6. Thakur, V. C., Active tectonics of the Himalaya. In *Recent Advances in Earth System Sciences* (eds Gupta, H. and Fareeduddin), Geological Society of India, Bangalore, 2008, pp. 227–258.
7. Yeast, R. S. and Thakur, V. C., Active faulting south of the Himalayan Front: establishing a new plate boundary. *Tectonophysics*, 2007, **453**, 63–73.
8. Thakur, V. C. and Pandey, A. K., Active deformation of Himalayan Frontal Thrust and Piedmont zone south of Dehradun in respect of seismotectonics of Garhwal Himalaya. *Himalayan Geol.*, 2004, **25**, 23–31.
9. Prakash, B., Kumar, S., Rao, M. S., Giri, S. C., Kumar, S., Gupta, S. and Srivastava, P., Holocene tectonic movements and stress field in the western Gangetic plains. *Curr. Sci.*, 2000, **79**, 438–449.
10. Murray, A. S. and Wintle, A. G., Luminescence dating of quartz using an improved single-aliquot regenerative dose protocol. *Radiat. Measure.*, 2000, **32**, 57–73.
11. Singhvi, A. K. and Aitken, M. J., Americium-241 for Alpha irradiations. *Ancient TL*, 1978, **3**, 2–9.
12. Middlemiss, C. S., The Kangra earthquake of 4 April 1905. *Mem. Geol. Surv. India*, 1910, **29**, 229.
13. Hough, S. E., Bilham, R., Ambreseys, N. and Feldl, N., *The 1905 Kangra and Dehradun Earthquakes*, Geological Survey of India, Special Publication, 2005, vol. 85, pp. 16–22.
14. Powers, P. M., Lillie, R. J. and Yeats, R. S., Structure and shortening of the Kangra and Dehradun re-entrants, sub-Himalaya, India. *Geol. Soc. Am. Bull.*, 1998, **110**, 1010–1027.
15. Pandey, D. N., Gupta, A. K. and Anderson, D. M., Rainwater harvesting as an adaptation to climate change. *Curr. Sci.*, 2003, **85**, 46–58.
16. Kale, V. S., Gupta, A. and Singhvi, A. K., Late Pleistocene–Holocene palaeohydrology of Monsoon Asia. In *Palaeohydrology: Understanding Global Change* (eds Gregory, K. J. and Benito, G.), John Wiley and Sons, Chichester, 2003, pp. 213–232.
17. Ruhland, K., Phadtare, N. R., Pant, R. K., Sangode, S. J. and Smol, J. P., Accelerated melting of Himalayan snow and ice triggers pronounced changes in a valley peatland from northern India. *Geophys. Res. Lett.*, 2006, **33**, L15709.
18. Banerjee, N. R., The iron age in India. In *Indian Prehistory* (eds Mishra and Matte), Poona, 1965, pp. 177–218.
19. Alchin, R. and Bridget, *The Rise of civilization in India and Pakistan*, Cambridge University Press., New Delhi, 1996, p. 373.

ACKNOWLEDGEMENTS. We thank Director, WIHG, Dehradun for technical and administrative support, Director, BSIP, Lucknow for ^{14}C dating of the samples; the DST for financial support under Kangra project. We acknowledge the support provided by Prof. Vinod Nautiyal, Prof. R. C. Bhatt, Dr P. M. Saklani, Dr Y. S. Farswan and the support staff of the Department of History, Ancient Indian History and Culture and Archaeology of the H.N.B. Garhwal University, Srinagar for archaeological excavation and study. Dr N. R. Phadatare provided useful inputs.

Received 19 March 2009; revised accepted 22 March 2010

A ground-dwelling rhacophorid frog from the highest mountain peak of the Western Ghats of India

S. D. Biju[1],*, Yogesh Shouche[2], Alain Dubois[3], S. K. Dutta[4] and Franky Bossuyt[5],*

[1]Systematics Lab, Department of Environmental Studies, University of Delhi, Delhi 110 007, India (e-mail: sdbiju@cemde.du.ac.in)
[2]National Centre for Cell Science, Pune University Campus, Pune 411 007, India (e-mail: yogesh@nccs.res.in)
[3]Reptiles et Amphibiens, UMR 7205 OSEB, Département de Systématique and Evolution, Muséum National d'Histoire Naturelle, CP 30, 25 rue Cuvier, 75005 Paris, France (e-mail: adubois@mnhn.fr)
[4]Department of Zoology, North Orissa University, Takatpur, Baripada 400 023, India (e-mail: sk_dutta@yahoo.com)
[5]Amphibian Evolution Lab, Biology Department, Unit of Ecology and Systematics, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium (e-mail: fbossuyt@vub.ac.be)

A new rhacophorid frog is described from Eravikulam National Park in the Western Ghats of India. The species is morphologically dissimilar from any known member of this family in having a bright orange to reddish colouration, multiple macroglands on the body and extremely short limbs. Phylogenetic analyses of mitochondrial genes indicate that this new frog is nested in a radiation of shrubfrogs that had its origin on the Indian subcontinent, and which is here recognized as a distinct genus, *Raorchestes* gen. nov. The new species, *Raorchestes resplendens* sp. nov. is likely restricted to less than 3 sq. km on the summit of Anamudi, and deserves immediate conservation priority.

Keywords: Endotrophic development, macroglands, mitochondrial phylogeny, *Raorchestes* gen. nov., *Raorchestes resplendens* sp. nov., Western Ghats.

THE Rhacophoridae constitute a radiation of about 300 species of frogs[1] with a distribution in the tropical regions of Asia and Africa. A large part of their taxonomy has traditionally been based on the variety of reproductive strategies, such as the use of foam nests or development without going through a free-swimming tadpole stage. Molecular evidence has recently solved the phylogenetic position of many rhacophorid species[2–7] and has resulted in the erection of new genera, such as *Gracixalus*[3], *Feihyla*[4], *Liuixalus*[5] and *Ghatixalus*[6]. Although rhacophorids find breeding microhabitats from the soil to the forest canopy, calling males are often found in vegetation layers[8], and the family as a whole is therefore usually considered arboreal. Here we describe an exceptional glandular rhacophorid with extremely short limbs from Anamudi summit (2695 m asl) in the Western Ghats of India. We performed molecular analyses to infer its phylogenetic position within the family and studied its reproduction and development.

---

*For correspondence.

We constructed a data matrix of 3370 bp mtDNA containing a part each of 12S rRNA, tRNA^{VAL}, 16S rRNA, ND1, tRNA^{ILE}, tRNA^{GLN} and tRNA^{MET} genes for a variety of rhacophorid frogs to infer the phylogenetic position of the new species within the family (GenBank accession number GU808563 for BNHS 5301). Maximum parsimony (MP) and maximum likelihood (ML) analyses were executed with the software PAUP* 4.0b10[9], Bayesian analyses and calculation of posterior probabilities were performed with MrBayes[10]. Our results largely agree with previous studies[6,11,12] and show that frogs traditionally classified in the genus *Philautus*[1] do not form a monophyletic group. Consistent with recent analyses[5,12], they form a clade with a main distribution on the Sunda shelf (*Philautus sensu stricto*), and a group with its centre of diversification on the Indian subcontinent. MP, ML and Bayesian analyses all place the new species in the latter clade of direct developing frogs, a group that in itself consists of two reciprocally monophyletic clades (Figure 1, left): the largest part of direct developing frogs form a distinct radiation with a notably large diversity in the Western Ghats. Its sister clade is a mainly Sri Lankan radiation, which has known a single dispersal event to the Indian mainland, resulting in few extant species in the Western Ghats[11]. Although the name *Kirtixalus* has been proposed for the latter clade[13], the older name *Pseudophilautus* Laurent 1943 is available for this island radiation[14,15] and its nested Indian members[11]. The type species of *Pseudophilautus*, *Ixalus temporalis* Günther 1864, is considered to be extinct[16], but clearly is a member of the Sri Lankan radiation of direct developing frogs. *Pseudophilautus* can be defined in a phylogenetic framework as the most inclusive clade including the species *Ixalus temporalis* Günther 1864 and excluding the species *I. glandulosus* Jerdon 1854. To distinguish species of the mainland radiation, we here suggest recognizing this remarkable and fairly large radiation (Figure 1, left) as a distinct genus.

***Raorchestes* gen. nov.** Type species, *Ixalus glandulosus* Jerdon 1854

Etymology: The generic epithet is derived from the name 'Rao' and the scientific nomen '*Orchestes*'. The former is chosen in honour of C. R. Narayan Rao, in recognition of his contribution to Indian batrachology. The latter is based on the first generic nomen coined for frogs of the *Philautus* group, *Orchestes* Tschudi 1838.

Diagnosis: We distinguish different kinds of taxognoses[17] and define the new genus according to two of them: *Idiognosis* (brief characterization of a taxon through characters): relatively small frogs, adult snout-vent length between 15 and 45 mm; vomerine teeth absent; large gular pouch transparent while calling; largely nocturnal species; direct development without free-swimming tadpoles in all species for which the development is known. *Entexognosis* (characterization of a taxon in a phylogenetic framework, through inclusion and exclusion of taxa or organisms): the most inclusive clade including *Ixalus glandulosus* Jerdon 1854 and excluding *I. temporalis* Günther 1864.

Distribution: Most species are from the Western Ghats of India, but recent molecular phylogenetic analyses supporting a nested position for '*Philautus*' *menglaensis*, *longchuanensis* and *gryllus* in this clade[12,15] indicate that the range of *Raorchestes* extends at least to southern China, Laos and Vietnam[1]. *Raorchestes* is absent from Sri Lanka.

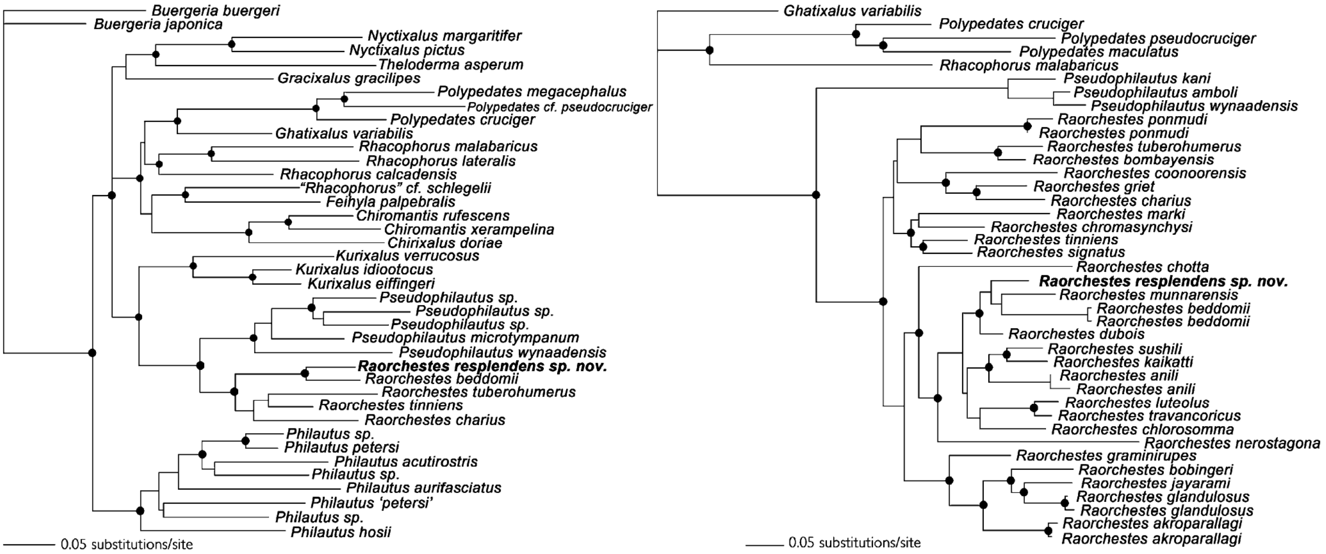

Figure 1. Left, Maximum likelihood tree based on a 3370 bp data matrix of mtDNA, showing the nested phylogenetic position of *Raorchestes resplendens* in the genus. Right, Maximum likelihood tree for known *Raorchestes* species (all except *R. ochlandrae*) of the Western Ghats, based on a 1488 bp data matrix of mtDNA. Black circles indicate Bayesian posterior probabilities above 95%.

Table 1. Morphometric measurements (all in mm; range, mean and standard deviation) of *Raorchestes resplendens* sp. nov. Abbreviations are defined in the text

	Male (*N* = 5)								Female (*N* = 2)				
	BNHS 4087	BNHS 5301	BNHS 5302	BNHS 5303	ZSIC A9140	Range	Mean	SD	BNHS 5304	BNHS 5305	Range	Mean	SD
SVL	24.0	24.5	22.7	24.0	24.5	22.7–24.5	23.9	0.7	28.3	25.2	25.2–28.3	26.8	2.2
HW	9.4	9.6	8.6	9.2	9.5	8.6–9.6	9.3	0.4	10.6	10.2	10.2–10.6	10.4	0.3
HL	9.1	8.9	8.1	8.7	9.1	8.1–9.1	8.8	0.4	10.1	9.8	9.8–10.1	10.0	0.2
SL	3.0	3.3	3.0	3.4	3.4	3.0–3.4	3.2	0.2	3.6	3.6	3.6	3.6	0.0
EL	2.4	2.6	2.7	2.6	2.6	2.4–2.7	2.6	0.1	2.7	2.8	2.7–2.8	2.6	0.1
IUE	2.7	3.1	2.9	2.9	2.8	2.7–3.1	2.9	0.1	3.3	3.4	3.3–3.4	3.4	0.1
UEW	1.6	1.3	1.3	1.5	2.1	1.3–2.1	1.6	0.3	1.3	1.3	1.3	1.3	0.0
FLL	4.8	5.0	4.7	4.6	5.0	4.6–5.0	4.8	0.2	5.4	5.3	5.3–5.4	5.4	0.1
HAL	6.0	6.3	5.8	6.6	6.3	5.8–6.6	6.2	0.3	6.9	6.6	6.6–6.9	6.8	0.2
ShL	8.3	8.2	7.8	8.2	8.3	7.8–8.3	8.2	0.2	9.8	8.7	8.7–9.8	9.3	0.8
TL	8.8	9.1	8.3	9.0	9.4	8.3–9.4	8.9	0.4	10.6	9.1	9.1–10.6	9.9	1.1
TFOL	12.9	12.6	11.8	12.8	13.2	11.8–13.2	12.7	0.5	14.7	12.4	12.4–14.7	13.6	1.6
FOL	8.5	9.1	7.0	8.5	8.9	7.0–9.1	8.4	0.8	1.1	9.1	9.1–10.1	9.6	0.7

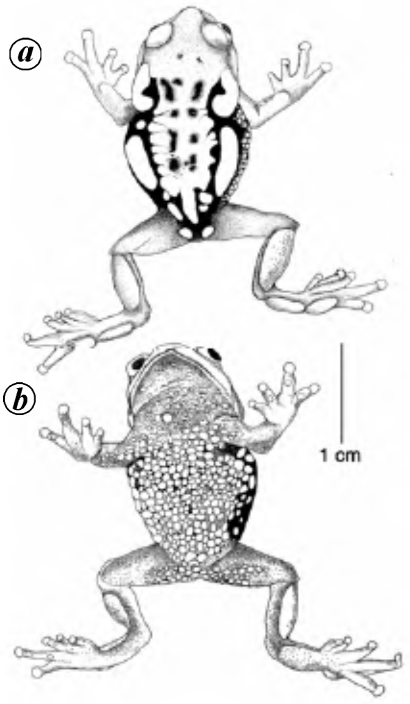

Figure 2. *Raorchestes resplendens* sp. nov. holotype. ***a***, Dorsal view; ***b***, Ventral view.

Raorchestes resplendens sp. nov. *Holotype*: BNHS 4087 (Figures 2, 3*a* left animal), an adult male collected by SDB at an altitude of 2695 m asl, at Anamudi summit, 10°10′N 77°05′E, Idukki District, Eravikulam National Park, Kerala, India. This specimen is kept in the Bombay Natural History Society (BNHS), Mumbai, Maharashtra, India. *Paratypes*: four adult males, BNHS 5301, 5302, 5303 and ZSIC A9140 (Kolkata, West Bengal, India); two adult females, BNHS 5304 and 5305. All were collected along with the holotype (Table 1).

Etymology: The species epithet '*resplendens*' is a Latin term meaning 'bright-coloured, glittering, resplendent'. It refers to the bright red or orange colouration. Suggested vernacular name: 'resplendent shrubfrog'.

Diagnosis: Raorchestes resplendens can be distinguished from all members of the genus by its multiple prominent glandular swellings; laterally behind the eyes, on the side of the dorsum, on the anterior side of the vent, on the dorsal side of the forearms and shanks, and on the posterior side of tarsus and metatarsus (Figures 2 and 3). Additionally, the colour of the iris is invariably bright red (Figure 3) and the legs are extremely short (Figure 4).

Phylogeny: To infer a more precise phylogenetic position of *R. resplendens*, we constructed a 1488 bp data matrix covering part of the 16S rRNA, part of the ND1, the complete tRNA^{ILE} and tRNA^{GLN}, and part of the tRNA^{MET} genes for all known extant species (except for *R. ochlandrae*) from the Western Ghats[2]. MP, ML and Bayesian are in agreement with previous analyses[2]. Additionally, *R. resplendens* comes out as a close relative of *R. beddomii*, *R. munnarensis* and *R. dubois* (Figure 1, right). The low support for relationships within this clade however indicates that either of the latter three species may be the sister taxon of *R. resplendens*.

Description: The description (all measurements in mm) of the holotype follows terminology used elsewhere[2,18–20]. Medium sized frog (SVL 24); head slightly wider than long (HL 9.1; HW 9.4; MN 7.4; MFE 6.6; MBE 4.1); outline of snout in dorsal view nearly rounded, its length (SL 3.0) larger than the horizontal diameter of the eye (EL 2.4); canthus rostralis indistinct; loreal region vertically acute; distance between posterior margins of eyes (IBE 8.0) 2.1 times in distance between anterior margins of eyes (IFE 3.8); interorbital area (IUE 2.7) larger than upper eyelid (UEW 1.6); tympanum (TYD 1.3) rather distinct, rounded; vomerine ridge absent;

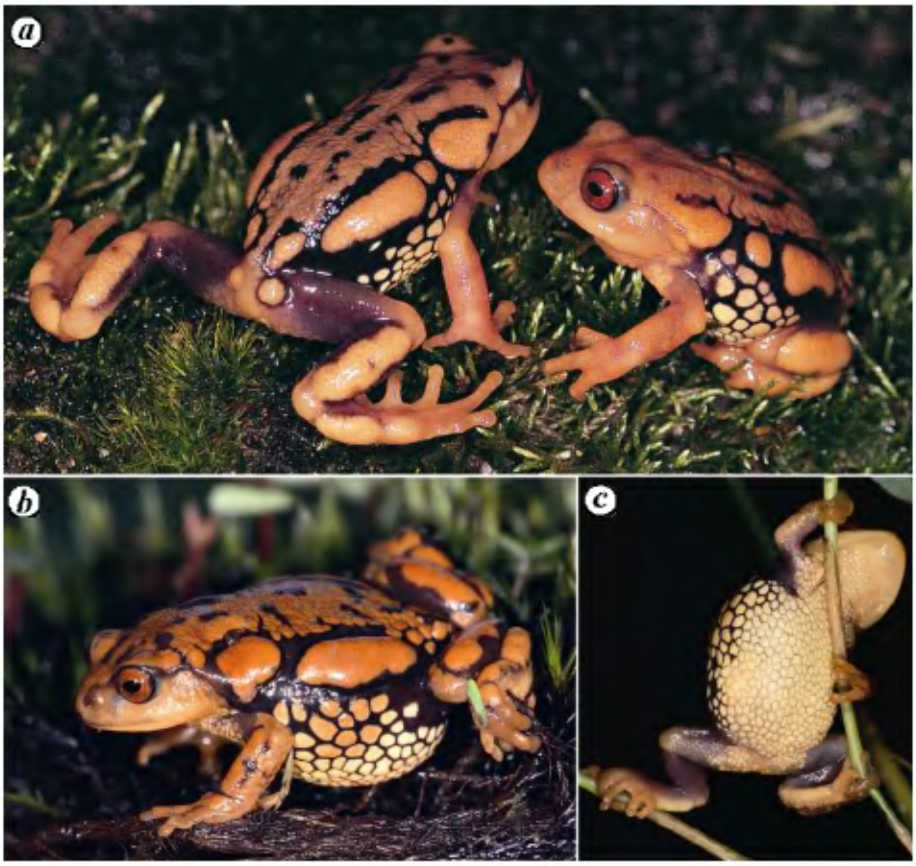

Figure 3. *Raorchestes resplendens* sp. nov. in life. ***a***, Holotype (BNHS 4087, left-hand side); paratype (BNHS 5302, right-hand side); ***b***, Paratype (BNHS 5304), profile; ***c***, Paratype (BNHS 5304), ventral side, showing granulation.

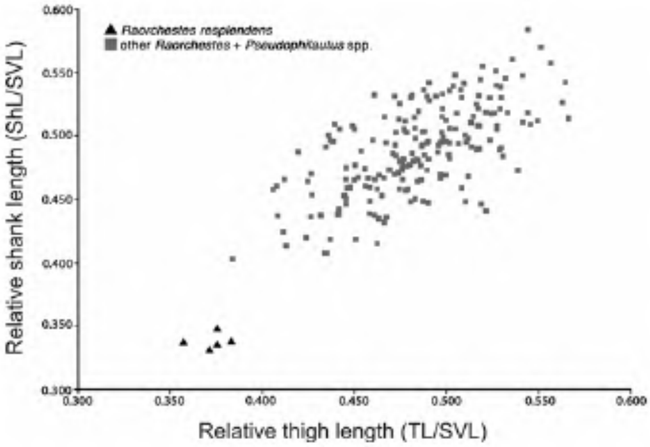

Figure 4. Plot of relative thigh length (x-axis, TL/SVL) versus relative shank length (y-axis, ShL/SVL) for 200 males of Indian *Raorchestes* and *Pseudophilautus* species. The plot shows a wide ecomorph diversity, likely corresponding to different microhabitat preferences. The extremely short legs of *Raorchestes resplendens* reflect its terrestrial ecology.

tongue cordate, without a papilla; supratympanic fold from posterior corner of upper eyelid to base of forelimb. Forelimb length (FLL 4.8) shorter than hand (HAL 6.0); tips of fingers with discs, with distinct circummarginal grooves; webbing on fingers absent; fingers without lateral dermal fringe; subarticular tubercle indistinct, prepollex oval; supernumerary tubercles absent, nuptial pads absent. Hind limbs moderately short; shank about 3 times longer (ShL 8.3) than wide (ShW 2.6), shorter than thigh length (TL 8.8), slightly shorter than distance from base of inner metatarsal tubercle to tip of toe IV (FOL 8.5; TFOL 12.9); tips of toes with discs and distinct circummarginal grooves; webbing reduced, reaching just below the 2nd subarticular tubercle on inside of toe IV and up to the 2nd subarticular tubercle on outside of toe IV; dermal fringe along toe V absent; subarticular tubercles rather indistinct; supernumerary tubercle absent; inner metatarsal tubercle indistinct.

Skin of snout smooth; between eyes shagreened; upper eyelids sparsely granular; anterior and posterior part of back and flanks with symmetrical glandular swellings: a kidney-shaped gland behind eye, a rather long and wide latero-dorsal gland all along upper part of flank, a small rounded gland on anterior side of vent; dorsal parts of limbs with glandular swellings: a long gland all along dorsal part of forelimbs (from elbow to base of hand); a rather long gland on dorsal part of shank, on posterior

Figure 5. ***a–g***, *Raorchestes resplendens* developmental stages in life. ***a***, Eggs after 3 h; ***b***, neural fold at 30 h; ***c***, head, limb bud and tail differentiation at 80 h and beginning of embryo rotation; ***d***, hind limb differentiation at 140 h; ***e***, elongation of toe and forelimb differentiation at 230 h; ***f***, froglet with reduced tail and mouth differentiated into upper and lower lips at 380 h and tail and yolk considerably reduced in this stage; ***g***, fully mobile froglets measuring SVL 4.5 ± 0.7 mm emerged after 540 h (about 22 days).

side of tarsus, and on posterior side of metatarsus of toe V; a few less prominent glands throughout the dorsal and lateral parts of the body (Figure 3*a*, left); ventral side of throat slightly granular, belly coarsely granular (oval to hexagonal); thigh and lower arm sparsely granular.

Colour of holotype: In life (Figure 3*a*, left): The predominant colour of dorsum is deep brick red, which sharply contrasts with the black filling irregular furrows on the dorsum; the dorsal parts of limbs, fingers, toes and tips are uniform deep brick red; glandular swellings are surrounded with black patches; posterior lateral abdominal area, groin and inner side of the thighs are black; ventral side light yellow, with irregular oval to hexagonal granulation; iris bright red. In alcohol, the dominant brick red colour changed into brownish grey which contrasts with the black furrows; lateral side light yellowish; limbs are reddish grey; ventral side light greyish white.

Breeding and development: Breeding observations were conducted in the natural habitat without handling the animals. During a late afternoon (16 h) in July, a pair of *R. resplendens* in amplexus was located on the ground in bamboo thickets. Initial amplexus was inguinal for a period of about 3 h during which time the female was almost motionless. After that, the amplexus became axillary, the female started to search for a suitable oviposition site, and at 20 h, eggs were burrowed under the moss covered forest floor, deep inside the base of bamboo clumps. The male and female left the nest immediately after completion of spawning. Several other clutches were located within a radius of 7 m, and all were at the base of bamboo clumps (number of eggs: 18–28, $N = 7$).

The female, male and egg clutches were collected and developmental stages were observed under laboratory conditions with a temperature difference from natural conditions of maximum 3°C. As in other species of this genus, *R. resplendens* undergoes direct development, i.e. complete development in the eggs, without a free-swimming larval stage. After oviposition (eggs: $N = 24$, diameter 4.1 ± 0.4 mm), the female's oviduct still contained mature embryos ($N = 18$, diameter 3.8 ± 0.5 mm). This indirectly suggests that the female may mate with multiple males and/or may breed more than once in a single season. The developmental time from embryo to hatchling varied from 22 to 27 days ($N = 7$). Descriptions of embryo morphology are based on observation of living and preserved material. The major features of eight stages are illustrated in Figure 5 *a–g*.

Comments on morphology: The combination of a unique morphology and nested phylogenetic position of the new species points to a quick morphological divergence from congeners. The most striking character of *R. resplendens* is the presence of numerous macroglands. These are absent in all species of *Philautus*, *Pseudophilautus* and *Raorchestes* presently known and thus are derived characters. The presence, distribution and size of the macroglands shows no sexual dimorphism, so we hypothesize that the primary function will not be involved in reproduction, but this needs further testing. The quick morphological evolution is also visible when plotting relative limb length of *Pseudophilautus* and *Raorchestes* species (Figure 4). These measurements indicate that the new species has much shorter limbs than

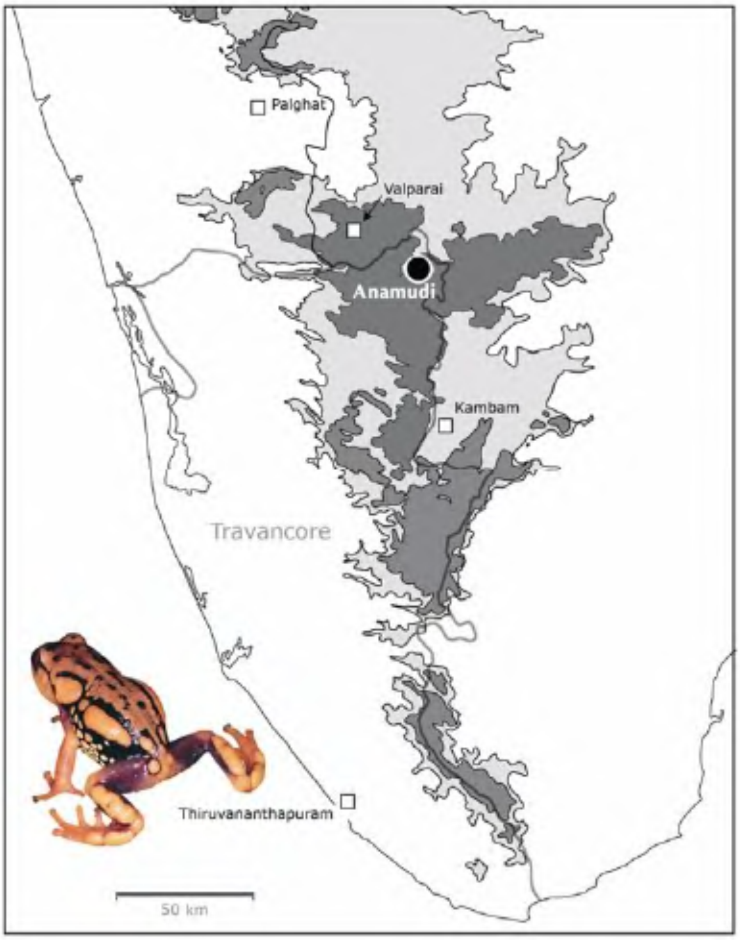

Figure 6. Map showing the type locality of *Raorchestes resplendens* at Anamudi, in the Western Ghats. Map modified from Inger *et al.*[21]. Shaded contours showing above 300 m asl (light) and above 1000 m asl (dark).

its congeners and members of the sister clade, pointing to a rapid morphological evolution that is dissociated from molecular evolution. These short limbs have resulted in a much more pronounced crawling behaviour in this species compared to its congeners.

Comments on conservation concern: R. resplendens is known only from the type locality (Figure 6). The highest temperature reported for the Anamudi summit is 30°C in May 1980 and the lowest is –3°C in June 1980 (ref. 22). The vegetation, climate and temperature of the hills are different from other regions of the Western Ghats, and share several floristic elements with Himalayas[22–24]. Most importantly, despite intensive searches in suitable habitats close to the type locality, we were unable to locate this species in any other place. It is therefore possible that the entire range of this species does not exceed a few square kilometres. We suggest immediate action to make this highly endangered species a top priority for conservation.

1. Frost, D. R., Amphibian Species of the World: an online reference. Version 5.3 (1 February 2009). Electronic Database accessible at http://research.amnh.org/herpetology/amphibia/index.html. American Museum of Natural History, New York, USA.
2. Biju, S. D. and Bossuyt, F., Systematics and phylogeny of *Philautus* Gistel, 1848 (Anura, Rhacophoridae) in the Western Ghats of India, with descriptions of 12 new species. *Zool. J. Linn. Soc.*, 2009, **155**, 374–444.
3. Delorme, M., Dubois, A., Grosjean, S. and Ohler, A., Une nouvelle classification générique et subgénérique de la tribu des Philautini (Amphibia, Anura, Ranidae, Rhacophorinae). *Bull. Mens. Soc. Linn. Lyon*, 2005, **74**, 165–171.
4. Frost, D. R. *et al.*, The amphibian tree of life. *Bull. Am. Mus. Nat. Hist.*, 2006, **297**, 1–370.
5. Li, J., Che, J., Bain, R. H., Zhao, E. and Zhang, Y., Molecular phylogeny of Rhacophoridae (Anura): a framework of taxonomic reassignment of species within the genera *Aquixalus*, *Chiromantis*, *Rhacophorus* and *Philautus*. *Mol. Phylogenet. Evol.*, 2008, **48**, 302–312.
6. Biju, S. D., Roelants, K. and Bossuyt, F., Phylogenetic position of the montane treefrog *Polypedates variabilis* Jerdon, 1853 (Anura: Rhacophoridae), and description of a related species. *Organ., Divers. Evol.*, 2008, **8**, 267–276.
7. Grosjean, S., Delorme, M., Dubois, A. and Ohler, A., Evolution of reproduction in the Rhacophoridae (Amphibia, Anura). *J. Zool. System. Evol. Res.*, 2008, **46**, 169–176.
8. Biju, S. D. and Bossuyt, F., A new species of frog (Ranidae, Rhacophorinae), *Philautus* from the rainforest canopy in the Western Ghats, India. *Curr. Sci.*, 2005, **88**, 175–178.
9. Swofford, D. L., PAUP*: Phylogenetic Analysis Using Parsimony (*and Other Methods) version 4.0b10, Sinauer Associates, Sunderland, MA, 2002.

10. Ronquist, F. and Huelsenbeck, J. P., MrBayes 3: Bayesian phylogenetic inference under mixed models. *Bioinformatics*, 2003, **19**, 1572–1574.
11. Bossuyt, F. *et al.*, Local endemism within the Western Ghats–Sri Lanka biodiversity hotspots. *Science*, 2004, **306**, 479–481.
12. Yu, G., Rao, D., Zhang, M. and Yang, J., Re-examination of the phylogeny of Rhacophoridae (Anura) based on mitochondrial and nuclear DNA. *Mol. Phylogenet. Evol.*, 2009, **50**, 571–579.
13. Dubois, A., Miscellanea taxinomica batrachologica (I). *Alytes*, 1987, **5**, 7–95.
14. Laurent, R., Contribution à l'ostéologie et à la systématique des Rhacophorides non africains. *Bull. Mus. R. Hist. Nat. Belg.*, 1943, **19**, 1–16, pl. I–II.
15. Li, J., Che, J., Murphy, R. W., Zhao, H., Zhao, E., Rao, D. and Zhang, Y., New insights to the molecular phylogenetics and generic assessment in the Rhacophoridae (Amphibia: Anura) based on five nuclear and three mitochondrial genes, with comments on the evolution of reproduction. *Mol. Phylogenet. Evol.*, 2009, **53**, 509–522.
16. Manamendra-Arachchi, K. and Pethiyagoda, R., The Sri Lankan shrub-frogs of the genus *Philautus* Gistel, 1848 (Ranidae: Rhacophorinae), with description of 21 new species. In *Contributions to Biodiversity Exploration and Research in Sri Lanka* (eds Yeo, D. C. J., Ng, P. K. L. and Pethiyagoda, R.), The Raffles Bulletin of Zoology, Singapore, Supplement, 2005, vol. 12, pp. 163–303.
17. Dubois, A. and Raffaëlli, J., A new ergotaxonomy of the family Salamandridae Goldfuss, 1820 (Amphibia, Urodela). *Alytes*, 2009, **26**, 1–85.
18. Dubois, A. and Ohler, A., A new species of *Leptobrachium* (*Vibrissaphora*) from northern Vietnam, with a review of the taxonomy of the genus *Leptobrachium* (Pelobatidae, Megophryinae). *Dumerilia*, 1998, **4**, 1–32.
19. Dubois, A. and Ohler, A., Asian Oriental toads of the *Bufo melanostictus*, *Bufo scaber* and *Bufo stejnegeri* groups (Amphibia, Anura): a list of available and valid names and redescription of some name-bearing types. *J. South Asian Nat. Hist.*, 1999, **4**, 133–180.
20. Bossuyt, F. and Dubois, A., A review of the frog genus *Philautus* Gistel, 1848 (Amphibia, Anura, Ranidae, Rhacophorinae). *Zeylanica*, 2001, **6**, 1–112.
21. Inger, R. F., Shaffer, H. B., Koshy, M. and Bakde, R., A report on a collection of amphibians and reptiles from the Ponmudi, Kerala, South India. *J. Bombay Nat. Hist. Soc.*, 1984, **81**, 406–570.
22. Rice, C. G., The behavior and ecology of the Nilgiri tahr (*Hemitragus hylocrius* Ogilby, 1838), Unpublished PhD dissertation, 1984, Texas A&N University, USA, pp. 254.
23. Biju, S. D., Pushpangadan, P. and Mathew, P., *Stictocaedia sivarajanii*, a new species of Convolvulaceae from Kerala, India. *Novon*, 1999, **9**, 147–149.
24. Daniels, R. J. R., Endemic fishes of the Western Ghats and the Satpura hypothesis. *Curr. Sci.*, 2001, **81**, 240–244.

ACKNOWLEDGEMENTS. We thank Kim Roelants, R. F. Inger, Rohan Pethiyagoda, I. Das, Stephen Mahony and Rachunliu G. Kamei for critical review of an early draft of the manuscript. SDB is supported by a research grant from Department of Biotechnology, Govt of India (DBT) and University of Delhi (Scheme to strengthen R&D doctoral research programme). S.D.B. thanks T. M. Manoharan, Principal Chief Conservator of Forests, Kerala for his constant source of inspiration and financial support, and the Kerala Forest Department for giving necessary permission to survey.

Received 17 September 2009; revised accepted 22 March 2010

BOOK REVIEWS

Annual Review of Nuclear and Particle Science, 2009. Barry R. Holstein, Wick C. Haxton and Abolhassan Jawahery (eds). Annual Reviews, 4139 El Camino Way, P.O. Box 10139, Palo Alto, California, USA. Vol. 59. ix + 568 pp. Price: US$ 214.

The *Annual Review of Nuclear and Particle Science* is produced annually and is a useful handbook on the most recent advances in the field. The collection of 21 articles in the present volume is indeed at the frontier and at the intersection of several frontiers, those of theory, experiment and observation in the fields of elementary particle physics and cosmology. The collection also contains highly theoretical articles based on string theory, a popular candidate for the unification of all forces including gravitation, and on its recent attempts to make contact with disparate phenomena. While there are common threads that run through some of the articles, each in itself represents a landmark contribution summarizing the state of knowledge in the field that each of the articles purports to address. Besides being pedagogical and lucid, the articles also contain useful bibliographies which would allow the interested student and scholar to peruse the topic of his or her choice.

As is the tradition with the Annual Reviews, the opening articles are often of biographical or autobiographical nature of a scientific kind. These volumes often contain articles which pay tribute to the contributions of specific individuals, and indeed the present volume has such tributes to three neutrino pioneers, John Bahcall, Raymond Davis Jr and Yoji Totsuka. The first of these is 'The Scientific Life of John Bahcall' by Wick Haxton, the second 'The life of Raymond Davis Jr and the beginning of neutrino astronomy' by Kenneth Lande and finally 'Yoji Totsuka (1942–2008) and the discovery of neutrino mass' by Henry W. Sobel and Yoichiro Suzuki. Indeed, Bahcall and Davis together over four decades established the solar neutrino problem, while Totsuka pioneered the study of astrophysical neutrinos using large water detectors.

The neutrino itself is a particle that was first introduced by Wolfgang Pauli around 1930 to explain the continuous energy spectrum of emitted electrons in nuclear beta decay. It was given the name neutrino subsequently by Enrico Fermi. As discoveries took place, it was established that there are three types, electron, muon and τ-type neutrinos. Neutrinos are produced in copious quantities in the sun in reactions that power the sun take place. Nevertheless, due to their very tiny interaction cross-sections, terrestrial experiments to detect them required the construction of highly specialized detectors. Davis pioneered a radiochemical technique to detect them by looking for radioactive argon produced in neutrino-induced reactions on chlorine nuclei. Over decades of painstaking experimentation he established that there was a shortfall in the numbers of neutrinos reaching the earth, which crucially required accurate computations of the expected rates at the earth, which in turn were pioneered by Bahcall. Thus, the present volume honours the two pioneers of the solar neutrino problem.

It may be noted that while M. Koshiba who shared the 2002 Nobel prize with Davis started the first large water Kamiokande experiment, it was Yoji Totsuka who took the technique to significantly higher levels with the super-Kamiokande experiment but sadly succumbed recently to cancer. The great achievement of super-Kamiokande was to prove beyond doubt the phenomenon of neutrino oscillation from one type to another which in turn proved the existence of mass for these particles. Thus, the first signs of physics beyond the standard model were detected.

Of immediate interest is the article 'The Sudbury Neutrino Observatory' by Nick Jelley *et al.*, which reports the achievements of the eponymous observatory which definitely established neutrino oscillation by the use of heavy water targets as the solution of the solar neutrino problem. The article recalls touchingly the history of the project which can be traced to the work of Herbert Chen who proposed the experiment in 1984 and died within five years of leukemia.

Neutrino physics is of immediate relevance of astrophysics as already seen above and also to cosmology. Indeed, there is an open question of the existence of sterile neutrinos which will not show up in particle physics considerations, but could easily leave their imprint on cosmology and on the future of the Universe. This subject is reviewed in the article entitled 'The role of sterile neutrinos in cosmology and astrophysics' by Alexey Boyarsky *et al.*

There are many sources of information from cosmology, but precisely how does one derive conclusions from some observations. Andrew R. Liddle in 'Statistical methods for cosmological parameter selection' explains how this is done. In the context of cosmology, one of the abiding mysteries is the origin of high energy cosmic rays. This subject is reviewed in 'The highest-energy cosmic rays' by James J. Beatty and Stefan Westerhoff, while the scenarios for how such cosmic rays come about is reviewed in 'The physics of cosmic acceleration' by Robert R. Caldwell and Marc Kamionkowski.

Of the many problems facing cosmology, the observed homogeneity and isotropy of the microwave background radiation is one of the most notable. Some decades ago an inflationary epoch soon after the big bang was proposed as a solution to the problem, with origins in grand unified theories, linking the microscopic to the macroscopic. Decades later and many satellite and balloon-borne experiments later, with the establishment of Wilkinson Microwave Anisotropy Probe providing accurate information on the primordial density fluctuations which seeded structure formation, cosmology in turn poses challenges to elementary particle physics. Such a challenge has been confronted by string theory. In the present volume, the article 'Advances in inflation in string theory' by Daniel Baumann and Liam McAllister gives a status summary of the subject. The present volume also includes review articles on more specialized topics in string theory; 'D-Brane instantons in type II orientifolds' by Ralph Blumenhagen *et al.* Interesting applications of string theories based on its internal consistency include those to strong interactions, summarized in this volume in the article 'From gauge-string duality to strong interactions: a pedestrian's guide' by Steven S. Gubser and Andreas Karch.

While the standard model has assumed a hegemonic standing in elementary particle physics, there are several sectors of it which are continuously studied at higher precision both in theory and in effective field theories where conventional methods fail. What precisely does the standard model hold for simple bound states of the strong interactions such as