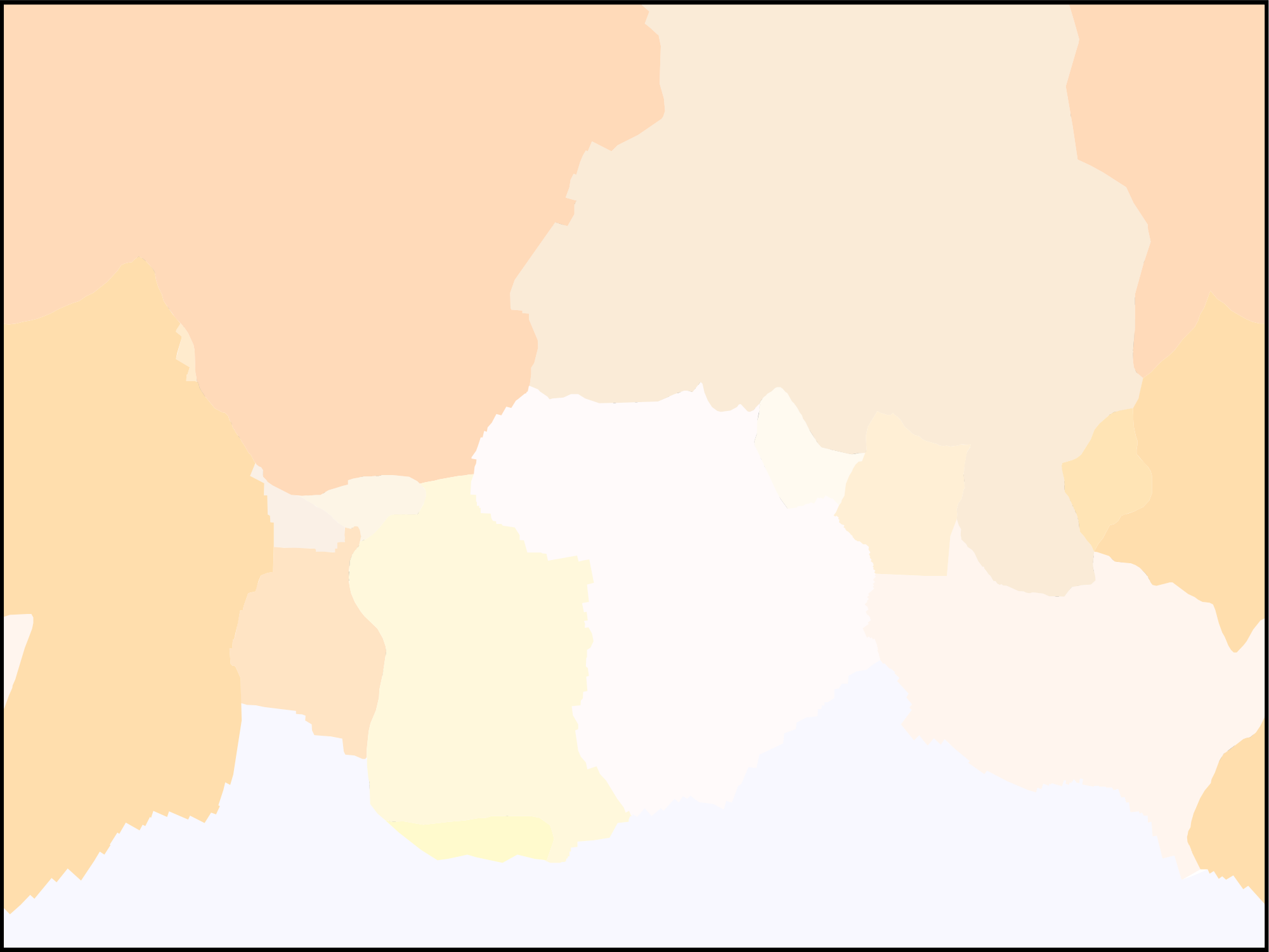
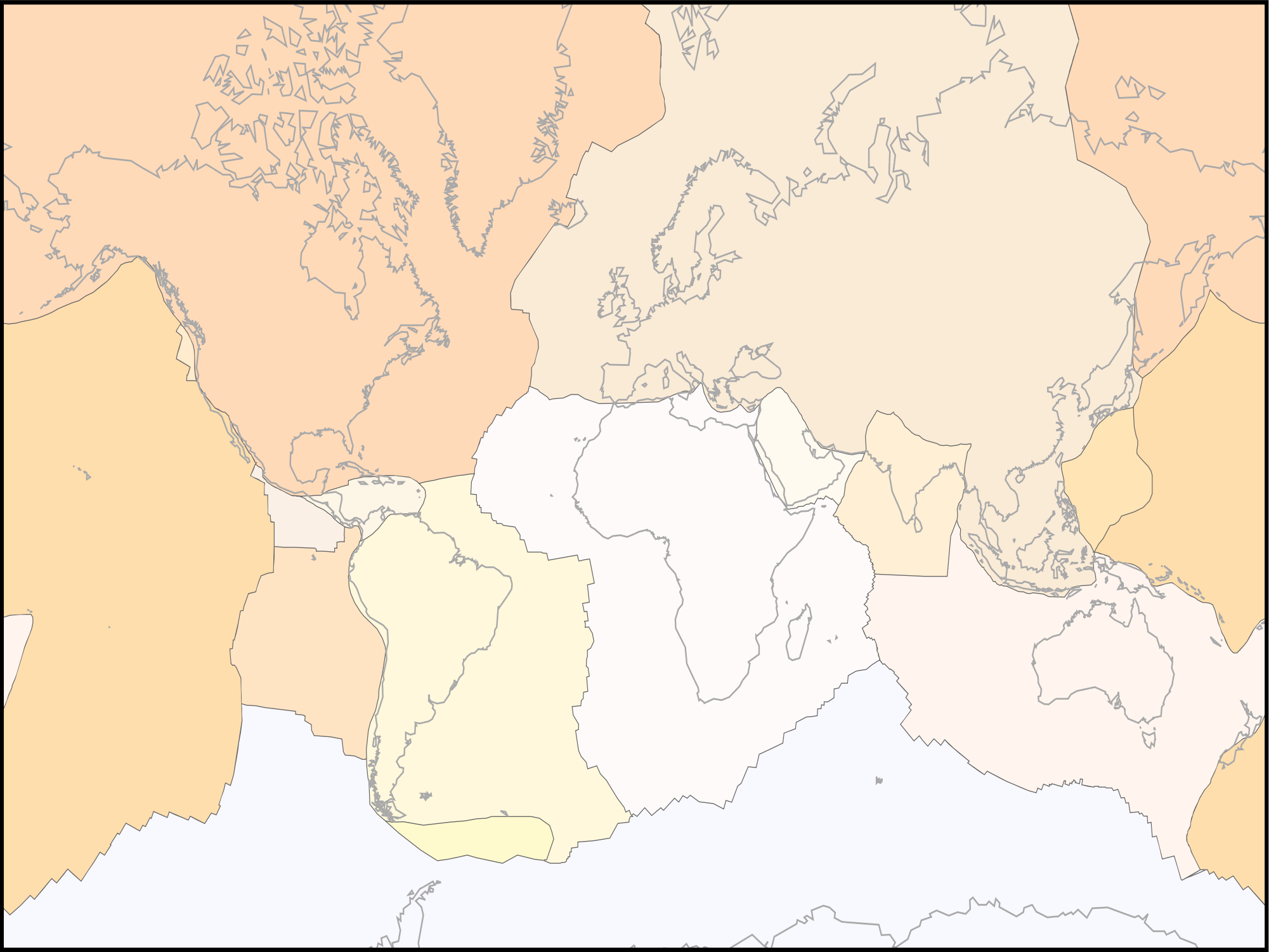
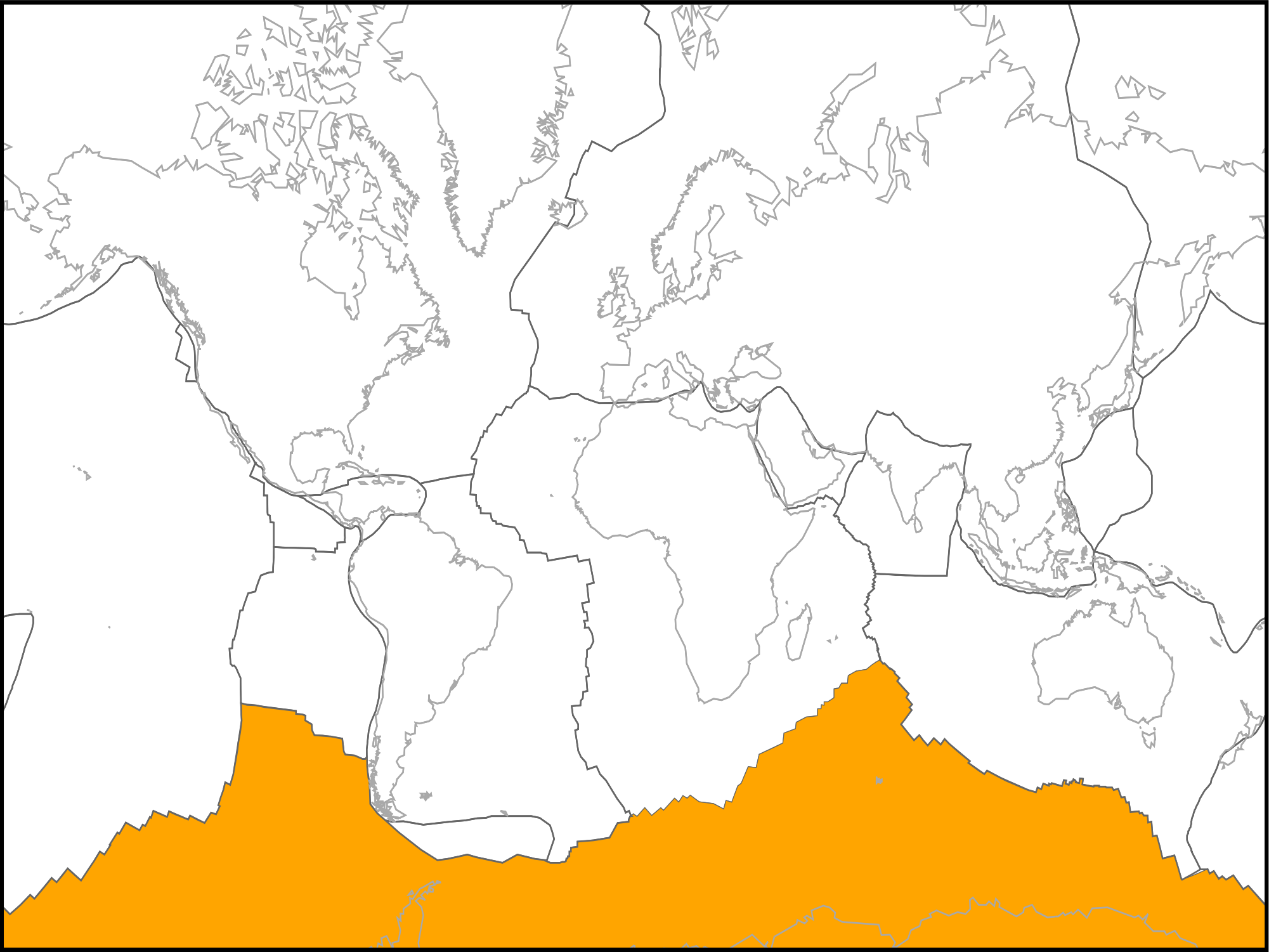
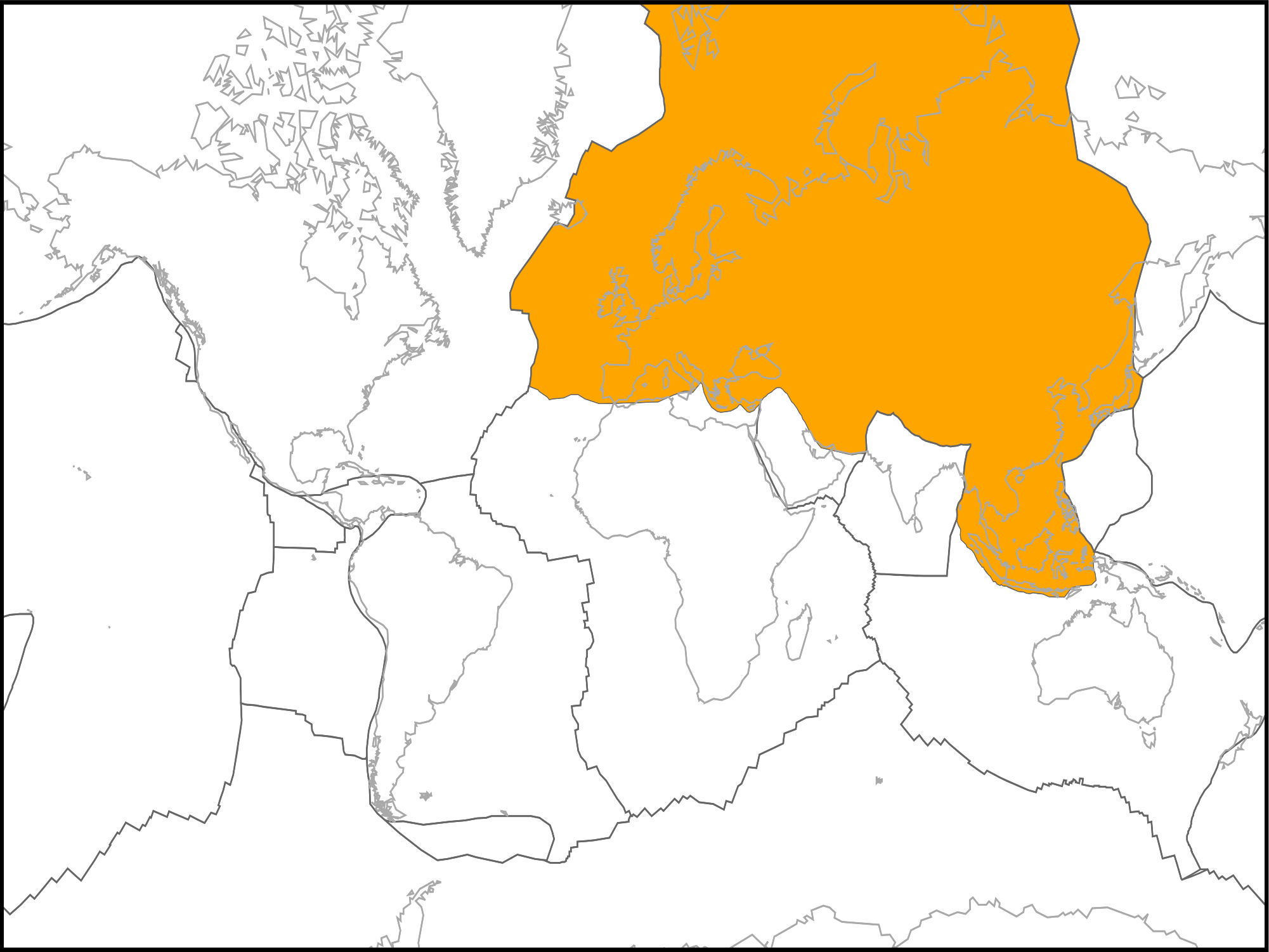
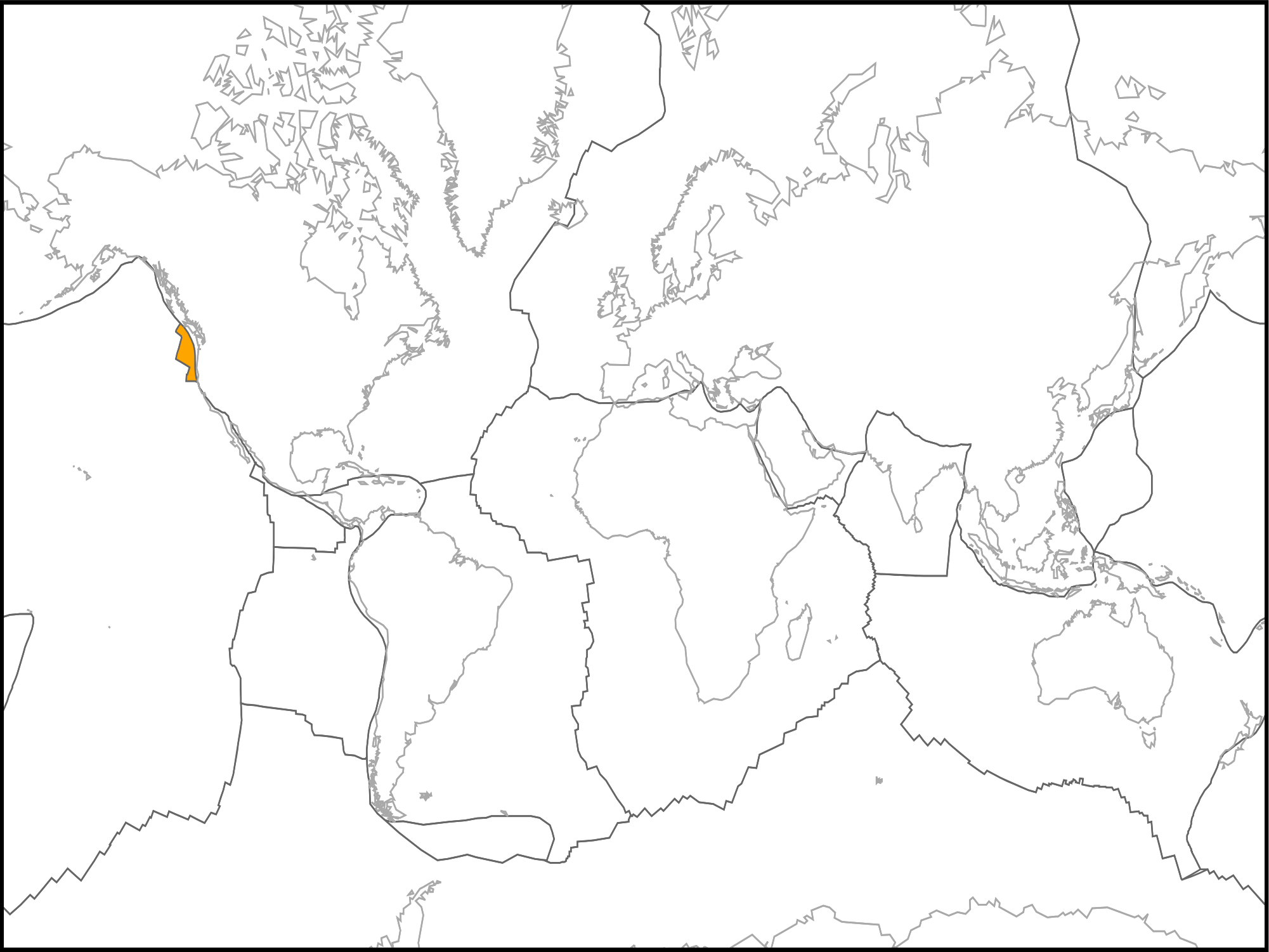
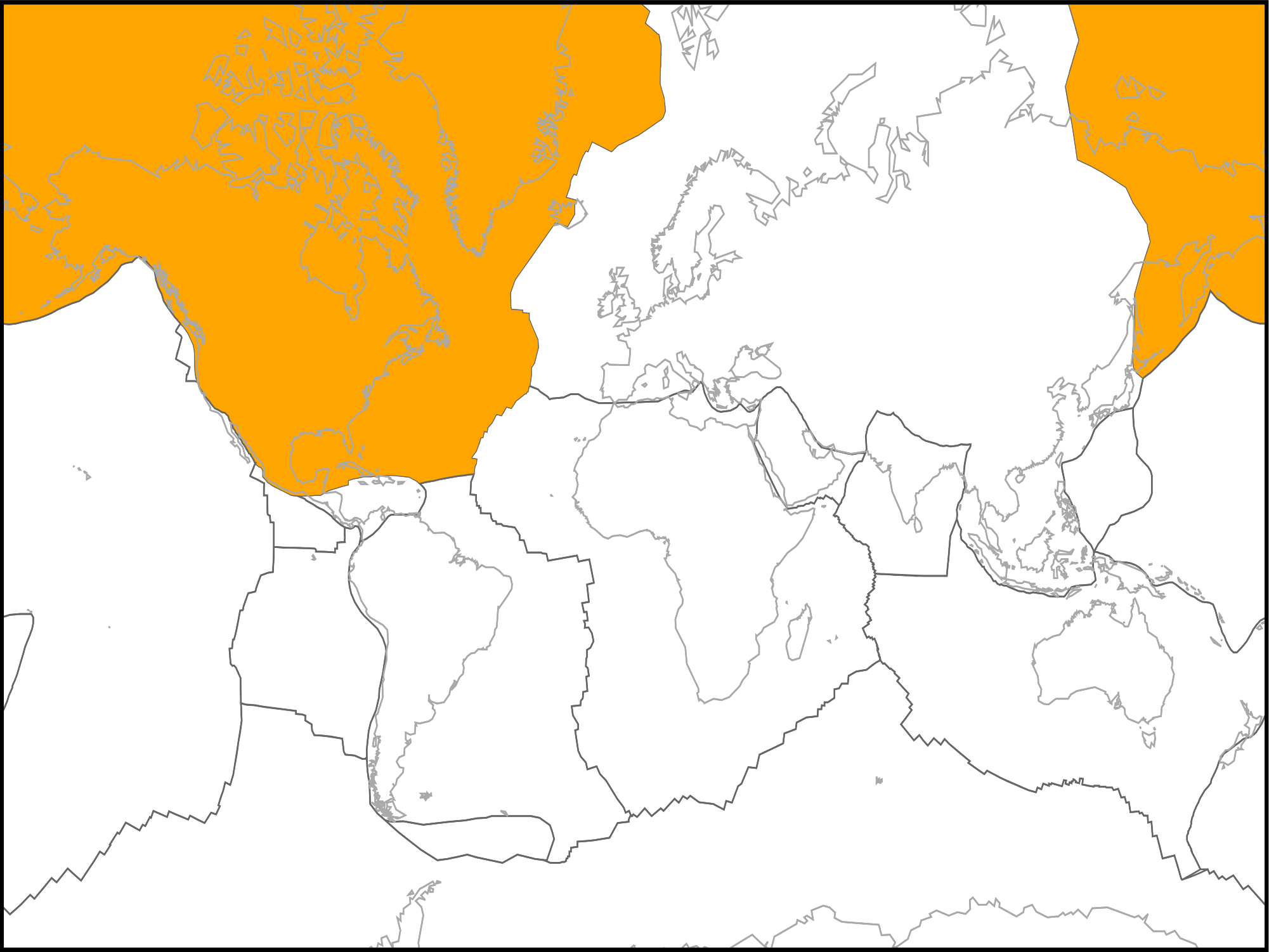












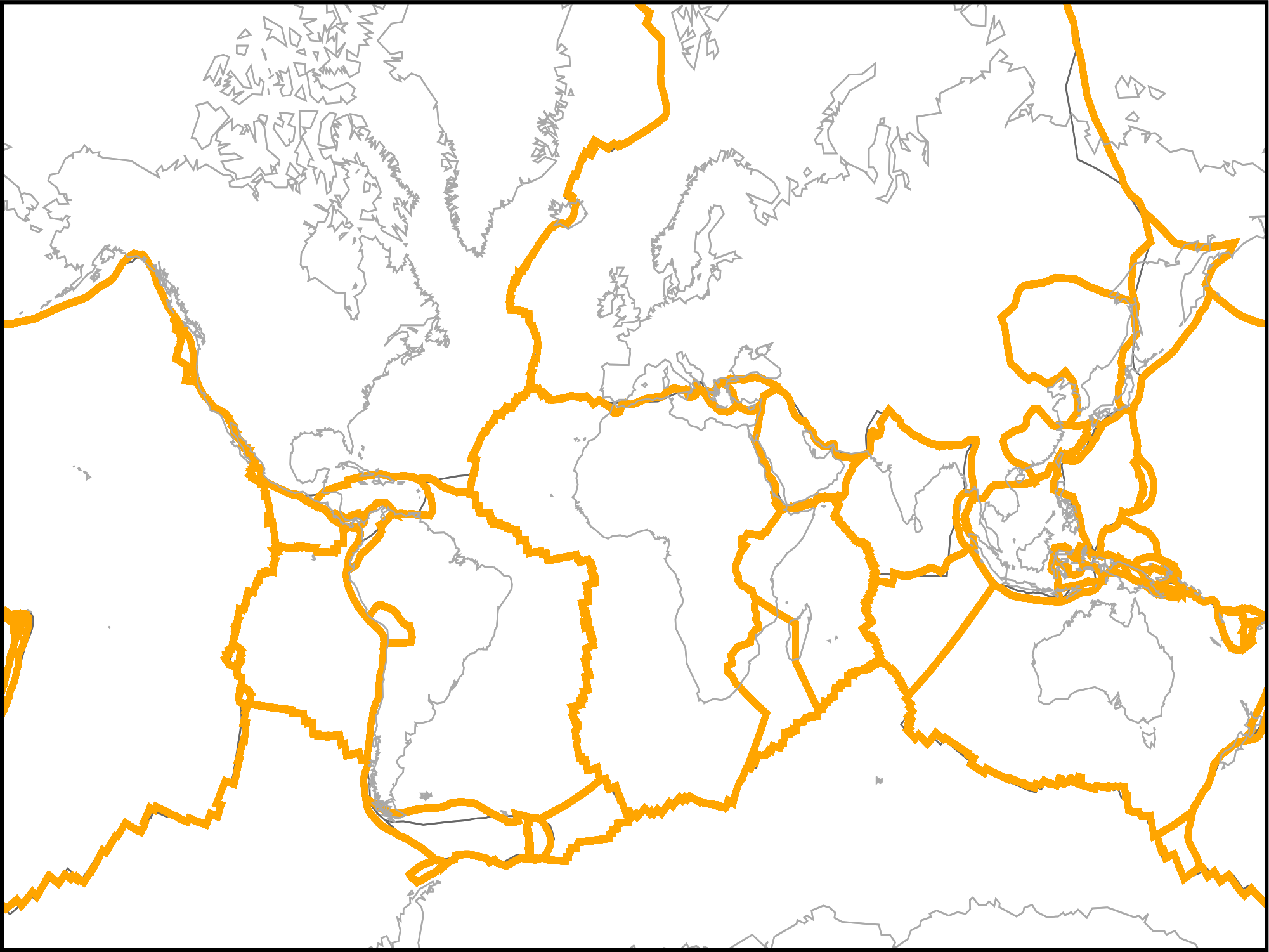
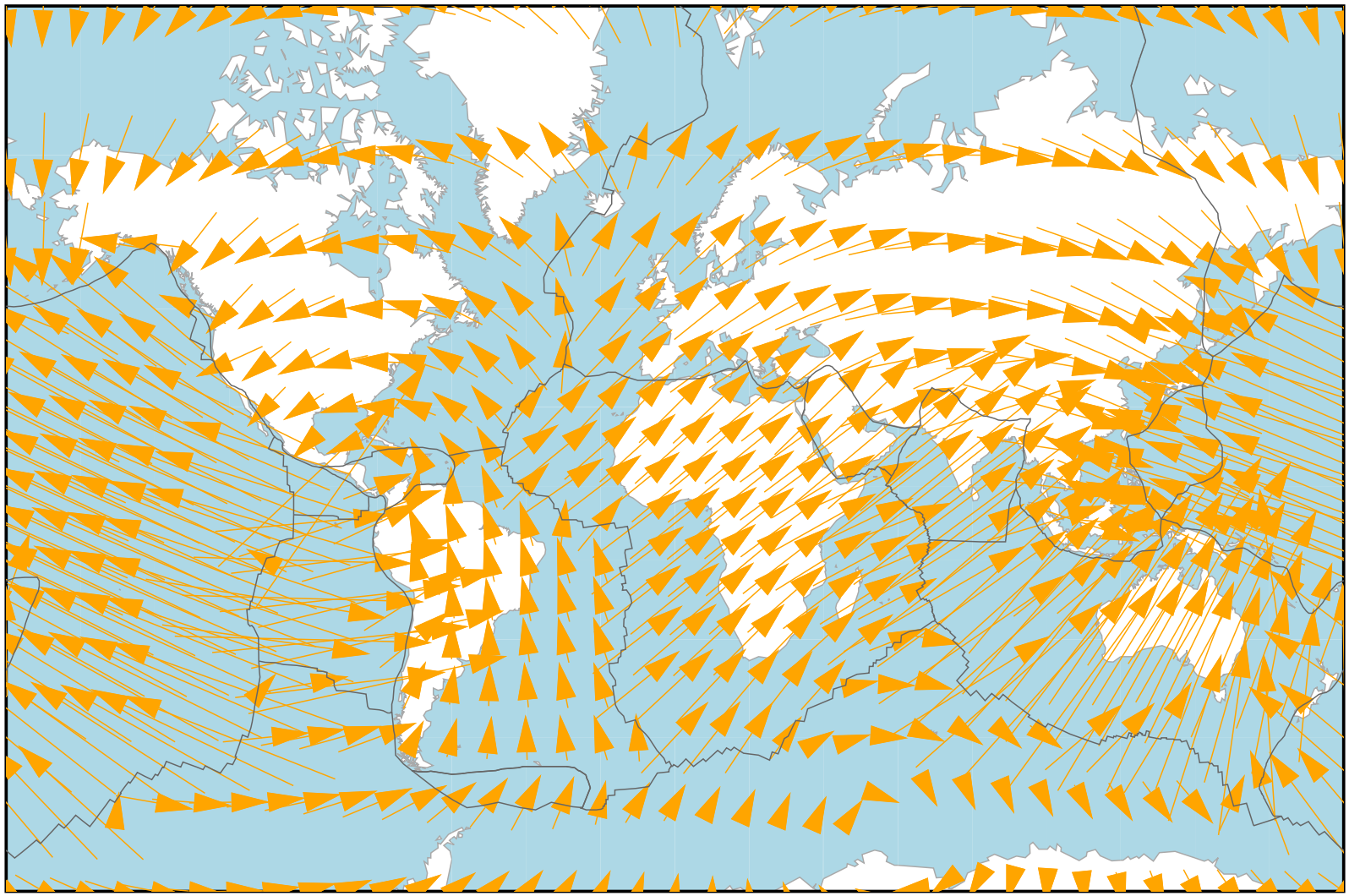
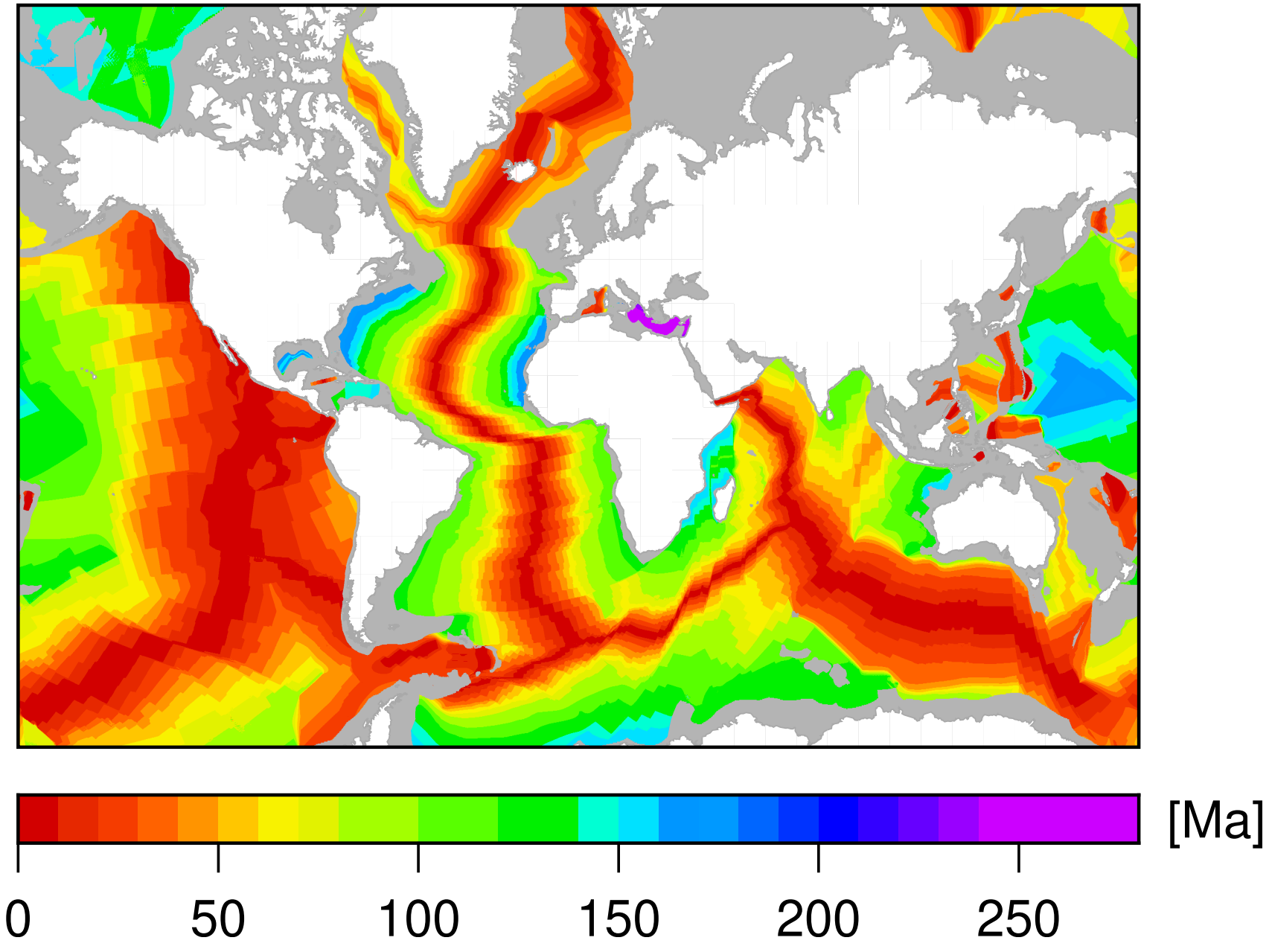


Figure: http://www.ucmp.berkeley.edu/history/wegener.html

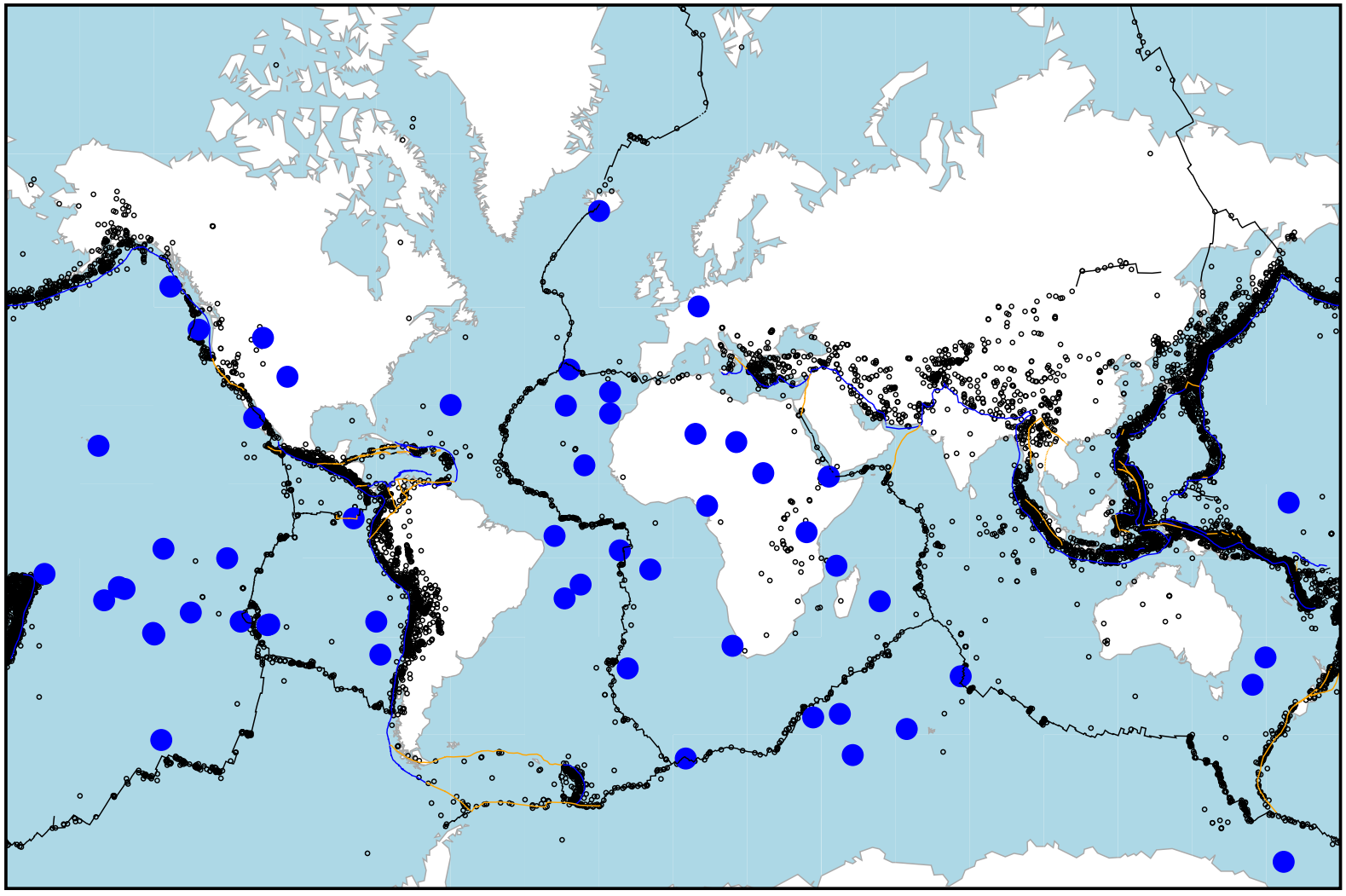


How do we know this velocities?

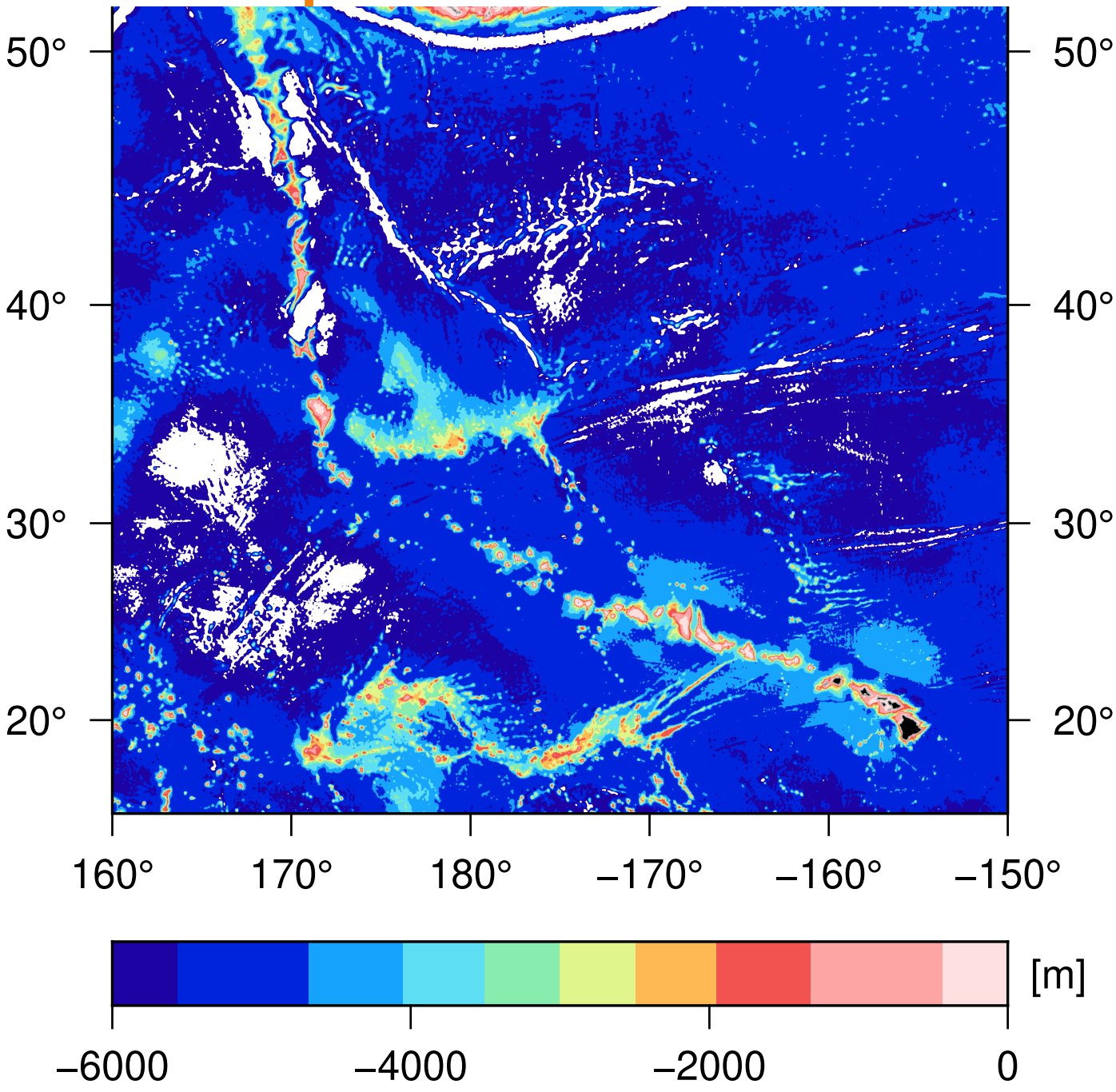
Ocean floor age



Hotspots



Hotspot – example



How can we describe plate motion?

How can we describe plate motion?

Euler theorem

Euler pole position (Φ, Λ)

angular velocity (Ω)

(counterclockwise)

Table S4. NNR-MORVEL56 angular velocities and full covariance matrix

NNR-MORVEL56 Angular Velocities
(no-net-rotation frame fixed)

Ab	Lat deg N	Lon deg E	Omega deg/Ma
pa	-63.5756	114.6975	0.6509
am	63.1704	-122.8242	0.2973
an	65.4235	-118.1053	0.2500
ar	48.8807	-8.4909	0.5588
au	33.8612	37.9414	0.6316
ca	35.1956	-92.6236	0.2862
co	26.9346	-124.3074	1.1978
cp	44.4352	23.0880	0.6080
eu	48.8509	-106.5007	0.2227
in	50.3722	-3.2898	0.5438
jf	-38.3086	60.0379	0.9513
lw	51.8860	-69.5195	0.2856
na	-4.8548	-80.6447	0.2087
nb	47.6763	-68.4377	0.2921
mq	49.1891	11.0524	1.1440
nz	46.2348	-101.0564	0.6957
ps	-46.0242	-31.3615	0.9098
ri	20.2450	-107.2861	4.5359
sa	-22.6179	-112.8327	0.1090
sc	22.5244	-106.1485	0.1464
sm	49.9506	-84.5154	0.3393
sr	-32.4957	-111.3224	0.1072
su	50.0558	-95.0218	0.3368
sw	-29.9420	-36.8671	1.3616
yz	63.0285	-116.6180	0.3335
SL	50.7058	-143.4675	0.2677
BH	-39.9983	100.4994	0.7988

```
MO    14.2480    92.6656     0.7742
SS    -2.8685   130.6236     1.7029
WL     0.1050   128.5186     1.7444
CR   -20.3985   170.5303     3.9232
FT   -16.3322   178.0679     5.1006
KE    39.9929     6.4584     2.3474
NI    -3.2883  -174.4882     3.3136
TO    25.8737     4.4767     8.9417
PM    31.3510  -113.9038     0.3171
AS    19.4251   122.8665     0.1239
AT    40.1121    26.6585     1.2105
GP     2.5287    81.1806     5.4868
EA    24.9729    67.5269    11.3343
JZ    34.2507    70.7429    22.3676
OK    30.3022   -92.2813     0.2290
NB   -45.0406   127.6370     0.8563
SB     6.8767   -31.8883     8.1107
MN    -3.6699   150.2676    51.5690
NH     0.5684    -6.6018     2.4688
BR   -63.7420   142.0636     0.4898
CL   -72.7849    72.0525     0.6066
MA    11.0533   137.8404     1.3061
ND    17.7331  -122.6815     0.1162
AP    -6.5763   -83.9776     0.4881
BU    -6.1254   -78.1008     2.2287
MS     2.1477   -56.0916     3.5655
BS    -1.4855   121.6413     2.4753
TI    -4.4363   113.4976     1.8639
ON    36.1163   137.9182     2.5391
--   --------   --------     ------
```

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \Omega \cdot \cos\Phi \cdot \sin(\lambda - \Lambda)$$
$$\frac{\mathrm{d}\lambda}{\mathrm{d}t} = \Omega \cdot [\sin\Phi - \cos(\lambda - \Lambda) \cdot \mathrm{tg}\,\varphi \cos\Phi]$$

EU NNR-NUVEL1

$$\Omega = 0{,}2337\,^\circ\,\mathrm{Myr}^{-1},$$
$$\Lambda = 247{,}725^\circ,$$
$$\Phi = 50{,}631^\circ$$

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \Omega \cdot \cos\Phi \cdot \sin(\lambda - \Lambda)$$
$$\frac{\mathrm{d}\lambda}{\mathrm{d}t} = \Omega \cdot [\sin\Phi - \cos(\lambda - \Lambda) \cdot \mathrm{tg}\,\varphi \cos\Phi]$$

V_n, V_e, V_u ?
V, α ?

EU NNR-NUVEL1

$\Omega = 0{,}2337\,^\circ\,\mathrm{Myr}^{-1}$,
$\Lambda = 247{,}725^\circ$,
$\Phi = 50{,}631^\circ$

EU NNR-NUVEL1

$$\omega_X = -0.000981,$$
$$\omega_Y = -0.002395,$$
$$\omega_Z = \quad 0.003153 \text{ rad Myr}^{-1}$$

$$V_X = \omega_Y Z - \omega_Z Y$$
$$V_Y = \omega_Z X - \omega_X Z$$
$$V_Z = \omega_X Y - \omega_Y X$$

EU NNR-NUVEL1

$$\omega_X = -0.000981,$$
$$\omega_Y = -0.002395,$$
$$\omega_Z = \quad 0.003153 \text{ rad Myr}^{-1}$$

Transformation to local frame

Transformation to local frame

$$\begin{bmatrix} V_e \\ V_n \\ V_u \end{bmatrix} = \begin{bmatrix} -\sin\lambda & \cos\lambda & 0 \\ -\sin\varphi\cos\lambda & -\sin\varphi\sin\lambda & \cos\varphi \\ \cos\varphi\cos\lambda & \cos\varphi\sin\lambda & \sin\varphi \end{bmatrix} \cdot \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix}$$

Exercise

Listing 1: Geocentric coordinates of geodetic sites `http://itrf.ensg.ign.fr/ITRF_solutions/2008/doc/ITRF2008_GNSS.SSC.txt`

	SITE NAME	X	Y	Z
1	Paris	4202777.371	171367.999	4778660.203
2	Grasse (OCA)	4581690.900	556114.836	4389360.797
3	Toulouse	4627851.828	119640.020	4372993.552
4	Brest	4231162.576	-332746.678	4745130.921
5	Chize	4427603.244	-31506.045	4575621.805
6	La Rochelle	4424632.565	-94175.229	4577544.083
7	Marseille	4630532.763	433946.308	4350142.730
8	AJACCIO	4696989.436	723994.469	4239678.545
9	Saint-Jean-des-	4433469.856	362672.821	4556211.713
10	HVITANES	2979075.679	-353362.257	5609834.842
11	Reykjavik	2587383.624	-1043032.734	5716564.496
12	Hofn	2679689.965	-727951.215	5722789.280
13	TROMSO	2102928.478	721619.454	5958196.252
14	DOMEN	1844607.287	1109719.214	5983936.149
15	STAVANGER	3275753.666	321111.042	5445042.136
16	TRONDHEIM	2820170.846	513486.054	5678936.003
17	KIRUNA	2251420.796	862817.223	5885476.713
18	KIRUNA/ESRANGE	2248123.188	865686.682	5886425.775
19	BORAS	3328984.527	761910.265	5369033.689
20	METSAHOVI	2892570.788	1311843.445	5512634.137
21	VAASA	2699864.334	1078264.009	5658064.890
22	JOENSUU	2564139.085	1486149.767	5628951.440
23	Klaipeda	3359228.136	1297490.480	5246690.347
24	GRAZ LUSTBUEHEL	4194423.817	1162702.695	4647245.414
25	Sofia	4319372.089	1868687.782	4292063.938
26	PENC	4052449.467	1417681.124	4701407.105

Exercise

(cont.)

```
    27    Bucarest            4093760.865   2007793.806   4445129.975
    28    Pecny - Ondrejo     3979316.121   1050312.473   4857067.096
    29    DUBROVNIK           4465940.064   1460594.462   4299291.412
    30    Jozefoslaw - Wa     3664940.165   1409153.867   5009571.391
    31    Borowiec            3738358.454   1148173.710   5021815.773
    32    Borowa Gora         3633738.972   1397434.133   5035353.476
    33    LAMKOWKO            3524522.920   1329693.628   5129846.342
    34    Wroclaw             3835751.296   1177249.957   4941605.243
    35    Uzhgorod            3907587.455   1602428.695   4763783.762
    36    Riga                3183899.192   1421478.489   5322810.797
    37    MENDELEEVO          2844672.078   2161070.173   5266363.871
    38    Irkoutsk            -968332.392   3794425.410   5018167.738
    39    Kharkiv             3312984.324   2428203.433   4863307.827
    40    Novossibirsk         433605.577   3655558.530   5191286.701
    41    Tashkent            1695945.191   4487138.554   4190140.700
    42    Yuzhno-Sakhalin    -3465320.945   2638269.371   4644085.415
    43    Zwenigorod          2886335.855   2155987.574   5245818.809
    44    Krasnoyarsk         -174281.918   3571333.030   5264196.041
    45    Svetloe             2730155.353   1562364.734   5529989.270
    46    SELEZASCHITA        1046790.610   4540257.078   4342920.786
    47    YAKUTSK            -1914999.069   2308241.487   5610225.560
    48    MAGADAN            -2825810.299   1581232.932   5477005.449
    49    Petropavlovsk -    -3580828.469   1399698.093   5072185.152
    50    GOLOSIIV - KIEV     3512888.954   2068979.881   4888903.201
    51    Bishkek             1243767.185   4513678.517   4317880.340
    52    Tixi Seismic st    -1264873.191   1569455.782   6031003.428
    53    KHABAROVSK         -2995266.469   2990444.592   4755575.888
    54    Arti                1843956.719   3016203.112   5291261.735
    55    Bilibino           -2321893.075    560096.849   5894691.796
    56    NORILSK              64537.191   2253782.862   5946363.499
```

Exercise

(cont.)

```
    57    Obninsk/Moscow     2936432.057  2178364.553  5208858.249
    58    Lviv               3765296.991  1677559.204  4851297.409
    59    NOVOSIBIRSK, SN     452288.549  3635913.142  5203396.792
    60    Lampedusa          5073164.753  1134512.567  3683181.149
    61    Medicina           4461400.747   919593.579  4449504.774
    62    Genova             4507892.319   707621.483  4441603.515
    63    Noto               4934546.226  1321265.012  3806456.123
    64    Torino I           4476537.409   600431.429  4488761.333
    65    CAGLIARI           4893379.972   772650.479  4004180.031
    66    Matera             4641951.448  1393053.660  4133280.862
    67    VENEZIA            4379724.776   957495.887  4521605.272
    68    PADOVA             4389531.133   923253.791  4519256.440
    69    BOLZANO            4312657.485   864634.660  4603844.443
    70    Perugia            4555145.744   997822.430  4337432.738
    71    BRUSSELS           4027893.747   307045.824  4919475.121
    72    REDU               4091423.358   368380.588  4863179.807
    73    Herstmonceux Ca    4033460.920    23537.800  4924318.255
    74    NORTH SHIELDS T    3664792.063   -92117.113  5201903.820
    75    Aberdeen           3466272.255  -125904.227  5334662.438
    76    TEDDINGTON         3985500.300   -23625.451  4962941.695
    77    HERMITAGE          3981776.535   -89239.026  4965284.635
    78    SHEERNESS          3983074.296    51683.176  4964639.794
    79    Bartinney          4079953.941  -395930.245  4870196.957
    80    Morpeth            3645667.836  -107277.235  5215053.530
    81    SAN FERNANDO       5105519.005  -555145.872  3769803.377
    82    VILLAFRANCA        4849833.695  -335049.025  4116014.939
    83    Madrid-Robledo     4849202.371  -360328.967  4114913.202
    84    ROQUETES - TORT    4833520.152    41537.108  4147461.549
    85    Yebes              4848724.704  -261632.206  4123094.153
    86    BELLMUNT DE SEG    4775849.397   116814.368  4213018.970
```

Exercise

(cont.)

87	Cap de Creus	4715420.300	273177.788	4271946.702
88	Alicante	5009051.187	-42072.192	3935057.740
89	A Coruna	4594489.710	-678367.774	4357066.133
90	Almeria	5105220.093	-219278.521	3804387.130
91	CANTABRIA	4625924.478	-307096.516	4365771.399
92	VALENCIA	4929533.829	-29050.408	4033710.161
93	Palma de Mallor	4919369.466	225499.854	4039849.833
94	Ceuta	5150601.792	-478834.385	3718884.864
95	KOOTWIJK	3899225.130	396731.939	5015078.427
96	WESTERBORK	3828735.863	443304.957	5064884.712
97	EIJSDEN	4023086.268	400395.097	4916655.543

To do

For your individual site compute the plate motion velocities in local horizontal frame.