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Great ape genetic diversity and population history

A full list of authors and affiliations appears at the end of the article.

Summary

Most great ape genetic variation remains uncharacterized[1,2]; however, its study is critical for understanding population history[3–6], recombination[7], selection[8], and susceptibility to disease[9,10]. Here, we sequence to high coverage a total of 79 wild- and captive-born individuals representing all six great ape species and seven subspecies and report ~88.8 million single nucleotide polymorphisms. Our analysis provides support for genetically distinct populations within each species, novel signals of gene flow, and the split of common chimpanzees into two distinct groups: Nigeria-Cameroon/Western and Central/Eastern populations. We find extensive inbreeding in almost all wild populations with Eastern gorillas being the most extreme. Inferred effective population sizes have varied radically over time in different lineages and this appears to have a profound effect on the genetic diversity at or close to genes in almost all species. We comprehensively discover and assign 1,982 loss-of-function variants throughout the human and great ape lineages, determining that the rate of gene loss has not been different in the human branch compared to other internal branches in the great ape phylogeny. This comprehensive catalog of great ape genome diversity provides a framework for understanding evolution and a resource for more effective management of wild and captive great ape populations.

We sequenced great ape genomes to a mean of 25-fold coverage per individual (Table 1, Supplementary Note, Table S1) sampling natural diversity by selecting captive individuals of known wild-born origin as well as individuals from protected areas in Africa (Figure 1a). We also included nine human genomes—three African and six non-African individuals[11]. Variants were called using the software package GATK[12] (Methods), applying several quality filters, including conservative allele balance filters, and requiring that genomes

[+]Corresponding authors: Tomas Marques-Bonet, Institut de Biologia Evolutiva, (UPF-CSIC), Pl. Charles Darwin 1, 08003 Barcelona, Spain, Tel.: +34 933 160 887, tomas.marques@upf.edu. Evan E Eichler, Department of Genome Sciences, Howard Hughes Medical Institute, University of Washington, Seattle, Washington, USA, eee@gs.washington.edu.
[*]Equal contribution.

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AUTHOR CONTRIBUTIONS

EEE and TM-B designed the study. JP-M, PHS, JMK, JLK, BL-G, MD, MF-C, JCM, CDB, EEE, and TM-B analyzed the raw data and performed the variant calling. JP-M, PHS, MM, JHG, IH, CB, LV, AR-H, and CC validated the different variants. JP-M, PHS, BL-G, CA, FH, EEE, and TM-B analyzed large variants. KV, AW, and MH analyzed the X/Autosome diversity. DT, GS, AC, CT, FC, HL, KP, MP, ML, NP, DC, JB, AN, and AMA performed selection analyses. JP-M, PHS, TDO, HL, DR, KM, AH, AEH, MHS, CH, JMA, TM, CDB, EEE, and TM-B analyzed different aspects of demography. MLW, LS, TA, IK, RWP, AP, FL, JK, EL, HS, MKG, SAT, RB, OAR, and BHH provided critical samples and participated in the discussion of phylogeny. LF, RKW, JB, EEE, MM, LA-C, MG, and IGG generated genome libraries and produced the genome sequence associated with this project. All authors contributed to data interpretation. JP-M, PHS, EEE and TM-B drafted the manuscript with input from all authors.

showed <2% contamination between samples (Methods and Supplementary Note). In order to assess the quality of single nucleotide variant (SNV) calls, we performed three sets of independent validation experiments with concordance rates ranging from 86%–99% depending on allele frequency, the great ape population analyzed, and the species reference genome used (Supplementary Note, Table S2). In total, we discovered ~84.0 million fixed substitutions and ~88.8 million segregating sites of high quality (Table 1, Table S3) providing the most comprehensive catalog of great ape genetic diversity to date. From these variants we also constructed a list of potentially ancestry-informative markers (AIMs) for each of the surveyed populations, although a larger sampling of some subspecies is still required (Supplementary Note).

We initially explored the genetic relationships between individuals by constructing neighbor-joining phylogenetic trees from both autosomal and mitochondrial genomes (Supplementary Note). The autosomal tree identified separate monophyletic groupings for each species/subspecies designation (Suppl. Figure 8.5.1) and supports a split of extant chimpanzees into two groups. Nigeria-Cameroon and Western chimpanzees form a monophyletic clade (>97% of all autosomal trees) while Central and Eastern chimpanzees form a second group (72% of all autosomal trees).

Genome-wide patterns of heterozygosity (Figure 1b) reveal a threefold range in single nucleotide polymorphism (SNP) diversity. Non-African humans, Eastern lowland gorillas, bonobos, and Western chimpanzees show the lowest genetic diversity (~0.8×10^{-3} heterozygotes/bp). In contrast, Central chimpanzees, Western lowland gorillas, and both orangutan species show the greatest ($1.6–2.4 \times 10^{-3}$ heterozygotes/bp). These differences are also reflected by measures of inbreeding from runs of homozygosity[13] (Figure 1c, Supplementary Note). Bonobos and Western lowland gorillas, for example, have similar distributions of tracts of homozygosity as human populations that have experienced strong genetic bottlenecks (Karitiana and Papuan). Eastern lowland gorillas appear to represent the most inbred population, with evidence that they have been subjected to both recent and ancient inbreeding.

To examine the level of genetic differentiation between individuals we performed a principal component analysis (PCA) of SNP genotypes (Supplementary Note). Chimpanzees were stratified between subspecies with PC1 separating Western and Nigeria-Cameroon chimpanzees from the Eastern and Central chimpanzees and PC2 separating Western and Nigeria-Cameroon chimpanzees. In gorillas, PC1 clearly separates Eastern and Western gorillas while the Western lowland gorillas are distributed along a gradient of PC2, with individuals from the Congo and Western Cameroon positioning in opposite directions along the axis. The isolated Cross River gorilla is genetically more similar to Cameroon Western lowland gorillas and can be clearly differentiated with PC3 (Suppl. Figure 8.2.9).

We explored the level of shared ancestry among individuals within each group[14] using an admixture model (FRAPPE). In chimpanzees, the four known subspecies are clearly distinguished when fitting the model using four ancestry components (K=4) (Figure 1d). Additional substructure is identified among the Eastern chimpanzees Vincent and Andromeda (K=6), who hail from the most Eastern sample site (Gombe National Park,

Tanzania). As in Gonder et al[2] we have identified three Nigeria-Cameroon samples (Julie, Tobi and Banyo, K=3–5) with components of Central chimpanzee ancestry. However, taking Central chimpanzees and the remaining Nigeria-Cameroon chimpanzees as ancestral populations shows no evidence of gene flow by either the F3 statistic or HapMix. This suggests these three samples are not the result of a recent admixture and may represent a genetically distinct population (Supplementary Note).

In gorillas, following the separation of Eastern and Western lowland species (K=2), an increasing number of components further subdivide Western lowland populations distinguishing Congolese and Cameroonian gorillas—a pattern consistent with the structure observed in the PCA analysis (Suppl. Figure 8.2.9). One striking observation is the extent of admixed ancestry predicted for captive individuals when compared to wild-born. Our analysis suggests that most captive individuals included in this study are admixed from two or more genetically distinct wild-born populations leading to an erosion of phylogeographic signal. This finding is consistent with microsatellite analyses of captive gorillas[15] and the fact that great ape breeding programs have not been managed at the subspecies level.

As great apes have been evolving on separate lineages since the middle Miocene, we attempted to reconstruct the history of these various species and subspecies by applying methods sensitive to branching processes, changes in effective population size (N_e), and gene flow occurring at different time scales. Using a combination of speciation times inferred from a haploid pairwise sequential Markovian coalescent (PSMC) analysis[16], a coalescent hidden Markov model (CoalHMM)[3], and incomplete lineage sorting approaches, we were able to estimate the most ancient split times and effective population sizes among the great ape species. By combining these estimates with an approximate Bayesian computation (ABC)[17] analysis applied to the more complex chimpanzee phylogeny, we constructed a composite model of great ape population history over the last ~15 million years (Figure 2). This model presents a complete overview of great ape divergence and speciation events in the context of historical effective population sizes.

PSMC analyses of historical N_e (Figure 3) suggests that the ancestral *Pan* lineage had the largest effective population size of all lineages >3 million years ago (Mya), after which the ancestral bonobo-chimpanzee population experienced a dramatic decline. Both PSMC and ABC analyses support a model of subsequent increase in chimpanzee N_e starting ~1 Mya, prior to their divergence into separate subspecies. Following an Eastern chimpanzee increase in N_e (~500 thousand years ago, kya), the Central chimpanzees reached their zenith ~200–300 kya followed by the Western chimpanzee ~150 kya. Although the PSMC profiles of the two subspecies within each of the major chimpanzee clades (Eastern/Central and Nigeria-Cameroon/Western) closely shadow each other between 100 kya and 1 Mya, the Western chimpanzee PSMC profile is notable for its initial separation from that of the other chimpanzees, followed by its sudden rise and decline (Supplementary Note, Figure 3). The different gorilla species also show variable demographic histories over the past ~200 ky. Eastern lowland gorillas have the smallest historical N_e, consistent with smaller present-day populations and a history of inbreeding (Figure 1c). A comparison of effective population sizes with the ratio of non-synonymous to synonymous substitutions finds that selection has

acted more efficiently in populations wit higher Ne, consistent with neutral theory (Supplementary Note).

Although the phylogeny of bonobos and Western, Central and Eastern common chimpanzees has been well established based on genetic data[18], there is still uncertainty regarding their relationship to Nigeria-Cameroon chimpanzees[2,19]. Regional neighbor-joining trees and a maximum-likelihood tree estimated from allele frequencies both show that Nigeria-Cameroon and Western chimpanzees form a clade. A complex demographic history has been previously reported for chimpanzees with evidence of asymmetrical gene flow among different subspecies. For instance, Hey[4] identified migration from Western into Eastern chimpanzees, two subspecies that are currently geographically isolated. We find support for this using the D-statistic, a model-free approach that tests whether unequal levels of allele sharing between an outgroup and two populations that have more recently diverged (D(H,W;E,C)>16SD). However, no previous genome-wide analysis that has examined gene flow included chimpanzees from the Nigeria-Cameroon subspecies and a comparison of them with Eastern chimpanzees results in a highly significant D-statistic (D(H,E;W,N)>25SD). Furthermore, TreeMix, a model-based approach that identifies gene flow events to explain allele frequency patterns not captured by a simple branching phylogeny, infers a signal of gene flow between Nigeria-Cameroon and Eastern chimpanzees ($p=2x10^{300}$). A more detailed treatment of gene flow applying different models and methods may be found in the Supplementary Note.

Genetic diversity is depressed at or close to genes in almost all species (Suppl. Fig 11.1) with the effect less pronounced in subspecies with lower estimated N_e, consistent with population genetic theory. When we compare the relative level of X chromosome and autosomal (X/A) diversity across great apes as a function of genetic distance from genes, the Eastern lowland gorillas and Bornean orangutans are outliers, with substantially reduced X/A diversity compared to the neutral expectation of 0.75, regardless of the distance to genes. This pattern is consistent with a recent reduction in effective population size[20], clearly visible in the PSMC analysis for both species (Figure 3). However, bonobos also demonstrate a relatively constant level of X/A diversity regardless of distance from genes, with values very much in line with neutral expectations. All other subspecies demonstrate a pattern consistent with previous studies in humans[21] where X/A diversity is lower than 0.75 close to genes and higher farther away from genes.

It has been hypothesized that loss of gene function may represent a common evolutionary mechanism to facilitate adaptation to changes in an environment[22]. There has been speculation that the success of humans may have, in part, been catalyzed by an excess of beneficial loss-of-function mutations[23]. We, thus, characterized the distribution of fixed loss-of-function mutations among different species of great apes identifying nonsense and frameshift mutations resulting from SNVs (n=806) and indels (n=1080) in addition to gene deletion events (n=96) (Table S4). We assigned these events to the phylogeny and determined that the number of fixed loss-of-function mutations scales proportionally to the estimated branch lengths (R^2=0.987 SNVs, R^2=0.998 indels). In addition, we found no evidence of distortion on the terminal branches of the tree compared to point mutations based on a maximum likelihood analysis (Supplementary Note). Thus, the human branch in

particular showed no excess of fixed loss-of-function mutations even after accounting for human-specific pseudogenes[24] (Supplementary Note).

Our analysis provides one of the first genome-wide views of the major patterns of evolutionary diversification among great apes. We have generated the most comprehensive catalogue of SNPs for chimpanzees (27.2 million), bonobos (9.0 million), gorillas (19.2 million), and orangutans (24.3 million)(Table 1) to date and identified several thousand AIMs, which provides a useful resource for future analyses of ape populations. Humans, Western chimpanzees, and Eastern gorillas all show a remarkable dearth of genetic diversity when compared to other great apes. It is striking, for example, that sequencing of 79 great ape genomes identifies more than double the number of SNPs obtained from the recent sequencing of more than a thousand diverse humans[25]—a reflection of the unique out-of-Africa origin and nested phylogeny of our species.

We provide strong genetic support for distinct populations and subpopulations of great apes with evidence of additional substructure. The common chimpanzee shows the greatest population stratification when compared to all other lineages with multiple lines of evidence supporting two major groups: the Western and Nigeria-Cameroon and the Central and Eastern chimpanzees. The PSMC analysis indicates a temporal order to changes in ancestral effective population sizes over the last two million years, previous to which the *Pan* genus suffered a dramatic population collapse. Eastern chimpanzee populations reached their maximum size first, followed by the Central and Western chimpanzee. The Nigerian chimpanzee population size appears much more constant.

Despite their rich evolutionary history, great apes have experienced drastic declines in suitable habitat in recent years[26], along with declines in local population sizes of up to 75%[27]. These observations highlight the urgency to sample from wild ape populations to more fully understand reservoirs of genetic diversity across the range of each species and to illuminate how basic demographic processes have affected it. The ~80 million SNPs we identified in this study may now be used to characterize patterns of genetic differentiation among great apes in sanctuaries and zoos and, thus, are of great importance for the conservation of these endangered species with regard to their original range. These efforts will greatly enhance conservation planning and management of apes by providing important information on how to maintain genetic diversity in wild populations for future generations.

METHODS Summary

We sequenced to a mean coverage of 25X (Illumina HiSeq 2000) a total of 79 great ape individuals, representing 10 subspecies and four genera of great apes from a variety of populations across the African continent and Southeast Asia. SNPs were called using GATK[12] after BWA[28] mapping to the human genome (NCBI Build 36) using relaxed mapping parameters. Samples combined by species were realigned around putative indels. SNP calling was then performed on the combined individuals for each species. For indels, we used the GATK Unified Genotyper to produce an initial set of indel candidates applying several quality filters and removing variants overlapping segmental duplications and tandem repeats. We also removed groups of indels clustering within 10 bp to eliminate possible

artifacts in problematic regions. Conservative allelic imbalance filters were used to eliminate false heterozygotes that may affect demographic analyses, some of which are sensitive to low levels of contamination. We estimate that the application of this filter resulted in a 14% false negative rate for heterozygotes. Our multispecies study design facilitated this assessment of contamination, which may remain undetected in studies focused on assessing diversity within a single species. The amount of cross-species contamination was estimated from the amount of non-endogenous mitochondrial sequence present in an individual. Because we wished to compare patterns of variation between and within species, we report all variants with respect to coordinates of the human genome reference. For FRAPPE analyses, we used MAF0.06 (human, orangutan, and bonobo) and 0.05 (chimpanzee and gorilla) to remove singletons. For most of the analyses, we only used autosomal markers, except in the X/A analysis. To determine the amount of inbreeding, we calculated the heterozygosity genome-wide in windows of 1 Mbp with 200 kbp sliding windows. We then clustered together the neighboring regions to account for runs of homozygosity. For the PSMC analyses, we called the consensus bases using SAMtools[29]. Underlying raw sequence data is available through the SRA (PRJNA189439/SRP018689). Data generated in this work are available from http://biologiaevolutiva.org/greatape/. A complete description of the material and methods is provided in the Supplementary Note.

Supplementary Material

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Authors

Javier Prado-Martinez[1,*], Peter H. Sudmant[2,*], Jeffrey M. Kidd[3,4], Heng Li[5], Joanna L. Kelley[4], Belen Lorente-Galdos[1], Krishna R. Veeramah[6], August E. Woerner[6], Timothy D. O'Connor[2], Gabriel Santpere[1], Alexander Cagan[7], Christoph Theunert[7], Ferran Casals[1], Hafid Laayouni[1], Kasper Munch[8], Asger Hobolth[8], Anders E. Halager[8], Maika Malig[2], Jessica Hernandez-Rodriguez[1], Irene Hernando-Herraez[1], Kay Prüfer[7], Marc Pybus[1], Laurel Johnstone[6], Michael Lachmann[7], Can Alkan[9], Dorina Twigg[3], Natalia Petit[1], Carl Baker[2], Fereydoun Hormozdiari[2], Marcos Fernandez-Callejo[1], Marc Dabad[1], Michael L. Wilson[10], Laurie Stevison[11], Cristina Camprubí[12], Tiago Carvalho[1], Aurora Ruiz-Herrera[12,13], Laura Vives[2], Marta Mele[1], Teresa Abello[14], Ivanela Kondova[15], Ronald E. Bontrop[15], Anne Pusey[16], Felix Lankester[17,18], John A. Kiyang[17], Richard A. Bergl[19], Elizabeth Lonsdorf[20], Simon Myers[21], Mario Ventura[22], Pascal Gagneux[23], David Comas[1], Hans Siegismund[24], Julie Blanc[25], Lidia Agueda-Calpena[25], Marta Gut[25], Lucinda Fulton[26], Sarah A. Tishkoff[27], James C. Mullikin[28], Richard K. Wilson[26], Ivo G. Gut[25], Mary Katherine Gonder[29], Oliver A. Ryder[30], Beatrice H. Hahn[31], Arcadi Navarro[1,32,33], Joshua M. Akey[2], Jaume Bertranpetit[1], David Reich[5], Thomas Mailund[8], Mikkel H. Schierup[8,34], Christina Hvilsom[24,35], Aida M. Andrés[7], Jeffrey D. Wall[11], Carlos D. Bustamante[4], Michael F. Hammer[6], Evan E. Eichler[2,36,+], and Tomas Marques-Bonet[1,33,+]

Affiliations

[1]Institut de Biologia Evolutiva, (CSIC-Universitat Pompeu Fabra), PRBB, 08003 Barcelona, Spain [2]Department of Genome Sciences, University of Washington, Seattle, Washington, USA [3]Department of Human Genetics, University of Michigan, Ann Arbor, MI, USA [4]Department of Genetics, Stanford University, Stanford, CA, USA [5]Department of Genetics, Harvard Medical School, Boston, Massachusetts, USA [6]Arizona Research Laboratories, Division of Biotechnology, University of Arizona, Tucson, Arizona, USA [7]Department of Evolutionary Genetics, Max Planck Institute for Evolutionary Anthropology, 04103 Leipzig, Germany [8]Bioinformatics Research Centre, Aarhus University, DK-8000 Aarhus C, Denmark [9]Bilkent University, Ankara, Turkey [10]Department of Anthropology, University of Minnesota, Minneapolis, MN 55455, USA [11]Institute for Human Genetics, University of California San Francisco, San Francisco, California, USA [12]Departament de Biologia Cellular, Fisiologia i Immunologia, Universitat Autònoma de Barcelona, 08193 Cerdanyola del Vallès, Spain [13]Institut de Biotecnologia i de Biomedicina. Universitat Autònoma de Barcelona, 08193 Cerdanyola del Vallès, Spain [14]Parc Zoològic de Barcelona, 08003 Barcelona, Spain [15]Biomedical Primate Research Centre, P.O. Box 3306, 2280 GH, Rijswijk, The Netherlands [16]Department of Evolutionary Anthropology, Duke University, Durham, NC 27708, USA [17]Limbe Wildlife Centre, Limbe, Cameroon [18]Paul G. Allen School for Global Animal Health, Washington State University, WA 99164, USA [19]North Carolina Zoological Park. Asheboro, NC 27205. USA [20]Department of Psychology, Franklin and Marshall College, Lancaster, PA 17604, USA [21]Department of Statistics, Oxford University, 1 South Parks Road, Oxford OX1 3TG, UK [22]Department of Genetics and Microbiology, University of Bari, Italy [23]Department of Cellular and Molecular Medicine, University of California San Diego, CA, USA [24]Department of Biology, Bioinformatics, University of Copenhagen, Denmark [25]Centro Nacional de Análisis Genómico (CNAG), 08028 Barcelona, Spain [26]Genome Sequencing Center, Washington University School of Medicine, St Louis, MO 63108, USA [27]Department of Biology and Genetics. University of Pennsylvania, Philadelphia, USA [28]NISC, US NIH, Bethesda, Maryland, USA [29]Biological Sciences, University at Albany, State University of New York, Albany, NY 12222, USA [30]San Diego Zoo Institute for Conservation Research, San Diego Zoo Global, San Diego, CA, USA [31]Departments of Medicine and Microbiology, Perelman School of Medicine, University of Pennsylvania, Philadelphia, USA [32]Instituto Nacional de Bioinformatica, UPF, Barcelona, Spain [33]Institució Catalana de Recerca i Estudis Avançats (ICREA). 08010, Barcelona, Spain [34]Department of Bioscience, Aarhus University, DK-8000 Aarhus C, Denmark [35]Copenhagen Zoo, DK 2000 Frederiksberg, Denmark [36]Howard Hughes Medical Institute, Seattle, Washington, USA

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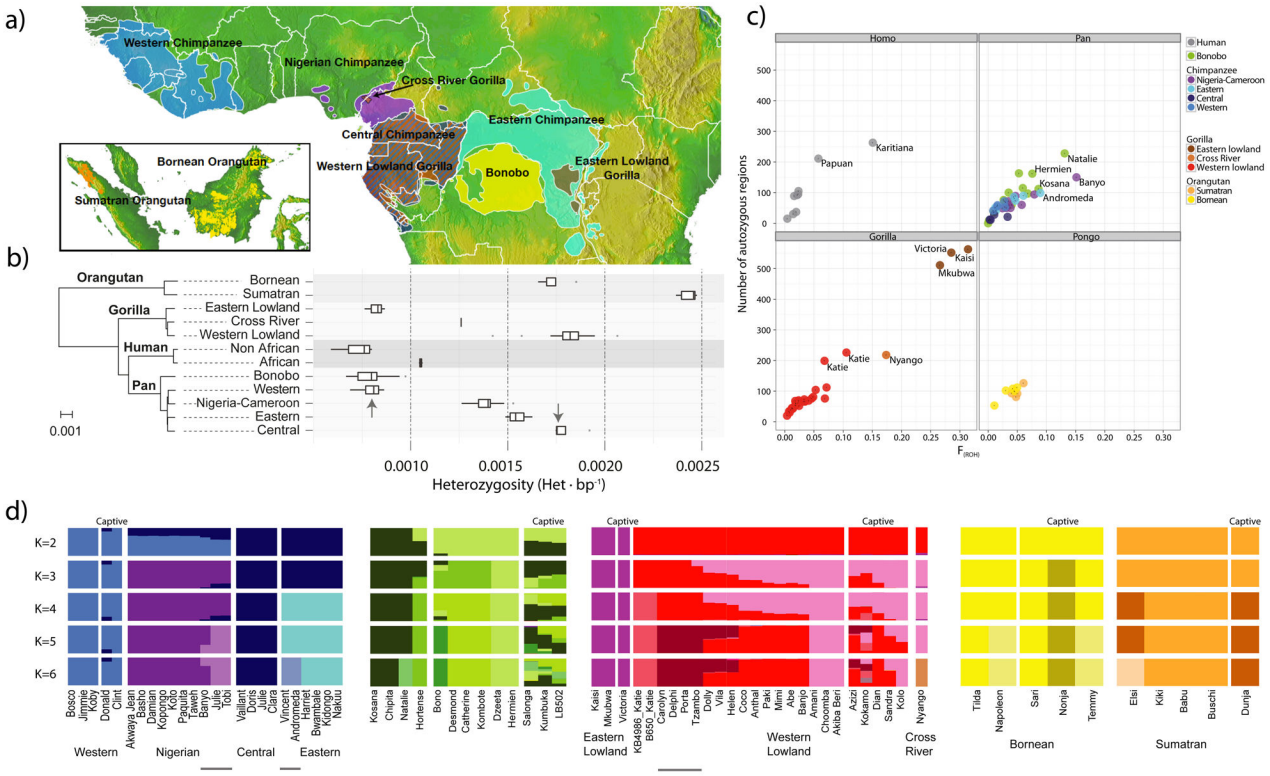

Figure 1. Samples, heterozygosity and genetic diversity

a. Geographical distribution of great ape populations across Indonesia and Africa sequenced in this study. The formation of the islands of Borneo and Sumatra resulted in the speciation of the two corresponding orangutan populations. The Sanaga River forms a natural boundary between Nigeria-Cameroon and Central chimpanzee populations while the Congo River separates the bonobo population from the Central and Eastern chimpanzees. Eastern lowland and Western lowland gorillas are both separated by a large geographical distance. **b.** Heterozygosity estimates of each of the individual species and subspecies are superimposed onto a neighbor-joining tree from genome-wide genetic distance estimates. Arrows indicate heterozygosities previously reported[30] for Western and Central chimpanzee populations **c.** Runs of homozygosity among great apes. The relationship between the coefficient of inbreeding (F_{ROH}) and the number of autozygous >1 Mbp segments is shown. Bonobos and Eastern lowland gorillas show an excess of inbreeding compared to the other great apes, suggesting small population sizes or a fragmented population. **d.** Genetic structure based on clustering of great apes. All individuals (columns) are grouped into different clusters (K=2 to K=6, rows) colored by species and according to their common genetic structure. Most captive individuals, labeled on top, show a complex admixture from different wild populations. A signature of admixture, for example, is clearly observed in the known hybrid Donald, a second-generation captive where we predict 15% admixture of Central chimpanzee on a Western background consistent with its pedigree. A gray line at the bottom denotes new groups at K=6 in agreement with the location of origin or ancestral admixture.

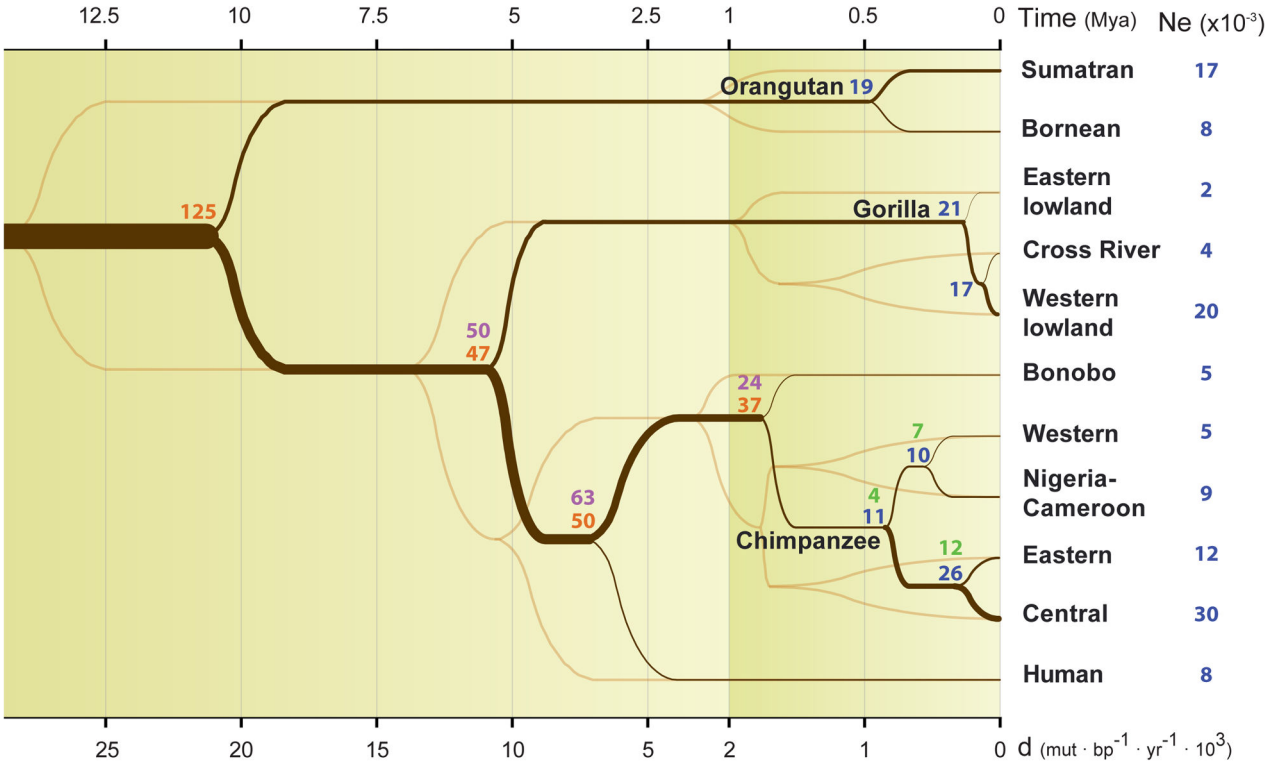

Figure 2. Inferred population history

Population splits and effective population sizes (N_e) during great ape evolution. Split times (dark brown) and divergence times (light brown) are plotted as a function of divergence (d) on the bottom and time on top. Time is estimated using a single mutation rate (μ) of $1{\cdot}10^{-9}$ mut/(bp·year). The ancestral and current effective population sizes are also estimated using this mutation rate. The results from several methods used to estimate N_e, (COALHMM, ILS COALHMM, PSMC and ABC are colored in orange, purple, blue and green respectively). The chimpanzee split times are estimated using the ABC method. The x-axis is rescaled for divergences larger than $2{\cdot}10^{-3}$ to provide more resolution in recent splits. All the values used in this figure can be found in Table S5.

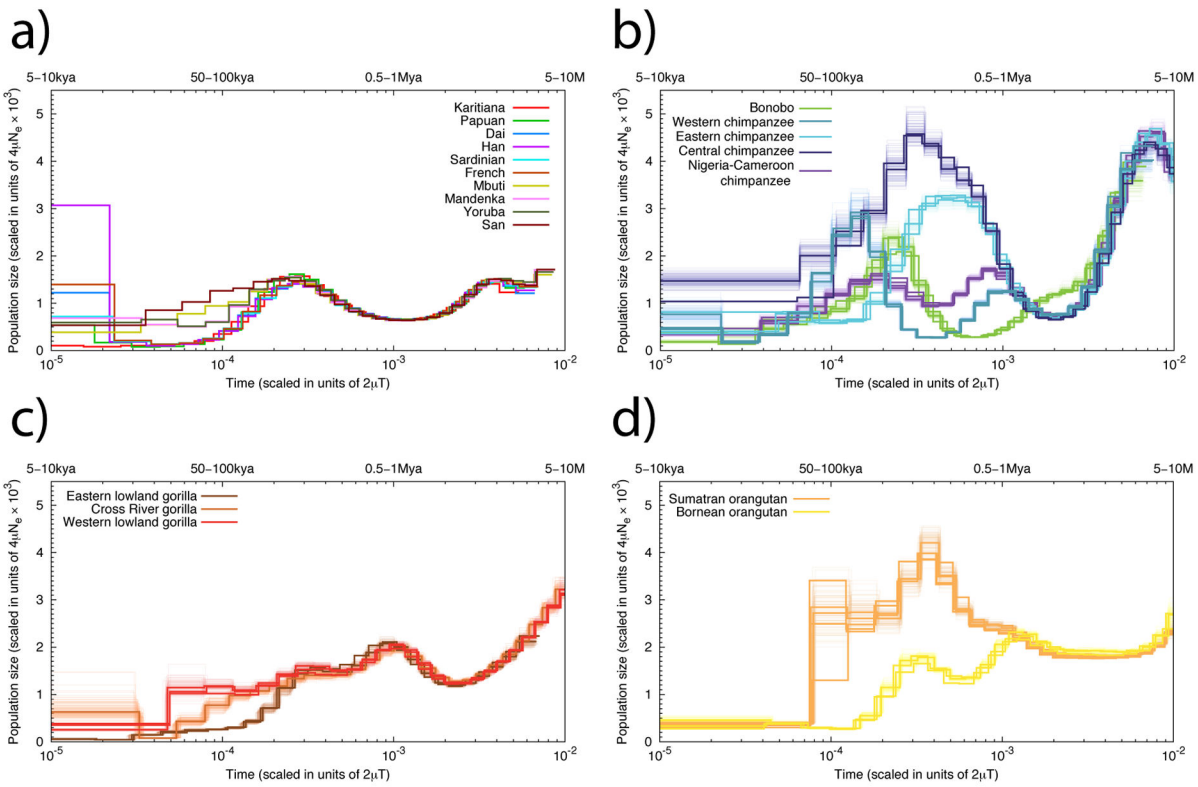

Figure 3. PSMC analysis

Inferred historical population sizes by PSMC. The lower x-axis gives time measured by pairwise sequence divergence and the y-axis gives the effective population size measured by the scaled mutation rate. The upper x-axis indicates scaling in years, assuming a mutation rate ranging from 10^{-9} to $5{\cdot}10^{-10}$ per site per year. The top left panel shows the inference for modern human populations. In the rest of the three panels, thin light lines of the same color correspond to PSMC inferences on 100 rounds of bootstrapped sequences.

Table 1

Genetic variation summary by species and subspecies

Summary statistics for each species and subspecies.

Genus	Scientific name Species/subspecies	Common name	N	Mean Coverage	Fixed Sites to Human reference	No. of SNVs[a]	Mean SNVs per Individual[a]	No. of Singletons[b]	Ancestry Informative Markers (AIMs)[c]	Ne (10-3)[d]
Homo		Non-African	6	18.3	386,974	5,887,443	2,639,546	1,379,448	12,316	9.7 – 19.5
		African	3	20.9	632,253	6,309,453	3,203,178	2,448,454	12,316	13.9 – 27.9
	Homo sapiens	Humans	9	19.2	224,660	9,172,573	3,061,604	3,827,902	-	13.1 – 16.2
Pan	*Pan troglodytes ellioti*	Nigerian-Cameroon	10	16.7	25,017,403	12,605,585	4,816,435	2,695,109	2,213	18.5 – 37.0
	Pan troglodytes schweinfurthii	Eastern	6	28.7	25,126,506	11,264,879	4,843,530	2,228,396	1,265	19.7 – 39.5
	Pan troglodytes troglodytes	Central	4	23.8	25,080,750	11,820,858	4,983,933	3,948,347	619	24.4 – 48.7
	Pan troglodytes verus	Western*	4	27.3	26,832,247	4,729,933	2,411,501	1,481,079	145,548	9.8 – 19.5
	Pan troglodytes	Common Chimpanzees	24	22.5	24,087,088	27,153,659	5,693,903	10,352,931	149,645	30.9 – 61.8
Pan	*Pan paniscus*	Bonobos	13	27.5	27,068,299	8,950,002	2,738,755	3,159,889	-	11.9 – 23.8
Gorilla	*Gorilla beringei graueri*	Eastern lowland	3	22.8	34,537,496	3,866,117	2,578,328	484,482	317,028	12.2 – 24.3
	Gorilla gorilla diehli	Cross river	1	17.6	35,553,861	2,585,360	2,585,360	165,482	35,693	14.9 – 29.8
	Gorilla gorilla gorilla	Western lowland	23	17.8	31,602,620	17,314,403	6,410,662	2,797,388	19,902	26.8 – 53.5
		Gorillas	27	18.3	31,376,203	19,177,989	6,492,831	3,447,352	372,623	28.4 – 56.9
Pongo	*Pongo abellii*	Sumatran	5	28.7	62,880,923	14,543,573	7,263,256	5,681,303	1,132,808	27.5 – 55.0
	Pongo pygmaeus	Bornean	5	25.8	64,249,235	10,321,213	5,763,354	3,555,596	1,132,808	19.5 – 39.0
		Orangutans	10	27.3	60,661,869	24,309,920	9,338,148	6,409,648	-	42.3 – 84.6
		All	83	23.0	83,954,672	83,580,213	-	-	-	-

[a] Polymorphic variants found in each species/subspecies after substracting fixed sites.

[b] Singletons and doubletons calculated combining all the samples within the species.

[c] Variants only found in a single group within each species.

[d] Calculated from Θw. μ = 1e-9 - 0.5e-9 mut·bp-1·yr-1 and g = 25 for Homo and Pan, 19 for Gorilla and 26 for Pongo.

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* Hybrid sample Donald and 4 related gorillas were excluded.