

Molecular identification of marbled newts and a justification of species status for *Triturus marmoratus* and *T. pygmaeus*

G. Espregueira Themudo^{1,2} & J.W. Arntzen²

¹CIBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Campus Agrário de Vairão, Vairão, Portugal

²National Museum of Natural History, P.O. Box 9517, 2300 RA Leiden, The Netherlands

The marbled newts *Triturus marmoratus* and *T. pygmaeus* are common and readily diagnosed species occurring in central Portugal, but difficult to survey in large and deep ponds. Conversely, embryos of both species are easy to locate but morphologically indistinguishable. We studied a panel of nuclear genetic loci by starch gel electrophoresis (the enzymes *Pep-A*, *Pep-B* and *Pep-D*) and isoelectric focusing techniques (the enzyme *Ldh-2*, post-embryonic stages only) that together yield a species-specific signature (Cohen's kappa = 1.00). On a locus by locus basis, the scores for correct classification range from kappa = 0.12 to kappa = 0.97. The method allows the reliable, fast and cheap identification of both species across life stages, with better behaviour and performance than mtDNA sequencing (i.e. bar-coding) and nuclear DNA microsatellite profiling. The observed distribution of *T. marmoratus* and *T. pygmaeus* over 25 aquatic breeding sites in the Caldas da Rainha area in western Portugal is parapatric, with no mixed populations and no F_1 interspecific hybrids. This demonstrates that *T. marmoratus* and *T. pygmaeus* are genetically isolated, even when populations are within the "dispersal distance per generation" range of one another. We consider the data adequate for supporting the species status of *T. marmoratus* and *T. pygmaeus* under the Biological Species Concept.

Key words: allozymes, Amphibia, principal coordinate analysis

INTRODUCTION

Newts are characterized by long annual periods (2–6 months) of pond breeding and dip-netting provides a mostly efficient and unbiased sampling technique for adults (Arntzen, 2002a,b). This allows reliable surveying over large areas for the purpose of, for example, the improved understanding of distribution patterns and the assessment of conservation status. In Portugal, we noted the frequent occurrence of newts in "albercas". These albercas are deep (>3 m) and sizable (diameter 3–8 m), mostly circular stone structures for agricultural and household water supply [for typical examples of albercas, see Malkmus (1982) and Figure 61 in Malkmus (2004)]. Albercas are exceedingly difficult to investigate. The dip-netting approach fails, because at the first sweep the adult newts dive beyond reach and hide in the crevices of the stone walls. The presence of adults, however, may be revealed by the easily spotted eggs that are individually attached to the leaves of submerged, floating and overhanging vegetation (Miaud, 1993). For the eggs to be useful in surveying, a method is required for species identification. The first aim of the present paper is thus to develop an efficient and reliable method for identifying the eggs of marbled newts (*Triturus marmoratus* and *T. pygmaeus*). Since the eggs of these species are morphologically indistinguishable, these will be molecular genetic tools. On a technical note, most eggs in the field will be fertilized and should be referred to as embryos, but for convenience we will use the terms interchangeably. Secondly, we apply and test the new method to qualify the distribution of both species in central Portugal over

and across a contact zone between them. Thirdly, we test the hypothesis of Garcia-Paris et al. (2001) that *T. marmoratus* and *T. pygmaeus* are full species under the Biological Species Concept.

MATERIALS AND METHODS

Research was carried out in an area of approximately 4000 km² around Caldas da Rainha to the north of Lisbon, Portugal, where *T. marmoratus* and *T. pygmaeus* have both been observed in a pilot study (J.W.A. & E. Froufe, unpubl. data). Ponds and other potential newt breeding sites were located by motorized field searches, assisted by military topographical maps and with help and information from local inhabitants. At each spot we checked the submerged, floating and marginal vegetation for the presence of marbled newt eggs, which are clearly distinguishable from those of other amphibians by size, structure and the way they are deposited. The eggs of the sympatric small bodied newt *T. boscai* (placed in the genus *Lissotriton* by Garcia-Paris et al., 2004 and in the genus *Lophinus* by Litvinchuk et al., 2005) are readily distinguished from marbled newt eggs on account of their small size, bipolar pigmentation and the round (as opposed to ovoid) shape of the jelly capsule around them. Eggs were collected from the vegetation all over the accessible parts of the water body and placed in Eppendorf vials. Occasionally, adult and larval marbled newts were caught by dip-netting. The adults were identified as *T. marmoratus* or *T. pygmaeus* on the basis of size, colour and colour-pattern, whereas larvae remained unidentified. Tail tips were removed and placed under buffer in indi-

vidual Eppendorf vials. All vials were placed in liquid nitrogen for transportation to the laboratory and then stored in a freezer at -80°C for future electrophoresis.

In the laboratory, the tail tips and entire embryos were homogenized in an aliquot amount of ice cold buffer (100 mM Tris, 1 mM EDTA, 0.05 mM NADP, adjusted to $\text{pH}=7.0$ with HCl) and centrifuged for 15 minutes at 13,000 rpm at 4°C . The supernatant was treated with dithiothreitol (120 μM DTT) for 1 hour at 37°C prior to electrophoresis and staining on starch gels for three peptidases (*Pep-A*, *Pep-B* and *Pep-D*) and on acrylamide gels with isoelectric focussing for the enzyme lactate dehydrogenase (*Ldh-2*), following standard protocols (e.g. Pinho et al., 2003). Electromorphs were interpreted as alleles at the corresponding genetic locus. We used the program Genepop (Raymond & Rousset, 1995) to test for population genetic differentiation by Fisher's exact test, to calculate expected heterozygosity (H_e) and to test for departure from Hardy-Weinberg equilibrium (HW) under standard Bonferroni correction.

Principal Coordinate Analysis (PCA) was performed on a binary data set with alleles as characters and presence (1) or absence (0) of alleles as character states. Character states were assumed to be independent, although in reality limited to a maximum of two scores of 1 per locus. Homozygotes were not distinguished from heterozygotes (i.e. they were represented by a single score of 1). The subroutine SIMQUAL of the program NTSYS 1.7 (Rohlf, 1992) was used to compare the enzyme profiles and to calculate a matrix with pairwise similarity coefficients. We chose the Jaccard similarity coefficient because it ignores joint absences. The subroutine DCENTER was used to transform the similarity matrix into scalar product form, after which it was factored using the subroutine EIGEN.

RESULTS

The presence of marbled newts was confirmed in 25 aquatic sites, from which we sampled 101 eggs and embryos, 41 larvae and 84 adults. In 14 sites we failed to catch any adults, either because of timing (adults had left the water) or because the site had inaccessible parts. Tissue samples from adults and larvae were scored for four loci (with few exceptions) and embryos were scored for the three peptidase loci.

Analysis of the results indicates the existence of two separate genetic units, corresponding to *T. pygmaeus* (17 populations) and *T. marmoratus* (eight populations) respectively. The observed number of alleles was four at *Pep-A*, three at *Pep-B*, eight at *Pep-D* and three at the *Ldh-2* locus. The allele frequencies are presented in Table I. Observed genetic heterozygosity averaged 0.20 ± 0.11 . A significant departure from Hardy-Weinberg equilibrium was observed for *Pep-D* in the sample from Valado dos Frades (population 4, $P<0.05$). No significant genetic differentiation was found between cohorts in any population. *Pep-A* showed significant population differentiation within *T. marmoratus* and *Pep-B* and *Pep-D* showed significant population differentiation within *T. pygmaeus* ($P<0.001$ in all three cases).

The PCA scores fell in two non-overlapping groups with values <-0.22 and >0.11 , that we term the "M"-group and the "P"-group, respectively. Seven adult *T. marmoratus* had a genetic make-up that placed them in the M-group and 77 adult *T. pygmaeus* had a genetic make-up that placed them in the P-group. Common alleles with diagnostic properties are *Pep-D^d* and *Pep-D^f* and, to a lesser extent, *Pep-A^a* and *Pep-A^d*. Individuals heterozygous for the *Pep-D* diagnostic alleles were observed in the populations from Alqueidão (population 3), São Bartolomeu dos Galegos (5), Genrinhas (15), Santa Susana (16) and Fonte da Pena da Couvinha (23) ($n=1$ in all five cases). Less common and rare alleles associated with either group are *Pep-A^b*, *Pep-A^e*, *Pep-D^a*, *Pep-D^b* and *Ldh-2^f* in the M-group and *Pep-D^e*, *Pep-D^g*, *Pep-D^h* and *Ldh-2^c* in the P-group. Alleles shared between the groups are *Pep-B^{bde}*, *Pep-D^c* and *Ldh-2^b* (Table I). Correct classification on a locus-by-locus basis is very good for *Pep-D* ($k=0.97$) and *Pep-A* ($k=0.92$), moderate for *Ldh-2* ($k=0.56$) and poor for *Pep-B* ($k=0.12$), in the terminology of Altman (1991). The distribution of the two groups was spatially structured to the extent that, first, all ponds yielded either M- or P-group individuals and not both, and second, ponds in the centre of the study area had M-group individuals whereas ponds at the fringe had P-group individuals. The average distance to the nadir point of the study area was 12.8 ± 4.3 km for M-ponds and 14.0 ± 7.5 km for P-ponds. Note that aspects of the spatial distribution of *T. marmoratus* and *T. pygmaeus* in western Portugal will be dealt with separately (Espregueira Themudo & Arntzen, in press).

DISCUSSION

We are interested in the distribution and ecology of amphibians from the Iberian peninsula, with the particular aim of elucidating those environmental correlates that help to reconstruct, explain, predict and understand species ranges (e.g. Teixeira et al., 2001; Arntzen, 2006). This requires extensive surveying based upon reliable species identification. In Portugal and Spain, as in most other temperate regions, amphibians gather in ponds and streams for breeding; this, if the time and place of the fieldwork are chosen advantageously, facilitates the gathering of data. In practice, most surveys concentrate on offspring, because adult pond presence may be short, as in "explosive breeders" (e.g. *Rana temporaria*), species that mate on land and only come to the water for offspring deposition (e.g. *Salamandra salamandra*), or species that are especially secretive (e.g. *Pelodytes punctatus*). As a rule, however, the earlier the life stage, the more problematic identification in the field proves to be. Classical keys for identification of eggs, spawn and larvae (Heron-Royer & Bambeke, 1889; Boulenger, 1891) have recently been upgraded (Miaud & Muratet, 2004), and most modern field guides will include identification keys for adults, larvae and eggs (e.g. Ferrand de Almeida et al., 2001; Duguet & Melki, 2003).

We set out to develop a molecular marker technique for the unambiguous species identification of marbled newt eggs that would allow all ponds to be investigated, in-

Table 1. Allele frequencies over four loci in marbled newts from the Caldas da Rainha area. Values in parentheses are the electrophoretic mobilities relative to the most common allele, shown as 100. Six alleles present elsewhere in Portugal were not encountered in the Caldas da Rainha area. Panels at the bottom present heterozygosity on the assumption of Hardy-Weinberg equilibrium and average score at the first PCA axis, with and without the locus *Ldh-2*.

Population	<i>Triturus pygmaeus</i>																	<i>T. marmoratus</i>											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25				
Total	13	19	12	22	6	8	8	9	8	1	7	10	8	2	7	3	4	9	8	10	21	10	7	4	10				
Sample size adults	0	19	12	22	0	5	0	0	1	1	7	10	0	0	0	0	0	4	0	0	1	0	2	0	0				
larvae	5	0	0	0	6	0	0	0	0	0	0	0	0	0	0	3	0	5	0	1	20	0	1	0	0				
embryos	8	0	0	0	0	3	8	9	7	0	0	0	8	2	7	0	4	0	8	9	0	10	4	4	10				
Locus and allele																													
<i>Pep-A</i>																													
a	(122)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.56	0.83	0.85	0.91	0.95	1.00	1.00	1.00	1.00			
b	(107)																												
d	(100)																	0.44	0.17	0.15	0.05	0.05							
e	(78)																												
<i>Pep-B</i>																													
b	(113)	0.13	0.29	0.07	0.08	0.19					0.15					0.17		0.11	0.06		0.07								
d	(100)	0.38	0.76	0.46	0.66	0.92	0.75	0.81	1.00	0.94	1.00	0.93	0.60	1.00	1.00	0.79	0.83	1.00	0.89	0.94	0.95	0.88	1.00	0.93	0.88	0.75			
e	(88)	0.62	0.11	0.25	0.27	0.06	0.19	0.06			0.07	0.25			0.21						0.05	0.05	0.07	0.13	0.25				
<i>Pep-D</i>																													
a	(125)																	0.06			0.14					0.07			
b	(121)																	0.06											
c	(117)																	0.06											
d	(112)																	0.78	1.00	1.00	0.86	1.00	0.93	1.00	1.00				
e	(106)																												
f	(100)	0.96	0.84	0.71	0.71	0.92	0.56	0.94	0.50	1.00	1.00	1.00	0.94	1.00	0.79	0.83	1.00	0.06											
g	(95)	0.04	0.05		0.11		0.06						0.06		0.14														
h	(88)																	0.21											
<i>Ldh-2</i>																													
b	(100)	1.00	1.00	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.56	1.00	1.00	0.45	1.00	1.00	1.00	1.00	1.00			
c	(72)																												
f	(36)																		0.44			0.55							
Three loci																													
He		0.19	0.23	0.38	0.32	0.11	0.35	0.15	0.18	0.22	0.00	0.05	0.20	0.04	0.00	0.25	0.22	0.38	0.14	0.12	0.22	0.03	0.10	0.08	0.13				
SE on He		0.15	0.12	0.20	0.16	0.06	0.18	0.10	0.18	0.16	0.00	0.05	0.20	0.04	0.00	0.13	0.11	0.09	0.09	0.08	0.02	0.03	0.05	0.08	0.13				
Weighted average		0.214±0.132																									0.163±0.063		
Four loci																													
He		0.05	0.09	0.25	0.19	0.08	0.25				0.00	0.04	0.15			0.25		0.39			0.26					0.13			
SE on He		0.05	0.06	0.15	0.13	0.05	0.15				0.00	0.04	0.15			0.08		0.11			0.07					0.13			
Weighted average		0.150±0.100																									0.284±0.084		
Average score along first PCA axis																													
Three loci		0.34	0.32	0.28	0.29	0.28	0.28	0.32	0.25	0.25	0.33	0.32	0.33	0.33	0.28	0.23	0.33	-0.44	-0.60	-0.66	-0.68	-0.73	-0.72	-0.72	-0.69				
Four loci		0.41	0.37	0.36	0.35	0.33	0.37				0.37	0.36	0.39			0.23		-0.36			-0.57					-0.51			

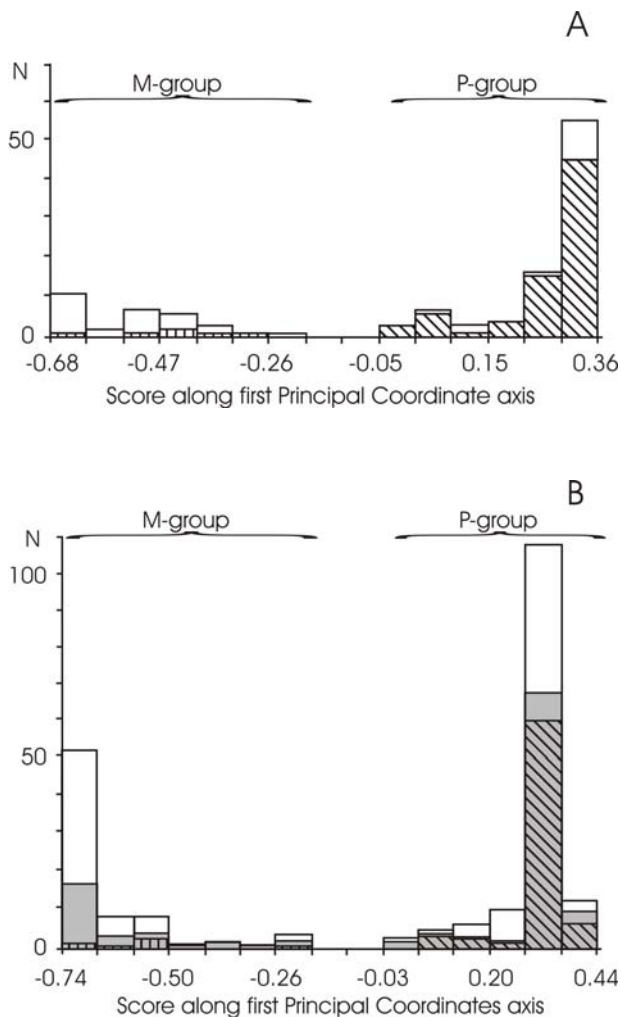


Fig. 1. Histograms representing the scores along the first principal coordinate axis for enzyme genetic markers in marbled newts from the Caldas da Rainha area in western Portugal, with four enzyme loci studied in 39 larvae and 82 adults (A) and three enzyme loci studied for an additional 101 embryos, two larvae and two adults (B). Individuals in B also figuring in A are marked by grey shading. Adults identified from morphology are shown by horizontal hatching (*Triturus marmoratus*, $n=6$) and diagonal hatching (*T. pygmaeus*, $n=76$). Note that these fall into different, non-overlapping M- and P- groups, respectively.

cluding technically problematic ones such as albercas and lakes. In ponds with aquatic vegetation absent, rare or out of reach, collecting may be facilitated by the introduction of strings of thin plastic liner available for egg-deposition, cut from, for example, garbage bags. With the phenotypic identification of adult *T. marmoratus* and *T. pygmaeus* as a reference and acknowledging the equivalent allelic expression among embryos, larvae and adults, the observed “M” and “P” enzyme profiles can be equated with *T. marmoratus* and *T. pygmaeus*, respectively. The single case of departure from Hardy-Weinberg equilibrium, with a lower than expected number of heterozygotes, may well be attributed to a less than optimal resolution of *Pep-D* zymogram, perhaps caused by

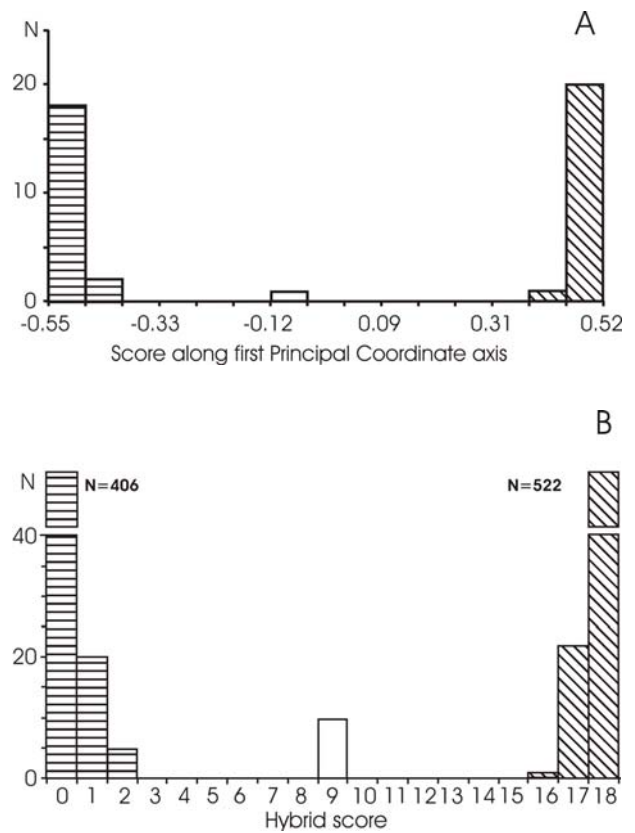


Fig. 2. Histograms representing the scores along the first principal coordinate axis derived from 87 alleles in a panel of 30 variable enzyme genetic markers in the newts *Triturus helveticus* and *T. vulgaris* in Mayenne, western France (A: after Arntzen et al., 1998) and hybrid index based on nine diagnostic enzyme genetic markers for the newts *T. cristatus* and *T. marmoratus* in the same area (B: after Arntzen & Wallis, 1991).

interference of the enzyme and the mucous components in larval tissue.

The method of identifying *T. marmoratus* versus *T. pygmaeus* through expressed protein loci is lethal when applied to embryos. However, considering the high fecundity of marbled newts (Arntzen & Hedlund, 1990) we presume that the effect will be negligible at the population level. Tissue sampling by clipping tail-tips has been shown to have no ill effects in adult big-bodied newts (Arntzen et al., 1999). The effect of tail-tip sampling of larvae has not yet been studied. For applying our method of species identification in other parts of the Iberian peninsula a note of warning is in place, since we observed geographic variation in the level of discrimination achieved by *Pep-B* and *Pep-D* (unpublished data). This reservation is in line with the observed population genetic differentiation in the Caldas da Rainha area for both species. An alternative technique for species identification would be the DNA sequencing of a mitochondrial gene such as COI, currently known as “bar-coding” (Hebert et al., 2003; Vences et al., 2005). An important shortcoming of this marker is that, in a phylogenetic sense, it may not represent the species from which it is isolated correctly, due to hybridization or incomplete lineage sorting, in

combination with maternal inheritance and low effective population size compared to nuclear genetic markers. This phenomenon, that ultimately may involve the complete “mtDNA-capture” by one species from the other, appears fairly frequent in salamanders. Discordance between the signature of mitochondrial and nuclear genetic markers has been found in various genera of plethodontid (e.g. *Batrachoseps*, Wake & Jockusch, 2000) and salamandrid salamanders (e.g. *Chioglossa*, Sequeira et al., 2005; *Salamandra*, Garcia-Paris et al., 2003; *Taricha*, Kuchta & Tan, 2005). Well-documented cases in big-bodied newts (genus *Triturus*) include 1) the near-complete bias for *T. cristatus* mothered hybrids in *T. marmoratus* x *T. cristatus* interspecies hybrids in western France (Arntzen & Wallis, 1991) and 2) the presence of mtDNA typical of *T. karelinii* in *T. carnifex* and *T. dobrogicus* over a large area of northern Serbia (Wallis & Arntzen, 1989; Arntzen & Wallis, 1999). An example among small-bodied newts, genus *Triturus* (or *Lissotriton* or *Lophinus*) is the replacement across the entire Carpathian mountain range of the original *T. montandoni* mtDNA by that of *T. vulgaris* (Babik et al., 2005). Under the notion that flawed inferences from mtDNA may not be infrequent, its choice as a species marker was in this study rejected *a priori*. Nuclear microsatellite DNA markers have been successfully used to uncover genetic variation in *T. marmoratus* (Jehle et al., 2001, 2005; Krupa et al., 2002), but in our experience, it is not easy to isolate and amplify nuclear DNA from freshly deposited embryos. This technique may require a larger number of copies of nuclear DNA than is available in this life stage, the one most frequently observed in the field, and its application would involve raising the embryos in the laboratory.

The contact zone between *T. marmoratus* and *T. pygmaeus* runs over approximately 600 km across central to western Iberia, from approximately Madrid in central Spain to north of Lisbon in Portugal. None of the 25 ponds around Caldas da Rainha had a mixed population and individuals with intermediate enzyme profiles were not found (Fig. 1). This suggests the absence in our sample of F_1 interspecies hybrids. On the other hand, the pattern of allozyme discrimination here revealed is flat U-shaped (Fig. 1), rather than more sharply \perp -shaped as in the *T. helveticus*–*T. vulgaris* and *T. cristatus*–*T. marmoratus* situations (Fig. 2). The extent to which the shape of the curve represents incomplete diagnosticity of the enzyme genetic markers (as in *T. marmoratus* and *T. pygmaeus* and *T. helveticus*–*T. vulgaris*) versus gene flow has yet to be determined.

The minimum observed distance between *T. marmoratus* and *T. pygmaeus* populations in this study was 3.3 km. This contrasts to observations in Spain where the recorded minimum distance between the species was about 26 km between Cilleros and Zarza la Mayor in western Spain and about 6 km between Hoyo de Manzanares and Villalba in central Spain (García-París et al., 2001). With just three localities of *T. marmoratus* and eight localities of *T. pygmaeus* recorded in the province of Madrid (García-Paris et al., 1993), both species are locally rare and the contact zone between them has presumably

deteriorated, effectively forming a residual contact zone, *sensu* Szymura (1993).

In the section of the *T. marmoratus*–*T. pygmaeus* distribution considered here, the contact zone between the species is firmly parapatric. Moreover, the data point to the complete or near-complete genetic isolation of the taxa, therewith supporting their specific status under the Biological Species Concept. The taxonomic change was first put forward by García-París et al. (2001) and implemented by, for example, Frost (2004) and Montori et al. (2005). Our study differs from theirs in the following respects: 1) a fully diagnostic panel of nuclear genetic markers; 2) utilization of the mitochondrial genetic marker rejected; 3) larger number of populations (25 versus six); 4) small minimum inter-pond distances (3.3 km versus 6.0 km); and 5) not part of a residual contact zone. All too frequently, taxonomic and nomenclatorial change is proposed on the basis of a single type of data, including cases that rely on mtDNA data exclusively (e.g. *Salamandrina*, Mattoccia et al., 2005; *Plethodon*, Mead et al., 2005; *Carlia*, Couper et al., 2005). This contrasts with studies that integrate evidence from two or more sources, such as morphology, allozymes, mtDNA and nuclear DNA (e.g. *Calotriton*, Carranza & Amat, 2005; *Scaphiophryne*, Glos et al., 2005; *Salamandrina*, Nascetti et al., 2005; *Hyla*, Salducci et al., 2005).

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