Common features and characteristics of archeo- and paleomagnetic field models

Wardinski & Terra-Nova & Thebault

SETS OF OBSERVATIONS

+ observations of the geomagnetic field
  - direct observations made by ground-based or satellite-based geomagnetic measurements

    $\rightarrow$ geomagnetic field models (spherical harmonics degree 1-20)

  - indirect observations from sampling the magnetic recordings of rocks, sediments and kilns

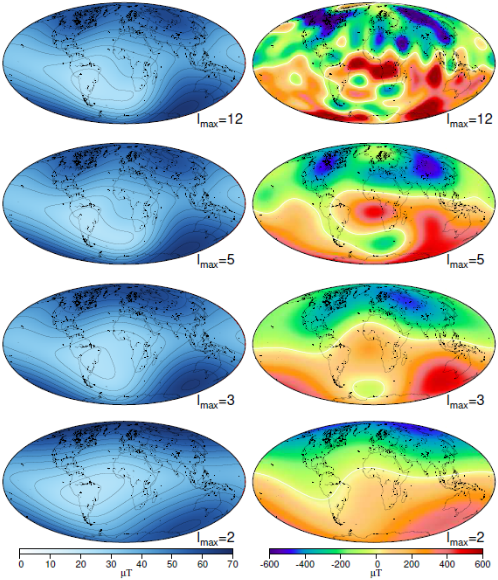
    $\rightarrow$ archeo and paleo-geomagnetic field models (spherical harmonics degree 1-10)

+ numerical experiments based on ab-inito calculations of magnetic field generation and heat transfer between Earth's core and mantle

SETS OF OBSERVATIONS

+ paleo-geomagnetic field models are based on data that un-evenly sample Earth's magnetic field in time and space
+ severely, temporal uncertainties range from a few decades to 10^6 years, depending on the age of the sample
+ uneven hemispherical distribution of the data limits model interpretation on southern hemisphere,
+ spatial data distribution allows, at maximum, to resolve spherical harmonic degree $\sim$6 (Brown et al., 2018)

SPATIAL RESOLUTION



total field at Earth's surface radial field at the CMB (Brown et al.2018)

SET OF MAGNETIC FIELD MODELS

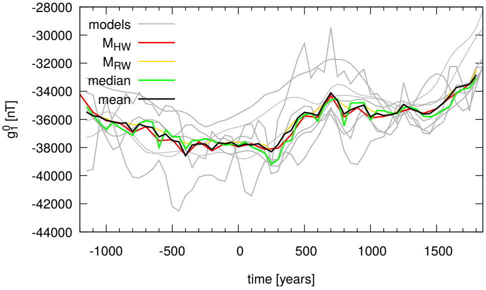
Models based on stochastic inversion				
CALS10k.2	past 10 kyrs	10	cubic B-splines	A & L & S
HFM.OL.A1	past 10 kyrs	10	cubic B-splines	A & L & S
SHA.DIFF.14k	past 14 kyrs	10	cubic B-splines	A & L
SHAWQ2k	past 2.3 kyrs	10	cubic B-splines	A & L & S
GGF100k	past 100 kyrs	10	cubic B-splines	A & L & S
GGFSS70k	15-75kyrs BC	6	cubic B-splines	A & L & S

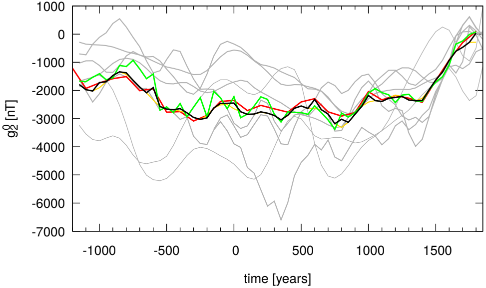
Models based on ensemble and Bayesian approaches				
pfm9k.2	past 9 kyrs	5		A & L & S
COV-ARCH & COV-LAKE A_FM, ASD_FM, ASDI_FM	past 3 kyrs	5		A & L & S
BIGMUDI4k	past 4 kyrs	8		H & A & L
ArchKalmag14k.r	past 14 kyrs	8		H & A & L

METHOD – SUMMARIZING FIELD MODELS

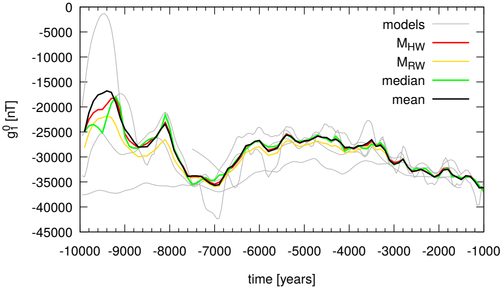
+ deriving statistical mean and median from set of models
  $\rightarrow$ **mean model**, **median model**
+ deriving spherical mean from set of models
  - compute field components on a spherical grid for each model
  - iterative inversion of the grids for set of averaged Gauss coefficients
  - at each iteration step: define a new weights for each data point
  - favor Huber-weights, less sensitive to large outliers $\rightarrow$ resulting model $\mathbf{M}_{HW}$
+

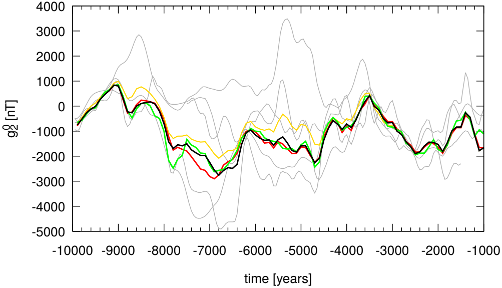
AVERAGED ARCHEO MODELS g_1^0, g_2^0



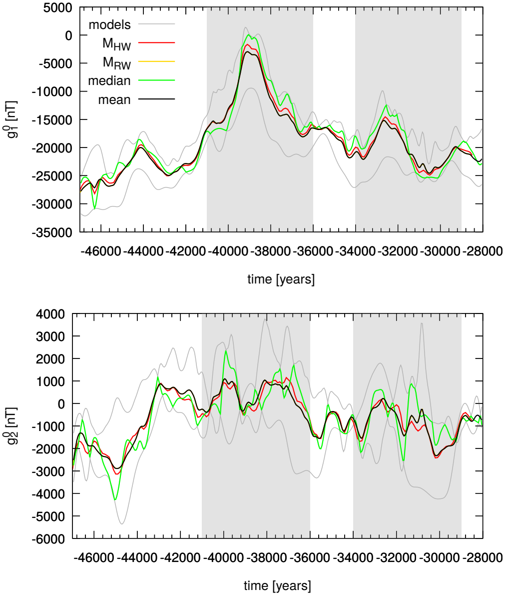


AVERAGED HOLOCENE MODELS g_1^0, g_2^0





AVERAGED PLEISTOCENE MODELS g_1^0, g_2^0



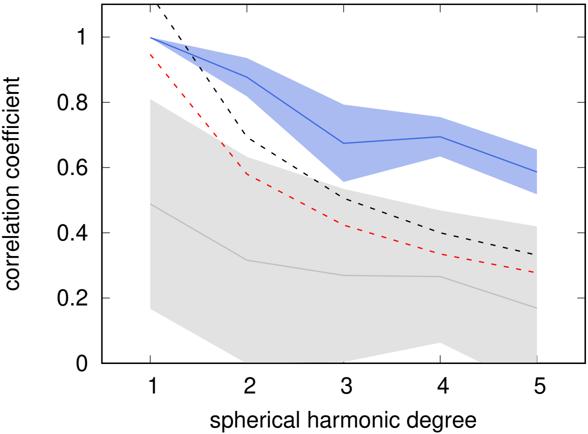
COMMON FEATURES OF THE MODELS

+ deriving degree correlation between mean model and individual models as:

$$r_{\rm i}(\ell) = \frac{\sum_{m=0}^{n}(\hat{g}_\ell^m g_{i,\ell}^m + (\hat{h}_\ell^m h_{i,\ell}^m)}{\sqrt{\sum_{m=0}^{n}((\hat{g}_\ell^m)^2(\hat{h}_\ell^m)^2 \sum_{m=0}^{n}((g_{i,\ell}^m)^2(h_{i,\ell}^m)^2}} ,$$

to measure the spatial correlation between models

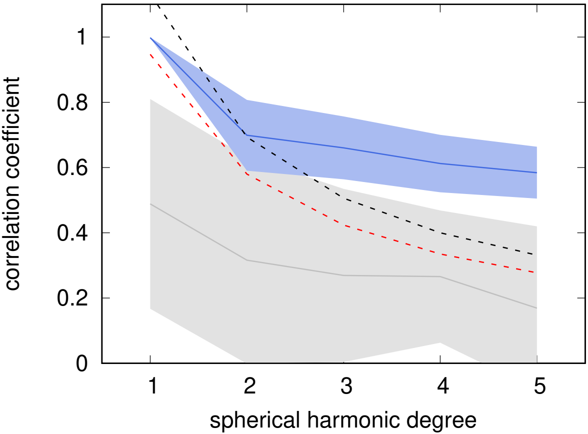
DEGREE CORRELATION OF THE ARCHEO MODELS



averaged degree correlation mean model and individual models

averaged degree correlation of mean model and randomly shuffled models

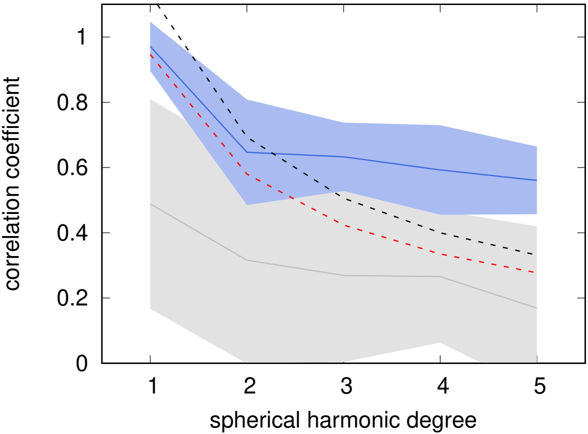
DEGREE CORRELATION OF THE HOLOCENE MODELS



averaged degree correlation mean model and individual models

averaged degree correlation of mean model and randomly shuffled models

DEGREE CORRELATION OF THE PLEISTOCENE MODELS



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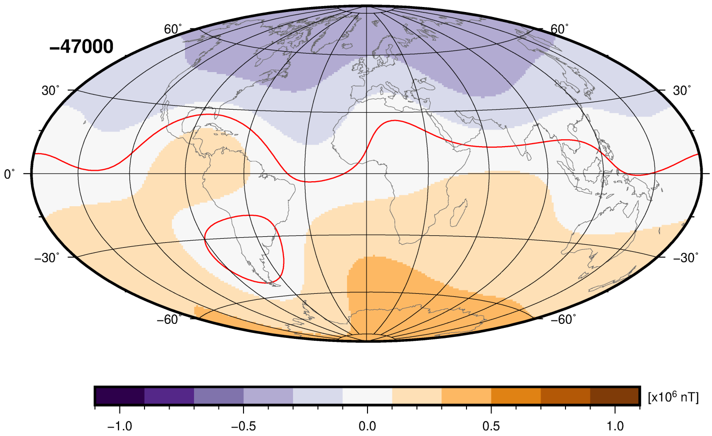
Mean geomagnetic field during the Pleistocene



EARTH'S LIKENESS OF DYNAMO SIMULATIONS

+ Christensen et al. 2010
  → relative axial dipole power

$$AD/NAD = P_{10}/(P_{11} + \sum_{n=2}^{8} (a/c)^{2n-2} \sum_{m=0}^{n} P_{nm})$$

with

$$P_{nm} = (n+1)(g_{nm}^2 + h_{nm}^2)$$

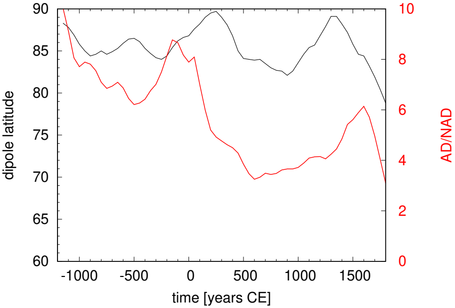
  → equatorial symmetry

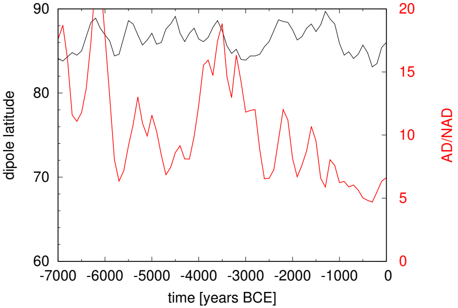
$$\text{odd} = n + m \rightarrow \text{equatorial anti-symmetric}$$
$$\text{even} = n + m \rightarrow \text{equatorial symmetric}$$

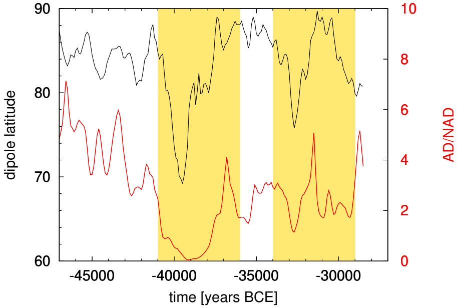
  → zonality
  relative power of axisymmetric components in the non-dipole field (Z/NZ)
  → dipole latitude

$$\theta = \tan^{-1}\left(\frac{g_1^0}{\sqrt{(g_1^1)^2 + (h_1^1)^2}}\right),$$

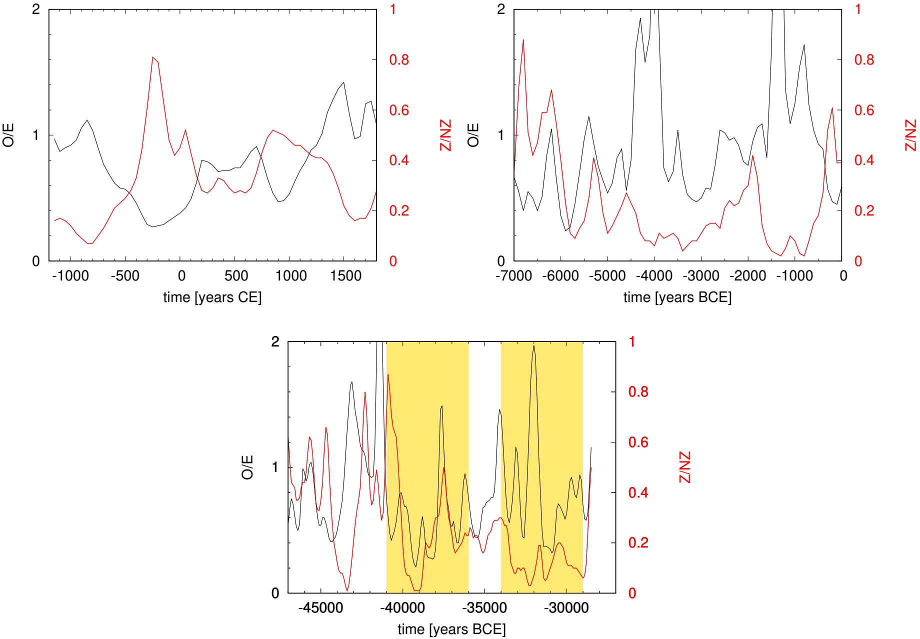
DIPOLARITY OF THE MEAN MODEL







SYMMETRIES OF THE MEAN MODEL



SUMMARY OF THE EARTH-LIKENESS VALUES

	AD/NAD	O/E	Z/NZ	dip. latitude
range	0.05–22.56	0.21–3.47	0.01–0.88	69.2–89.7
Pleistocene	2.75 ± 1.59	0.80 ± 0.43	0.26 ± 0.18	83.58 ± 4.02
Holocene	10.58 ± 4.28	0.96 ± 0.62	0.23 ± 0.18	86.33 ± 1.62
archeo	4.63 ± 1.25	0.84 ± 0.27	0.35 ± 0.11	85.38 ± 2.72
COV-OBS.x1	1.14	0.95	0.26	85.50 ± 2.73

CONCLUSION

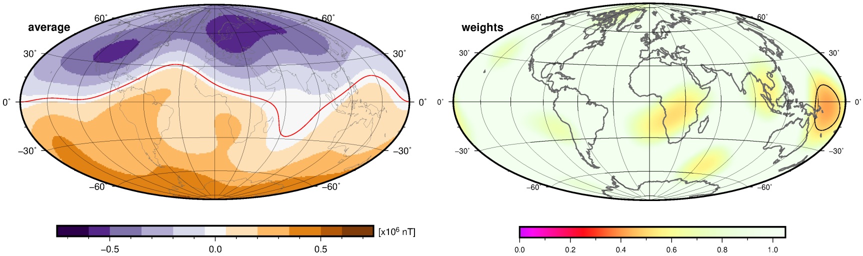
+ derivation of mean characteristics of the archeo- and paleomagnetic field that are robustly resolved independently of the model priors
+ low dipolarity in the last 3 kyr, high dipolarity in the Holocene
+ the mean characteristics (spatially and maybe temporally) ease comparison to dynamo simulations
+ finding larger ranges of the field dipolarity and symmetries allows to consider a wider set of numerical simulations to be Earth's-like
+ large temporal variability of the dipolarity suggests variability of dynamo reversibility

$\rightarrow$ regime changes of the geodynamo?

$\rightarrow$ state transitions in/at the heat engine of the core?

SPIN OFFS

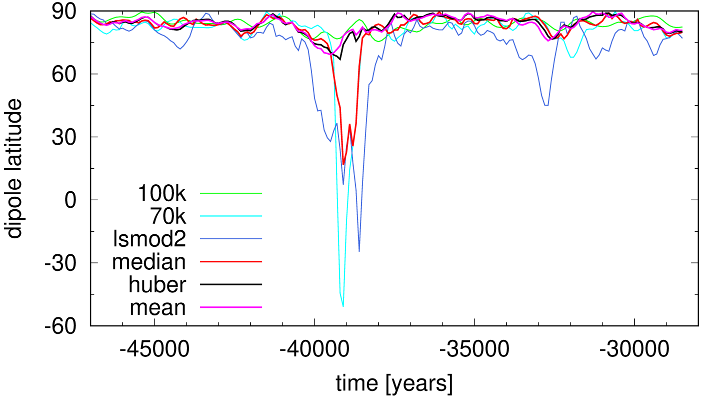
+ Huber weighting of models allows to identify regions of large data and model uncertainties



Left: Map of the radial magnetic field component (1000 CE), averaged using Huber weights.
Right: Maps of the Huber weights. Intense color identify regions with discrepancies between individual models and data inconsistency.

SPIN OFFS

+ derivation of dipole tilt involves only dipole terms, develop new formalism to compute magnetic pole positions using also non-dipole terms.



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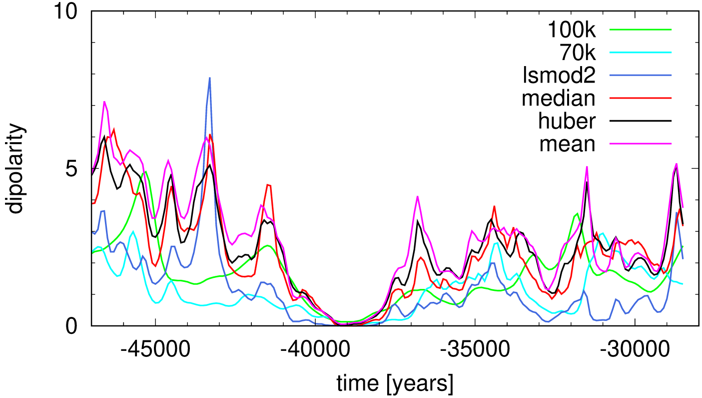
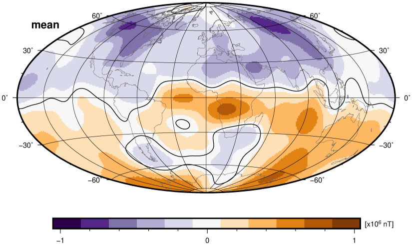
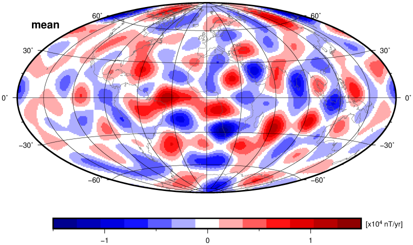


SPIN OFFS

+ refined models of paleo secular variation to derive temporal characteristics of the archeo- and paleomagnetic field (westward drift, P_{sv}, etc.)





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