

Reassortment of Influenza A Viruses in Wild Birds in Alaska before H5 Clade 2.3.4.4 Outbreaks

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Sampling of mallards in Alaska during September 2014–April 2015 identified low pathogenic avian influenza A virus (subtypes H5N2 and H1N1) that shared ancestry with highly pathogenic reassortant H5N2 and H5N1 viruses. Molecular dating indicated reassortment soon after interhemispheric movement of H5N8 clade 2.3.4.4, suggesting genetic exchange in Alaska or surrounds before outbreaks.

The emergence of highly pathogenic avian influenza (HPAI) A virus subtype H5 of clade 2.3.4.4 in East Asia followed by spread into North America in 2014 highlights the importance of ecologic interactions along the Pacific Rim to the incursion of novel viruses. Introduction of influenza A subtype H5N8 into North America is hypothesized to have occurred through wild bird movement across the Bering Strait (1,2); the virus then spread through Canada to the continental United States, concurrently infecting wild birds (ducks, geese, passerines, and raptors) and poultry (turkeys and chickens) (3). Reassortment of H5N8 with low pathogenic avian influenza (LPAI) A virus in North America generated 3 subtypes (H5N8, H5N2, and H5N1, collectively referred to as H5Nx) that followed different trajectories in local bird populations. HPAI H5N2 became the most widespread in US poultry, prompting the culling of ≈49 million chickens and turkeys in 15 states (4). During the outbreaks (November 2014–December 2015),

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surveillance efforts increased; consequently, later stages of the epidemic were better characterized (5,6) relative to the beginning. Analysis of wild bird viruses from Alaska preceding outbreaks remains one of the few avenues for elucidating how H5N8 entered and reassorted with North American lineage viruses.

Our sampling of mallards (*Anas platyrhynchos*) from urban ponds in Anchorage, Alaska, during September 2014–April 2015 identified LPAI H5N2 and H1N1 (online Technical Appendix Figure 1, Table 1, <https://wwwnc.cdc.gov/EID/article/23/4/16-1668-Techapp1.pdf>). These viruses were the closest relatives for 4 of the 8 North American segments that contributed to the H5Nx reassortants based on the time of most recent common ancestry (tMRCA) analysis (online Technical Appendix Figures 2–12). All North American segments of the H5N2 reassortant (basic polymerase protein 1, nucleoprotein, and neuraminidase) shared most recent common ancestry with LPAI H5N2 that circulated in Anchorage mallards and a concurrently sampled wild bird population at Izembek National Wildlife Refuge in western Alaska (1) (online Technical Appendix Figures 3, 5, 8, 9). Molecular dating indicated reassortment of H5N8 and LPAI H5N2 (or precursors) shortly after the interhemispheric movement of H5N8. We estimated that ancestors of the H5N2 reassortant emerged among wild birds in Alaska during August 2013–May 2014, based on tMRCAs of multiple segments (Figure 1, panel A), followed by emergence of the H5N2 reassortant during May–September 2014. Our analysis refines the hypothesis of Beringia introduction (1,2) by indicating that H5N8 reassorted with viruses shed by waterfowl in Alaska (or nearby high latitudes) shortly after introduction into North America (May 2014–October 2014, 95% highest posterior density January 2014–January 2015) (Figure 1, panel A). Accuracy of molecular dating hinges on the availability of virus sequences from relevant hosts, which were lacking from North American poultry and wild birds during the year preceding outbreaks (Figure 1, panel B). Our sampling was fortuitous, being one of the few in Alaska conducted before the outbreaks, underscoring the importance of routine sampling where interhemispheric mixing of viruses occurs with high frequency.

The rapid reassortment of H5N8 clade 2.3.4.4 within North America is premised on the movement of at least a single infected bird across the Bering Strait followed by

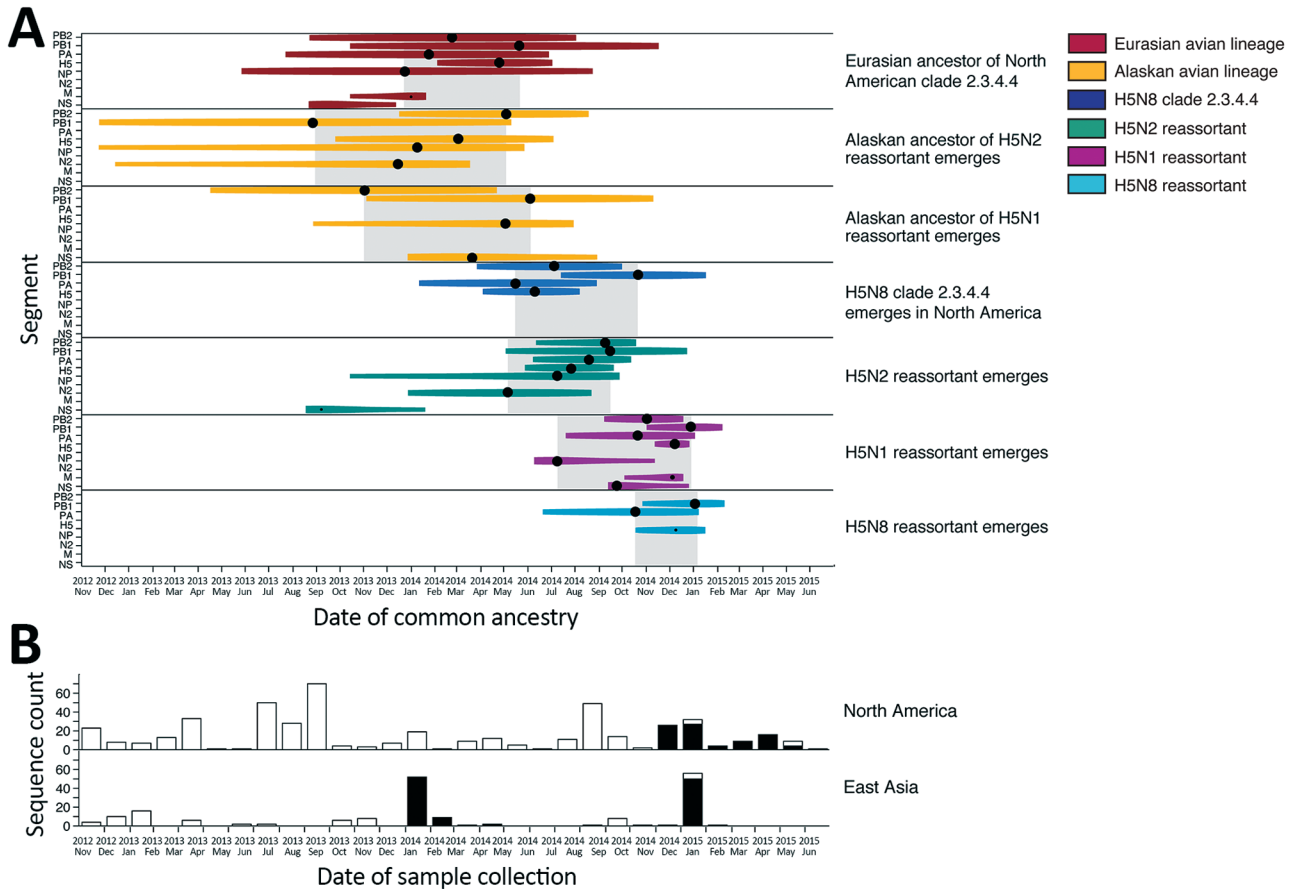


Figure 1. Molecular dating of the emergence of H5 clade 2.3.4.4 influenza A virus in Eurasia and North America and concurrent trends in surveillance effort. A) Events contributing to the evolution of H5 clade 2.3.4.4 estimated using multiple influenza segments. Time of most recent common ancestry (indicated by a black circle) is size-scaled by the posterior probability (0.0–1.0), and the 95% highest posterior density is color-coded by lineage. Gray shading indicates time of most recent common ancestry of multiple segments with a posterior probability >0.85. B) Surveillance effort estimated by the number of hemagglutinin sequences (high and low pathogenicity) available in the Influenza Research Database (<https://www.fludb.org>). Black bars indicate surveillance effort for H5 clade 2.3.4.4; white bars indicate surveillance effort for other clades. M, matrix gene; N2, neuraminidase 2 gene; NP, nucleoprotein gene; PA, polymerase acidic, PB1, basic polymerase protein 1 gene; PB2, basic polymerase protein 2 gene; tMRCAs, time of most recent common ancestry.

infection of a host population at high latitude. Interhemispheric movement during spring 2014 (or earlier) is most plausible given the circulation of the Eurasian ancestor of North American clade 2.3.4.4 during December 2013–May 2014 (95% highest posterior density October 2013–January 2015) (Figure 1, panel A), an event that preceded introduction. The presence of overwintering birds in Alaska, a known area for influenza exchange between East Asia and North America (7,8), might enhance opportunities for viruses originating in Eurasia to reassort with LPAI in local bird populations. Mallards from this study are a prime example of an overwintering population, occupying urban ponds that remained thawed because of human activity, which allows some birds to remain in southcentral Alaska from September through April, when many migratory waterfowl have since flown south. We found evidence

that LPAI H5N2 shed by overwintering mallards from Anchorage (south-central Alaska) and wild birds from Izembek (western Alaska) were highly related and formed monophyletic clades (online Technical Appendix Figures 5, 6, 8–10). This provided evidence of regional dispersal of LPAI in Alaska concurrent with the proposed timing of H5N8 introduction and reassortment.

Anchorage mallards shed viruses that shared ancestry with 2 of 4 North American segments (basic polymerase protein 1 and nonstructural) of the H5N1 reassortant (online Technical Appendix Figures 2, 5, 12). Emergence of the H5N1 reassortant probably occurred after July 2014 (Figure 1, panel A), after the H5N2 reassortant emerged. Molecular dating of tMRCAs of H5N8 reassortants was confounded by long branch lengths of parental lineages indicative of unsampled ancestors; however, estimates based

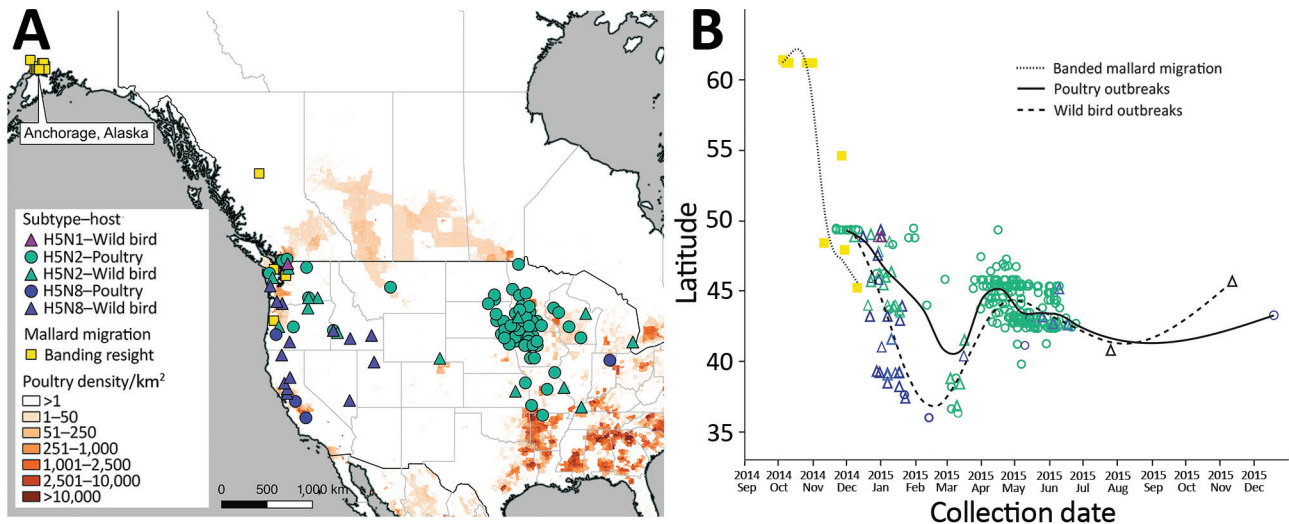


Figure 2. Spatial and temporal distribution of H5N2.3.4.4 influenza A virus outbreaks among wild birds and poultry across North America. A) Spatial distribution of H5N2.3.4.4 influenza A virus outbreaks in wild birds (triangles) and poultry (circles) across North America, color-coded by subtype, relative to poultry density. The location of mallards from Anchorage, Alaska, based on resighting of banded birds, is indicated. B) Temporal distribution of H5N2.3.4.4 influenza A virus detections during the course of the outbreaks relative to the migration of mallards banded in Anchorage.

on 2 segments suggest emergence after October 2014. The H5N1 and H5N8 reassortants possessed a highly similar polymerase acidic segment (online Technical Appendix Figure 6), suggesting a similar evolutionary trajectory of the two subtypes that later diverged. Our tMRCA estimates for H5N1 are consistent with reassortment during or after the breeding season for mallards in Alaska followed by southward dispersal along the Pacific Flyway during autumn (Figure 2). These results suggest that H5N1 is a multiple reassortant that acquired PB1 and NS segments in Alaska (or surrounds) followed by polymerase acidic and neuraminidase 2 from different host populations before detection in Washington (9) and Oregon (4) in early 2015.

Arrival of mallards banded in Anchorage at the high-density poultry region of the Fraser Valley, British Columbia, Canada, in November 2014 is compatible with the chronology of evolution and subsequent detection of the H5Nx subtypes (Figure 2). The migration chronology of banded mallards might be broadly representative of other dabbling duck species that breed in Alaska, such as the American green-winged teal (*Anas carolinensis*), American wigeon (*Anas americana*), and northern pintail (*Anas acuta*), in which H5Nx was detected at lower latitudes. Consequently, mallards and other waterfowl species probably were involved in the southward dispersal and reassortment of H5Nx followed by spillover to poultry. Observations of wild birds congregating at water bodies on poultry farms in the Fraser Valley support the scenario of indirect transmission from migratory birds to poultry, seeding outbreaks at lower latitudes (10). Later divergence of H5N2

into multiple lineages during May–November 2014 (online Technical Appendix Figure 8) implies that outbreaks were seeded by different H5N2 strains, although the mode of dispersal through wild bird migration, farm-to-farm poultry movement, or poultry workers remains unclear.

Since introduction of HPAI H5 of clade 2.3.4.4 into the Pacific Northwest in late 2014, little evidence exists for additional reassortment, despite continued spread of H5N2 and H5N8 until late 2015 (Figure 2, panel B). Lack of further reassortment implies a change from wild bird-mediated dispersal to intermittent spillover between wild birds and poultry or indirect transmission among poultry farms via fomites, wind, or other undetermined vectors. The spatiotemporal pattern of outbreaks in wild birds and poultry appeared correlated during this later phase (Figure 2, panel B). Correlation might be a function of outbreak investigation procedures that require concurrent sampling of poultry and wild birds inhabiting the control zone. However, our phylogenetic analysis lends support for frequent spillover given that lineages of H5Nx were mixed by host, rather than poultry and wild birds clustering separately (online Technical Appendix Figures 4–12). Our analysis and the August 2016 detection of HPAI H5N2 in mallards from Fairbanks, Alaska (11), an area lacking commercial poultry, implicates waterfowl as playing an important role in reassortment, spread, and possibly long-term circulation of H5Nx viruses.

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Dr. Hill is a postdoctoral associate at the Massachusetts Institute of Technology, Cambridge, Massachusetts, USA. Her primary research interests include the ecology and evolution of influenza viruses in natural and man-made systems.

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Reassortment of Influenza A Viruses in Wild Birds in Alaska before H5 Clade 2.3.4.4 Outbreaks

Technical Appendix

Methods

Sampling of Wild Birds

The sampling locations were predominately at Cuddy Family Midtown Park, Anchorage, Alaska (61.184981°, -149.880597°) and Westchester Lagoon, Anchorage, Alaska (61.202333°, -149.90333°), two urban locations that attract overwintering mallards (online Technical Appendix Figure 1, panel A). Between September 2014 and April 2015 we sampled a total of 484 individual birds and recaptured 216. Baited swim and walk-in traps were used to capture mallards. We obtained a cloacal and tracheal swab from each bird and fitted each bird with an aluminum federal tarsus band. Polyester-tipped applicators were used to collect swabs, placed in viral transport media (VTM: Remel, KS) and kept on ice until transfer to -80 freezers in the laboratory.

Banding Data and Outbreak Analysis

We obtained recovery/recapture data for mallards banded in Anchorage from the U.S. Geological Survey Bird Banding Laboratory. Of the 468 ducks banded, a total of 75 (16.03%) bands were reported between 2014 and 2016, mostly representing hunter-shot ducks. Band returns were mapped using QGIS 2.0 (Open Source Geospatial Foundation Project. <http://qgis.osgeo.org>) to describe connectivity of the Anchorage mallard population with other regions in North America. Poultry (chicken) density layers were obtained from the Gridded Livestock of the World (1) available online. Location and timing of all H5 clade 2.3.4.4 outbreaks were obtained from federal agency Web sites for the U.S. (U.S. Department of Agriculture [2]) and Canada (Canadian Food Inspection Agency [3]). A smoothing average for the spatiotemporal pattern of outbreaks was plotted separately for wild bird and poultry cases

separately (JMP Pro 12.2, SAS), as well as the chronology of mallard migration (Figure 2, panel B).

Virus Isolation and Sequencing

Viral RNA was extracted using the Omega Mag-Bind Viral DNA/RNA Kit (Omega Bio-Tek, Norcross, GA) and a Kingfisher magnetic particle processor (Thermo Scientific, Waltham, MA). RNA was screened for the presence of influenza A virus (IAV) using qScript XLT one-step RT-qPCR Tough Mix (Quanta Biosciences, Gathersburg, MD) targeting the matrix gene. PCR assays were run on an ABI 7500 real-time PCR System (Applied Biosystems, Foster City, CA). PCR-positive samples (Ct value <45) were subjected to a H5-specific rRT-PCR to identify potentially highly pathogenic samples (4). All H5-positive samples were sent to the U.S. National Poultry Research Center, USDA to culture potential HPAI viruses. To amplify virus, positive VTM (100ul) was inoculated into the allantoic cavity of 9–11 day old embryonating specific pathogen free chicken eggs (Charles River, CT) and incubated at 37°C for 72 hours or until embryo death, as detected by daily candling. RNA was extracted from the allantoic fluid and the matrix rRT-PCR repeated (5). Whole-genome sequencing was performed at the J. Craig Venter Institute in Rockville, MD as described by Nelson et al. (6) and all sequences deposited into GenBank (online Technical Appendix Table 1). Subtyping was confirmed by BLASTn of the sequence against isolates in GenBank and identifying the subtype match that showed highest percentage identity.

Multiple Sequence Alignment

Global IAV sequences were downloaded from the Influenza Research Database (IRD [7]) and Global Initiative on Sharing All Influenza Data (GISAID) during the period between 1/17/16 - 2/16/16. Only full genomic segments (PB2, PB1, PA, H5, NP, N2, N1, M and NS) of isolates collected during the period (1976 – 2016) were considered. Only sequences associated with a full date of collection (DD/MM/YYYY) were included. To facilitate filtering out duplicate sequences, taxa names were edited to remove apostrophes, brackets and all hyphens were replaced with underscores. Sequences containing misreads (NNNs) were deleted to improve the quality of alignments and subsequent trees. Sequences were then aligned using MUSCLE v3.8.31 (8), inspected visually in Geneious v7.1.5 to remove indels and taxa containing premature termination codons, then re-aligned once again using MUSCLE.

Down-Sampling before Tree Reconstruction

The aligned global sequence datasets were down-sampled to reduce the number of sequences to a size suitable for molecular clock Bayesian phylogenetic analysis (~300 taxa). The goal of down-sampling was 3-fold: 1) preserve all clade 2.3.4.4 isolates from North America; 2) preserve basal avian and mammalian lineages to accurately root the tree in deep evolutionary time; and 3) random down-sampling of non-clade 2.3.4.4 isolates stratified by time (3–5 isolates randomly preserved per year) to ensure confidence in tree topology from root to tips (online Technical Appendix Figure 13). Down-sampling was conducted using a series of Python scripts (available for download: [10.5281/zenodo.61923](https://doi.org/10.5281/zenodo.61923)). A preliminary phylogenetic tree using the global sequence alignment for each segment was constructed using the GTRGAMMA substitution model in RAxML v 8.1.16 (9). The resulting maximum likelihood trees were used to compute patristic distances between a designated ‘taxa-of-interest’ group and the rest of the global dataset. This taxa-of-interest group included recent isolates from Anchorage and Izembek (2014) and all clade 2.3.4.4 isolates from North America.

To determine the minimum number of closest relatives to the taxa-of-interest needed to construct a well-sampled Bayesian phylogenetic tree we evaluated 3 metrics in TreeStat v1.8.2: i) time of most recent common ancestry (tMRCA); ii) tree height/root age; and iii) treeness (tree shape). These values were generated for the closest 10 and 25 relatives of the in-group by constructing preliminary Bayesian trees in BEAST v 1.8.3 (10). At least 3 independent Bayesian Markov Chain Monte Carlo (MCMC) chains, of 40 – 80 million generations each, were run and sampled under the Bayesian skyride coalescent model and the uncorrelated lognormal distribution, to produce 10,000 trees. In all cases we used a GTR + gamma substitution model. MCMC chains were visually assessed in Tracer v1.6.0 (<http://tree.bio.ed.ac.uk/software/tracer>) to ensure convergence on the same optimal tree. After removing 10 – 30% burn-in from each chain we combined trees and constructed maximum clade credibility trees. High similarity between the closest 10 and 25 relatives for the 3 metrics tested (online Technical Appendix Table 2) validated our decision to use the closest 10 relatives to reduce computational burden without compromising the reproducibility of the Bayesian trees. This data-driven approach guided how to down-sample the internal segments. For the H5 and N2 segments, we included the closest 100 relatives, and for N1, we included the closest 25 relatives owing to the limited taxa available.

To achieve down-sampling stratified by time – a strategy we used to increase accuracy of molecular dating of divergence events, a maximum of 100 taxa were randomly selected from our global datasets, spanning 1996–2016, with an average of 3–5 isolates per year. The 1996 cutoff was chosen because it marks the emergence of the A/goose/Guangdong/1/1996 lineage. A compiled BEAST dataset was obtained by combining recent Alaskan isolates, the in-group of clade 2.3.4.4 isolates and randomly selected taxa. The down-sampled datasets contained the following numbers of taxa: PB2 = 321, PB1 = 334, PA = 309, H5 = 370, NP = 347, N2 = 311, N1 = 277, M = 362, and NS = 374.

Bayesian Phylogenetic Analysis

Dated phylogenetic trees for each segment were constructed using BEAST v1.8.3. At least 4 independent MCMC chains, of 40 – 80 million generations each, were run using the GMRF Bayesian skyride coalescent tree prior and uncorrelated lognormal distribution to produce 10,000 trees. To ensure MCMC chains converged on the same optimal tree, runs were visually inspected in Tracer v1.6.0. After removing 10 – 30% burn-in from each chain, the trees were combined to produce a single maximum clade credibility (MCC) tree.

Molecular Dating Analysis

The time of most recent common ancestry (tMRCA) for each taxon was inferred from the nodes of the MCC tree inspected in FigTree v1.4.3. The tMRCA dates and 95% highest posterior densities (95% HPD) for all segments were used to assess the order of gene introduction events (Figure 1, panel A). We also considered the posterior probabilities associated with each branch node when estimating gene segment introduction events. Only gene segment introductions associated with a posterior probability greater than 0.85 were considered such that bifurcating nodes with low support were ignored. We considered this an important step in view of the uneven sampling regime (targeting poultry farms) and low number of viruses sequenced during the outbreak period. As a result, not all influenza segments contributed equally to this analysis. For the matrix (M) and non-structural (NS) genes, low posterior probabilities for branch nodes (Technical Appendix Figure 12) combined with reverse branching (ambiguity in the exact timing of divergence events) precluded their use for estimating gene introduction events. These conserved segments were of limited value for estimating the rapid evolution of H5 clade 2.3.4.4, especially in view of the low number of sequences available before the outbreaks.

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Technical Appendix Table 1. List of 12 influenza A virus strains (H5N2 and H1N1) isolated from mallards in Anchorage, Alaska, that were precursors to the reassortment event with highly pathogenic H5N8 clade 2.3.4.4

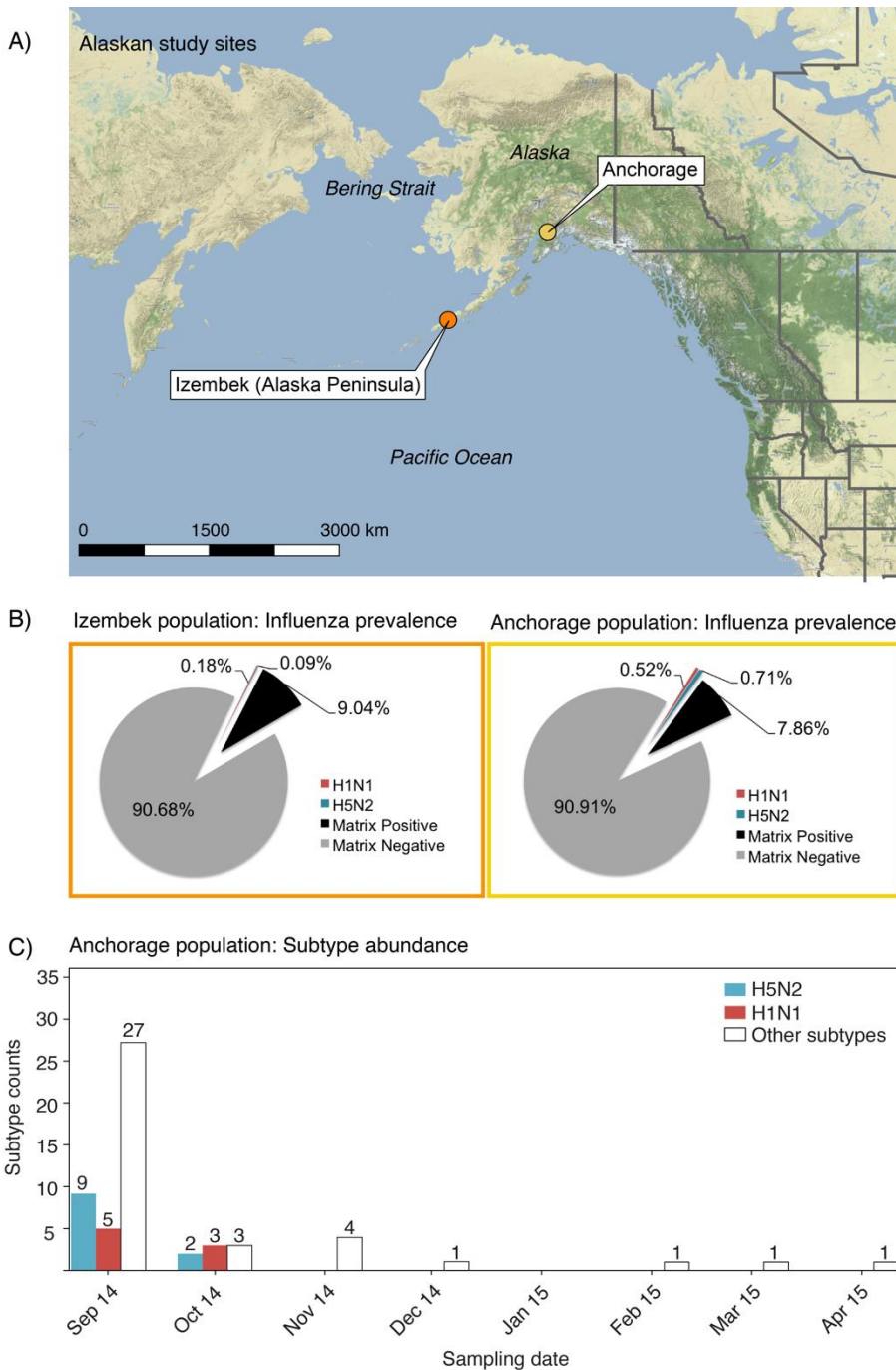
| Strain name | Accession numbers | Subtype | Sampling date | Swab type | Mallard age | Band number |
|---|-------------------|---------|---------------|-----------|------------------|-------------|
| A/mallard/Southcentral Alaska/12ML00957/2014 | CY206693-CY206700 | H1N1 | 19-Sep-14 | Cloacal | Hatch-year | 2047–55491 |
| A/mallard/Southcentral Alaska/12ML00991/2014 | CY194156-CY194163 | H5N2 | 22-Sep-14 | Cloacal | Hatch-year | 2047–55121 |
| A/mallard/Southcentral Alaska/12ML00985/2014 | CY194147-CY194155 | H5/3N2 | 22-Sep-14 | Cloacal | Hatch-year | 2047–55110 |
| A/mallard/Southcentral Alaska/12ML00988_AAF1/2014 | CY194181-CY194188 | H5N2 | 22-Sep-14 | Oral | Hatch-year | 2047–55104 |
| A/mallard/Southcentral Alaska/12ML00977/2014 | CY194139-CY194146 | H5N2 | 22-Sep-14 | Cloacal | Hatch-year | 2047–55107 |
| A/mallard/Southcentral Alaska/12ML00995/2014 | CY206733-CY206740 | H1N1 | 22-Sep-14 | Cloacal | Hatch-year | 2047–55113 |
| A/mallard/Southcentral Alaska/12ML01009/2014 | CY206741-CY206748 | H1N1 | 22-Sep-14 | Cloacal | Hatch-year | 2047–55117 |
| A/mallard/Southcentral Alaska/12ML01048_AAF1/2014 | CY194213-CY194220 | H5N2 | 23-Sep-14 | Cloacal | Hatch-year | 2047–55138 |
| A/mallard/Southcentral Alaska/12ML01045/2014 | CY206781-CY206788 | H1N1 | 23-Sep-14 | Cloacal | Hatch-year | 2047–55136 |
| A/mallard/Southcentral Alaska/12ML01175/2014 | CY206797-CY206805 | H1N1 | 20-Oct-14 | Cloacal | After hatch-year | 2047–55005 |
| A/mallard/Southcentral Alaska/12ML01443/2014 | CY206806-CY206813 | H1N1 | 24-Oct-14 | Cloacal | Hatch-year | 2047–55025 |
| A/mallard/Southcentral Alaska/12ML01469/2014 | CY194164-CY194172 | H5/9N2 | 24-Oct-14 | Cloacal | Hatch-year | 2047–55065 |

Technical Appendix Table 2. Time of most recent common ancestry (tMRCA) for each of the 8 influenza segments

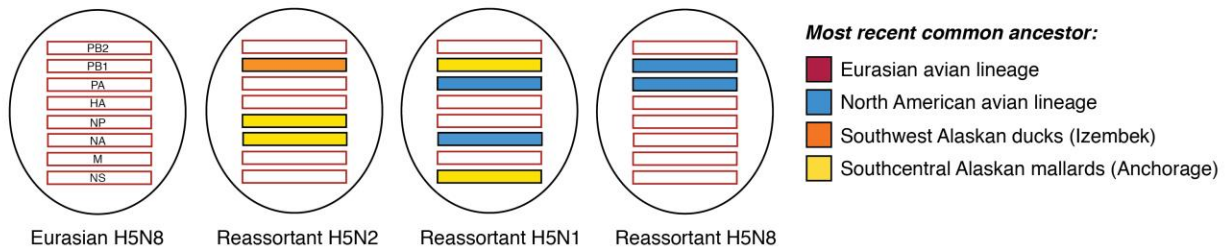
| Segment | Emergence event | Posterior probability | tMRCA | Maximum tMRCA | Minimum tMRCA |
|---------|--|-----------------------|-----------|---------------|---------------|
| PB2 | Eurasian ancestor of North American clade 2.3.4.4 | 0.999 | 23-Feb-14 | 27-Jul-14 | 6-Sep-13 |
| PB2 | H5N8 clade 2.3.4.4 emerges in North America | 1.000 | 5-Jul-14 | 27-Sep-14 | 4-Apr-14 |
| PB2 | H5N1 reassortant emerges | 0.881 | 2-Nov-14 | 17-Dec-14 | 12-Sep-14 |
| PB2 | H5N2 reassortant emerges | 0.960 | 9-Sep-14 | 19-Oct-14 | 15-Jun-14 |
| PB2 | Alaskan ancestor of H5N2 reassortant | 1.000 | 4-May-14 | 14-Aug-14 | 27-Dec-13 |
| PB2 | Alaskan ancestor of H5N1 reassortant | 1.000 | 2-Nov-13 | 15-Apr-14 | 2-May-13 |
| PB1 | Eurasian ancestor of North American clade 2.3.4.4 | 1.000 | 12-May-14 | 2-Nov-14 | 21-Oct-13 |
| PB1 | H5N8 clade 2.3.4.4 emerges in North America | 1.000 | 22-Oct-14 | 8-Jan-15 | 9-Jul-14 |
| PB1 | Alaskan ancestor of H5N2 reassortant | 0.999 | 22-Aug-13 | 16-Apr-14 | 1-Dec-12 |
| PB1 | H5N2 reassortant emerges | 1.000 | 15-Sep-14 | 19-Dec-14 | 13-May-14 |
| PB1 | Alaskan ancestor of reassortant H5N1 | 1.000 | 31-May-14 | 30-Oct-14 | 16-Nov-13 |
| PB1 | H5N1 reassortant emerges | 1.000 | 25-Dec-14 | 1-Feb-15 | 23-Oct-14 |
| PB1 | H5N8 reassortant emerges | 1.000 | 28-Dec-14 | 9-Feb-15 | 6-Nov-14 |
| PA | Eurasian ancestor of North American clade 2.3.4.4 | 1.000 | 24-Jan-14 | 22-Jun-14 | 6-Aug-13 |
| PA | H5N8 clade 2.3.4.4 emerges in North America | 1.000 | 16-May-14 | 25-Aug-14 | 21-Jan-14 |
| PA | North American ancestor of H5N8 & H5N1 reassortant | 1.000 | 10-Mar-14 | 7-Nov-14 | 7-May-13 |
| PA | H5N2 reassortant emerges | 1.000 | 19-Aug-14 | 10-Oct-14 | 13-Jun-14 |
| PA | H5N8 reassortant emerges | 1.000 | 18-Oct-14 | 4-Jan-15 | 29-Jun-14 |
| PA | H5N1 reassortant emerges | 0.995 | 21-Oct-14 | 31-Dec-14 | 27-Jul-14 |
| H5 | Eurasian ancestor of North American clade 2.3.4.4 | 1.000 | 25-Apr-14 | 30-Jun-14 | 10-Feb-14 |
| H5 | H5N8 clade 2.3.4.4 emerges in North America | 0.999 | 10-Jun-14 | 5-Aug-14 | 9-Apr-14 |
| H5 | North American ancestor of H5N8 & H5N1 reassortant | 0.992 | 1-Nov-14 | 20-Nov-14 | 27-Sep-14 |
| H5 | H5N1 reassortant emerges | 1.000 | 8-Dec-14 | 26-Dec-14 | 14-Nov-14 |
| H5 | H5N2 reassortant emerges | 0.998 | 27-Jul-14 | 18-Sep-14 | 2-Jun-14 |
| H5 | Alaskan ancestor of H5N2 reassortant | 1.000 | 3-Mar-14 | 29-Jun-14 | 7-Oct-13 |
| H5 | H5N8 reassortant emerges | 0.225 | 9-Dec-14 | 11-Jan-15 | 15-Oct-14 |
| NP | Eurasian ancestor of North American clade 2.3.4.4 | 0.990 | 24-Dec-13 | 15-Aug-14 | 15-Jun-13 |
| NP | H5N2 reassortant emerges | 0.993 | 9-Jul-14 | 24-Sep-14 | 26-Oct-13 |
| NP | Alaskan ancestor of H5N2 reassortant | 0.992 | 9-Jan-14 | 23-May-14 | 11-Dec-12 |

| Segment | Emergence event | Posterior probability | tMRCA | Maximum tMRCA | Minimum tMRCA |
|---------|---|-----------------------|-----------|---------------|---------------|
| NP | Alaskan ancestor of H5N1 reassortant | 0.806 | 3-May-14 | 28-Jul-14 | 7-Sep-13 |
| N1 | H5N1 reassortant emerges | 1.000 | 9-Jul-14 | 9-Nov-14 | 16-Jun-14 |
| N2 | H5N2 reassortant emerges | 0.992 | 6-May-14 | 18-Aug-14 | 7-Jan-14 |
| N2 | Alaskan ancestor of H5N2 reassortant | 0.918 | 15-Dec-13 | 12-Mar-14 | 1-Jan-13 |
| M | Eurasian ancestor of North American clade 2.3.4.4 | 0.005 | 1-Jan-14 | 19-Jan-14 | 18-Oct-13 |
| NS | Eurasian ancestor of North American clade 2.3.4.4 | 0.001 | 24-Sep-13 | 12-Dec-13 | 25-Aug-13 |
| NS | Alaskan ancestor of reassortant H5N1 | 0.996 | 21-Mar-14 | 29-Aug-14 | 3-Jan-14 |
| NS | H5N1 reassortant emerges | 0.999 | 24-Sep-14 | 26-Dec-14 | 16-Sep-14 |
| NS | H5N2 reassortant emerges | 0.001 | 7-Sep-13 | 19-Jan-14 | 22-Aug-13 |

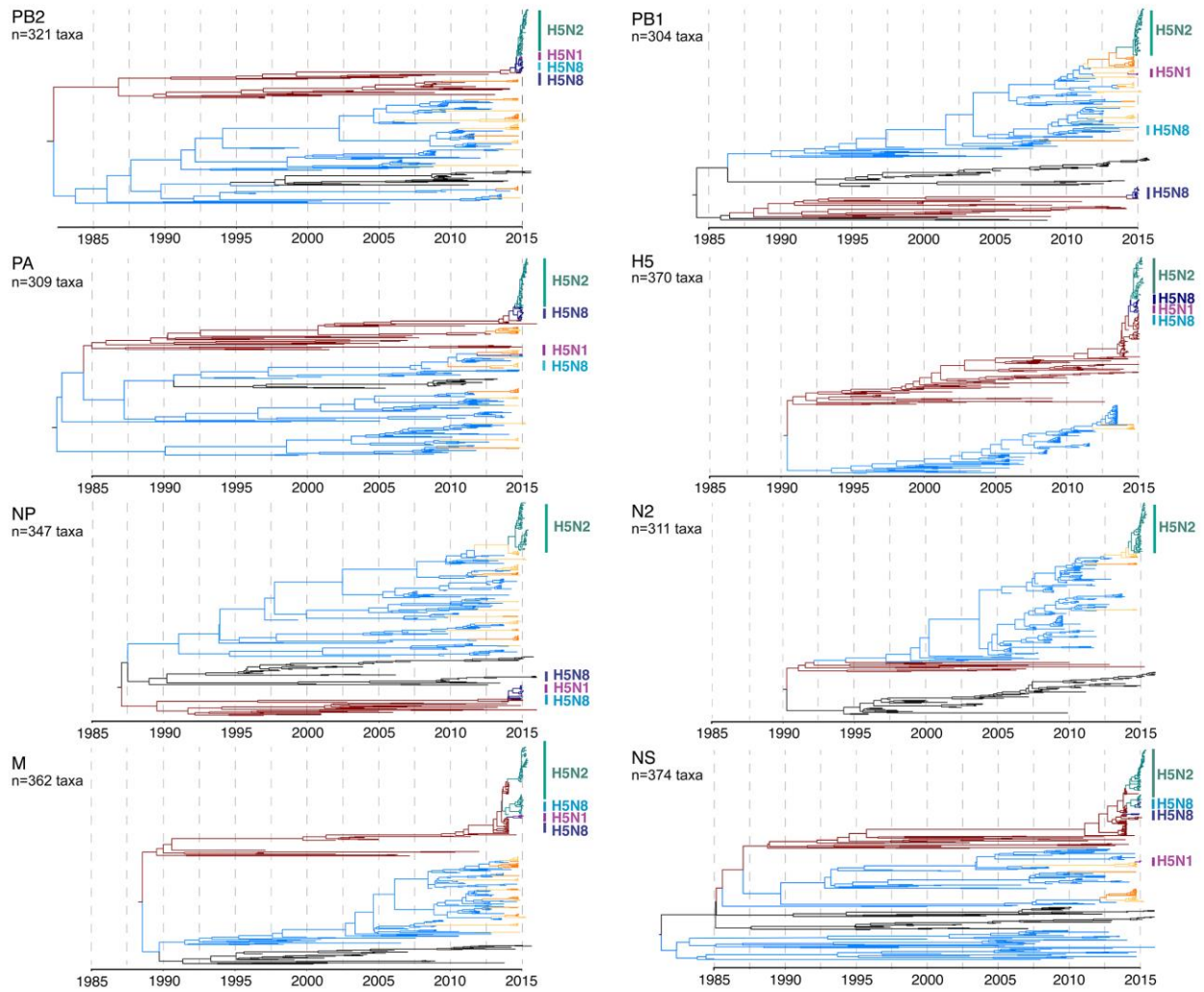
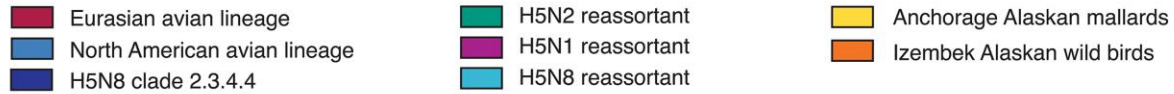
*tMRCA estimates with posterior probabilities >0.85 are highlighted in bold. Segments with Alaskan ancestry based on phylogenetic trees (online Technical Appendix Figures 4–12) are shaded in gray.



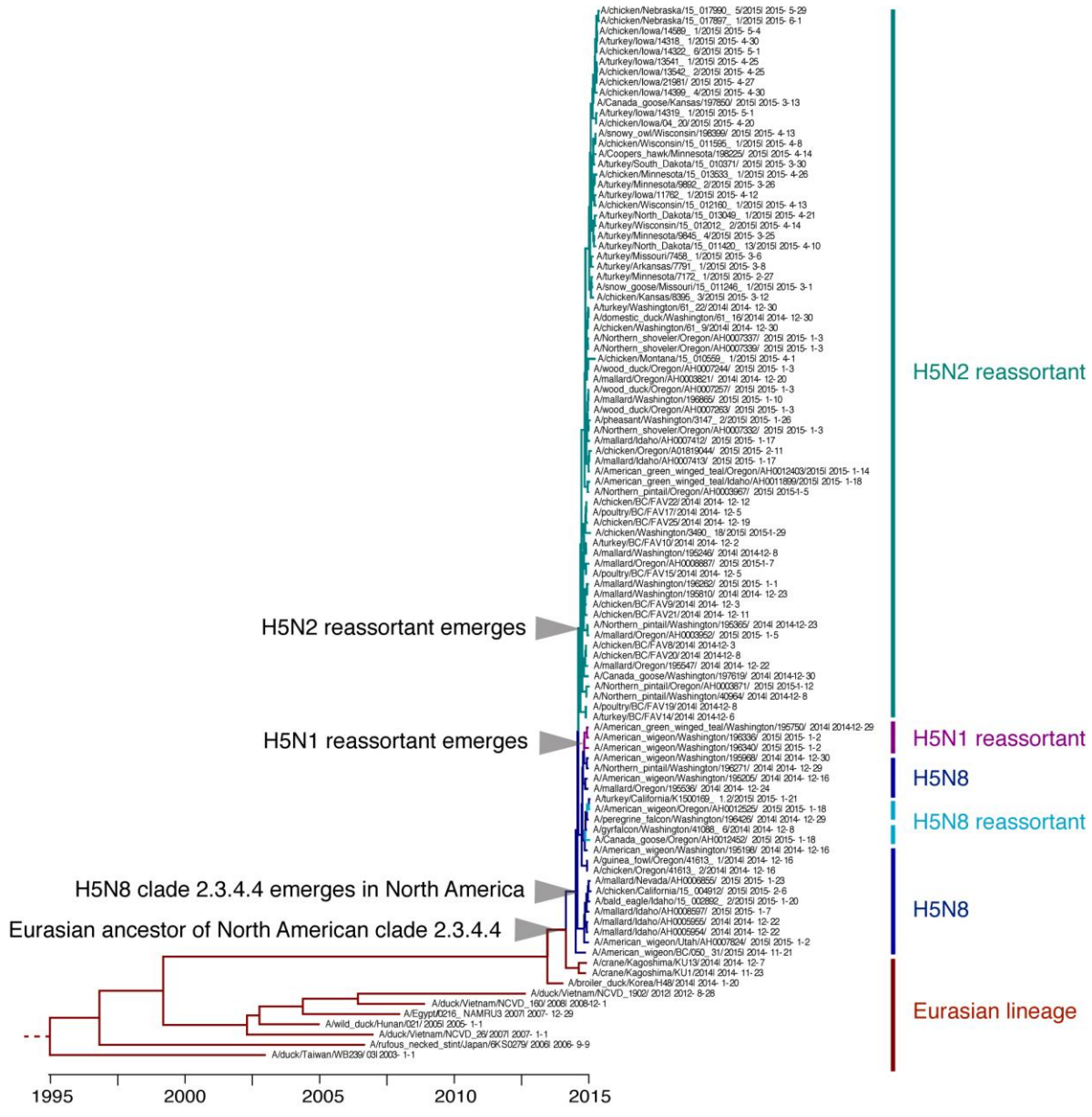
Technical Appendix Figure 1. Location of the Anchorage study site relative to the concurrently sampled Izembek site and prevalence of influenza A virus and the low pathogenic H5N2 subtype at each of the 2 sites. A) Location of the Anchorage study site relative to the concurrently sampled Izembek site, Alaska Peninsula. These were the only sites sampled in Alaska before the 2014 outbreaks. B) Prevalence of influenza A virus and the low pathogenic H5N2 subtype at each of the 2 sites, 2014–2015. C) Abundance of the low pathogenic H5N2 and H1N1 subtypes over the course of the winter among the Anchorage mallard population.



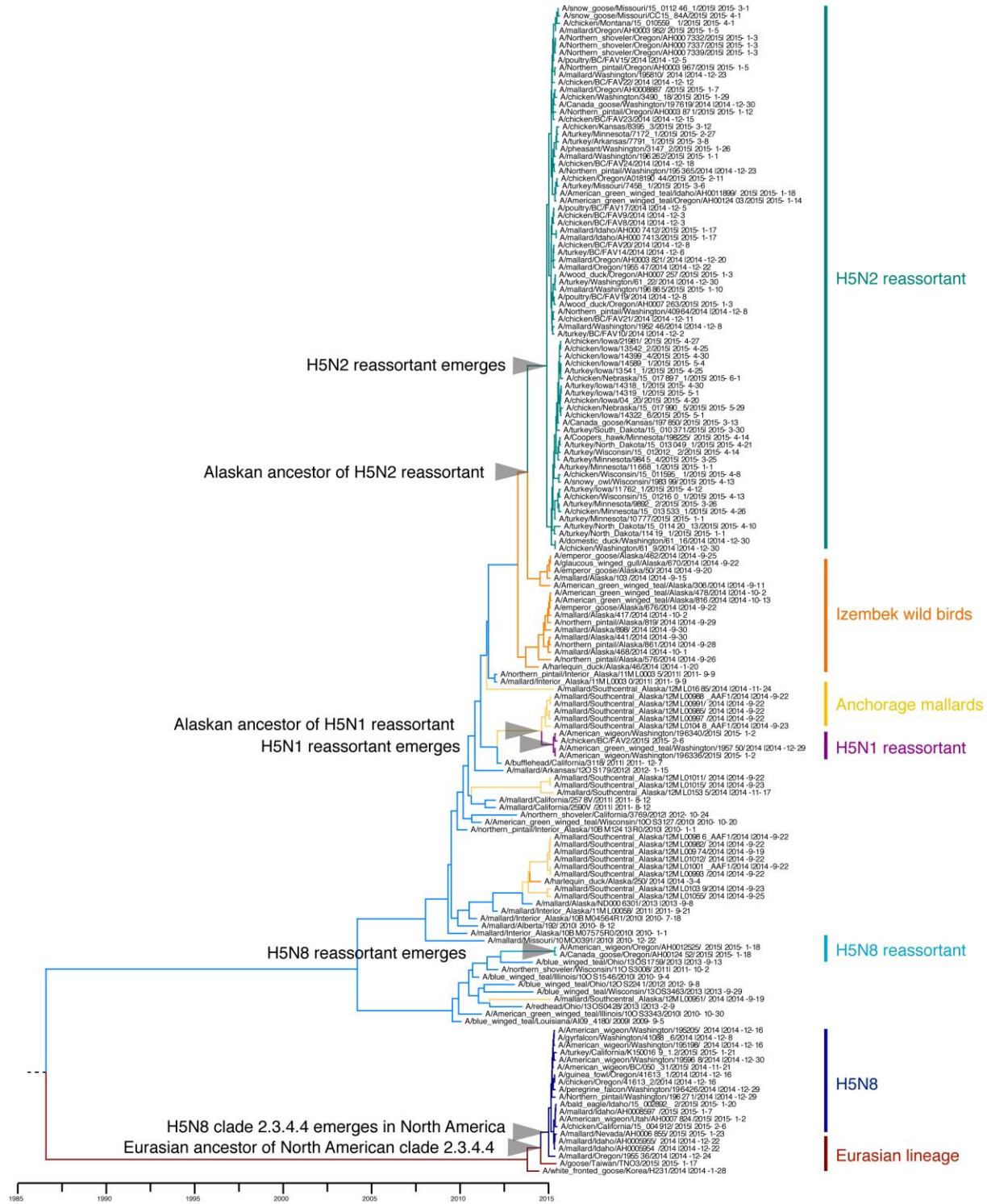
Technical Appendix Figure 2. Proposed genotypes of highly pathogenic influenza A virus H5Nx (reassortant H5N2, H5N1 and H5N8). Segments are color coded according to the most recent common ancestor for each genotype, based on phylogenetic tree reconstructions (Technical Appendix Figures 4–13).



Technical Appendix Figure 3. Phylogenetic tree reconstruction using Bayesian inference was used to date the ancestry of clade 2.3.4.4 viruses for each of the 8 influenza segments. The ancestry of the 3 subtypes: H5N8 (blue), H5N2 (green), H5N1 (purple) is shown relative to viruses shed by the Alaskan wild populations from Anchorage (yellow) and Izembek (orange).



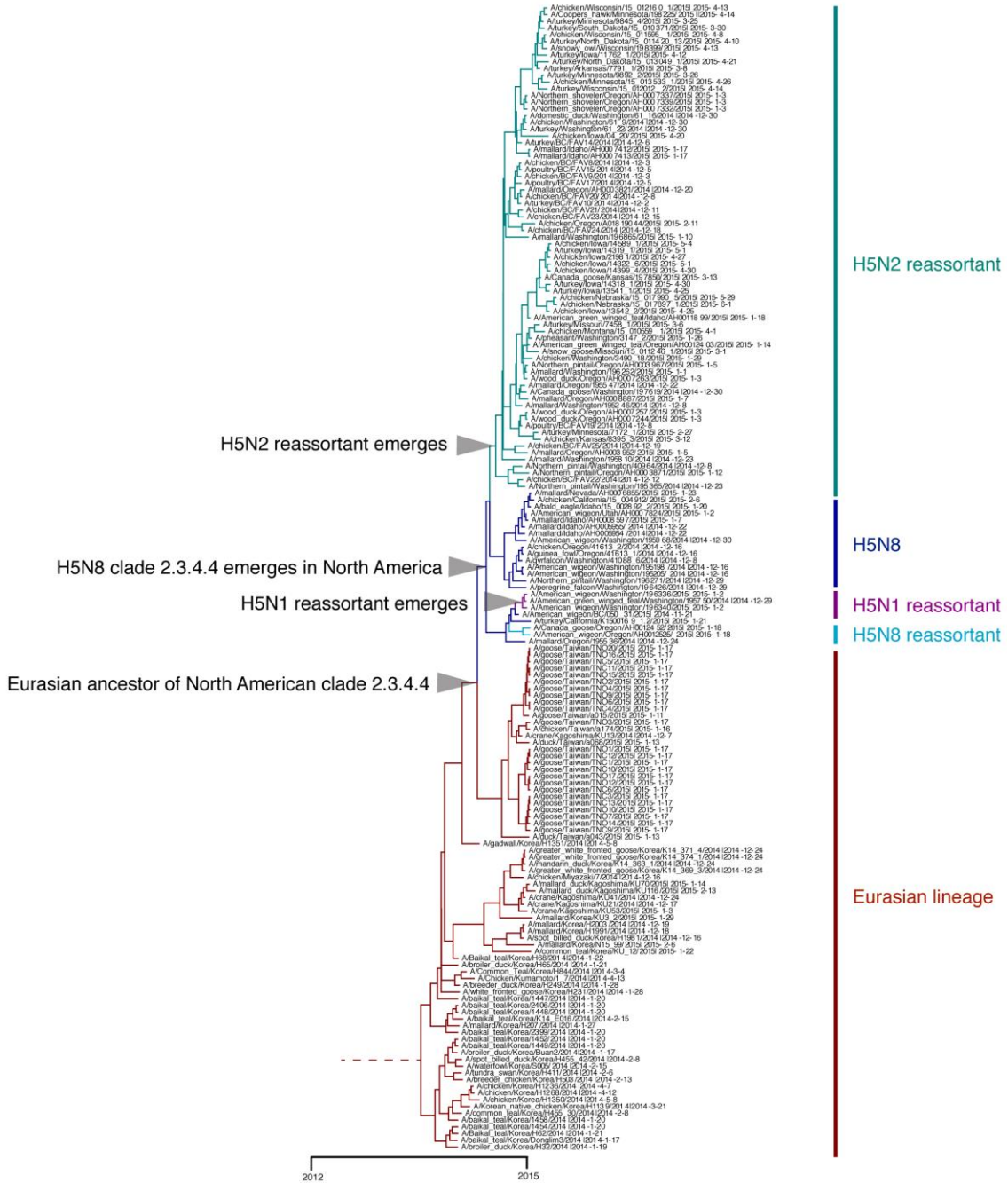
Technical Appendix Figure 4. Bayesian phylogenetic tree for the PB2 segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCAs: posterior probabilities >0.85) are marked with gray arrows.



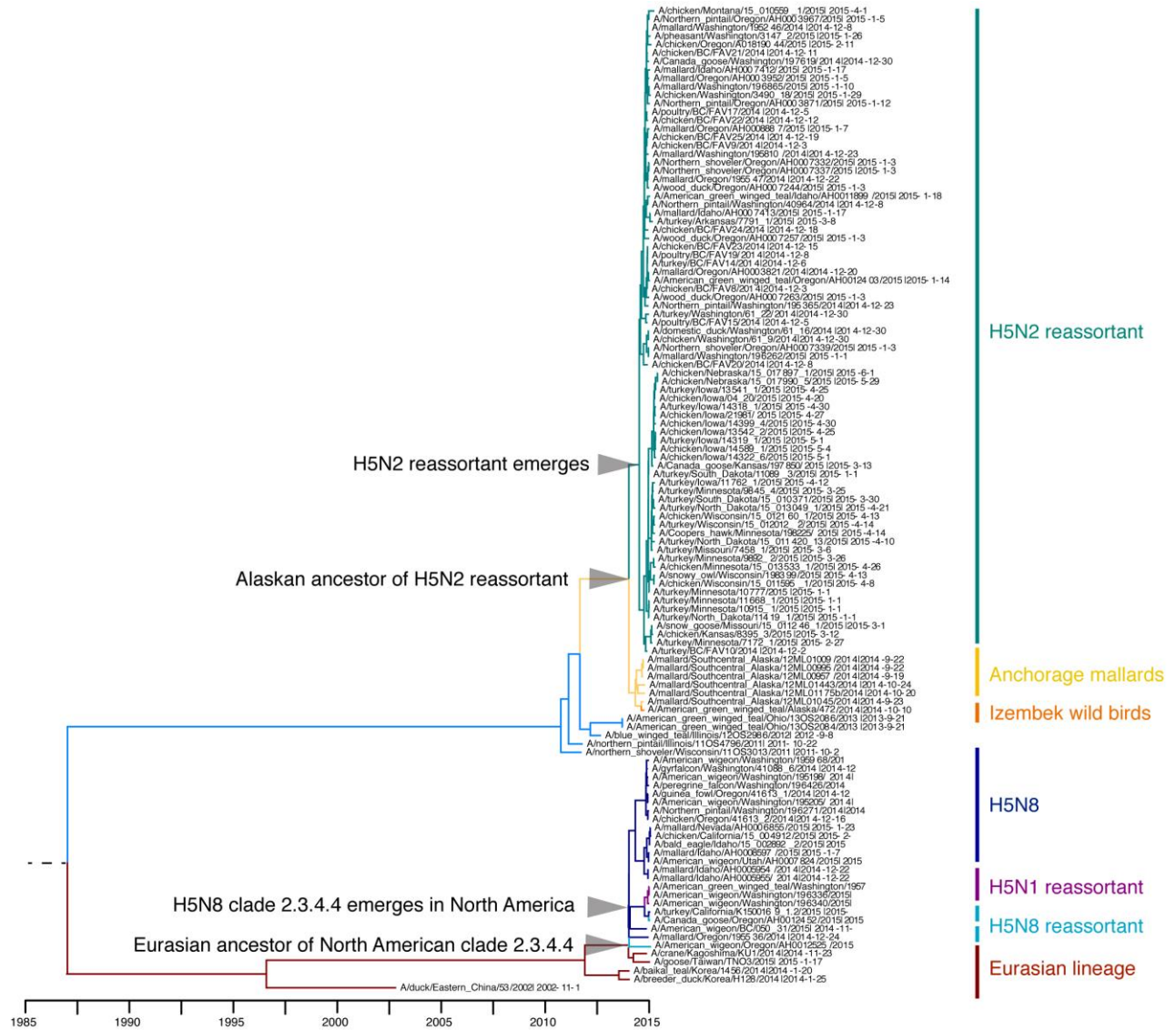
Technical Appendix Figure 5. Bayesian phylogenetic tree for the PB1 segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCA: posterior probabilities >0.85) are marked with grey arrows.



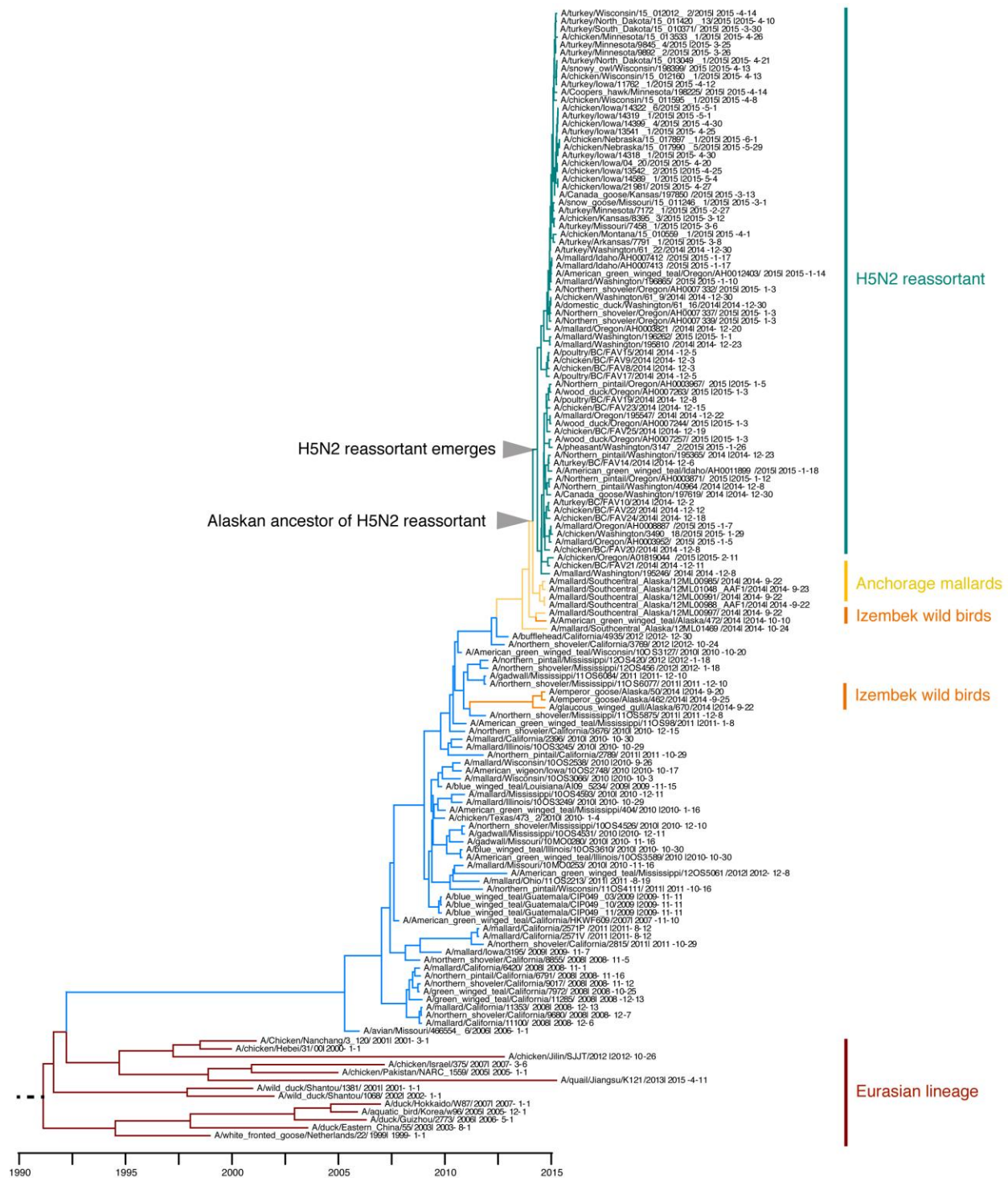
Technical Appendix Figure 6. Bayesian phylogenetic tree for the PA segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCA: posterior probabilities >0.85) are marked with grey arrows.



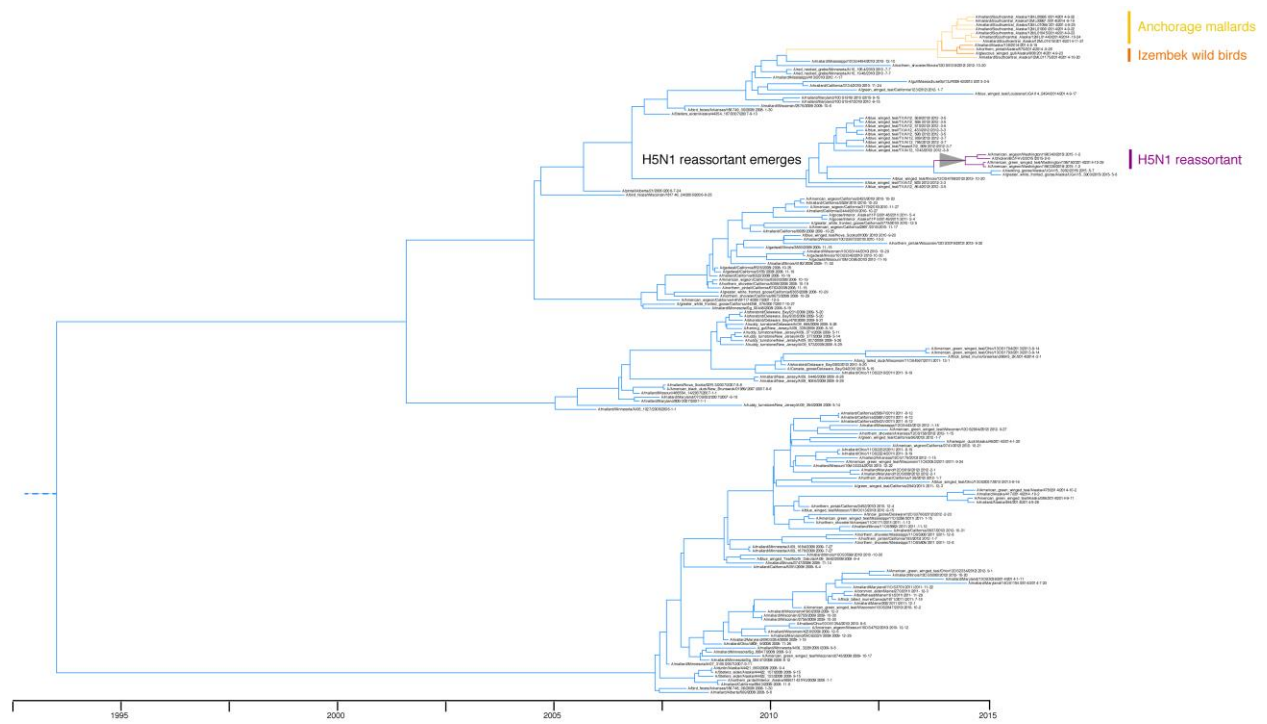
Technical Appendix Figure 7. Bayesian phylogenetic tree for the H5 segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCA: posterior probabilities >0.85) are marked with gray arrows.



Technical Appendix Figure 8. Bayesian phylogenetic tree for the NP segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCA: posterior probabilities >0.85) are marked with gray arrows.



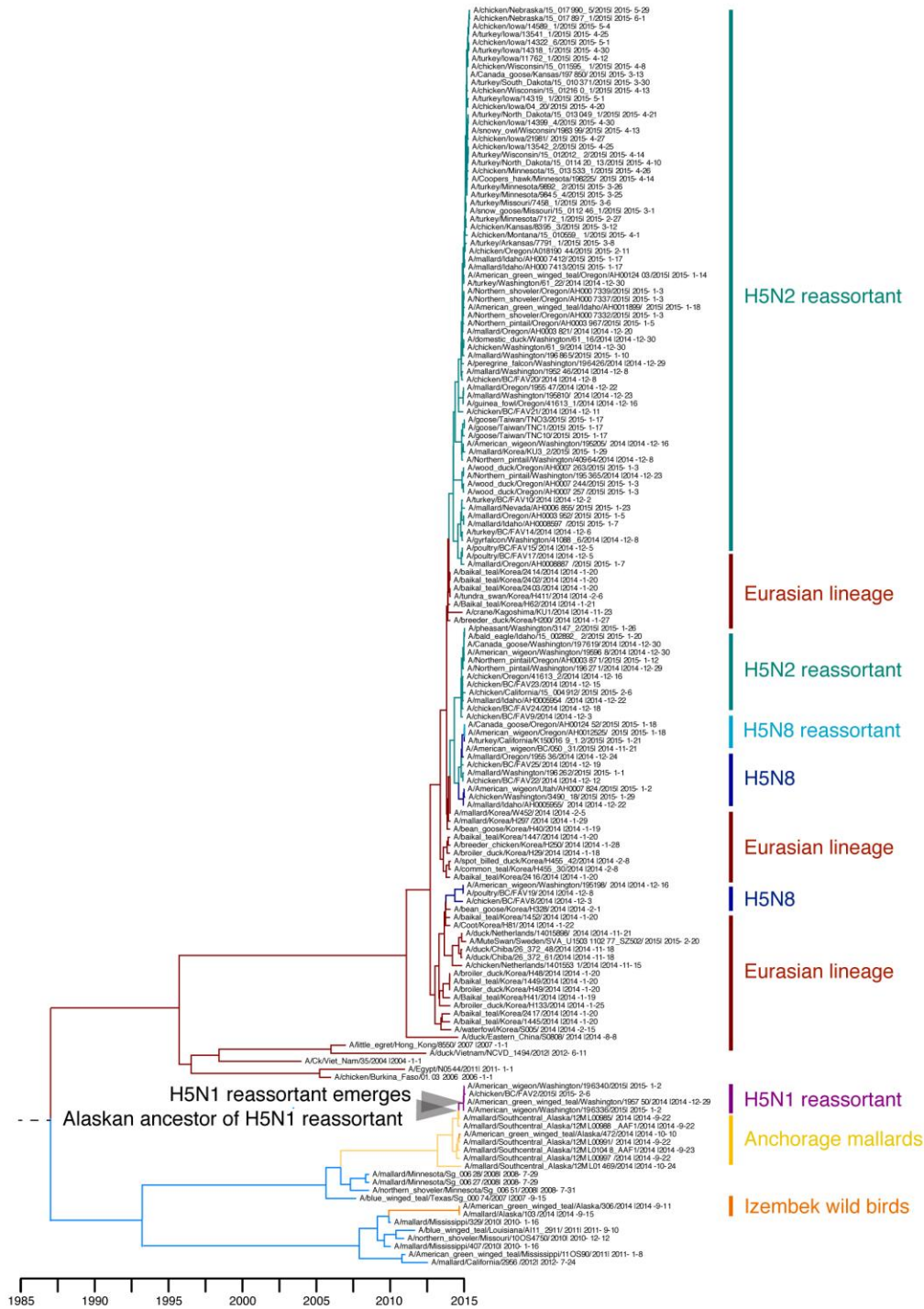
Technical Appendix Figure 9. Bayesian phylogenetic tree for the N2 segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCA: posterior probabilities >0.85) are marked with gray arrows.



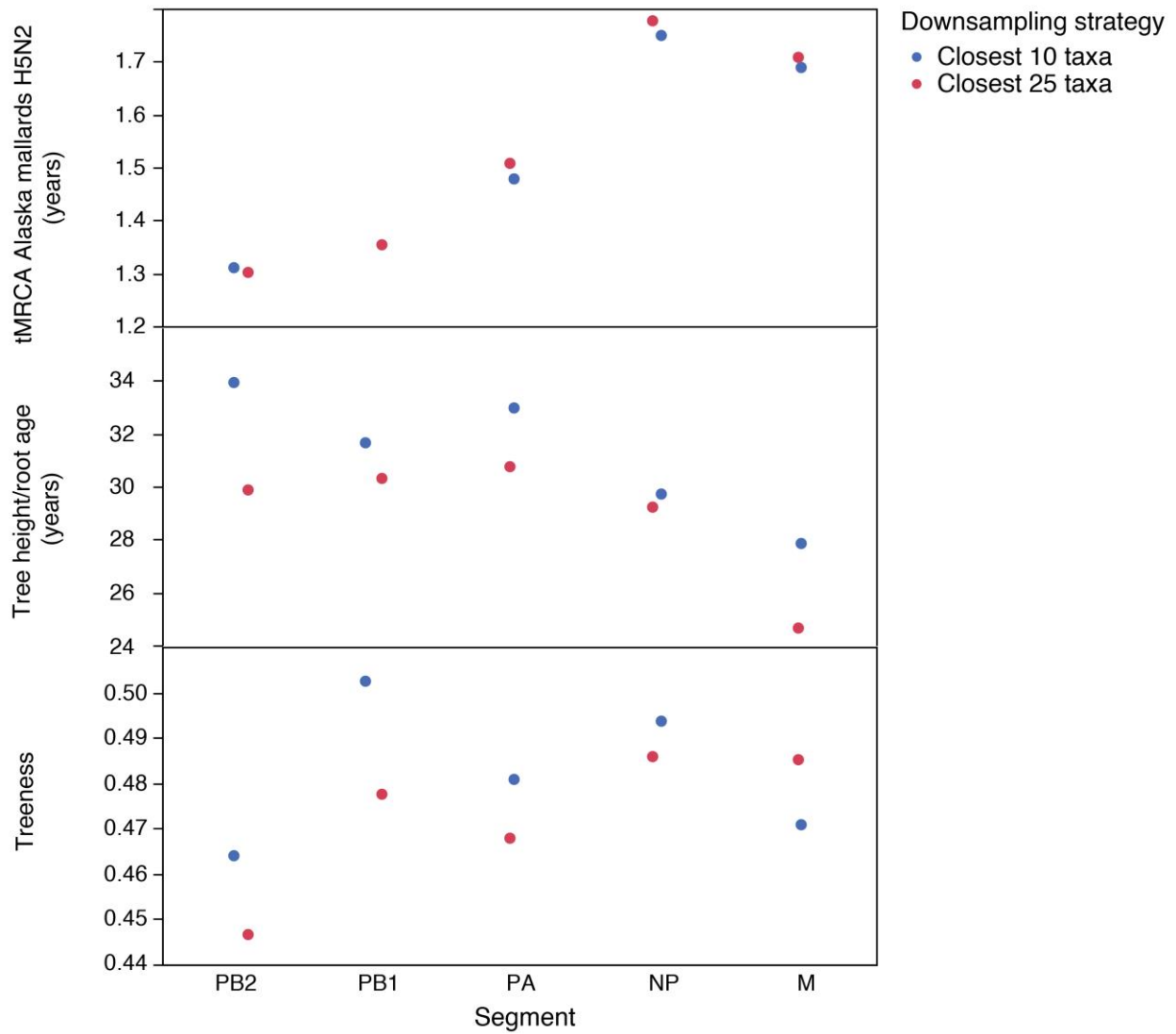
Technical Appendix Figure 10. Bayesian phylogenetic tree for the N1 segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCA: posterior probabilities >0.85) are marked with gray arrows.



Technical Appendix Figure 11. Bayesian phylogenetic tree for the M segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCA: posterior probabilities >0.85) are marked with gray arrows.



Technical Appendix Figure 12. Bayesian phylogenetic tree for the NS segment constructed using sequences from clade 2.3.4.4 North American outbreaks. The tree has been time-calibrated using a relaxed molecular clock and branch lengths represent years. Nodes used to calculate time of most recent common ancestry (tMRCA: posterior probabilities >0.85) are marked with gray arrows.



Technical Appendix Figure 13. The optimal down-sampling strategy for internal segments was determined using Bayesian tree statistics to compare the reliability of trees generated with the closest 10 or 25 relatives to the in-group (i.e., H5N8 clade 2.3.4.4 and Alaskan isolates from Anchorage and Izembek). The non-structural gene (NS) was not included due to allelic divergence.