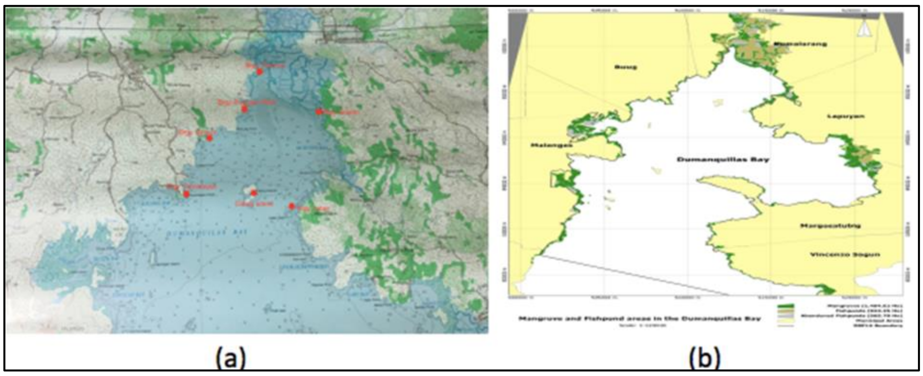

Figure 2. (a) Map of the Muduing Bay showing the study areas (Brgy. Picsanan, Brgy. Buyogan West, Brgy. Gusom, Brgy. Bualan, Brgy. Pamintayan, Brgy. Latas); (b) Mangrove and Fishpond areas in the Dumanquillas Bay.

Data acquisition. The shell shape of the *T. sulcata* species was studied using landmark-based geometric analysis methods. A total of 314 specimens were utilized for analysis.

Analysis of data. A high-quality digital camera was used to capture the images of the shells. The columella in an aperture view or in the orientation where the apex is visible was always at 90° of the x-axis in the images of the shells. Images that were obtained were processed using geometric morphometric techniques. The *T. sulcata*'s spherical shell has three to five sutures and a small oval opening. A uniform approach was used for each sample to capture digital pictures (ventral) (Figure 3). The specimens' position, orientation, and scale were all controlled for in the landmark-based methodology used to study shell shape. The ventral or apertural region of the shell's 23 anatomical features was utilized (Figure 3).

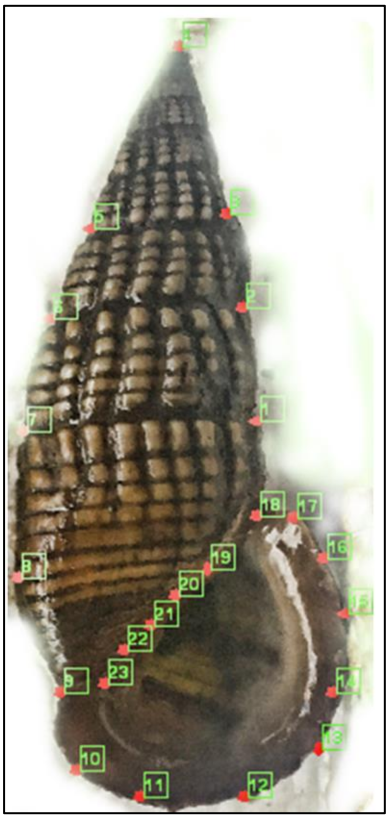

Figure 3. Landmarks describing the x,y coordinates used to describe the shape of the ventral view of the shell *Terebralia sulcata.*

TpsDig freeware 2.12, an image analysis and processing program, was used to make this possible (Rohlf 2006). By facilitating the collection and maintenance of landmark data from digitized images, TpsDig facilitates the statistical analysis of landmark data in morphometrics. The shell's landmarks 1, 2, and 3 are located at the right body line, Landmark 4 is at the apical top, Landmarks 5, 6, 7, and 8 are at the left body line, Landmarks 10, 11, 12, 13, 14, 15, and 16 are at the outer aperture, and Landmarks 18 to 23 are positioned along the inner aperture (Jamasali et al. 2014).

The coordinates were imported into the Microsoft Excel program so the data could be grouped. For each shell, the two-dimensional coordinates of these markers were determined. The Generalized Procrustes Analysis (GPA) superimposition method was then used to construct the generalized orthogonal least squares Procrustes average configuration of landmarks. A software called tpsRelw, version 1.46 (Rohlf 2007), was used to calculate the GPA. Following the GPA, the alignment-scaling approach was used to calculate the relative warps (RWs), the principal components of the covariance matrix of the partial warp scores. Using the PAST software, histograms and box plots were produced using the relative warps of the shell shapes. A powerful presentation for comparing distributions is the histogram or box plot. They give a condensed picture of the data's distribution over the variable's range and where the data are concentrated. To identify population variations in across-group shape, a discriminant function analysis (DFA) was performed. Hotelling's t-squared test was used for equality between the means of the compared groups and showed a p-value. The proportion of correct classification equal to or greater than the 75% cut-off score deemed significantly different is also calculated using this method (Hammer et al 2001). A Canonical variance analysis (CVA) was also performed to compare the patterns of population variance. The multivariate analysis of variance (MANOVA) test was used to see whether there were any significant differences between the species in terms of the morphology of their shells. This type of study provides numerous statistical metrics, like Hotelling's p(same), Wilk's lambda, and Pillai trace. The Hotelling's test makes a pairwise comparison of the mean shape. Wilk's lambda is determined by contrasting the error variance/covariance matrix and the effect variance/covariance matrix. It would establish the connections between various variables.

According to Torres et al (2010), Wilk's lambda has two values: a small (near to 0) value indicates that the groups are well divided, and a high (close to 1) value means that they are not well separated. The Pillai trace determines whether two sets of variables are independent: their effect's contribution to the variation increases with the Pillai trace value. The PAST software was used for all statistical operations (Hammer et al 2001).

Results. The results presented below use the Relative warp analysis of geometric morphometrics for assessing localized shape changes in *T. sulcata*. The Procrustes-filled landmark points, represented as shape spaces, resulted in numerous deformed and/or altered shape spaces, relative warp scores, a computed mean or consensus configuration. This is where the different iterations of various shape modifications are also built. Significant relative warp values are those with relative warp scores (greater/or equal to) 5%. The important relative warps, representing the varied deviating transformation grids and accounting for the total variances, are used to depict shape variations. Each relative warp provides two distorted shape spaces or grids, the negatively (-) deviated and positively (+) deviated.

The relative distribution of the variances, projected as a boxplot and a histogram, offers a decision factor in determining which population is closer to the mean shape, that generates a significant part of the total variances. Using landmark points in the shell of *T. sulcata*, variations in the morphological forms were identified. Then, using a variety of geometric morphometric tests, such as the relative warp analysis, Hotelling's tests, DFA, multivariate analysis of variance (MANOVA), and CVA, these landmark points were evaluated for shape variability. The histograms' left-side projections are thought to represent differences in shell form that are predicted as negative standard deviations from the mean along the axis of the relative warps. Then, differences in shell form are indicated as positive, which means positive divergences in the axis of the relative warps on the right side. The mean shape of the samples is depicted in the top figure. The primary characteristics of shape variation among specimens are shown as deformations by the relative warps, which are the principal component vectors (Tabugo et al 2010).

Between stations analysis. Relative warp analysis was used to describe phenotypic variations within populations of *T. sulcata* in Brgy. Picanan and Brgy. Bualan. The results are shown graphically in Figures 4 and 5 and are described in Tables 1 and 2. It demonstrates a considerable difference in the ventral shell of *T. sulcata*'s body shape.

Table 3 compares the statistical differences in the body form between the two stations in Village Boyugan West, Kumalarang, Zamboanga del Sur. The body shape exhibits a substantial difference with a p(same) value of 6.521E-07. Figure 6 shows the DFA and CVA plots, with a percentage value of 86.42%, illustrating the distribution of relative warp scores on the body shape variability. Additionally, the variations described by relative warp analysis are shown in Figure 7 and qualitatively described in Table 4.

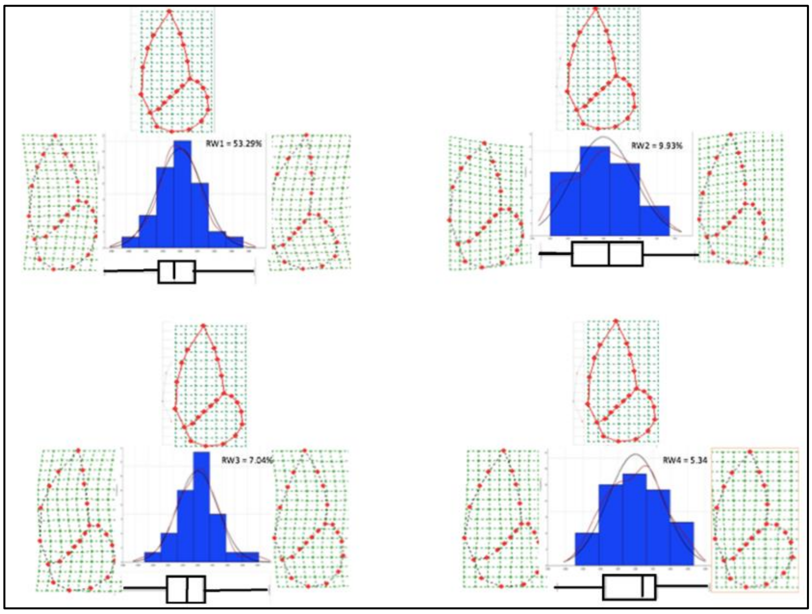

Figure 4. Relative warp, box plot and histogram showing variations in the shape of the ventral shell portion of *Terebralia sulcata* found in Village Picanan.

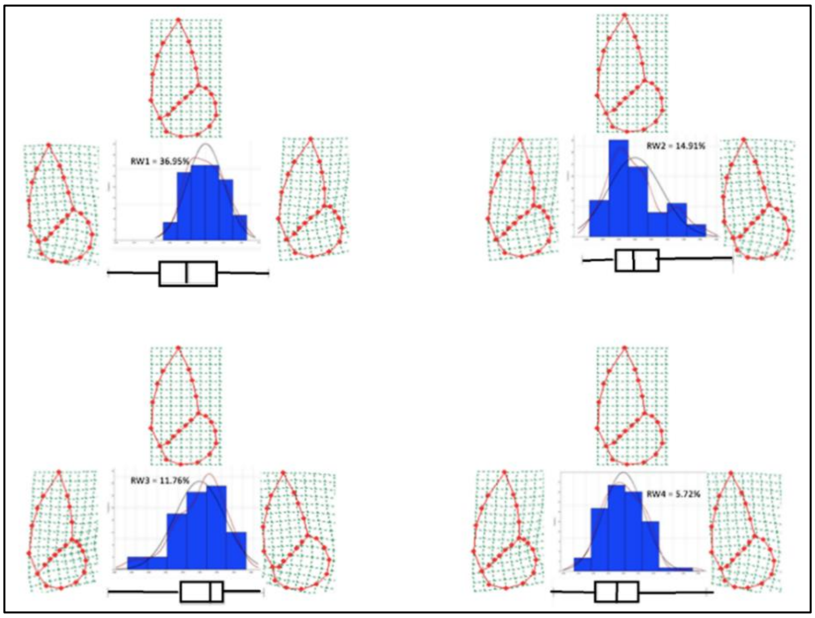

Figure 5. Relative warp, box plot and histogram showing variations in the shape of the ventral shell portion of *Terebralia sulcata* found in Village Bualan.

Table 1

Variance and description of variations in the ventral shell of *Terebralia sulcata* as explained by significant warps in Village Picanan

RW Variation %	*Apertural shell*	*Brgy. Picanan*
RW1 53.29%	Variation is greatly caused by the apical landmark and inner apertural landmark, right body and left body landmark that determines the body length and width; shell apertural shape also contributes to the variation	(+) shell has a shorter body length and wider body width; it has a wider apertural opening (-) has a longer and narrower body shape and has a half-circular aperture >> tends toward negative deviation
RW2 9.93%	Distance between the apical landmark and inner aperture landmark and	(+) has wider and shorter body shape

RW Variation %	*Apertural shell*	*Brgy. Picanan*
	between the right and left body shape determines the body shape	(-) has a narrower and longer body shape >> near mean
RW3 7.04%	The distance between the right body landmark and the inner apertural landmark determines the body shape	(+) shell body shape is slightly curved (-) shell has a straight body >> near mean
RW4 5.34%	Distance between right and left body landmarks (2,3,5&6) determines the variation of body shape	(+) the shell tip is slightly pointed (-) the shell tip is wider >>>> tends toward positive deviation

Table 2

Variance and description of variations in the ventral shell of *Terebralia sulcata* as explained by significant warps in Village Bualan

RW Variation %	*Apertural shell*	*Brgy. Bualan*
RW1 36.95%	Distance between right and left body landmarks determines the body shape	(+) shell has a pronounced body curved (-) has less pronounced body curved >> near mean
RW2 14.91%	Distance between the apical landmark and inner aperture landmark and between right and left body shape determines the body shape	(+) has wider and shorter body shape; has less pronounced body curved (-) has a longer body shape and more pronounced body curved >>>> tends toward negative deviation
RW3 11.76%	Shape of the aperture: The relative distance between apical and aperture landmarks, right and left body landmarks determines the body shape and aperture shape	(+) shell length is shorter and has a narrower aperture (-) shell has a wider body shape and a wider opening of the aperture >>>> tends toward positive deviation
RW4 5.72%	Distance between right and left body landmarks determines the variation of body shape	(+) the shell has a less pronounced body curved (-) the shell has a more pronounced body curved >>mean

Table 3

Confirmatory results of MANOVA on the variances of the shape of the ventral portion of *Terebralia sulcata* collected from pooled individuals of the 2 stations of the Village Buyogan West, Kumalarang, Zamboanga del Sur

Between	*Wilk's lambda*	*Pillai trace*	*p(same)*	*Remarks*
Station 1 and Station 2	0.4753	0.5247	6.521E-07	significant

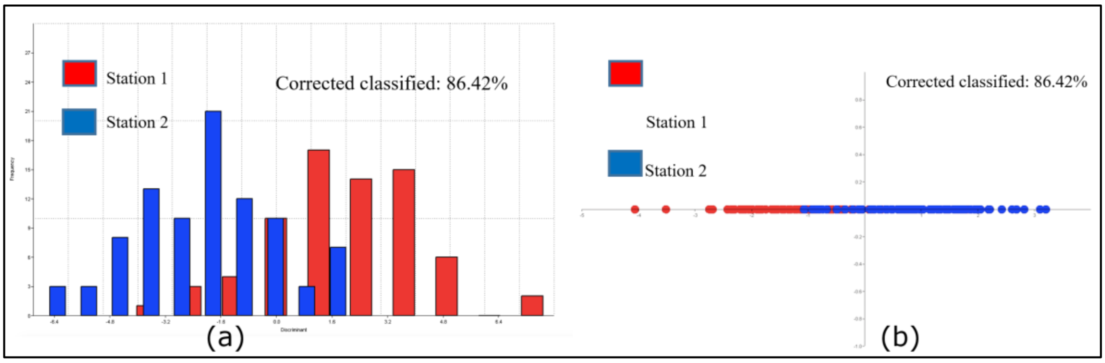

Figure 6. (a) Discriminant Function Analysis (DFA) and (b) Canonical Variate Analysis (CVA) plots showing the distribution of relative warp scores on the shape of the ventral shell portion of *Terebralia sulcata* between pooled populations from Village Buyogan West.

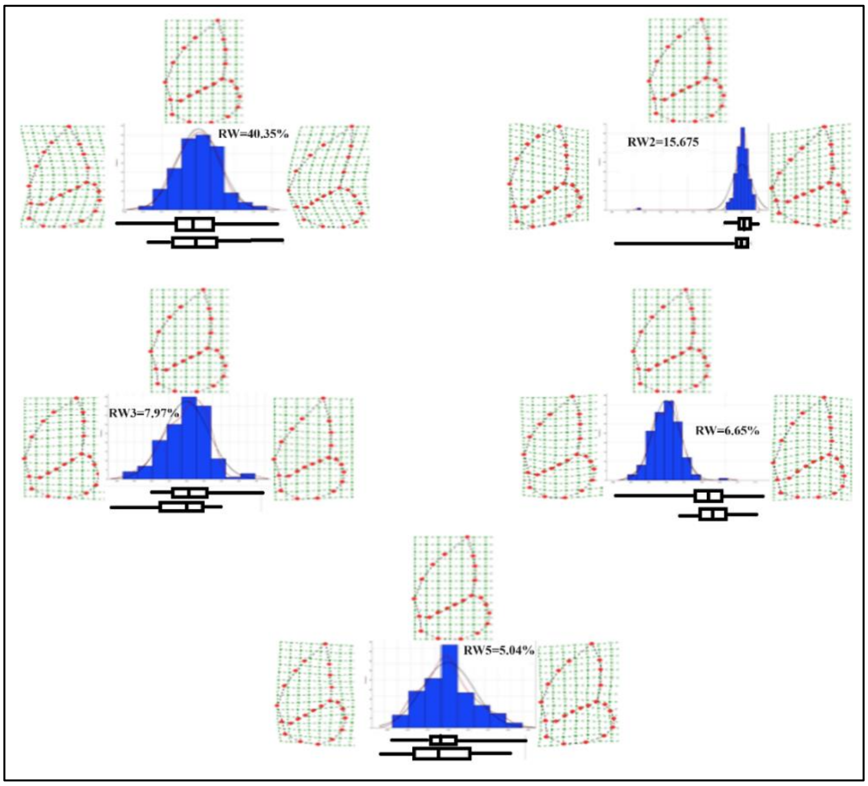

Figure 7. Relative warp, box plot and histogram showing variations in the shape of the ventral shell portion of *Terebralia sulcata* found in Village Buyogan West.

Table 4

Variance and description of variations in the ventral shell of *Terebralia sulcata* as explained by significant warps in Village Buyogan West

RW variation %	*Apertural shell*	*Brgy. Buyogan West*
RW1 40.35%	Distance between right and left body landmarks determines the body shape; relative distance between apical landmark and inner apertural opening determines the body length	(+) shell has a shorter length and wider width; the apertural opening is half-oblongated (-) has a more pronounced body curved and longer body length. It has a narrower body, half-circular aperture >> Station 2 tends toward positive deviation, while Station 1 near mean
RW2 16.67%	Distance between right and left body landmarks (5,6 & 7) determines the body shape	(+) shell has a less pointed tip (-) has pointed tip >> Station 1 tends toward positive deviation, while Station 1 tends towards negative deviation
RW3 7.97%	Distance between right body landmarks and left body landmarks determines the variation of body shape	(+) shell has a wider body width (-) narrower body width >> Both station 1&2 tends toward positive deviation
RW4 6.65%	Distance between right and left body landmarks determines the variation of body shape	(+) the shell has neither a narrow nor wider body shape (-) the shell has neither a narrow nor wider body shape >>Both station 1&2 near mean deviation
RW5 5.04%	Distance between right and left body landmarks determines the variation of body shape	(+) shell shows a straighter or less curved body shape (-) has a wider body shape and a less pronounced body-curved >>Both station 1&2 tends toward negative deviation

Table 5 illustrates how the form of the ventral section of *T. sulcata* varies between the two stations in Village Pamintayan, Buug, and Zamboanga Sibugay. With a p(same) value of 4.034E-18, it demonstrates a considerable difference in body shape. Since it is greater than the cut-off score of 75% (Figure 8), the DFA and CVA plots of the relative warp scores on the body shape variability are determined to be statistically different (Hammer et al 2009). The changes identified by relative warp analysis are further illustrated in Figure 9, and the variations are described in Table 6.

Table 5

Confirmatory results of MANOVA on the variances of the shape of the ventral portion of *Terebralia sulcata* between pooled individuals of the two stations of Village Pamintayan, Buug, Zamboanga Sibugay

Between	*Wilk's lambda*	*Pillai trace*	*p(same)*	*Remarks*
Station 1 and Station 2	0.3231	0.6769	4.034E-18	significant

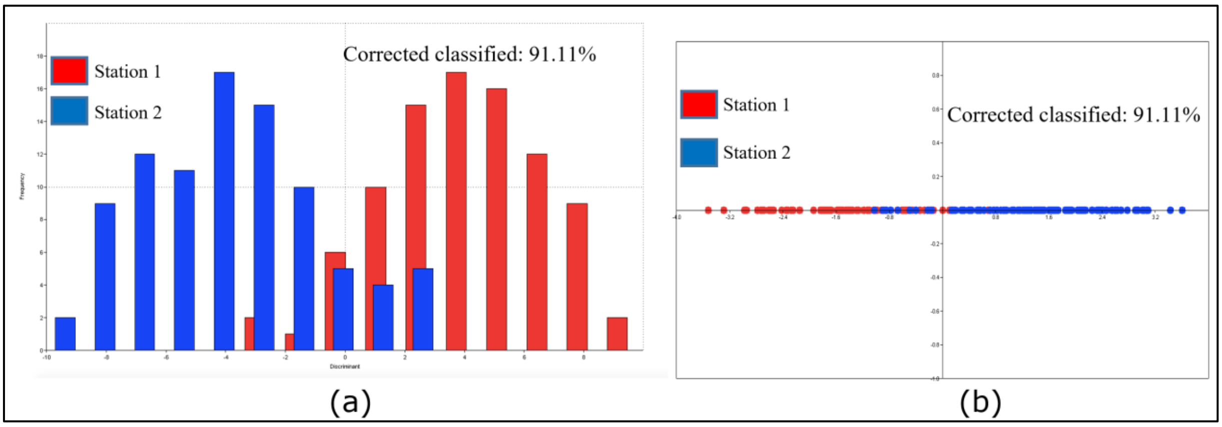

Figure 8. (a) Discriminant Function Analysis (DFA), (b) Canonical Variate Analysis (CVA) plots showing the distribution of relative warp scores on the shape of the ventral shell portion of *Terebralia sulcata* between pooled populations from Village Pamintayan.

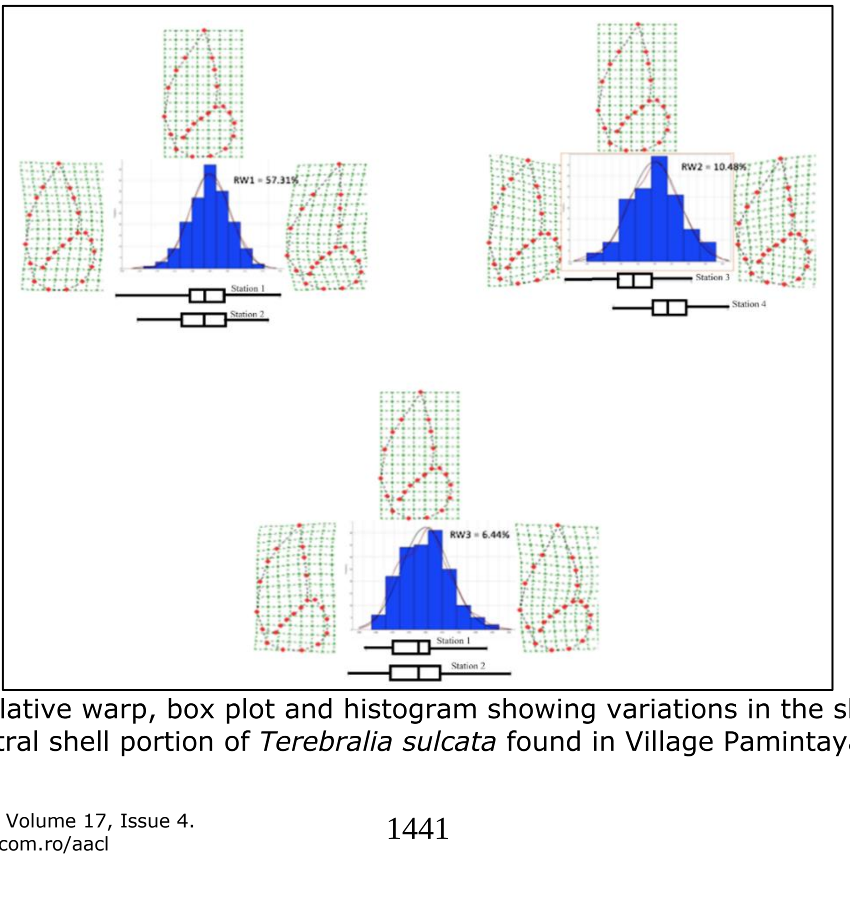

Figure 9. Relative warp, box plot and histogram showing variations in the shape of the ventral shell portion of *Terebralia sulcata* found in Village Pamintayan.

Table 6

Variance and description of variations in the ventral shell of *Terebralia sulcata* as explained by significant warps in Village Pamintayan

RW variation %	*Apertural shell*	*Brgy. Pamintayan*
RW1 57.31%	Variation is greatly caused by the distance between apical landmark and inner aperture landmarks, between right and left body landmarks, shell shape aperture	(+) shell has a wider width and shorter length body shape; has a wider apertural opening (-) has a narrower and longer body shape, half-circular aperture >> Both stations 1 & 2 near mean deviation
RW2 10.48%	Distance between right and left body landmarks, the relative distance between inner and outer aperture determining the variances of the body shape	(+) has a wider body shape width, half-oblongated aperture (-) narrower body width and half-circular aperture >>Station 1 tends toward negative deviation, while Station 2 tends toward positive deviation
RW3 6.44%	Relative distance between right and left body landmarks (2, 3, 4, 5 & 6) determines the body shape.	(+) shell has neither a wide nor narrow body shape (-) shell has neither wide nor narrow body shape >> Both stations tend toward positive deviation

DFA and CVA plots showing the distribution of relative warp scores on the body shape variability with a percentage value of 86.67% (Figure 10) are considered to be significantly different since it is higher than the cut-off score of 75% (Hammer et al 2009). Table 7 illustrates the significant difference in the body shape of *T. sulcata* between the two stations of Village Latas, Lapuyan, Zamboanga del Sur. The relative warp analysis described modifications are shown in Figure 11 and described in Table 8.

Table 7

Confirmatory results of MANOVA on the variances of the shape of the ventral portion of *Terebralia sulcata* between pooled individuals of the two stations of Villages Latas, Lapuyan, Zamboanga del Sur using landmark-based GM analysis

BETWEEN	*Wilk's lambda*	*Pillai trace*	*p(same)*	*Remarks*
Station 1 and Station 2	0.4083	0.5917	2.701E-12	significant

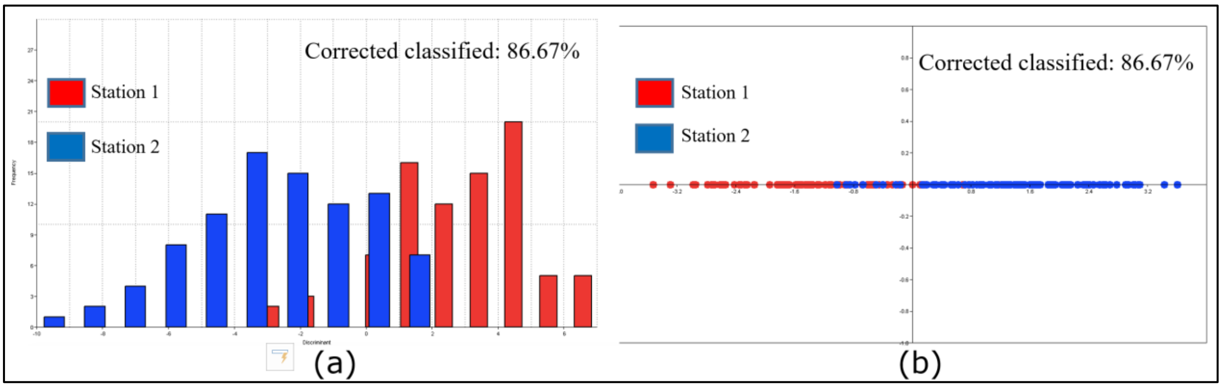

Figure 10. (a) Discriminant Function Analysis (DFA) (b) canonical Variate Analysis (CVA)plots showing the distribution of relative warp scores on the shape of the ventral shell portion of *Terebralia sulcata* between pooled populations from Village Latas.

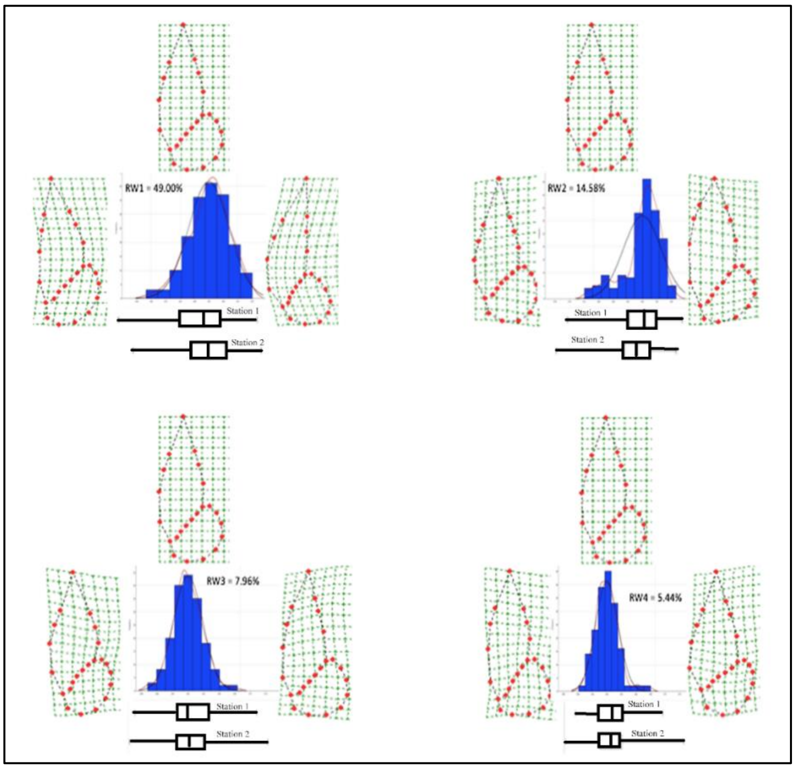

Figure 11. Relative warp, box plot, and histogram showing variations in the shape of the ventral shell portion of *Terebralia sulcata* found in Village Latas.

Table 8

Variance and description of variations in the ventral shell of *Terebralia sulcata* as explained by significant warps in Village Pamintayan

RW variation %	*Apertural shell*	*Brgy. Pamintayan*
RW1 49.99%	Variation is greatly caused by the distance between apical landmark and inner aperture landmarks, between right and left body landmarks, shell shape aperture	(+) shell has a wider width and shorter length body shape, and less pronounced curved body shape; half-oblongated aperture (-) has a narrower and longer body shape and a more pronounced body curved, half-circular aperture >> Both stations 1 & 2 tend towards positive deviation
RW2 14.58%	Distance between right and left body landmarks, the relative distance between inner and outer aperture determining the variances of the body shape	(+) has narrower body shape width and shorter body length; half-circular aperture (-) wider body width and longer body length; and half-oblongated aperture >> Both stations 1 & 2 tend towards positive deviation
RW3 7.96%	Shell shape aperture; distance between right and inner aperture landmark, and distance between apical and inner aperture landmarks determining the variations	(+) shell has neither a wide nor narrow body shape and has a shorter body length; the apertural opening is globose (-) shell has neither a wide or narrow body shape, has a longer body length; half-circular aperture >> Both stations tend toward negative deviation
RW4 5.44%	Shell shape aperture	(+) half-circular apertural opening (-) half-oblongated aperture shape >> both stations 1 & 2 near mean deviation

Table 8 provides the MANOVA p-values demonstrating the statistically significant differences in the shell morphologies of the three populations of *T. sulcata* in Village Gusom, Kumalarang, Zamboanga del Sur. Figure 12's matching CVA scatter plot further demonstrates the shape variability of *T. sulcata* in the 3 stations. Low levels of overlap suggest more significant differences in those areas. The relative warp analysis-described alterations are shown in Figure 13 and described in Table 9.

Table 9
p-values generated from MANOVA showing significant differences between the shell shapes of the three populations of *Terebralia sulcata* in Village Gusom, Kumalarang, Zamboanga del Sur.

	Station 2	*Station 3*
Station 1	1.85E-08	1.45E-23
Station 2	-	4.87E-26
Station 3		-

Wilk's lambda: 0.171, p(same): 2.712E-48, Pillai tace: 1.122

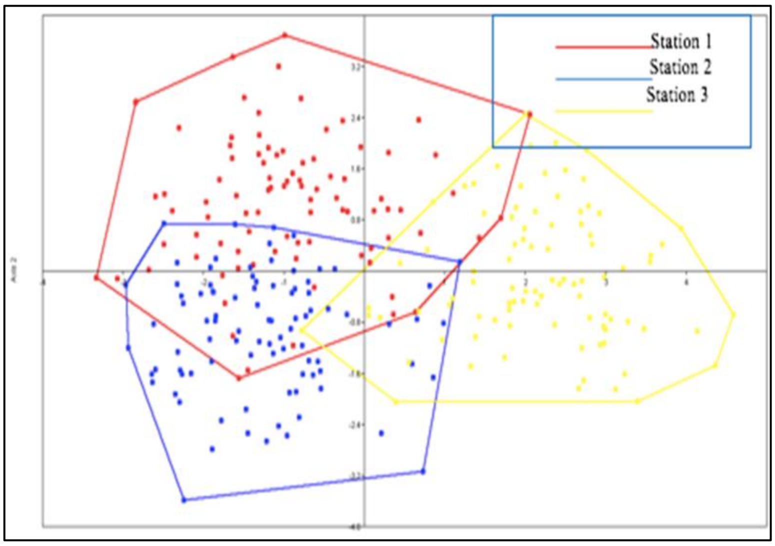

Figure 12. CVA scatter plot showing the shape variability of the ventral shell portion of *Terebralia sulcata* between pooled individual populations found in Gusom Village.

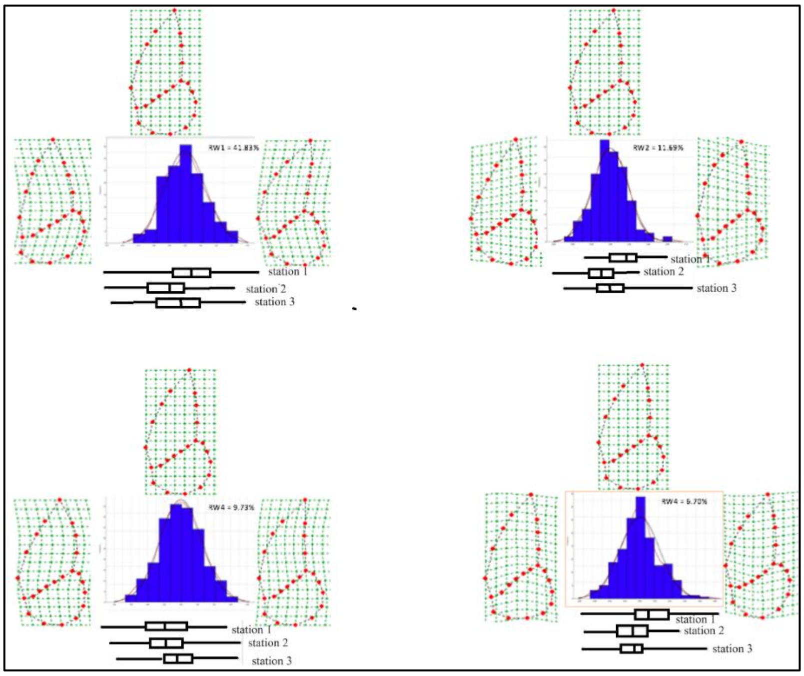

Figure 13. Relative warp, box plot, and histogram showing variations in the shape of the ventral shell portion of *Terebralia sulcata* found in Gusom Village.

Table 10

Variance and description of variations in the ventral shell of *Terebralia sulcata* as explained by significant warps in Gusom Village

RW variation %	*Apertural shell*	*Gusom Village*
RW1 (41.83%)	Variation is greatly caused by the distance between right and left body landmarks, shell shape aperture	(+) shell has a wider width and less pronounced curved body shape; half-oblongated aperture (-) has a narrower and more pronounced body with a curved, globose aperture >> Station 1 tends toward the near mean, station 2 tends toward negative deviation, while station 3 tends toward positive deviation
RW2 (11.69%)	Distance between right and left body landmarks, determining the variances of the body shape	(+) has a narrower body shape width (-) wider body width >> Both stations 1 & 2 tend toward negative deviation, while station 3 tends toward positive deviation
RW3 (9.73%)	Shell shape aperture; distance between right and inner aperture landmark, and distance between apical and inner aperture landmarks determining the variations	(+) shell has a wider body shape and a shorter body length; the apertural opening is globose (-) shell has a narrower body shape and longer body length; half-circular aperture >> Both stations 2 & 3 tend toward negative deviation, while station 1 tends toward positive
RW4 (5.70%)	Distance between right and left body landmarks, determining the variances of the body shape	(+) neither narrow nor wide body shape (-) neither narrow nor wide body shape >> Both stations 1 & 2 tend towards negative while station 3 tends toward positive deviation

Between populations (Villages). *T. sulcata* body shape variation from between the six villages (Picanan, Boyugan Wests, Gusom, Bualan, Pamintayan, and Latas) exhibits a significant difference with a p(same) value of 2.701E-12 (Table 10). Figure 14 depicts the matching CVA scatter plot—areas with less overlap show more variances. Among the six villages, Villages Boyugan Wests, Gusom, and Bualan share commonalities with the other villages in terms of the *T. sulcata's* body structure, but Villages Picanan, Pamintayan, and Latas do not.

Table 11

p-values generated from MANOVA showing significant differences between the shell shapes of the six populations of *Terebralia sulcata*

	Boyugan West	*Gusom*	*Bualan*	*Pamintayan*	*Latas*
Picanan	5.99E-25	2.31E-38	1.74E-22	6.55E-61	9.83E-70
Boyugan West	-	2.17E-36	2.81E-28	2.23E-81	7.86E-10
Gusom		-	1.76E-19	3.66E-11	5.39E-12
Bualan			-	7.93E-58	1.59E-53
Pamintayan				-	3.17E-91

Wilk's lambda: 0.4083, p(same): 2.701E-12, Pillai trace: 0.5917

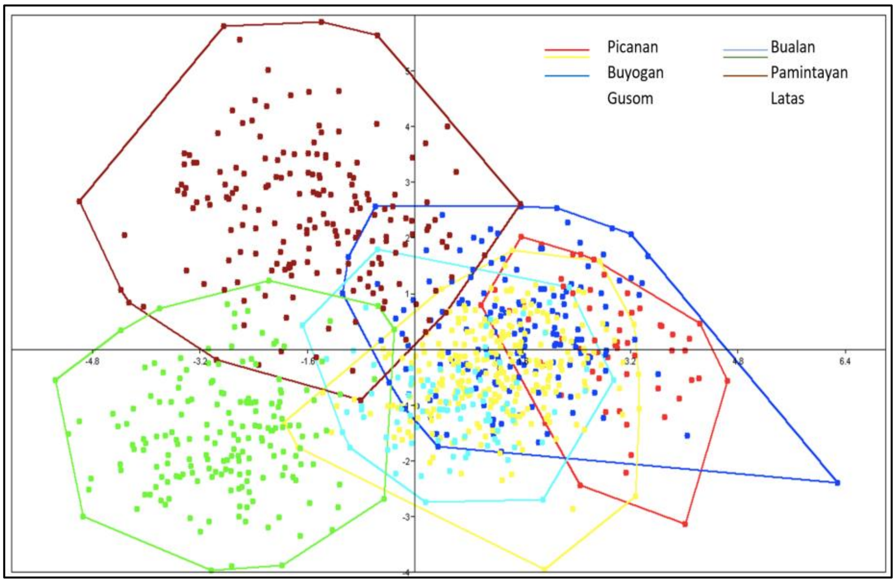

Figure 14. CVA scatter plot showing the shape variability of the ventral shell portion of *Terebralia sulcata* between pooled individual populations found in 6 villages.

Figure 15 and Table 11 show the decriptions of morphological shape variations of the six villages' ventral shells of *T. sulcata*. The principal variations in the *T. sulcata* shell shapes are typically related to the distance between the apical and inner apertural landmarks, to the distance between body markers that define whether the length is shorter or longer and if the breadth is broader or narrower, and also to the shape of the aperture.

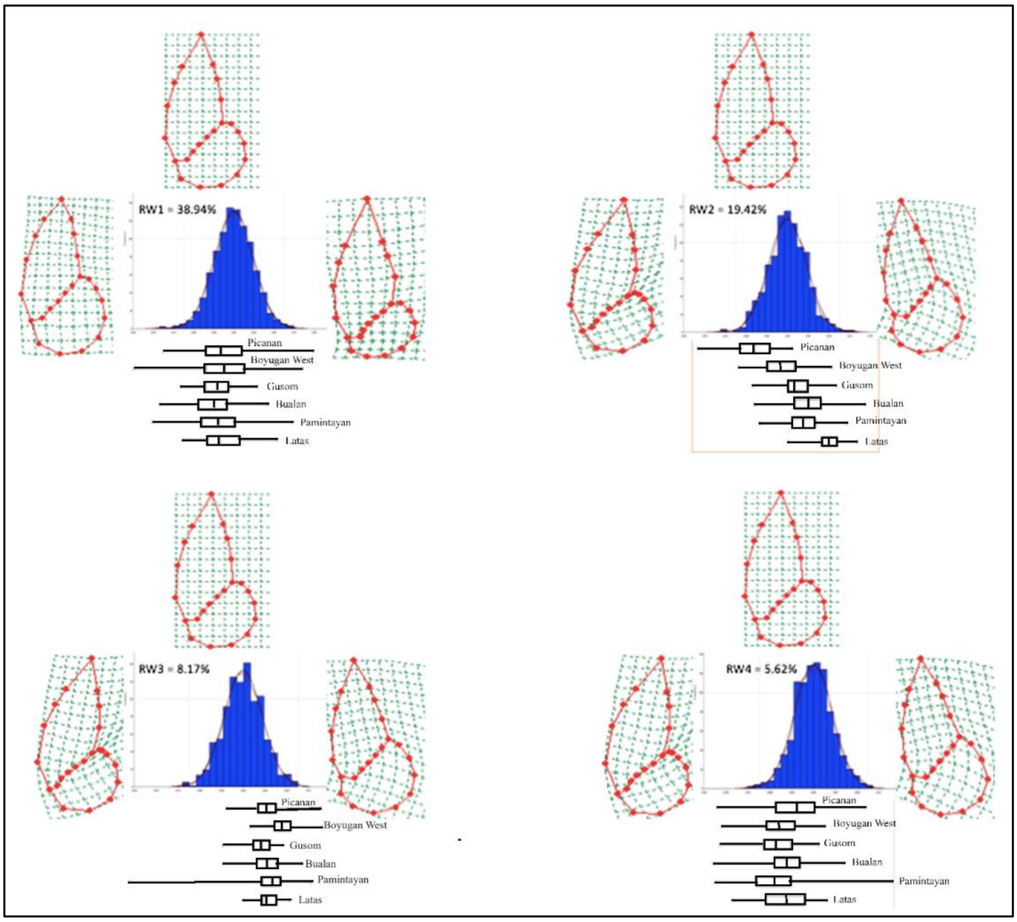

Figure 15. Relative warp, box plot and histogram showing variations in the shape of the ventral shell portion of *Terebralia sulcata* found in the six villages.

Table 12

Variance and description of variations in the ventral shell of *Terebralia sulcata* as explained by significant warps

RW variation %	*Apertural shell*	*Population*					
		Picanan	*Buyogan West*	*Gusom*	*Bualan*	*Pamintayan*	*Latas*
RW1 38.94%	Distance between apical and inner apertural landmarks, between body landmarks determines whether the length is shorter or longer and the width is broader or narrower; the shape of the aperture significantly caused the variations.	(+) The shells have a shorter body length and wider opening of the aperture (-) has a longer body length and narrower apertural opening >> Mean deviation	(+) the shells have wider body widths and narrower opening (-) has a narrower body width and wider opening of the aperture >>tends toward negative deviation	(+) the apertural opening is neither too wide nor too narrow; it has a wider body width (-) narrower body width and longer body length; has wider apertural opening >> tends toward negative deviation	(+) the shells have shorter body length and neither too wide nor too narrow apertural opening (-) wider body width and neither too wide or narrow aperture >> tends toward negative deviation	(+) has a wider body with a wider apertural opening (-) the shells have narrow body widths but longer body lengths with narrow apertural opening >> tends toward positive deviation	(+) neither narrow nor wider apertural opening and has a wider body width and shorter body length (-) has narrower body width and longer body length; neither narrow nor wider aperture >> tends toward positive deviation
RW2 19.42%	Variation is greatly caused by the values between outer apertural landmarks and inner apertural landmarks and right body landmarks and left body landmarks determining the body width and apertural shape.	(+) shells have half-oblongated aperture and have a wider body width (-) more globose aperture and narrower body width >> tends toward positive deviation	(+) shells show a half-oblongated apertural opening and wider body width (-) circular aperture and narrower body width >> tends toward positive deviation	(+) globose aperture (-) half-oblongated apertural opening; neither too narrow nor too wide body width >> tends toward positive deviation	(+) globose aperture (-) half-circular aperture >> tends toward positive deviation	(+) half-oblongated opening of the aperture (-) half-circular apertural shape >> tends toward negative deviation	(+) globose aperture (-) half-oblongated apertural shape >> tends toward negative deviation
RW3 8.17%	Distance between apical landmark and inner aperture landmarks, between right body and inner aperture landmarks determining the body length,	(+) shorter body length (-) longer body length >> tends toward negative deviation	(+) the shells have wider body widths with shorter body length (-) narrower width and longer body length	(+) the shell has a shorter length and wider body width (-) has a longer body length and narrower body width >> tends toward	(+) narrower body width and shorter body length (-) has a longer body length and wider body width >> tends toward	(+) neither long nor short body length and width (-) neither long nor short body length and width >> tends toward positive deviation	(+) has a shorter body length (-) longer body length >> tends toward negative deviation

RW variation %	Apertural shell	Population					
		Picanan	Buyogan West	Gusom	Bualan	Pamintayan	Latas
	body width and shape		>> tends toward positive deviation	negative deviation	negative deviation		
RW4 5.62%	Distance between right body landmarks with inner apertural landmarks and left body landmarks with outer apertural landmarks determines the body shape and apertural size and shape.	(+) the shells have straighter body shape and have a globose aperture (-) less curved body shape and globose aperture >> tends toward positive deviation	(+) less pronounced body curves and have a half-oblongated apertural shape (-) less pronounced body curves and have a half-oblongated apertural shape >> tends toward negative deviation	(+) shells have straighter body shape with wider opening of the aperture (-) less pronounced body curved with a wider opening of the aperture >> tends toward positive deviation	(+) straighter body shape and half-circular aperture (-) less pronounced body curved and half-circular aperture >> tends toward negative deviation		(+) straighter body shape and half-circular aperture (-)(+) straighter body shape and half-oblongated apertural shape >> tends toward positive deviation

Discussion. Overall, the study's findings indicated the advantage of using relative warp analysis in detecting a sizable variation in body shapes in *T. sulcata* populations. The most apparent shell shape variants are found in the height, body width, and aperture openings. These observed variations within the populations may attributed to physicochemical environmental factors and to predation (Minton et al 2011; Patiluna & Demayo 2015), tidal and wave exposure (Steffani & Branch 2003; Funk & Reckendorfer 2008; Valladares et al 2010), sediment type (Funk & Reckendorfer 2008; Valladares et al 2010), and matrix stratification (Briones & Guiñez 2005; Valladares et al 2010). Environmental factors may have contributed to the variations, seen as a strategy because it gives organisms that cannot change their genes a way to change their phenotypes to meet the demands of the environment (Hollander 2010), improving their survival chances in shifting environmental conditions. Besides, they stimulate adaptations like predation, camouflage, defensive behavior, and reproductive strategies (Minton et al 2011; Moneva et al 2012). The internal volume of shell material ratio (Kemp & Bertness 1984) can also be affected ecologically by factors including food availability and quality, feeding time, and densities of conspecifics and competing species (Saunders et al 2009; Patiluna & Demayo 2015), which can lead to variations in shell shape. According to some (Janson 1982; Reid 1993; Hollander et al 2006; Makinen et al 2008; De la Rosa et al 2010; Jamasali 2014), the variety in the shell shape of *T. sulcata* is not only influenced by environmental and ecological factors, but also by phenotypic plasticity, genetic variations, and evolutionary change. Many studies (Kitching et al 1966; Kitching & Lockwood 1974; Vermeij 1972, 1973; Seeley 1986) show that different intertidal coastlines have varied intertidal gastropod shell variants. This is partly because of the varying crab predation rates. Predator-induced morphological defenses are a singular instance of phenotypic plasticity where the predator or a cue linked with the predator (typically chemical in nature) stimulates the production of features in the prey that prevent predation (Trussell 1996). As a result of its ability to change the link between the genotype and the phenotype, the goal of selection, plasticity impacts how organisms evolve and respond to their environment (Trussell & Etter 2001). A trait's reaction to selection depends on its heritability and genetic relationship to other qualities that are also under selection (Roff 1997). According to Trussell & Etter (2001), plasticity can impact both variables, leading to unexpected changes in the direction and rate of evolution.

Conclusions. The findings of this study suggest that morphological variations in gastropod shell patterns were clearly described using relative warp analysis, Hotelling's tests, discriminant function analysis, multivariate analysis of variance, and canonical variate analysis. Different geometric morphometric techniques help identify minimal variations in the group composition, according to the shell shape. The body length, breadth, and aperture opening of six populations of *T. sulcata* in Muduing Bay were significantly different, according to a landmark-based geometric morphometric analysis of shell shape variations. Environmental variables, phenotypic plasticity, genetic variances, and evolutionary change may all be to blame for the variability in shell morphology. More research is necessary to determine the impact of these elements, though.

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