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Ancient Hepatitis B viruses from the Bronze Age to the Medieval

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Abstract

Hepatitis B virus (HBV) is a major cause of human hepatitis. There is considerable uncertainty about the timescale of its evolution and its association with humans. Here we present 12 full or partial ancient HBV genomes between ~0.8-4.5 thousand years old. The ancient sequences group either within or in sister relationship to extant human or other ape HBV clades. Generally, the genome properties follow those of modern HBV. The root of the HBV tree is projected to between 8.6-20.9 thousand years ago (kya), and estimate a substitution rate between 8.04×10^{-6}-1.51×10^{-5} nucleotide substitutions per site per year (s/s/y). In several cases, the geographic locations of the ancient genotypes do not match present day distributions. Genotypes that today are typical of Africa and Asia, and a subgenotype from India, are shown to have an early Eurasian presence. The geographic and temporal patterns we observe in ancient and modern HBV genotypes are compatible with well-documented human migrations during the Bronze and Iron Ages[1,2]. We show evidence for the creation of genotype A via recombination and a long-term association of modern HBV genotypes with humans, including the discovery of a human genotype that is now extinct. Taken together, the data expose a complexity of HBV evolution that is not evident when considering modern sequences alone.

HBV is transmitted perinatally or horizontally via blood or genital fluids[3]. The estimated global prevalence is 3.6%, ranging from 0.01% (UK) to 22.38% (South Sudan)[4]. In high endemicity areas, where prevalence is > 8%, 70-90% of the adult population show evidence of past or present infection[5,6]. The young and the immunocompromised are most likely to develop chronic HBV infection, which can

result in high viremia over years to decades[3]. Approximately 257 million people are chronically infected[5] and around 887,000 died in 2015 due to associated complications[5].

Despite the prevalence and public health impact of HBV, its origin and evolution remain unclear[7,8]. Inference of HBV nucleotide substitution rates is complicated by the fact that the virus genome consists of four overlapping open reading frames[9], and mutation rates differ between phases of chronic infection[10]. Studies based on heterochronous sequences, sampled over a relatively short time period, find higher substitution rates, whereas rates estimated using external calibrations tend to be lower, leading to a wide range of estimated substitution rates (7.72×10^{-4}-3.7×10^{-6}) for HBV[11-13]. Human HBV is classified into at least nine genotypes, A-I, roughly corresponding to sequence similarity of at least 92.5% within genotypes[14], with a heterogeneous global distribution (Fig. 1a)[8,9]. Attempts to explain the origin of genotypes using human migrations have been inconclusive. The hypothesis that HBV co-evolved with ancient modern humans as they left Africa has been contested due to the basal phylogenetic position of genotypes F and H, found exclusively in the Americas[7]. HBV also infects non-human primates (NHP), and the human and other great ape HBV are interspersed in the phylogenetic tree, possibly due to cross-species transmission[15]. Given the variability of estimated substitution rates, the incongruence of the tree topology with some human migrations, and the mixed topology of the NHP and human HBV sequences in the phylogenetic tree, considerable uncertainty remains about the evolutionary history of HBV.

104 Recent advances in the sequencing of ancient DNA (aDNA) have yielded important
105 insights into human evolution, past population dynamics[16], and diseases[17,18].
106 However, ancient sequences have been recovered for only a handful of exogenous
107 human viruses, including influenza (~100 years)[19], variola (~350 years)[20], and HBV
108 (~340 years and ~450 years)[21,22]. The knowledge gained from these few cases
109 emphasizes the general importance of ancient sequences for the direct study of long-
110 term viral evolution. HBV has several characteristics that make it a good candidate for
111 detection in an aDNA virus study: its extended high viremia during chronicity[3], the
112 relative stability of its virion[23], and its small, circular, and partially double-stranded
113 DNA genome[9].
114
115 Shotgun sequence data were generated from 167 Bronze Age[1] and 137 predominantly
116 Iron Age[2] individuals from Central to Western Eurasia with a sample age range of
117 ~7.1-0.2 kya. We identified reads that matched the HBV genome in 25 samples
118 (Table 1, Extended Data Table 1a, SI Table 3), spanning a period of almost 4000
119 years, from several different cultures and a broad geographical range (Fig. 1b, Table
120 1, Extended Data Table 1a, SI Table 3). Using TaqMan PCR, we tested two samples
121 with high genome coverage (DA195, DA222) and two samples with low coverage
122 (DA85, DA89) for the presence of HBV. The high-coverage samples tested positive,
123 whereas the low-coverage samples tested negative (Extended Data Table 1b). This is
124 consistent with shotgun sequencing being more effective than targeted PCR for
125 analysing highly degraded DNA[24]. Based on availability of sample material, libraries
126 from 14 samples were selected for targeted enrichment (capture) of HBV DNA
127 fragments (SI Tables 1 and 2). This resulted in increased genome coverage and an
128 average of a 2.4-fold increase in number of HBV positive reads (Extended Data Table

129 1a, SI Table 3). In total, we obtained 17.9 to 100% HBV genome coverage from the
130 sequence data, with genomic depth ranging from 0.4x to 89.2x (Table 1, Extended
131 Data Table 1a). We selected 12 samples for phylogenetic analyses. Criteria for
132 inclusion were at least 50% genome coverage and clear aDNA damage patterns after
133 capture (Extended Data Fig. 1).
134
135 For an initial phylogenetic grouping, we estimated a Maximum Likelihood (ML) tree
136 using the ancient HBV genomes together with modern human, NHP, rodent, and bat
137 HBV genomes (Dataset 1, see Methods). All ancient viruses fell within the diversity
138 of Old World primate HBV genotypes, which includes all human and other great ape
139 genotypes, except human genotypes F and H (Extended Data Fig. 2).
140
141 Recombination is known to occur in HBV[25]. We found strong evidence that an
142 ancient sequence, HBV-DA51, and an unknown parent recombined to form the
143 ancient genotype A sequences. Although that cannot literally be the case due to
144 sample ages, the logical interpretation is that an ancestor of HBV-DA51 was involved
145 in the recombination. The same recombination is also suggested for the two modern
146 genotype A sequences that were included in the analysis. The ancient genotype B
147 (HBV-DA45), a modern genotype B, and two modern genotype C sequences were not
148 similarly flagged, suggesting that the possible recombination occurred after genotypes
149 A, B, and C had diverged. The predicted recombination break points (Extended Data
150 Table 2, Extended Data Fig. 3) correspond closely to the polymerase gene. Thus, it is
151 possible that the polymerase from an unknown parent and the remainder of the
152 genome from an HBV-DA51 ancestor recombined to form the now ubiquitous
153 genotype A about 7.4-9 kya (Fig. 2, Extended Data Table 3b, Methods). Similar

154 recombinations events, involving the creation of genotypes E and G and a currently
155 circulating B/C recombinant, have also been identified[25].
156
157 For detailed phylogenetic analyses, we used a set of 112 reference human and NHP
158 HBV sequences (Dataset 2, see Methods). An ML phylogenetic tree based on these
159 reference sequences and all ancient sequences was constructed (Extended Data Fig.
160 4). Regression of root-to-tip genetic distances against sampling dates, as well as date
161 randomisation tests, showed a clear temporal signal in the data (Extended Data Fig. 5,
162 SI Figs. 1-3), suggesting that molecular clock models can be applied. A dated
163 coalescent phylogeny was constructed using BEAST2[26] (Fig. 2). The molecular clock
164 was calibrated using tip dates. Strict and relaxed lognormal molecular clocks were
165 tested with coalescent constant, exponential, and Bayesian skyline population priors
166 (Extended Data Table 3a). Model comparisons favoured a relaxed molecular clock
167 model with lognormally distributed rate variation and a coalescent exponential
168 population prior (Extended Data Table 3a). The median root age of the resulting tree
169 is estimated to 11.6 kya (95% Highest Posterior Density (HPD) interval: 8.6 to 15.3
170 kya) and the median clock rate is 1.18×10^{-5} s/s/y (95% HPD interval: 9.21×10^{-6} to
171 1.45×10^{-5} s/s/y). Under a strict molecular clock, a coalescent Bayesian skyline
172 population prior was favoured, in which case the median root age is 15.6 kya (95%
173 HPD interval: 13.7 to 17.8 kya) and the median substitution rate 9.48×10^{-6} s/s/y (95%
174 HPD interval: 8.3×10^{-6} to 1.07×10^{-5} s/s/y) (Extended Data Tables 3a-c).
175
176 Under all model parameterisations used here, the substitution rate we find is lower
177 than rates estimated from phylogenies built using either modern heterochronous
178 sequences[11] or sequences from mother-to-child transmissions[27], but higher than rates

179 inferred using external calibrations based on human migrations[12]. A lower rate is
180 consistent with Tedder et al. (2013)[28], who found that although mutation rates may be
181 high, mutations within an individual often revert back to the genotype consensus, and
182 thus rarely lead to long-term sequence change. It is also consistent with the so-called
183 time-dependent rate phenomenon, observed for many viruses, which shows that short-
184 term evolutionary rates are higher than long-term rates[29].
185
186 The knowledge of ancient HBV genomes enables us to formally evaluate hypotheses
187 concerning HBV origins using path sampling of calibrated phylogenies based on
188 appropriate external divergence date assumptions. We tested several calibration points
189 implied by a co-expansion of HBV with humans after leaving Africa for support of
190 congruence between migrations and geographical locations of HBV clades[12]. We find
191 weak evidence for a split of the F/H clade between 13.4 and 25.0 kya under a strict,
192 but not a relaxed clock model. We do not find support for the divergence of
193 subgenotype C3 strains between 5.1-12.0 kya, leading to a distribution in different
194 regions of Polynesia, or for divergence of Haitian A3 strains from other genotype A
195 strains between 0.2-0.5 kya under either strict or relaxed clock models (Extended Data
196 Table 3d).
197
198 In the dated coalescent phylogeny, four ancient sequences (from youngest to oldest:
199 HBV-DA119, -DA195, -RISE386, and -RISE387) group with genotype A. The first
200 three fall well within the 7.5% nucleotide divergence criterion used to delimit
201 membership in HBV genotypes. HBV-RISE387 is right on this limit (Extended Data
202 Table 4a)[14]. The three oldest samples lack a six nucleotide insertion at the carboxyl
203 end of the Core gene that is present in all modern genotype A viruses (Table 2)[9].

204 HBV-RISE387 encodes a stop codon in its pre-Core peptide that would have ablated
205 the expression of the immune modulator HBe antigen (HBeAg), a phenomenon
206 known in modern HBV infections (Table 2). This characteristic viral mutant is usually
207 found in chronic HBV carriers who seroconverted from HBeAg to anti-HBe.
208 Interestingly, RISE386 and RISE387 are archaeologically dated only ~100 years apart
209 and both come from the Bulanovo site in Russia, but their viruses show only 93.34%
210 sequence identity (Extended Data Table 4b), indicating the existence of significant
211 localized HBV diversity ~4.2 kya.
212
213 The ancient sequence HBV-DA45 phylogenetically groups with genotype B and has
214 97.65% sequence identity with modern genotype B (Extended Data Table 4a).
215
216 Sequences HBV-DA51, -DA27, -DA222, and -DA29 phylogenetically group with the
217 modern genotype D. They have high sequence identity (96.99 to 98.74%) with
218 modern genotype D sequences (Extended Data Table 4a), and have the typical 33
219 nucleotide deletion in the PreS1 sequence of the S-gene, encoding the three HBV
220 surface proteins[9] (Table 2).
221
222 Sequences HBV-RISE154, -RISE254, and -RISE563 are in sister relationship to the
223 Chimpanzee/Gorilla HBV clade (Fig. 2). HBV-RISE254 and -RISE563 have the same
224 33 nucleotide deletion in the PreS1 sequence that is shared with NHP HBV and
225 human genotype D (Table 2). HBV-RISE563 does not encode a functional pre-Core
226 peptide (Table 2). Based on sequence similarity across the whole genome, HBV-
227 RISE563 and -RISE254 together might be classified as a new human genotype that is
228 extinct today, and HBV-RISE154 as possibly another (Extended Data Table 4).

229 However, HBV-RISE154 has low genome coverage, which precludes an exact
230 calculation. The sister relationship of these three sequences with modern Chimpanzee
231 and Gorilla HBV could be interpreted as a consequence of relatively recent
232 transmission(s) of HBV from humans to NHPs[15]. However, other scenarios and
233 confounding factors are possible, as these lineages are deeply separated in the tree.
234 Incomplete lineage sorting combined with viral extinction (possibly boosted by
235 massive recent reductions in great ape populations) should be considered. More data
236 on current and, if possible, ancient NHP-associated HBV will be necessary to reach
237 definitive conclusions.
238
239 The geographic locations of some of the ancient virus genotypes do not match the
240 present-day genotype distribution, and also do not match dates and/or locations
241 inferred in previous studies of HBV. While it is important to keep in mind that the
242 data presented here are limited, they provide important spatiotemporal reference
243 points in the evolutionary history of HBV. Their synopsis suggests a more
244 complicated ancestry of present-day genotypes than previously assumed, especially in
245 light of recent insights into the history of human migration.
246
247 We find genotype A in South-Western Russia by 4.3 kya (RISE386, RISE387), in
248 individuals belonging to the Sintashta culture and in a sample (DA195) from the
249 Scythian culture. The western Scythians are related to the Bronze Age cultures of the
250 Western Steppe populations[2] and their shared ancestry suggests that the modern
251 genotype A may descend from this ancient Eurasian diversity and not, as previously
252 hypothesized, from African ancestors[30,31]. This is also consistent with the phylogeny
253 (Fig. 2), as well as the fact that the three oldest ancient genotype A sequences (HBV-

254 DA195, -RISE386, and -RISE387) lack the six nucleotide insertion found in the
255 youngest (HBV-DA119), and all modern genotype A sequences. The ancestors of
256 subgenotypes A1 and A3 could have been carried into Africa subsequently, via
257 migration from western Eurasia[32].
258
259 The ancient HBV genotype D sequences were all found in Central Asia. HBV-DA27,
260 found in Kazakhstan and dated to 1.6 kya, falls basal to the modern subgenotype D5
261 sequences that today are found in the Paharia tribe from eastern India[33]. DA27 and the
262 Paharia people in India are linked by their Tibeto-Burman ancestry[2,34], possibly
263 explaining the similar viruses.
264
265 Based on the observation that genotypes go extinct and can be created by
266 recombination, our data show that the diversity we observe today is only a subset of
267 the diversity that has ever existed. Our data support a scenario in which all present
268 day HBV diversity arose only after the split of the Old World and New World
269 genotypes (25-13.4 kya). Any attempt to interpret the currently known HBV tree
270 based on human migrations that happened before this event will necessarily result in
271 anomalies that cannot be reconciled, such as the basal position of genotypes F/H and
272 the apical position of subgenotype C4, which is exclusively found in indigenous
273 Australians[9]. If HBV did co-evolve with ancient modern humans as they left Africa as
274 proposed previously[7], most of the pattern of earlier diversity has been replaced by
275 changes that happened after the split of the Old and New World genotypes. Genotypes
276 F and H would therefore be remnants of the earlier now-extinct diversity, and the
277 arrival of subgenotype C4 in Australia would have taken place long after the Old/New
278 World split, as supported by our tree in Figure 2. Alternatively, there could have been

279 a New World origin of HBV or the introduction of HBV into humans from a different
280 host. Our data do not allow us to speculate either way.
281
282 To our knowledge, we report the oldest exogenous viral sequences recovered from
283 DNA of humans or any vertebrate. We show for the first time that is possible to
284 recover viral sequences from samples of this age. We show that humans throughout
285 Eurasia were widely infected with HBV for thousands of years. Despite the age of the
286 samples and the imperfect diagnostic test, our dataset contained a surprisingly high
287 proportion of HBV-positive individuals. The actual ancient prevalence during the
288 Bronze Age and thereafter might have been higher, reaching or exceeding the
289 prevalence typically found in contemporary indigenous populations[6]. This clearly
290 establishes the potential of HBV as powerful proxy tool for research into human
291 spread and interactions. The ancient data reveal aspects of complexity in HBV
292 evolution that are not apparent when only modern sequences are considered. They
293 show the existence of ancient HBV genotypes in locations incongruent with their
294 present-day distribution, contradicting previously suggested geographic or temporal
295 origins of genotypes or sub-genotypes; evidence for the creation of genotype A via
296 recombination and the emergence of the genotype outside Africa; at least one now-
297 extinct human genotype; ancient genotype-level localized diversity; and demonstrate
298 that the viral substitution rate obtained from modern heterochronously sampled
299 sequences is misleading. These suggest that the difficulty in formulating a coherent
300 theory for the origin and spread of HBV may be due to genetic evidence of an earlier
301 evolutionary scenario being overwritten by relatively recent alterations, as also
302 suggested by Simmonds et al., in the context of recombination[25]. The lack of ancient
303 sequences limits our understanding of the evolution of HBV and, very likely, of other

viruses. Discovery of additional ancient viral sequences may provide a clearer picture of the true origin and early diversification of HBV, enable us to address questions of paleo-epidemiology, and broaden our understanding of the contributions of natural and cultural changes (including migrations and medical practices) to human disease burden and mortality.

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Author Contributions

All authors contributed to the interpretation of the results.

BM, TJ, PD, MA, SR, MS, LO, LV, DS, DG, RF, CD, EW wrote the paper.

BM, TJ: screened and analysed data, created display items.

PD, MA: conducted sampling and generated sequence data.

IS, AL, EU, IP, BB, TB, KT, VM, NL, DV, EK, AE, DP, MV, TDP, VM, VS: excavated, curated, and analysed samples and archaeological context.

AH: designed virus capture probes.

LV: designed virus capture probes, performed TaqMan PCR and target enrichment experiments.

AO: initiated and provided critical input on the development of NGS bioinformatics tools.

DS, DG, RF: computational analysis.

CD: analysed data, PCR probe design.

KS, KK: conducted sampling and archaeological background.

EW: initiated the work, led sampling and generation of the sequence data.

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Tables

451 **Table 1: Overview of samples used for phylogenetic analyses**

Sample	^{14}C age (standard deviation)	Median cal BP age, or estimate (years)	Approx. sample age (years)	Site	Culture or period	Sex	Reads included in consensus	Coverage	
								Consensus	Depth
RISE563	3955 (35)	4421	4488	Osterhofen-Altenmarkt, Germany	Bell Beaker	M	4383	100%	79.3x
DA222	N/D	1200-1000	1167	Butakty, Kazakhstan	Karluk	M	4132	100%	89.2x
DA195	2479 (35)	2578	2645	Sandorfalva-Eperjes, Hungary	Hungarian Scythian	F	1445	99.9%	29.2x
DA51	2220 (37)	2230	2297	Keden, Kyrgyzstan	Saka	M	712	99.2%	14.5x
RISE254	3631 (29)	3942	4009	Szàzhalombatta-Földvàr, Hungary	Vatya	M	1491	99.0%	36.6x
DA119	N/D	1500	1567	Poprad, Slovakia	North Carpathian	M	2597	98.8%	53.1x
RISE386	3758 (34)	4121	4188	Bulanovo, Russia	Sintashta	M	331	97.8%	7.0x
DA27	1641 (33)	1543	1610	Halvay 3, Kazakhstan	Hun-Sarmatian	M	890	90.0%	14.3x
DA29	849 (25)	755	822	Karasyur, Kazakhstan	Medieval	M	222	87.5%	4.8x
DA45	2083 (27)	2053	2120	Omnogobi, Mongolia	Xiongnu	M	215	87.2%	4.3x
RISE387	3822 (33)	4215	4282	Bulanovo, Russia	Sintashta	N/D	284	86.6%	6.2x
RISE154	3522 (24)	3784	3851	Szczepankowice, Poland	Unetice	F	128	57.2%	2.0x

452 Samples included in phylogenetic analysis, by decreasing genome coverage. Criteria for inclusion were at least
453 50% genome coverage and sufficient aDNA damage patterns after capture. The read count indicates the number
454 of reads used to make consensus sequences. N/D (not determined) indicates samples where dating was not
455 performed or where osteological sex was undetermined. See Methods for information on sequence matching,
456 consensus making, and sample dating.

457

458 **Table 2: Genome properties of ancient sequences included in phylogenetic analyses**

Sample	Genotype of closest sequence	Sequence identity to closest sequence	Genome length	Sero-type	Insertions / deletions	Predicted HBeAg status
DA119	A3	97.8%	3221	*adw2*	6nt insert at the C-terminus of core region	Positive
DA195	A3	96.2%	3215	*adw2*	None	Positive
RISE386	A	95.2%	3215	*adw2*	None	Positive
RISE387	A	92.5%	3215	*adw2*	None	Negative PreC stop codon
DA45	B1	96.6%	3215	*ayw1*	None	Positive
DA29	D3	98.5%	3182	*ayw2*	33nt deletion at the N-terminus of the preS1 region	Positive
DA222	D3	98.7%	3182	*ayw2*	33nt deletion at the N-terminus of the preS1 region	Positive
DA27	D1	97.2%	3182	*ayw2*	33nt deletion at the N-terminus of the preS1 region	Positive
DA51	D1	96.7%	3182	*ayw2*	33nt deletion at the N-terminus of the preS1 region	Positive
RISE154	Chimp.	92.5%	Ambiguous	*adw2*[*]	Ambiguous	Positive
RISE254	Chimp.	95.2%	3182	*adw2*	33nt deletion at the N-terminus of the preS1 region	Positive
RISE563	Gorilla	92.7%	3182	*adw2*	33nt deletion at the N-terminus of the preS1 region	Negative PreC stop codon

459 Genotype groups are sorted by increasing sample age. [*] Serotype could not be determined unambiguously, due
460 to lack of coverage.

461

462 # Figure legends

463 **Figure 1: Geographic distribution of analysed samples and modern genotypes**

464 **a,** Distribution of modern human HBV genotypes[8]. Genotypes relevant to the manuscript are shown in colour.
465 Coloured shapes indicate the locations of the HBV-positive samples included for further analysis, as in panel **b**.
466 **b,** Locations of analysed Bronze Age samples[1] are shown as circles, Iron Age and later samples[2], as triangles.
467 Coloured markers indicate HBV-positive samples. Ancient genotype A samples are found in regions where
468 genotype D predominates today, and DA27 is of sub-genotype D5 which today is found almost exclusively in
469 India.

470

471 **Figure 2: Dated maximum clade credibility tree of HBV**

472 A lognormal relaxed clock and coalescent exponential population prior were used. Grey horizontal bars indicate
473 the 95% HPD interval of the age of the node. Larger numbers on the nodes indicate the age and 95% HPD
474 interval of the age under a strict clock and Bayesian skyline tree prior. Clades of genotypes C (except clade C4),
475 F, and H are collapsed and shown as dots. Taxon names indicate: genotype / subgenotype, accession number,
476 sample age, country abbreviation of sequence origin, region of sequence origin, host species, and optional
477 additional remarks.

478

Methods

HBV datasets

The following HBV datasets were used in the present study. Full listings of accession numbers are given in the Supplementary Methods.

Dataset 1: 26 HBV genomes, covering all species in the *Orthohepadnaviridae*. This includes one sequence each from the human HBV genotypes (A-J), Orangutan, Chimpanzee, Gorilla, Gibbon, Woolly monkey, Woodchuck, Ground squirrel, Arctic ground squirrel, Horseshoe bat, and four sequences from Roundleaf bats and three from Tent-making bats, largely following Drexler et al.[35]

Dataset 2: 124 HBV genomes, from humans and NHP. This set contains 92 sequences from Paraskevis et al.[12] (excluding their incomplete sequences), 7 additional genotype D sequences, the Korean mummy genotype C sequence[21], the 12 ancient sequences from the present study, and 12 full genomes selected from a set of 9066 full HBV genomes downloaded from NCBI[36] on 2017-08-24 (Entrez query: hepatitis b virus[organism] not rna[title] not clone[title] not clonal[title] not patent[title] not recombinant[title] not recombination[title] and 3000:4000[sequence length]) corresponding to the closest, non-artificial match for each of the ancient sequences. Dates for these sequences were acquired by looking for a date of sample collection in the NCBI entry, or the paper where the sequence was first published. If a range of dates was mentioned, the mean was used. If no date of sample collection was found in this way, either the year of the publication of the paper, or the year of addition of the sequence to GenBank was used, whichever was earlier.

Dataset 3: 124 HBV genomes, from humans, NHP, and a variety of other Orthohepadnavirus host species, including Woolly monkey, Roundleaf and Tent-making bat, Ground and Arctic ground squirrel, Woodchuck, and Snow goose. This set contains 113 sequences that are the

503 union of a selection of 91 sequences from Paraskevis et al.[12] and 29 from Drexler et al.[35], and
504 11 additional sequences.
505 **Dataset 4**: 3505 HBV genomes. 3384 are from Bell et al., (2016)[37], divided into ten human
506 genotypes. To these we added 17 Chimpanzee, 56 Gorilla, 12 Gibbon and 36 Orangutan full
507 HBV genome sequences downloaded from NCBI on 2017-01-18, resulting in 14 genome
508 categories.

509 Dating of ancient samples

510 Sample ages were determined by direct ^{14}C-dating. These ages were calibrated using OxCal[38]
511 (version 4.3) using the IntCal13 curve[39]. Table 1 shows the ^{14}C age and standard deviation for
512 each sample. This is followed by the median probability calibrated age before present (cal
513 BP), where "present" is defined as 1950. RISE386 was ^{14}C dated twice, with ages (standard
514 deviation) of 3740 (33) and 3775 (34), so a rounded mean of 3758 (34) was used for its
515 calibration. DA29 was dated at 822 years using ^{14}C and also at ~700 years using multi-proxy
516 methods, the former was used for consistency. The dates for DA119, DA222, RISE548,
517 RISE556, RISE568, and RISE597 are best estimates, based on sample context.

518 Data and data processing

519 We analysed 101 Bronze Age samples published in Allentoft, et al.[1], 137 predominantly Iron
520 Age samples published in Damgaard et al.[2], and 66 additional samples from the Bronze Age.
521 A total of 114.58×10^9 Illumina HiSeq 2500 sequencing reads were processed.
522
523 AdapterRemoval[40] (version 2.1.7) was used with its default settings to remove adaptors from
524 all sequences, to trim N bases from the ends of reads, and to trim bases with quality ≤ 2.
525 Reads were aligned against a human genome (GRCh38[41]) using BWA[42] (version 0.7.15-

526 r1140, mem algorithm). Reads that did not match the human genome were then mapped
527 against the NCBI viral protein reference database containing 274,038 viral protein sequences
528 (downloaded on 2016-08-31) using DIAMOND[43] (version 0.8.25). Protein matches were
529 grouped into their corresponding viruses. Reads matching HBV were found in 25 samples.
530
531 The non-human reads from the HBV-positive samples that had more than three reads
532 matching HBV using DIAMOND were selected for a subsequent BLAST[44] (version 2.4.0)
533 analysis. A BLAST database was made from Dataset 3, and samples were matched using
534 blastn (with arguments -task blastn -evalue 0.01). Matching reads with bit scores greater than
535 50 for all samples (except DA222 (70) and DA45 (55)) were selected for subsequent
536 processing. The number of reads selected from the BLAST matches, per sample, is shown in
537 Table 1, with additional detail in Extended Data Table 1. Across all samples 11,149 reads
538 matched against HBV sequences.

539 **PCR confirmation**

540 Real-time PCR was established using primers and TaqMan probes as described by Drosten et
541 al.,[45] which amplifies a 91 base pair amplicon of the HBV genome. Primers and probe were
542 added to QuantiTect PCR mix (Qiagen #204343) in a final concentration of 400 nM or 200
543 nM, respectively, in a total reaction volume of 25 ul, including 5 ul template. Using the
544 Roche LC480 or Agilent Mx3006p instruments, PCRs were incubated for 15 min. at 95°C
545 followed by 45 cycles of 15 seconds at 94°C and 60 seconds at 60°C, measuring fluorescence
546 from the 6-carboxy-fluorescein/BHQ1-labelled probe and the passive dye (ROX) at the end
547 of each cycle.
548 Careful precautions were taken to prevent PCR contamination. PCR mastermixes were
549 prepared in dedicated ancient DNA clean lab facilities, in which no prior targeted work has
550 been carried out on HBV. Ancient DNA extracts and non-template controls (NTC) were

551 added into PCR reactions in this location too, which were not subsequently opened. Positive
552 control material was handled in labs in a physically separated building. Here, standard
553 material, diluted to 5-50 copies/reaction, was added to duplicate PCR reactions along with
554 additional NTCs.

555 **Virus capture**

556 14 samples with sufficient sample material were selected for virus capture (DA27, DA29,
557 DA45, DA51, DA85, DA89, DA119, DA195, DA222, RISE254, RISE386, RISE416,
558 RISE568, RISE556). The viral reference genomes for probes were selected as follows. The
559 International Committee for Taxonomy of Viruses (ICTV) 2012 listed 2618 viral species. As
560 many had no associated reference genomes or merely partial sequence information, we
561 selected 2599 sequences of full-length viral genomes, available from GenBank (June 2014),
562 representing viral species found in vertebrates excluding fish. Sequences <1000 nt were
563 discarded. Sequences with identical length and organism ID were regarded as duplicates and
564 thus reduced to 1. For a number of specific viral taxa for which a large number of similar
565 reference sequences are available, we manually selected representative genomes or genome
566 segments (SI Tables 1 and 2). For example, among 72 available Hepatitis C virus genome
567 sequences, we selected one genome per subtype (1a-c, g; 2a-c, i, k; 3a, b, i, k; 4a-d, f, g, k-r,
568 t; 5a; 6a-u; 7a). Likewise, 12 HIV-1 genomes were selected representing groups M (subtypes
569 A-D, F1, F2, H, J, K, N, O, and P). For influenza A virus, we included only sequences from
570 segment 7 and segment 5 encoding the conserved matrix proteins M1/M2 and the
571 nucleocapsid protein NP, respectively. We selected 82 M1/M2 segments and 115 NP
572 segments among the available segments sequences. All available segments were included
573 from genomes belonging to *Arenaviridae*, *Bunyaviridae*, and *Reoviridae*. For members of
574 *Poxvirinae* for which full genomes were unavailable (Skunk-, Racoon-, and Volepox virus)
575 sequences representing the conserved gene encoding the DNA-dependent RNA polymerase

576 were included (n=22). In addition, 2 partial genomes of Squirrelpox virus were included. By
577 mistake 2 and 9 partial sequences were included from *Iridoviridae* (1.5-2.5 kb) and
578 *Coronaviridae* (1.3-14.5 kb), respectively, already represented by full genomes. Likewise,
579 sequences representing Merkel cell polyomavirus and KI polyomavirus were not included
580 among the reference genomes used for probe design. SeqCap EZ hybridization probes were
581 designed and synthesized by Roche NimbleGen (Madison, USA) based on the resulting
582 reference sequences.
583 Capture was performed on double-indexed libraries prepared from ancient DNA, following
584 the manufacturer's protocol (version 4.3) with the following modifications. Briefly, 1.8 to 2.2
585 µg of pooled libraries were hybridized at 47°C for 65-70 hours with low complexity C_0T-1
586 DNA, specific P5/P7 adaptor-blocking oligonucleotides each containing a hexamer motif of
587 inosine nucleotides to match individually indexed adapters, hybridization buffer containing
588 10% formamide, and the capture probes. Dynabeads M-270 (Invitrogen) were used to recover
589 the hybridized library fragments. After washing and eluting the libraries, the post-capture
590 PCR amplification was performed with KAPA Uracil+ polymerase (Kapa Biosystems). PCR
591 cycling conditions were as follows: 1 cycle of 3 min at 95°C, followed by 14 cycles of: 20
592 sec denaturation at 98°C, 15 sec annealing at 65°C and 30 sec elongation at 72 °C, ending
593 with 5 min at 72°C. The amplified captured libraries were purified using AMPureXP beads
594 (Agencourt).
595 Shotgun sequencing data was generated as described in Allentoft et al. (2015)[1]. Sequencing
596 of target-enriched libraries was performed on Illumina Hiseq2500 SR80bp, V4 chemistry.
597 The resulting reads were compared to Dataset 2 using BLASTn (with arguments -task blastn -
598 evalue 0.01). Matching reads with bit scores greater than 50 for all samples (except DA222
599 (70) and DA45 (55)) were selected for subsequent processing. In total, 6757 reads matched
600 HBV after capture.

601 ## Sequence authenticity

602 The following evidence leads us to believe that the ancient HBV sequences are authentic and
603 that the possibility of contamination can be excluded:

604 (1) Standard precautions for working with ancient DNA were applied[46].
605 (2) Sequences were checked for typical ancient DNA damage patterns using
606 mapDamage[47] (version 2.0.6). Whenever sufficient amounts of data were
607 available (>200 HBV reads), we found C>T mutations at the 5' end, typical of
608 ancient DNA[48] (see Extended Data Fig. 1a,c).
609 (3) Capture was performed on sample DA222 DNA extracts with and without pre-
610 treatment by Uracil-Specific Excision Reagent (USER)[49]. After USER treatment
611 (3h at 37°C) of the aDNA extract, the damage pattern is eliminated (Extended
612 Data Fig. 1b).
613 (3) As the ancient viruses are from three different HBV genotypes (A, B, D) and a
614 clade in sister relationship to NHP viruses, any argument that samples were
615 contaminated would have to account for this diversity as well as the sequence
616 novelty.
617 (4) HBV sequences were identified in 25 of 305 analysed samples (Table 1), showing
618 that the findings cannot be due to a ubiquitous laboratory contaminant.
619 (5) Despite the low frequency of positive samples, we sequenced extraction blanks to
620 provide additional evidence against the possibility that the HBV sequences
621 stemmed from sporadic incorporation, amplification, and sequencing of
622 background reagent contaminants into the ancient DNA libraries. The negative
623 extraction controls were amplified for 40 PCR cycles, and BLAST was used to
624 match the read sequences against Dataset 3, with the same parameters used for the
625 ancient samples. Because the ancient HBV positive reads used to assemble

626 genomes all had bit scores of at least 50 (see Data and Data Processing, above),
627 we filtered the negative extraction control BLAST output for reads with a bit
628 score ≥45. No reads (out of 23 million) matched any HBV genome at that level.
629 (6) HBV is a blood-borne virus that is mainly transmitted by exposure to infectious
630 blood and that does not occur in the environment[3], making contamination during
631 archaeological excavation extremely unlikely.

632 **Consensus sequences**

633 Reads from the original sequencing and from the capture were aligned to a reference genome
634 (SI Table 3) in Geneious[50] (version 9) using Medium Sensitivity / Fast and Iterate up to 5
635 times. Because aDNA damage often clusters towards read termini[48], the resulting alignments
636 were carefully curated by hand to remove non-matching termini of reads if the majority of the
637 read showed a very good match with the reference sequence.

638 **Genotyping**

639 All reads used to construct the ancient HBV consensus sequences were matched against the
640 full NCBI nucleotide (nt) database (downloaded December 28, 2016) using BLAST. 97.5%
641 of the reads had HBV as their top match. All ancient consensus sequences were matched
642 against the full HBV genomes of Dataset 4 with the Needleman-Wunsch algorithm[51], as
643 implemented in EMBOSS[52] (version 6.6.0.0). For each ancient sequence, the percent
644 sequence identity for each modern genotype and four NHP species is listed in Extended Data
645 Table 4a. The Needleman-Wunsch algorithm was also used to calculate the pairwise
646 sequence similarity between all ancient sequences (Extended Data Table 4b).

647 **Recombination analysis**

648 The Recombination Detection Program[53], version 4 (RDP4) was used to search for evidence
649 of recombination within the 12 ancient sequences and a selection of 15 modern human and
650 NHP sequences (Supplementary Methods). Recombination with HBV-RISE387 as the
651 recombinant and HBV-DA51 as one parent, was suggested at positions 1567-2256, by seven
652 recombination methods (RDP[54], GENECONV[55], BootScan[56], MaxChi[57], Chimaera[58],
653 SiScan[59], and 3Seq[60]) with p-values from 1.179×10^{-6} to 5.336×10^{-11} (Extended Data Table 2).
654 The same recombination was suggested for all 4 ancient genotype A and two modern
655 genotype A sequences. Graphical evidence of the recombination and the predicted break
656 point distribution for sequences HBV-RISE386 and HBV-RISE387 from three methods
657 (MaxChi, Bootscan, and RDP) is shown in Extended Data Fig. 3.

658 Phylogenetic analysis

659 **Initial maximum likelihood phylogenies**

660 An initial Maximum Likelihood (ML) tree was generated to ascertain that the ancient
661 sequences fall within the primate HBV clades. Dataset 1 and the ancient sequences were
662 aligned in MAFFT[61] (version 7). The ML tree was constructed using PhyML[62] (version
663 20160116), optimizing topology, branch lengths, and rates. We used a GTR substitution
664 model, with base frequencies determined by ML, and an ML-estimated proportion of
665 invariant sites and 100 bootstraps (Extended Data Fig. 2). Furthermore, an ML tree (Extended
666 Data Fig. 4) was generated based on a MAFFT alignment of Dataset 2 and the ancient
667 sequences, using the same parameters as outlined above. The final trees show nodes with
668 support values less than 70 as polytomies.

669 **Dated coalescent phylogenies**

670 In order to check for a temporal signal in the data, a root-to-tip regression and date
671 randomisation tests were performed. For the root-to-tip regression, input trees were
672 calculated using Dataset 2 with the addition of a Woolly Monkey sequence (GenBank

673 Accession Number: AF046996) as an outgroup. Three phylogenetic algorithms were used,
674 Neighbour Joining, ML (PhyML), and Bayesian (MrBayes[63] (version 3.2.5)) methods (SI
675 Figs. 1-3). Root-to-tip distances were extracted using TempEst[64] (version 1.5). For ML and
676 Bayesian, root distances for tip taxa (in substitutions per site) were extracted from optimized
677 tree topologies (ML and Maximum Clade Credibility trees, respectively). For NJ, root-to-tip
678 distances were averaged over 1000 bootstrap replicates. Regression analyses were performed
679 with Scipy[65] (version 0.16.0). For the date randomisation tests, we used three different
680 approaches to randomise tip dates: First, tip dates were randomised between all sequences in
681 the phylogeny. Second, tip dates were randomised only among the ancient sequences
682 presented in this paper, as well as the Korean mummy sequence (accession number
683 JN315779). The modern sequences retained their correct ages. Third, dates were randomised
684 within a clade. For each of the three approaches, we performed three independent
685 randomisations. This resulted in a total of nine analyses, which were run for 100,000,000
686 generations each, under the relaxed lognormal clock model and coalescent exponential tree
687 prior. We also ran the same analyses under a strict clock and coalescent Bayesian skyline tree
688 prior, which were run for 20,000,000 generations. We used a GTR substitution model with
689 unequal base frequencies, four gamma rate categories, estimated gamma distribution of rate
690 variation, and estimated proportion of invariant sites, as found by bModelTest[66] (version
691 1.0.4). None of the analyses using the relaxed clock converged (Estimated Sample Size (ESS)
692 < 200). This is most likely because the mis-specification of the dates leads to an incongruence
693 between the sequence and time information. Under the strict clock model, all runs converged,
694 and none of the 95% HPD intervals of the tree height overlapped between the randomised
695 and the non-randomised runs, fulfilling the criteria for evidence of a temporal signal[67].
696 Dated phylogenies were estimated using BEAST2[26] (version 2.4.4, prerelease). We used a
697 MAFFT alignment of Dataset 2. Using bModelTest[66], we selected a GTR substitution model

698 with unequal base frequencies, four gamma rate categories, estimated gamma distribution of
699 rate variation, and estimated proportion of invariant sites. Proper priors were used
700 throughout. Path sampling, as implemented in BEAST2, was performed to select between
701 strict or relaxed lognormal clock and a coalescent constant, exponential, or coalescent
702 Bayesian skyline tree prior (Extended Data Table 3a). Likelihood values were compared
703 using a Bayes factor test. According to Kass and Raftery[68], a Bayes factor in the range of 3-
704 20 implies positive support, 20-150 strong support, and >150 overwhelming support. The
705 relaxed lognormal clock model in combination with a coalescent exponential tree prior was
706 favoured. For the final tree, a Markov chain Monte Carlo analysis was run until parameters
707 reached an ESS > 200, sampling every 2000 generations. Convergence and mixing were
708 assessed using Tracer[69] (version 1.6). The final tree files were subsampled to contain 10,000
709 or 10710 (for the relaxed lognormal clock, coalescent exponential tree prior) trees, with the
710 first 25% of samples discarded as burn-in. Maximum clade credibility trees were made using
711 TreeAnnotator[26] (version 2.4.4 prerelease).
712
713 In order to formally test the Out of Africa hypothesis, calibration points were tested using
714 path sampling as implemented in BEAST2. Calibration points were constrained as follows.
715 Split of genotypes F and H: The MRCA of all genotype F and H sequences was constrained
716 using a uniform(13,400: 25,000) distribution, as this is the range of estimates for when the
717 Americas were first colonized[70,71]. Split of subgenotype A3 in Haiti: The MRCA of FJ692598
718 and FJ692611 was constrained using a uniform(200: 500) distribution, due to the timing of
719 the slave trade to Haiti[72]. Split of C3 in Polynesia: The MRCA of X75656 and X75665 was
720 constrained using a uniform(5,100: 12,000) distribution, due to the range of estimates for the
721 MRCA of Polynesian populations[12,73]. Calibration points were tested under both a relaxed

722 lognormal clock, coalescent exponential tree prior, and a strict clock, Bayesian skyline tree
723 prior.
724
725 **Data availability**
726 The complete sequences in this study have been deposited in the European Nucleotide
727 Archive under sample accession numbers ERS2295383-ERS2295394.
728
729
730

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Extended Data table and figure titles and legends

Extended Data Table 1 | Extended overview of samples with reads matching HBV and PCR results

a, Extended overview of samples with reads matching HBV. Rows are sorted by decreasing consensus coverage. Explanation of column titles, from left to right starting from the second column: ^{14}C age and standard deviation; Median cal BP age or estimate (in years); approximate sample age in years; site; culture or period; gender; number of sequencing reads that matched HBV using DIAMOND[43]; number of HBV proteins matched by those reads; number of sequencing reads that matched HBV using a BLASTn[44] database built from Dataset 3 (see Methods); the number of reads from the capture that matched HBV using BLASTn (as above); the bit score cut-off above which matching reads were used to form consensus sequences; the percentage of the consensus genome covered by matching reads; average depth of coverage across the reference genome, as reported by Geneious[50]. When reading sample information across a row, an empty cell will be encountered when processing on that sample was concluded, either (in column 6) due to too few matching reads or (penultimate column) consensus coverage less than 50%. **b,** TaqMan PCR results. Four extracts from samples with HBV reads were selected for TaqMan PCR confirmation: two with a large proportion of HBV reads (DA222 and DA195), two with a small proportion of HBV reads (DA85 and DA89), and one with no HBV reads (DA351). HBV was detected in extracts from DA222 and DA195, whereas the three low- and zero-read samples were negative, as were all non-template controls.

Extended Data Table 2 | Genotype A predicted recombination break points and p-values

a, The p-values assigned to the predicted genotype A recombination by the seven methods used by RDP4[53], in the order given by RDP. The number of sequences in which the

863 recombination was predicted is always 6, corresponding to the 4 ancient and two modern
864 genotype A sequences. **b,** The predicted start and end break points for each of the 6
865 genotype A sequences. Sequences are ordered from oldest to youngest. The 99%
866 confidence intervals for the start and end points are shown (n=15 sequences analysed in all
867 cases), and are identical for all sequences. The predicted break points are close to the
868 boundaries of the polymerase. For example, for the modern genotype A sequence
869 LC074724, the polymerase is found in regions 1-1623 and 2307-3221 and the predicted
870 break points are 1622 and 2256. If recombination formed an HBV-RISE387/6 ancestor, it is
871 possible that the entire polymerase gene was contributed by one parent.
872
873 **Extended Data Table 3 | Model testing and inferred age of genotypes**
874 Models were compared using Path Sampling, as implemented in BEAST2[28]. Likelihood
875 values were compared using a Bayes factor test. A positive value for the Bayes factor
876 implies support for model 1, a negative value support for model 2. According to Kass and
877 Raftery[68], a Bayes factor in the range of 3-20 implies positive support, 20-150 strong
878 support, and >150 overwhelming support. **a,** Results of testing different clock models and
879 population assumptions to be used for dated phylogenies. Positive numbers indicate support
880 for the columns model, negative number for the rows model. **b,** MRCA age of individual
881 nodes under a strict clock and Bayesian skyline tree prior or under a relaxed lognormal clock
882 and coalescent exponential tree prior. **c,** Root age and substitution rates under different
883 clock models and tree priors. **d,** Results of testing different calibration point hypotheses
884 under a strict clock and Bayesian skyline tree prior or under a relaxed lognormal clock and
885 coalescent exponential tree prior.
886
887 **Extended Data Table 4 | Consensus sequence identity**
888 **a,** Best consensus sequence identity with 14 groups of HBV full genomes. The Needleman-
889 Wunsch algorithm (as implemented in EMBOSS[52]) was used to globally align each sample
890 consensus sequence against each of the 3384 full HBV genomes of Dataset 4 (see

891 Methods). The table shows the best nucleotide (nt) similarity percentage for each sample
892 consensus against 14 genome groups from the full set of HBV genomes. In cases where the
893 consensus length is less than the genome length, the given figure is the percentage of
894 identical nucleotides (nts) in the matching region, not counting any alignment gaps or
895 ambiguous consensus nts. For each sample, the genome group with the highest identity is
896 highlighted in bold. **b,** Inter-consensus sequence identity. The Needleman-Wunsch algorithm
897 was used to globally align all sample consensus sequences against one another. The table
898 shows the nt identity percentage for each alignment. In cases where the consensus lengths
899 were unequal, the given figure is the percentage of identical nts in the matching region, not
900 counting any alignment gaps or ambiguous consensus nts.
901
902 **Extended Data Figure 1 | Ancient DNA damage patterns**
903 The frequencies of the mismatches observed between the HBV reference sequences
904 (Extended Data Table 1) and the reads are shown as a function of distance from the 5' end.
905 C>T (5') and G>A (3') mutations are shown in red and blue, respectively. All other possible
906 mismatches are reported in gray. Insertions are shown in purple, deletions in green, and
907 clippings in orange. The count of reads matching HBV for each sample is shown in
908 parentheses. **a,** Damage patterns for RISE563, DA222, DA119, RISE254, DA195, DA27,
909 DA51, RISE386, RISE387, DA29, DA45**,** RISE154. **b,** Damage patterns for DA222 without
910 (left) and with (right) USER treatment. **c,** Damage patterns with 10, 20, 50, 100, 200, 500
911 and 1000 reads, where each opaque line corresponds to one replicate set of reads.
912
913 **Extended Data Figure 2 | Hepadnavirus Maximum Likelihood tree**
914 Shows 26 sequences from the Orthohepadnavirus species (Dataset 1, see Methods)
915 including the ancient HBV sequences. Ancient genotype A sequences are shown in red,
916 ancient genotype B sequences in orange, ancient genotype D sequences in blue and novel
917 genotype sequences in green. The tree was constructed in PhyML[62], optimizing for topology,

918 branch lengths, and rates, with 100 bootstraps (see Methods). Internal nodes with <70%
919 bootstrap support are shown as polytomies.
920
921 **Extended Data Figure 3 | Genotype A recombination break point evidence**
922 RDP4[53] was used to analyse the set of 12 ancient sequences plus a representative set of 15
923 modern human and NHP sequences (see Methods). The seven recombination programs
924 used by RDP4 suggested that all genotype A sequences are recombinants, with the
925 genotype D sequence HBV-DA51 as the minor parent and an unknown major parent. The
926 obvious interpretation is that recombination formed an ancestor of the oldest sequences,
927 evidence of which is still present in the less ancient and the modern representatives. The
928 panel shows the graphical evidence and predicted recombination break point distribution for
929 the two oldest genotype A sequences, HBV-RISE386 and HBV-RISE387, according to three
930 of the RDP4 methods (MaxChi, Bootscan, and RDP). In all sub-plots the predicted location
931 of the break points is shown by a dashed vertical line and the surrounding gray area shows
932 the 99% confidence interval for the break point. Sub-plots on the same row share their Y
933 axis and those in the same column share their X axis. **a,** HBV-RISE386 analysed by
934 MaxChi. **b,** HBV-RISE386 analysed by Bootscan. **c,** HBV-RISE386 analysed by RDP. **d,**
935 HBV-RISE387 analysed by MaxChi. **e,** HBV-RISE387 analysed by Bootscan. **f,** HBV-
936 RISE387 analysed by RDP.
937
938 **Extended Data Figure 4 | HBV Maximum likelihood tree**
939 The sequences from Dataset 2 (see Methods) and the ancient sequences were aligned in
940 MAFFT[61]. The tree was constructed in PhyML[62], optimizing for topology, branch lengths, and
941 rates, with 100 bootstraps (see Methods). Internal nodes with <70% bootstrap support are
942 shown as polytomies. Ancient genotype A sequences are shown in red, ancient genotype B
943 sequences in orange, ancient genotype D sequences in blue and novel genotype sequences
944 in green. Letters on internal branches indicate the genotype. Taxon names indicate:
945 genotype / subgenotype, GenBank accession number, age, country abbreviation of

946 sequence origin, region of sequence origin, host species, and optional additional remarks.
947 Note that the ML tree shows topological uncertainty (polytomies) in areas where the
948 BEAST2[26] tree (Figure 2) is well resolved. This is the case for two reasons. Firstly, BEAST2
949 always produces a fully-resolved binary topology without polytomies. Second, and more
950 important, BEAST2 creates a time tree and uses tip dates to constrain the possible
951 topologies under consideration. Thus BEAST2 can know that certain topologies are unlikely
952 or impossible, whereas ML cannot and thus inherently has greater uncertainty regarding tree
953 topology.
954
955 **Extended Data Figure 5 | Root-to-tip regression and date randomisation tests**
956 **a,** Regression of root-to-tip distances and ages performed in Scipy[65]. 124 branch lengths
957 were extracted using TempEst[64] from trees inferred using neighbour joining (NJ), ML, and
958 Bayesian methods. Shaded areas show 95% confidence intervals. Slopes: 1.01E-05, 1.20E-
959 05, 4.21E-06. Correlation coefficients: 0.45 (R2=0.2), 0.36 (R2=0.13), 0.51 (R2=0.26) for
960 ML, Bayesian, and NJ trees, respectively. **b,** Date randomisation tests under the strict clock
961 model. The median and 95% HPD interval for the substitution rates are given. The rate for
962 the correctly dated tree is shown in red. Dates were randomised within all sequences, within
963 the ancient sequences only, and within each genotype. We performed three replicates of
964 each. None of the 95% HPD intervals for the randomised runs overlap with the 95% HPD
965 intervals for the correctly dated runs, suggesting the presence of a temporal signal in the
966 data.
967