Large-scale distribution of hybridogenetic lineages in a Spanish desert ant

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Recently, a unique case of hybridogenesis at a social level was reported in local populations of the desert ants *Cataglyphis*. Queens mate with males originating from a different genetic lineage than their own to produce hybrid workers, but they use parthenogenesis for the production of reproductive offspring (males and females). As a result, non-reproductive workers are all inter-lineage hybrids, whereas the sexual line is purely maternal. Here, we show that this unorthodox reproductive system occurs in all populations of the ant *Cataglyphis hispanica*. Remarkably, workers are hybrids of the same two genetic lineages along a 400 km transect crossing the whole distribution range of the species. These results indicate that social hybridogenesis in *C. hispanica* allows their maintenance over time and across a large geographical scale of two highly divergent genetic lineages, despite their constant hybridization. The widespread distribution of social hybridogenesis in *C. hispanica* supports that this reproductive strategy has been evolutionarily conserved over a long period.

1. Introduction

Hybridogenesis, or hemi-clonality, is an unusual mode of reproduction whereby a hybrid female expresses the paternal genome that she inherited from her father, yet she fails to transmit that paternal genome to her offspring [1,2]. During oogenesis, the chromosome sets of the parents fail to recombine and the paternal genome is excluded from the ova. As a consequence, both the maternal and paternal genomes are expressed in somatic tissues, whereas only the maternal genome constitutes the germ line and is perpetuated across generations. Hybridogenesis has been reported in several taxa of vertebrates, including *Poeciliopsis* teleost fishes [2], *Rana* waterfrogs [3] and *Bacillus* stick-insects [4], where it has been shown to stem from hybridization between different species.

Remarkably, a form of hybridogenesis at the social level has been reported in some ant species [5–13]. The hallmark of ant societies is reproductive division of labour based on a system of caste differentiation. Workers usually forgo their own direct reproduction and perform all the tasks required for colony development and growth (foraging, defending and caring for the brood), whereas queens and males are responsible for reproducing the colony [14]. In hybridogenetic ants, populations consist of self-sustainable pairs of perpetually hybridizing genetic lineages. Queens of each lineage mate with males originating from the co-occurring alternative lineage to produce hybrid workers. By contrast, reproductive individuals arise from intra-lineage mating or parthenogenesis and maintain pure-lineage genomes. Such a reproductive system results in a strong caste–genotype association (see reviews [15,16]).

Various inheritance modes have been described in ants with interdependent lineages. In the *Pogonomyrmex barbatus/Pogonomyrmex rugosus* species complex [10–12] and in *Solenopsis xyloni × Solenopsis geminata* [13], both female castes are produced by sexual reproduction: inter-lineage mating produces workers, whereas intra-lineage mating produces queens. Therefore, colonies must contain both inter- and intra-lineage mating pairs to produce the two female castes. Colonies of *Pogonomyrmex* are headed by single queens mated multiple times with males from their own as well as the alternative lineage. By contrast, colonies of *S. xyloni* contain multiple queens, each mated with a single male. Queens mated with a male of their own species produce only reproductive females (new...
populations of clonal lineages. Workers combine alleles from both maternal and paternal genomes, whereas male genomes are therefore completely isolated, whereas female genomes have only a single genome: new queens are clones of their mothers. Another type of dependence is seen in species that produce inter-lineage sterile workers. By contrast, queens only use parthenogenesis for colony reproduction (i.e., new queens and males production). As a consequence, reproductive lines maintain non-recombinant pure-lineage genomes over time. Black and white colours represent nuclear genomes from the two genetic lineages.

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Figure 1. Social hybridogenesis in *C. hispanica*. Two genetic lineages, His1 and His2, coexist in each population of *C. hispanica*. Pure-lineage queens mate with a male originating from the alternative lineage than their own and use its sperm to produce inter-lineage sterile workers. By contrast, queens only use parthenogenesis for colony reproduction (i.e., new queens and males production). As a consequence, reproductive lines maintain non-recombinant pure-lineage genomes over time. Black and white colours represent nuclear genomes from the two genetic lineages.

2. Material and methods

(a) Biological model and sampling

*Cataglyphis hispanica* is found in the most arid habitats of the southwest of the Iberian Peninsula. In previously studied Andalusian populations, colonies were found to be headed by a single queen mated once [9]. Dispersal of colonies proceeds by budding: young mated queens leave the natal nest with the help of worker sisters and establish new colonies nearby.

To study the phylogeographic distribution of hybridogenetic lineages, we collected 68 colonies from 14 populations of *C. hispanica* along a 400 km north–south transect across the entire range of the species (figure 2). The number of colonies sampled per site ranged from three to seven (table 1). Colonies were excavated at the time of sexual production, in May 2012. Alate (virgin) queens and a sample of workers from each nest were directly preserved in 95% ethanol for subsequent genetic analyses. Mated wingless queens were taken alive to the laboratory for fresh dissection of their spermathecae.

(b) DNA isolation

DNA was extracted from adult ants by the Chelex 100 method [9]. To determine the number of mates of each queen and their
primer sets were tested on seven Lepais & Bacles [24]. The amplification of the corresponding conditions following a screening pipeline similar to the one use by [23] was used to select a set of 24 loci with dinucleotide repeats that of the mother nest. In this situation, the number of genotypes inferred from workers is indicated in brackets.) Because foundation of new colonies proceeds by budding, workers in newly started colonies are not daughters of the resident queen but derive from the queen of the mother nest. In this situation, the number of genotypes inferred from workers is indicated in brackets.)

<table>
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<th>locality</th>
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<th>queens (incl. inferred)</th>
<th>males (incl. inferred)</th>
<th>queen/colony (range)</th>
<th>males/queen (range)</th>
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<td>Bonares</td>
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<td>5</td>
<td>5</td>
<td>1</td>
<td>1</td>
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<td>5</td>
<td>5</td>
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<td>1</td>
</tr>
<tr>
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<td>5 (5)</td>
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<td>1</td>
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<tr>
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*Populations surveyed by Leniaud et al. [9].

First, we determined the number of queens per colony from field observations. Second, we estimated queen-mating frequency from the genotype of spermatheca contents. We considered the number of mates as equal to the maximum number of alleles at any locus. This method is straightforward because queens of C. hispanica typically mate singly (Leniaud et al. [9]; our present data). Third, we tested whether social hybridogenesis occurs across the species distribution range. To this aim, we considered three features of social
hybridogenesis [8,9]: (i) the pairing of reproductive individuals belonging to different genetic lineages, (ii) the production of hybrid workers by sexual reproduction, and (iii) the parthenogenetic production of queens. In each population sampled, we examined whether mating occurred between partners belonging to the same lineage or to different lineages based on the results of clustering analyses (see below). In addition, the mode of production of workers and new queens (i.e. parthenogenesis or sexual reproduction) was investigated using comparisons of parent–offspring genotypes. Sexually produced offspring bear one allele of their mother’s mate at all loci, whereas parthenogenetically produced offspring bear alleles that can all be attributed to the queen.

(e) Diversity of hybridogenetic lineages across the species range

We used three complementary clustering approaches to determine the number of hybridogenetic lineages pairs across the species range: Bayesian clustering analyses, genetic-distance-based principal coordinates analysis (PCoA) and neighbour-joining tree based on shared allele distance. Our dataset consists of the genotypes of all available reproductives (the collected queens and their male mates inferred from the sperm stored in each queen’s spermatheca), as well as of uncollected reproductives (inferred from workers genotypes; table 1). Because queens of C. hispanica are produced by parthenogenesis and disperse at short-range by budding, there was a high probability of sampling queens with identical multilocus genotype in each population. In this case, only one queen per multilocus genotype was included in our analyses. Haploid male genotypes were encoded as diploid by doubling their alleles. Bayesian clustering method implemented in STRUCTURE 2.3.3 [26] was used to determine the number of lineages (K) among reproductives. The program was run 10 times for each value of K = 1–10, with 100 000 Markov chain Monte Carlo iterations and a burn-in period of 40 000. Analyses were performed under the admixture model with independent allele frequencies and without prior population information. K-values that give consistent results between 10 runs are likely to represent real genetic structure. Therefore, the similarity coefficient among each pair of runs was calculated using the R-script STRUCTURE-sum-2009 [27]. The most probably number of genetic lineages was also investigated using the ad hoc d-K method [28]. Graphical outputs were created with DISTRUCT [29]. Although the STRUCTURE model assumes Hardy–Weinberg and linkage equilibrium, it has been shown to perform well on data from parthenogenetic organisms, which violate these assumptions [30–32]. Moreover, INSTRUCT analyses, an alternative to STRUCTURE that drops the assumption of Hardy–Weinberg equilibrium [33], were performed with the same input parameters and returned exactly the same results as those of STRUCTURE (data not shown). Nevertheless, for cross-validation of STRUCTURE results, we carried out two model-free analyses. First, genetic-distance-based PCoA

Table 2. Characteristics of 12 microsatellite loci in C. hispanica. (Primer names and sequences, fluorescent dye added to the 5’ end of the forward primer, repeat motif type, number of observed alleles (N_A), corresponding size range of the amplified fragment and GenBank accession numbers are given for each locus.)

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<th>motif</th>
<th>N_A</th>
<th>size range (bp)</th>
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</table>

*Loci previously developed for C. cursor [20]; for those loci, motifs information is taken from published C. cursor sequences.
was performed with GENALEX v. 6.41 [34]. Second, a neighbour-
joining tree based on shared allele distance (\(D_{AS}\)) was
constructed with POPULATIONS v. 1.2.31 [35].

To explore further the spatial structure of each genetic lineage,
we performed a second batch of STRUCTURE on identified lineages.
Also, we investigated isolation-by-distance within each lineage by
plotting \([F_{ST}/(1 - F_{ST})]\) coefficients between pairs of populations
against the ln of the geographical distance [36]. Significance of correlation coefficient was assessed with a Mantel test as
implemented in GENETIC [37].

3. Results

(a) Colony kin structure

In 12 of 14 populations sampled, all colonies excavated were
headed by a single queen \((n = 59)\). Multiple-queen colonies
were found in two populations (two colonies over four in
population 49 and five over five in population 41; table 1);
they were headed by two to six queens per colony. Sixty-
eight queens collected over the whole sampling area were
dissected for genetic analysis of their spermathecal content.
Among these, 65 queens contained sperm from a unique mul-
tilocus haploid genotype, while three queens (4.4%) had no
more than two male genotypes per spermatheca. Previous
work (Leniaud et al. [9]) showed that the probability of
non-detection of additional patrilines owing to two fathers
sharing the same alleles at all loci is lower than 0.04. These
results indicate that single mating of queens (monoandry) is
the rule in \(C. \) hispanica. Notably, all but five queens out of
68 (92.6%) had sperm from males of alternate lineage (see
results below for lineages diversity). All five queens mated
with males from their own lineage were found in multiple-
matriline colonies.

Across the 14 populations sampled, workers were highly
heterozygous (mean observed heterozygosity per locus \(\pm
\) s.d. = 0.93 \(\pm\) 0.06). All 408 workers analysed from the 68
colonies had inter-lineage genotypes resulting from hybrid
crosses between two lineages. Not a single purebred worker
was found, even in colonies with same-lineage mates. By
contrast, neither virgin queens nor mated queens showed a
genotype consistent with hybridization between two lineages.

Figure 3. \(C. \) hispanica consists of two hybridizing lineages. In this panel, colours distinguish lineages (His1 lineage, green; His2 lineage, red), as well as
gеographical variation within lineages (red and green values). Analyses are based on microsatellite data from 164 queens and males genotypes sampled across the
14 sites. (a) Plot of the first two axes from PCoA. The percentage of variation explained by each axis is indicated. (b) Population clustering analysis inferred with
STRUCTURE assuming two lineages and one to six within-lineage subpopulations. The highest probability run for each \(K\) is shown. (c) Neighbour-joining dendrogram
based on allele sharing genetic distances (\(D_{AS}\)). In (b,c), within-lineages reproductives are ordered according to their sampling localities; data are given according to
the south (S)–north (N) axis, which successively crosses Andalusia (AND), Extremadura (EXT) and Castile & León (CAS) regions.

(b) Diversity of hybridogenetic lineages across the
species range

We observed 164 different multilocus genotypes among a
total of 210 reproductive individuals (i.e. the queens and
their mates inferred from sperm or from workers genotypes,
see Material and methods). The three clustering approaches
showed strong lineage clustering (figure 3). On the PCoA
(figure 3d), the genotypes formed two clusters distinguish-
able by their first coordinate (PC1), which accounted for
42% of total genetic variation. Individuals of both sexes and
from all collecting sites were found in each cluster. The
neighbour-joining tree reflected the same assignments, but
each cluster had further regional structuring corresponding
to biogeographic zones (Castile & León, Extremadura and
Andalusia, figure 3c). Bayesian analyses using STRUCTURE
confirmed these results (figure 3b; see also the electronic
supplementary material, figure S1). Likelihood values
increased with the number of groups \((K)\), but the second-
order likelihood (\(\delta-K\)) was much higher for \(K = 2\). Moreover,
all runs performed with \(K = 2\) showed identical results, while
higher values of \(K\) gave inconsistent results. Separate ana-
lyses resulted in geographical structuring as seen in the
neighbour-joining tree, although the definition of clusters
was unstable over runs according to similarity coefficients
(see the electronic supplementary material, figure S1). For
each of the two groups, there was significant correlation
between population genetic differentiation and the geographi-
cal distance (Mantel test: His1, \(r = 0.37, p < 0.00001\); His2,
\(r = 0.47, p < 0.0001\)).

Altogether, these results indicate that the reproductive
individuals of \(C. \) hispanica belong to two lineages that are
sympatric across the entire range of the species. These
lineages correspond to the single pair His1/His2 previously described in Andalusian populations [9]. The two interbreeding lineages formed highly divergent gene pools: nine out of 12 loci (Cc11, Cc54, Cc93, Ch01, Ch05, Ch08, Ch12, Ch20 and Ch23) had distinctly different allele size distributions, with 63–97% of alleles being diagnostic of the lineage per locus (see the electronic supplementary material, figure S2). Allele size distributions were overlapping between the lineages for the remaining three loci (Ch06, Ch11 and Ch22).

4. Discussion

Our results show that social hybridogenesis is a major feature of the reproductive system of the desert ant C. hispanica. Social hybridogenesis occurs in all populations sampled along a 400 km transect crossing the whole distribution range of the species. In the 68 colonies studied: (i) the male and female sexuals are pure-lineage individuals, consistent with their parthenogenetic production; (ii) the queens and their mates generally belong to different genetic lineages; and (iii) all workers arise from hybrid crosses between the lineages. Remarkably, our data show that all workers are hybrids of the same two highly divergent genetic lineages across the 14 sampled populations.

A single queen usually heads each colony, but populations with multiple-queen colonies do exist (two to six queens per colony). Recently, social hybridogenesis was reported in multiple-queen colonies of C. velox and C. mauritanica, indicating that monogyny is not a prerequisite for the evolution of hybridogenesis in Cataloglyphis ants [8]. Queens of C. hispanica are mated once (rarely twice) with male(s) originating from the alternative lineage of their own and use sperm to produce hybrid workers by sexual reproduction. Rare intra-lineage mated queens were found (five out of 68) in multiple-queen populations. However, these queens seem to usurp multiple-queen colonies as not a single pure-lineage worker genotype was found, indicating that they do not contribute to worker production. By contrast with workers, daughter queens have identical multilocus genotypes and assuming a significance level of $\alpha = 0.05$, a third genetic lineage should occur at a maximum frequency of 0.018; thus, there are 55 times more individuals belonging to the lineages His1 and His2 than to a putative lineage His3. Our sampling does not allow determination of the ratio of the two lineages in C. hispanica. Skewed lineage ratios have been reported in dependent-lineage populations of Pogonomyrmex harvester ants, possibly owing to differences between lineages in sex ratio allocation [42].

The high percentage of diagnostic alleles in nine out of 12 loci surveyed supports a lack of current gene flow between the His1/His2 lineages. This interpretation requires some caution, however, because substantial gene flow may occur on restricted genome parts of lineages [43]. Introgression through rare hybrid queen production may therefore remain undetected while using only a handful of marker loci. Rare development of queens from hybrid eggs has been reported in other ant systems relying on hybridization between divergent lineages [18,44–46]. Though, not a single C. hispanica hybrid queen has been found so far [9]; this study). Future linkage studies using a larger number of nuclear makers [46] will help to determine whether His1/His2 have achieved complete genetic isolation or whether some parts of their genome are leaky.

The two lineages exhibit patterns of isolation by distance and similar genetic substructure (figure 3b,c). This was most notable on the neighbour-joining tree, which separates three to four geographical zones for each lineage that reflect major mountain chain and river barriers to gene flow between Andalusia, Extremadura and Castile & León regions. Strong genetic viscosity is expected in C. hispanica because females establish new colonies at a walking distance of their natal nest with the help of worker cohorts, resulting in the formation of clonal patches [9]. Males of C. hispanica disperse by flight, but do not contribute to the spatial genetic structure, as they do not transmit their genes to the reproductive offspring. In C. hispanica, the persistence of social hybridogenesis requires the maintenance of viable hybrid workers. As sympatric lineages do not recombine, the two members of a lineage pair must coevolve to maintain a worker caste. Ultimately, the long-term isolation of geographically co-adapted lineages may lead to the speciation of sublineages belonging to the His1/His2 pair. New lineage formation through geographical
isolation or population bottlenecks was previously suggested in dependent-lineage populations of *Pogonomyrmex* ants. A single ancestral lineage pair belonging to the *P. barbatus/rugosus* complex was assumed to give rise to at least three pairs of lineages that currently overlap somewhat (the pairs F, G and H [18]), although this subdivision of the ancestral pair has been questioned recently [46]. Our data do not allow testing of this issue in *C. hispanica*. Experimental crossing between partners belonging to alternative genetic lineages and from different populations would allow us to determine whether coevolution has taken place to an extent where geographically distant partners have become incompatible.

The origin and evolution of hybridogenetic lineages in *C. hispanica* remains uncertain. Schwander & Keller [47] proposed that lineage pairs are of recent origin. They expect lineages to be short-lived because queens should be under selection to stop the production of males, which do not transmit their genes to the reproductive offspring. Assuming that hybridogenetic lineages are dead-ends, they argued that only minor evolutionary steps are required to switch back and forth from social hybridogenesis to facultative parthenogenesis, a probable ancestral feature of the genus *Cataglyphis*. According to this scenario, social hybridogenesis would be a transitory system that regularly evolved in the genus. Alternatively, social hybridogenesis could have ancient genomic roots that have locked hybridogenetic *Cataglyphis* in this reproductive system since its origin. This could take place, for example, if social hybridogenesis is controlled by a supergene. Supergenes are clusters of tightly linked loci inherited as a single unit; they remain uncertain. Schwander & Keller [47] proposed that lineage pairs are of recent origin. They expect lineages to be short-lived because queens should be under selection to stop the production of males, which do not transmit their genes to the reproductive offspring. Assuming that hybridogenetic lineages are dead-ends, they argued that only minor evolutionary steps are required to switch back and forth from social hybridogenesis to facultative parthenogenesis, a probable ancestral feature of the genus *Cataglyphis*. According to this scenario, social hybridogenesis would be a transitory system that regularly evolved in the genus. Alternatively, social hybridogenesis could have ancient genomic roots that have locked hybridogenetic *Cataglyphis* in this reproductive system since its origin. This could take place, for example, if social hybridogenesis is controlled by a supergene. Supergenes are clusters of tightly linked loci inherited as a single unit; they maintain specific combinations of alleles. They have been described for a long time in a diverse array of organisms such as plants or mimic insects [48,49]. A supergene was recently reported to determine social organization in the fire ant *Solenopsis invicta*. This species exhibits two social forms, one with single-queen colonies and one with multiple-queen colonies that differ in many fundamental reproductive and social traits [50]. The two forms can be predicted based on genotypes at the Gp-9 gene, with queens from single-queen colonies being homozygous BB and queens from multiple-queen colonies being heterozygous Bb [51]. Phylogenetic analyses of Gp-9 sequences showed that the two allelic variants, B and b, are conserved in four species known to possess a polymorphism in social organization similar to the one found in *S. invicta*. In these species, queens from single-queen colonies only possess B-like alleles, whereas queens from multiple-queen colonies also harbour b-like alleles [51,52]. This suggests that the origin of b-like alleles inducing polygyny preceded the origin of these five species. The Gp-9 gene is part of the fire ant supergene, which corresponds to about half a chromosome arm. The causes and consequences of genetic caste determination in social ants. A recent work supported by a PhD fellowship (H.D.) as well as several grants (L.L. and S.A.) from the Belgian FRS-FNRS (Fonds National pour la Recherche Scientifique) and the Université Libre de Bruxelles (ARC 2010-2015 no. 5).

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