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Supporting information for article:

Structural studies of geranylgeranylglyceryl phosphate synthase, a prenyltransferase found in thermophilic Euryarchaeota

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Table S1 The species used in this study (and strain when provided), their optimal growth temperatures and the Interpro accession numbers for the GGGPS sequences used.

The sources for all temperature optima are also given, and their citations are given in the Supplementary References.

INTERPRO ID	Species (strain)	Optimal Growth Temp.	Citation
F4B7Z5	*Acidianus hospitalis (strain W1)*	80C	You et al., 2011
A0A1W6K008	*Acidianus manzaensis*	80C	Yoshida et al., 2006
D9Q2B2	*Acidilobus saccharovorans (strain DSM 16705 / JCM 18335 / VKM B-2471 / 345-15)*	80C	Prokofeva et al., 2009
A0A0P9ERW5	*Acidiplasma aeolicum*	45C	Golyshina et al., 2009
A0A0Q0VND7	*Acidiplasma cupricumulans*	54C	Golyshina et al., 2009
U3T8T9	*Aeropyrum camini SY1 = JCM 12091*	85C	Nakagawa et al., 2004
Q9YEF5	*Aeropyrum pernix (strain ATCC 700893 / DSM 11879 / JCM 9820 / NBRC 100138 / K1)*	90-95C	Sako et al., 1996
D2RIC4	*Archaeoglobus profundus*	83C	Burggraf et al., 1990
L0A8W1	*Caldisphaera lagunensis (strain DSM 15908 / JCM 11604 / IC-154)*	70-75C	Itoh et al., 2003
H1XUR2	*Caldithrix abyssi DSM 13497*	60C	Miroshnichenko et al., 2003
A8MDA4	*Caldivirga maquilingensis (strain ATCC 700844 / DSM 13496 / JCM 10307 / IC-167)*	85C	Itoh et al., 1999
A0RYM1	*Cenarchaeum symbiosum (strain A)*	10C	Preston et al., 1996
A0A1N5V0T5 & A0A1R4A7P9	*Cuniculiplasma divulgatum*	38.5C	Golyshina et al., 2016
E8RAQ6	*Desulfurococcus mucosus (strain ATCC 35584 / DSM 2162 / JCM 9187 / O7/1)*	85C	Wirth et al., 2011
S0AMG9	*Ferroplasma acidarmanus fer1*	42C	Dopson et al., 2004
A0A1V0N5B0	*Ferroplasma acidiphilum*	35C	Golyshina et al., 2000
I0A1J5	*Fervidicoccus fontis (strain DSM 19380 / JCM 18336 / VKM B-2539 / Kam940)*	65-70	Perevalova et al., 2010
A2BIS8	*Hyperthermus butylicus (strain DSM 5456 / JCM 9403 / PLM1-5)*	95-106C	Zillig *et al.*, 1990
A8A9K6	*Ignicoccus hospitalis (strain KIN4/I / DSM 18386 / JCM 14125)*	90C	Paper et al., 2007
A0A0U3FQL2	*Ignicoccus islandicus DSM 13165*	90C	Huber et al., 2000
E0SPG8	*Ignisphaera aggregans (strain DSM 17230 / JCM 13409 / AQ1.S1)*	92-95C	Niederberger et al., 2006
F4G258	*Metallosphaera cuprina (strain Ar-4)*	65C	Liu et al., 2011
A4YJ26	*Metallosphaera sedula (strain ATCC 51363 / DSM 5348 / JCM 9185 / NBRC 15509 / TH2)*	75C	Huber et al., 1989
A0A2A2H4Q5	*Methanobacterium bryantii*	37C	Boone 1987
A0A1D3KZY7	*Methanobacterium congolense*	37-42C	Cuzin et al., 2001
K2R1U0	*Methanobacterium formicicum (strain DSM 3637 / PP1)*	38C	Battumur et al., 2016
F0TCU3	*Methanobacterium lacus (strain AL-21)*	30C	Borrel et al., 2012

F6D3K2	*Methanobacterium paludis (strain DSM 25820 / JCM 18151 / SWAN1)*	32-37	Cadillo-Quiroz et al., 2014
A0A2H4VMB6	*Methanobacterium subterraneum*	20-40C	Kotelnikova et al., 1998
A0A1V6N4E8	*Methanobrevibacter arboriphilus JCM 13429 = DSM 1125*	30-40C	Morii et al., 1983
A0A166DZN3	*Methanobrevibacter curvatus*	30C	Leadbetter and Breznak, 1996
A0A166FBI9	*Methanobrevibacter cuticularis*	37C	Leadbetter and Breznak, 1996
A0A166CNZ6	*Methanobrevibacter filiformis*	30C	Leadbetter et al., 1998
A0A1H7P4I8	*Methanobrevibacter gottschalkii*	37C	Millier and Lin, 2002
A0A0U2V2J6 & A0A1G5V2Z4	*Methanobrevibacter millerae*	36-42	Rea et al., 2007
A0A126QZT3	*Methanobrevibacter olleyae*	28-42	Rea et al., 2007
A0A166BYF7	*Methanobrevibacter oralis*	36-38C	Ferrari et al., 1994
A5UJF1	*Methanobrevibacter smithii (strain ATCC 35061 / DSM 861 / OCM 144 / PS)*	38C	Miller and Lin, 2002
A0A076LAD0	*Methanocaldococcus bathoardescens*	82C	Stewart et al., 2015
C7P6M4	*Methanocaldococcus fervens (strain DSM 4213 / JCM 15782 / AG86)*	85C	Jeanthon et al., 1999
D5VS54	*Methanocaldococcus infernus (strain DSM 11812 / JCM 15783 / ME)*	85C	Jeanthon et al., 1998
Q58647	*Methanocaldococcus jannaschii (strain ATCC 43067 / DSM 2661 / JAL-1 / JCM 10045 / NBRC 100440)*	85C	Jones et al., 1983
N6VYK2	*Methanocaldococcus villosus KIN24-T80*	80C	Bellack et al., 2011
C9RGR5	*Methanocaldococcus vulcanius (strain ATCC 700851 / DSM 12094 / M7)*	80C	Jeanthon et al., 1999
Q12VH4	*Methanococcoides burtonii (strain DSM 6242 / NBRC 107633 / OCM 468 / ACE-M)*	23.4C	Franzmann et al., 1992
A0A0E3X1G9	*Methanococcoides methylutens MM1*	30-35C	Sowers and Ferry 1983
A6UW70	*Methanococcus aeolicus (strain ATCC BAA-1280 / DSM 17508 / OCM 812 / Nankai-3)*	46C	Kendall et al., 2006
A4G0J0	*Methanococcus maripaludis (strain C5 / ATCC BAA-1333)*	35-40C	Whitman et al., 1986
A6URI9	*Methanococcus vannielii (strain ATCC 35089 / DSM 1224 / JCM 13029 / OCM 148 / SB)*	20-40C	Jones et al., 1977
D7E9U9	*Methanohalobium evestigatum (strain ATCC BAA-1072 / DSM 3721 / NBRC 107634 / OCM 161 / Z-7303)*	50C	Zhilina et al., 1987
A0A285GCY6	*Methanohalophilus euhalobius*	37C	Obraztsova, A. Ya, et al., 1987
A0A1H2YC05 & A0A1L3Q1N6	*Methanohalophilus halophilus*	30C	L'Haridon et al., 2017
D5E8G9	*Methanohalophilus mahii (strain ATCC 35705 / DSM 5219 / SLP)*	37C	Paterek and Smith, 1988
A0A1L9C1Y8	*Methanohalophilus portucalensis FDF-1*	40C	Boone et al., 1993
A0A1I4TQ52	*Methanolobus profundi*	30C	Mochimaru et al., 2009
K4MDP2	*Methanolobus psychrophilus R15*	18C	Chen et al., 2012
W9DXN7	*Methanolobus tindarius DSM 2278*	25C	Konig and Stetter, 1982
A0A1G7NAI9	*Methanolobus vulcani*	40C	Kadam et al., 1995

L0KT38	*Methanomethylovorans hollandica (strain DSM 15978 / NBRC 107637 / DMS1)*	34-37C	Lomans et al., 1999
A0A1Y3GD48	*Methanonatronarchaeum thermophilum*	48-50C	Sorokin et al., 2018
Q8TXM0	*Methanopyrus kandleri (strain AV19 / DSM 6324 / JCM 9639 / NBRC 100938)*	98C	Kurr et al., 1991
G7WL36	*Methanosaeta harundinacea (strain 6Ac)*	34-37C	Ma et al., 2006
F7XPB7	*Methanosalsum zhilinae (strain DSM 4017 / NBRC 107636 / OCM 62 / WeN5)*	45C	Boone and Baker 2001
A0A0E3LPB8	*Methanosarcina barkeri MS*	37-42C	Maestrojuan and Boone 1991
A0A0P6V717	*Methanosarcina flavescens*	45C	Kern et al., 2016
A0A0E3SB17	*Methanosarcina horonobensis HB-1 = JCM 15518*	37C	Shimizu et al., 2011
A0A0E3S3Z1	*Methanosarcina lacustris Z-7289*	25C	Simankova et al., 2001
A0A0E3WPI1	*Methanosarcina mazei LYC*	40C	Liu et al., 1985
A0A0E3PQS5	*Methanosarcina siciliae C2J*	35C	Elberson and Sowers 1997
A0A0E3H913	*Methanosarcina thermophila (strain ATCC 43570 / DSM 1825 / OCM 12 / VKM B-1830 / TM-1)*	50C	Zinder et al., 1985
A0A0E3Q9Q5	*Methanosarcina vacuolata Z-761*	37-40C	Zhilina and Zavarzin 1987
A0A2A2HCS5	*Methanosphaera cuniculi*	35-40	Biavati et al., 1988
Q2NET5	*Methanosphaera stadtmanae*	36-40	Miller and Wolin, 1985
P0C882	*Methanothermobacter marburgensis (strain ATCC BAA-927 / DSM 2133 / JCM 14651 / NBRC 100331 / OCM 82 / Marburg)*	65C	Wasserfallen et al., 2000
O26652	*Methanothermobacter thermautotrophicus (strain ATCC 29096 / DSM 1053 / JCM 10044 / NBRC 100330 / Delta H)*	65-70	Wasserfallen et al., 2000
A0A1M4MRZ4	*Methanothermobacter wolfeii*	55-65	Wasserfallen et al., 2000
F8AM29	*Methanothermococcus okinawensis (strain DSM 14208 / JCM 11175 / IH1)*	60-65C	Takai et al., 2002
E3GXQ3	*Methanothermus fervidus (strain ATCC 43054 / DSM 2088 / JCM 10308 / V24 S)*	83C	Stetter et al., 1981
F4BW65	*Methanothrix soehngenii (strain ATCC 5969 / DSM 3671 / JCM 10134 / NBRC 103675 / OCM 69 / GP-6)*	37C	Huser et al., 1982
H1KZR8	*Methanotorris formicicus Mc-S-70*	75C	Takai et al., 2004
F6BDR0	*Methanotorris igneus (strain DSM 5666 / JCM 11834 / Kol 5)*	88C	Burggraf et al., 1990
A0A060HLD8	*Nitrososphaera viennensis EN76*	42C	Stieglmeier et al., 2014
A0A075LUG0	*Palaeococcus pacificus DY20341*	80C	Zeng et al., 2013
A0A1W2G543	*Picrophilus oshimae DSM 9789*	60C	Schleper et al., 1996
Q6L2N4	*Picrophilus torridus (strain ATCC 700027 / DSM 9790 / JCM 10055 / NBRC 100828)*	60C	Schleper et al., 1996
Q8ZTX5	*Pyrobaculum aerophilum (strain ATCC 51768 / IM2 / DSM 7523 / JCM 9630 / NBRC 100827)*	100C	Vokl et al., 1993
A4WLS7	*Pyrobaculum arsenaticum (strain DSM 13514 / JCM 11321)*	90C	Huber et al., 2000

A3MUU3	*Pyrobaculum calidifontis (strain JCM 11548 / VA1)*	90-95C	Amo et al., 2002
G7VET1	*Pyrobaculum ferrireducens*	90-95C	Slobodkina et al., 2015
A1RRN9	*Pyrobaculum islandicum (strain DSM 4184 / JCM 9189 / GEO3)*	100C	Huber et al., 1997
B1YAF0	*Pyrobaculum neutrophilum (strain DSM 2338 / JCM 9278 / V24Sta)*	85C	Chan et al., 2013
H6Q6Y4	*Pyrobaculum oguniense (strain DSM 13380 / JCM 10595 / TE7)*	90-94C	Sako et al., 2001
Q9UZN7	*Pyrococcus abyssi (strain GE5 / Orsay)*	96C	Erauso et al., 1993
Q8U213	*Pyrococcus furiosus (strain ATCC 43587 / DSM 3638 / JCM 8422 / Vc1)*	100C	Fiala and Stetter, 1986
O58851	*Pyrococcus horikoshii (strain ATCC 700860 / DSM 12428 / JCM 9974 / NBRC 100139 / OT-3)*	98C	González et al., 1998
A0A127BCD3	*Pyrococcus kukulkanii*	105C	Callac et al., 2016
F8AI63	*Pyrococcus yayanosii (strain CH1 / JCM 16557)*	98C	Birrien et al., 2011
A0A0P0N2L4 & A0A211YM74	*Pyrodictium delaneyi*	90-92C	Lin et al., 2016
A0A0V8RUK1	*Pyrodictium occultum*	105C	Uemori et al., 1995
G0EEI5	*Pyrolobus fumarii (strain DSM 11204 / 1A)*	106C	Blöchl et al., 1997
D7D9W0	*Staphylothermus hellenicus (strain DSM 12710 / JCM 10830 / BK20S6-10-b1 / P8)*	85C	Arab et al., 2000
A3DN81	*Staphylothermus marinus (strain ATCC 43588 / DSM 3639 / JCM 9404 / F1)*	85-98C	Fiala et al., 1986
Q4JAS3	*Sulfolobus acidocaldarius (strain ATCC 33909 / DSM 639 / JCM 8929 / NBRC 15157 / NCIMB 11770)*	70C	Takayanagi et al. (1996)
C3NFV6	*Sulfolobus islandicus (strain Y.N.15.51 / Yellowstone #2)*	75C	Zillig et al., 1993
D0KRV6	*Sulfolobus solfataricus (strain 98/2)*	75C	Zeparty et al., 2010
Q975W8	*Sulfolobus tokodaii (strain DSM 16993 / JCM 10545 / NBRC 100140 / 7)*	80C	Suzuki et al., 2002
F0LML7	*Thermococcus barophilus (strain DSM 11836 / MP)*	85C	Marteinsson et al., 1999
A0A218P232	*Thermococcus celer*	85C	Blamey et al. 1999
A0A161KIX4	*Thermococcus chitonophagus*	85C	Huber et al., 1995
I3ZVT5	*Thermococcus cleftensis*	88C	Hensley et al., 2014
A0A097QWB2	*Thermococcus eurythermalis*	85C	Zhao and Xiao, 2015
C5A615	*Thermococcus gammatolerans (strain DSM 15229 / JCM 11827 / EJ3)*	88C	Jolivet et al., 2003
A0A0X1KM71	*Thermococcus guaymasensis DSM 11113*	88C	Canganella et al., 1998
Q5JDY1	*Thermococcus kodakarensis (strain ATCC BAA-918 / JCM 12380 / KOD1)*	85C	Atomi et al., 2004
H3ZQN9	*Thermococcus litoralis (strain ATCC 51850 / DSM 5473 / JCM 8560 / NS-C)*	85-88C	Neuner et al., 1990
W8P1E7	*Thermococcus nautili*	87.5C	Gorlas et al., 2014

B6YWU0	*Thermococcus onnurineus (strain NA1)*	80C	Bae et al., 2006
A0A218P9M3	*Thermococcus pacificus*	80-88C	Miroshnichenko et al., 1998
W0I385	*Thermococcus paralvinellae*	82C	Hensley et al., 2014
A0A142CSB5	*Thermococcus peptonophilus*	85-90C	Gonzalez et al., 1995
A0A172WES0	*Thermococcus piezophilus*	75C	Dalmasso et al., 2016
C6A2A3	*Thermococcus sibiricus (strain MM 739 / DSM 12597)*	78C	Miroshnichenko et al., 2001
A0A0Q2MQY4	*Thermococcus thioreducens*	83-85C	Pikuta et al., 2007
S5ZDX3	*Thermofilum adornatus*	92C	Dominova et al., 2013
A1RXV6	*Thermofilum pendens (strain DSM 2475 / Hrk 5)*	88C	Zillig et al., 1983
A0A0F7FJA1	*Thermofilum uzonense*	85C	Toshchakov et al., 2015
I3TDA0	*Thermogladius calderae (strain DSM 22663 / VKM B-2946 / 1633)*	84C	Kochetkova et al., 2016
Q9HJH3	*Thermoplasma acidophilum (strain ATCC 25905 / DSM 1728 / JCM 9062 / NBRC 15155 / AMRC-C165)*	55-60C	Segerer et al., 1988
Q97AR4	*Thermoplasma volcanium (strain ATCC 51530 / DSM 4299 / JCM 9571 / NBRC 15438 / GSS1)*	60C	Segerer et al., 1988
F2L3U6	*Thermoproteus uzoniensis (strain 768-20)*	90C	Bonch-Osmolovskaya et al., 1990
D5U1U6	*Thermosphaera aggregans (strain DSM 11486 / M11TL)*	85C	Spring et al., 2010
E1QNR4	*Vulcanisaeta distributa (strain DSM 14429 / JCM 11212 / NBRC 100878 / IC-017)*	85-90C	Itoh et al., 2002

Table S2 The ancestral state reconstructions for the optimal temperatures of each node (*i.e.*, ancestor).

The estimated variance and 95% confidence intervals for each estimate are shown.

Tree Node	Temp	Variance	Lower 95% CI	Upper 95% CI
1	93.03221	9605.997216	-99.06776	285.13218
2	96.4774	1674.757942	16.26682	176.68814
3	92.79435	648.632867	42.87654	142.71216
4	91.10297	518.088288	46.49033	135.71561
5	82.2997	257.621605	50.84053	113.75886
6	82.65651	237.89871	52.42554	112.88748
7	84.88527	144.071905	61.3594	108.41114
8	85.31645	119.436728	63.89618	106.73672
9	86.16122	92.146914	67.34656	104.97589

10	87.43038	64.957312	71.63355	103.22722
11	82.02769	207.699253	53.78061	110.27477
12	76.7104	111.974101	55.97011	97.45069
13	75.25763	52.159132	61.10226	89.413
14	75.80126	91.711369	57.03111	94.5714
15	71.38636	59.730293	56.23843	86.5343
16	76.81363	64.764437	61.04027	92.587
17	78.89226	46.777663	65.487	92.29752
18	75.80415	52.307027	61.62872	89.97957
19	76.1871	173.667449	50.35764	102.01655
20	75.49371	106.903291	55.22848	95.75895
21	78.40682	128.699649	56.17143	100.64221
22	77.05006	119.760542	55.60077	98.49936
23	85.19901	115.79612	64.10773	106.2903
24	73.262	76.481206	56.12111	90.40289
25	81.46771	95.813373	62.28239	100.65304
26	86.3428	73.578989	69.53028	103.15533
27	88.57159	47.941268	75.00062	102.14256
28	85.50037	85.639605	67.3622	103.63854
36	86.01524	68.435719	69.80097	102.22951
29	89.21818	68.081459	73.04593	105.39043
30	91.39181	48.580544	77.73066	105.05296
31	92.9927	18.369031	84.59232	101.39309
32	92.66324	13.162218	85.5524	99.77407
33	93.50247	12.870349	86.47092	100.53402
34	91.69664	8.689022	85.91912	97.47416
35	94.41459	12.251171	87.55427	101.27492
37	70.28246	68.62459	54.04583	86.51909
38	84.34782	105.355564	64.22982	104.46582
39	87.65158	82.621933	69.83584	105.46731
40	65.61184	64.571829	49.86195	81.36174
41	41.86907	110.387477	21.27624	62.4619
42	64.01619	59.346365	48.91701	79.11536

112	76.92835	94.532031	57.87175	95.98496
113	89.31845	27.318282	79.07414	99.56276
131	94.08089	21.444707	85.00444	103.15734
132	97.31749	15.749929	89.539	105.09599
133	94.96766	15.030658	87.36886	102.56646
134	94.99135	7.756869	89.53253	100.45018
114	88.12057	20.814361	79.17851	97.06263
115	84.90241	13.746399	77.63548	92.16933
116	83.41504	12.401316	76.5128	90.31728
117	83.47786	9.239008	77.52029	89.43542
118	82.62321	10.567554	76.25169	88.99473
119	81.83092	10.481743	75.48532	88.17653
120	83.85631	12.212452	77.00683	90.70579
121	83.52585	10.732534	77.10479	89.94692
122	84.43102	9.095146	78.52002	90.34202
123	85.05203	8.078604	79.48114	90.62291
124	86.1246	3.97476	82.21698	90.03221
125	85.42638	7.713097	79.98298	90.86978
126	85.58758	7.19334	80.33078	90.84438
127	84.92941	6.986179	79.74886	90.10996
128	86.49216	5.239444	82.00575	90.97857
129	86.79283	4.865952	82.46929	91.11638
130	87.33876	4.076116	83.38164	91.29588
43	59.80287	55.205732	45.23996	74.36578
44	41.23075	58.098468	26.29117	56.17033
45	38.0119	48.687952	24.33566	51.68814
46	37.69763	33.545979	26.34553	49.04973
47	37.229	30.794498	26.35241	48.10558
48	34.68054	6.999255	29.49514	39.86594
49	33.57343	4.100204	29.60464	37.54223
50	31.793	3.094915	28.34489	35.2411
51	36.55576	24.88387	26.77855	46.33297
52	29.1463	15.276847	21.48552	36.80707

53	37.01942	20.560704	28.13201	45.90682
54	36.61479	17.778567	28.35052	44.87906
66	37.70238	21.095375	28.70016	46.7046
55	35.81378	18.448499	27.39525	44.23232
63	31.30279	22.292805	22.0486	40.55698
64	31.41501	4.10749	27.44269	35.38733
65	32.15407	2.051923	29.34646	34.96168
56	38.44862	5.705358	33.76698	43.13025
57	41.08018	4.627369	36.86396	45.2964
58	44.92462	3.566578	41.22308	48.62615
59	39.36348	2.161655	36.48177	42.24518
60	36.34638	4.174196	32.34193	40.35082
61	37.19473	4.110636	33.22089	41.16857
62	33.47129	4.026013	29.53856	37.40402
67	59.07069	54.387566	44.61609	73.52528
68	67.63042	36.601222	55.77263	79.48822
69	50.81211	26.111272	40.79667	60.82755
70	53.19988	16.036217	45.35101	61.04875
71	38.53088	15.234397	30.88076	46.18101
72	72.60077	30.271599	61.81692	83.38461
73	79.97899	18.267818	71.60178	88.3562
74	77.48899	24.430203	67.80131	87.17666
78	79.79294	25.445176	69.90607	89.67981
75	80.04694	23.282201	70.58962	89.50426
76	81.7435	12.904295	74.70268	88.78432
77	81.97502	11.373378	75.36503	88.58501
79	57.74427	55.974856	43.08026	72.40827
102	56.64158	68.109241	40.46603	72.81714
103	51.4763	48.49139	37.8277	65.12491
104	41.12921	33.24306	29.82848	52.42994
105	52.48242	40.94729	39.94037	65.02448
111	55.29695	45.138408	42.12867	68.46523
106	51.94387	36.913033	40.03567	63.85206

107	57.36533	29.780974	46.66923	68.06143
108	47.92577	33.878033	36.51763	59.33392
109	39.14075	6.401128	34.18186	44.09963
110	49.38249	6.954636	44.21365	54.55133
80	51.32602	55.127359	36.77346	65.87859
81	50.03373	38.845949	37.81773	62.24972
82	47.81335	34.938	36.22811	59.39859
83	39.22462	24.499367	29.52324	48.926
84	45.35709	31.585537	34.34169	56.37249
94	44.57464	29.07805	34.00552	55.14375
95	63.77835	6.890745	58.63331	68.9234
96	62.59746	1.018402	60.61951	64.57541
97	41.70681	26.602315	31.59763	51.81599
98	34.82999	10.76066	28.40052	41.25947
99	37.30314	17.557959	29.09031	45.51598
100	37.18856	17.820267	28.91461	45.46252
101	36.7494	17.920653	28.45217	45.04663
85	39.65447	28.284289	29.23061	50.07834
86	34.50243	16.461686	26.55012	42.45474
87	33.45978	13.178146	26.34464	40.57492
88	33.25405	12.829422	26.23369	40.27441
89	38.61082	25.794604	28.6563	48.56535
90	38.24291	21.022667	29.25621	47.2296
91	38.07529	17.990086	29.762	46.38857
92	38.88073	7.418855	33.54216	44.21929
93	37.66306	17.302279	29.51024	45.81588

Table S3 ANOVA with Tukey HSD statistical parameters and outputs.

Comparison	Q statistic	p-value
W vs. Y	3.7764	0.0419502
W vs. F	4.5375	0.0089827
W vs. Other	5.5086	0.0010053
Y vs. F	0.0737	0.8999947
Y vs. Other	0.1914	0.8999947
F vs. Other	0.1319	0.8999947

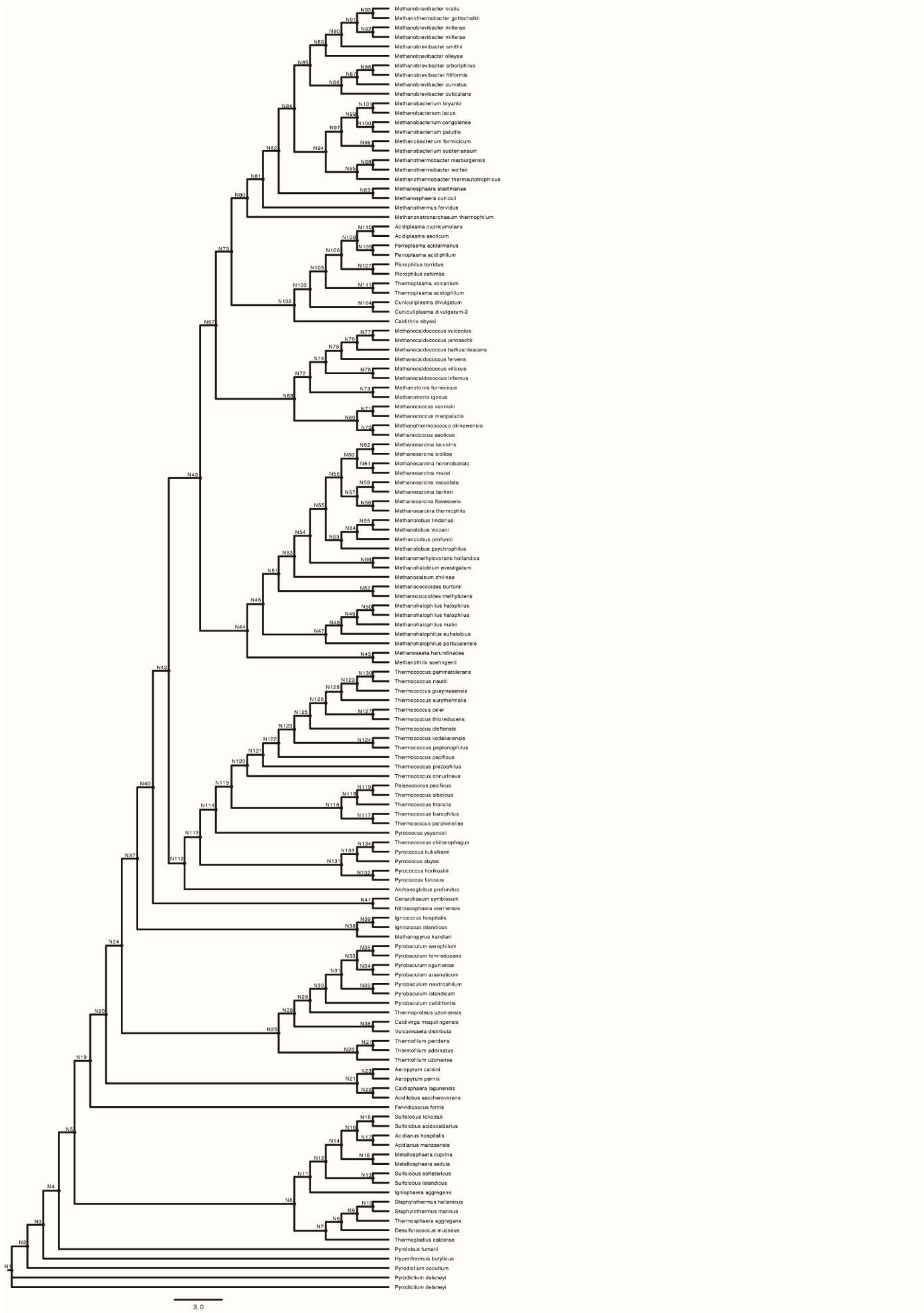
Methanobrevibacter oralis
Methanothermobacter gottschalkii
Methanobrevibacter millerae
Methanobrevibacter millerae
Methanobrevibacter smithii
Methanobrevibacter olleyae
Methanobrevibacter arboriphilus
Methanobrevibacter filiformis
Methanobrevibacter curvatus
Methanobrevibacter cuticularis
Methanobacterium bryantii
Methanobacterium lacus
Methanobacterium congolense
Methanobacterium paludis
Methanobacterium formicicum
Methanobacterium subterraneum
Methanothermobacter marburgensis
Methanothermobacter wolfeii
Methanothermobacter thermautotrophicus
Methanosphaera stadtmanae
Methanosphaera cuniculi
Methanothermus fervidus
Methanonatronarchaeum thermophilum
Acidiplasma cupricumulans
Acidiplasma aeolicum
Ferroplasma acidarmanus
Ferroplasma acidiphilum
Picrophilus torridus
Picrophilus oshimae
Thermoplasma volcanium
Thermoplasma acidophilum
Cuniculiplasma divulgatum
Cuniculiplasma divulgatum-2
Caldithrix abyssi
Methanocaldococcus vulcanius
Methanocaldococcus jannaschii
Methanocaldococcus bathoardescens
Methanocaldococcus fervens
Methanocaldococcus villosus
Methanocaldococcus infernus
Methanotorris formicicus
Methanotorris igneus
Methanococcus vannielii
Methanococcus maripaludis
Methanothermococcus okinawensis
Methanococcus aeolicus
Methanosarcina lacustris
Methanosarcina siciliae
Methanosarcina horonobensis
Methanosarcina mazei
Methanosarcina vacuolata
Methanosarcina barkeri
Methanosarcina flavescens
Methanosarcina thermophila
Methanolobus tindarius
Methanolobus vulcani
Methanolobus profundi
Methanolobus psychrophilus
Methanomethylovorans hollandica
Methanohalobium evestigatum
Methanosalsum zhilinae
Methanococcoides burtonii
Methanococcoides methylutens
Methanohalophilus halophilus
Methanohalophilus halophilus
Methanohalophilus mahii
Methanohalophilus euhalobius
Methanohalophilus portucalensis
Methanosaeta harundinacea
Methanothrix soehngenii
Thermococcus gammatolerans
Thermococcus nautili
Thermococcus guaymasensis
Thermococcus eurythermalis
Thermococcus celer
Thermococcus thioreducens
Thermococcus cleftensis
Thermococcus kodakarensis
Thermococcus peptonophilus
Thermococcus pacificus
Thermococcus piezophilus
Thermococcus onnurineus
Palaeococcus pacificus
Thermococcus sibiricus
Thermococcus litoralis
Thermococcus barophilus
Thermococcus paralvinellae
Pyrococcus yayanosii
Thermococcus chitonophagus
Pyrococcus kukulkanii
Pyrococcus abyssi
Pyrococcus horikoshii
Pyrococcus furiosus
Archaeoglobus profundus
Cenarchaeum symbiosum
Nitrososphaera viennensis
Ignicoccus hospitalis
Ignicoccus islandicus
Methanopyrus kandleri
Pyrobaculum aerophilum
Pyrobaculum ferrireducens
Pyrobaculum oguniense
Pyrobaculum arsenaticum
Pyrobaculum neutrophilum
Pyrobaculum islandicum
Pyrobaculum calidifontis
Thermoproteus uzoniensis
Caldivirga maquilingensis
Vulcanisaeta distributa
Thermofilum pendens
Thermofilum adornatus
Thermofilum uzonense
Aeropyrum camini
Aeropyrum pernix
Caldisphaera lagunensis
Acidilobus saccharovorans
Fervidicoccus fontis
Sulfolobus tokodaii
Sulfolobus acidocaldarius
Acidianus hospitalis
Acidianus manzaensis
Metallosphaera cuprina
Metallosphaera sedula
Sulfolobus solfataricus
Sulfolobus islandicus
Ignisphaera aggregans
Staphylothermus hellenicus
Staphylothermus marinus
Thermosphaera aggregans
Desulfurococcus mucosus
Thermogladius calderae
Pyrolobus fumarii
Hyperthermus butylicus
Pyrodictium occultum
Pyrodictium delaneyi
Pyrodictium delaneyi
3.0

Figure S1 The maximum-likelihood phylogeny of Euryarchaeota GGGPS sequence. All branches have been transformed to represent a cladogram. All of the ancestral nodes are labeled in order to identify their optimal growth temperatures listed in **Table S2**.

Also available are:

Supplementary File S1. The maximum-likelihood probabilities of the marginal reconstruction with indels.

Supplementary File S2. Sequences of the marginal reconstruction including indels.

Supplemental References

Amo, T., Paje, M. L. F., Inagaki, A., Ezaki, S., Atomi, H., & Imanaka, T. (2002). *Pyrobaculum calidifontis sp. nov., a novel hyperthermophilic archaeon that grows in atmospheric air*. *Archaea*, 1, 113-121.

Arab, H., H. Völker, & M. Thomm. (2000). *Thermococcus aegaeicus sp. nov. and Staphylothermus hellenicus sp. nov., two novel hyperthermophilic archaea isolated from geothermally heated vents off Palaeochori Bay, Milos, Greece*. *Int J Syst Evol Micr,* **50,** 2101-2108.

Atomi, H., Fukui, T., Kanai, T., Morikawa, M., & Imanaka, T. (2004). *Description of Thermococcus kodakaraensis sp. nov., a well studied hyperthermophilic archaeon previously reported as Pyrococcus sp. KOD1*. *Archaea*, **1**, 263-267.

Bae, S.S., Kim, Y.J., Yang, S.H., Lim, J.K., Jeon, J.H., Lee, H.S., Kang, S.G., Kim, S.J. & Lee, J.H. (2006). *Thermococcus onnurineus sp. nov., a hyperthermophilic archaeon isolated from a deep-sea hydrothermal vent area at the PACMANUS field*. *J Microbiol Biotechn*, **16**, 1826-1831.

Battumur, U., Yoon, Y. M., & Kim, C. H. (2016). *Isolation and characterization of a new Methanobacterium formicicum KOR-1 from an anaerobic digester using pig slurry*. *Asian Austral J Anim*, **29**, 586.

Bellack, A., Huber, H., Rachel, R., Wanner, G., & Wirth, R. (2011). *Methanocaldococcus villosus sp. nov., a heavily flagellated archaeon that adheres to surfaces and forms cell–cell contacts*. *Int J Syst Evol Micr*, **61**, 1239-1245.

Biavati, B., Vasta, M., & Ferry, J. G. (1988). *Isolation and characterization of" Methanosphaera cuniculi" sp. nov*. *Appl. Environ. Microbiol.*, **54**, 768-771.

Birrien, J.L., Zeng, X., Jebbar, M., Cambon-Bonavita, M.A., Quérellou, J., Oger, P., Bienvenu, N., Xiao, X. & Prieur, D. (2011). *Pyrococcus yayanosii sp. nov., an obligate piezophilic hyperthermophilic archaeon isolated from a deep-sea hydrothermal vent*. . *Int J Syst Evol Micr*, **61**, 2827-2881.

Blamey, J., Chiong, M., López, C. & Smith, E. (1999*). Optimization of the growth conditions of the extremely thermophilic microorganisms Thermococcus celer and Pyrococcus woesei*. *J Microbiol Meth*, **38**, 169-175.

Blöchl, E., Rachel, R., Burggraf, S., Hafenbradl, D., Jannasch, H.W. & Stetter, K.O. (1997) *Pyrolobus fumarii, gen. and sp. nov., represents a novel group of archaea, extending the upper temperature limit for life to 113 C*. *Extremophiles*, **1**, 14-21.

Bonch-Osmolovskaya, E.A., Miroshnichenko, M.L., Kostrikina, N.A., Chernych, N.A. & Zavarzin, G.A. (1990) *Thermoproteus uzoniensis sp. nov., a new extremely thermophilic archaebacterium from Kamchatka continental hot springs*. *Arch Microbiol*, **154**, 556-559.

Boone, D. R. & Baker, C. C. (2001). *Genus VI. Methanosalsum gen. nov*. *Bergey's Manual of Systematic Bacteriology*, vol. 1, 2nd edn.,pp. 287–289. Edited by D. R. Boone, R. W. Castenholz & G. M. Garrity. New York: Springer.

Boone, D.R. (1987). *Request for an opinion: replacement of the type strain of Methanobacterium formicicum and reinstatement of Methanobacterium bryantii sp. nov. nom. rev.(ex Balch and Wolfe, 1981) with MoH (DSM 863) as the type strain. Int J Syst Evol Micr*, **37**, 172-173.

Boone, D.R., Mathrani, I.M., Liu, Y., Menaia, J.A., Mah, R.A. & Boone, J.E. (1993). *Isolation and characterization of Methanohalophilus portucalensis sp. nov. and DNA reassociation study of the genus Methanohalophilus*. *Int J Syst Evol Micr*, **43**, 430-437.

Borrel, G., Joblin, K., Guedon, A., Colombet, J., Tardy, V., Lehours, A. C., & Fonty, G. (2012). *Methanobacterium lacus sp. nov., isolated from the profundal sediment of a freshwater meromictic lake*. *Int J Syst Evol Micr*, **62**, 1625-1629.

Burggraf, S., Fricke, H., Neuner, A., Kristjansson, J., Rouvier, P., Mandelco, L., Woese, C.R. & Stetter, K.O. (1990). *Methanococcus igneus sp. nov., a novel hyperthermophilic methanogen from a shallow submarine hydrothermal system*. *Syst Appl Microbiol*, **13**, 263-269.

Burggraf, S., Jannasch, H.W., Nicolaus, B. & Stetter, K.O. (1990). *Archaeoglobus profundus sp. nov., represents a new species within the sulfate-reducing archaebacteria*. *Syst Appl Microbiol*, **13**, 24-28.

Cadillo-Quiroz, H., Bräuer, S.L., Goodson, N., Yavitt, J.B. & Zinder, S.H. (2014). *Methanobacterium paludis sp. nov. and a novel strain of Methanobacterium lacus isolated from northern peatlands*. *Int J Syst Evol Micr*, **64**, 1473-1480.

Callac, N., Oger, P., Lesongeur, F., Rattray, J.E., Vannier, P., Michoud, G., Beauverger, M., Gayet, N., Rouxel, O., Jebbar, M. & Godfroy, A. (2016). *Pyrococcus kukulkanii sp. nov., a hyperthermophilic, piezophilic archaeon isolated from a deep-sea hydrothermal vent*. *Int J Syst Evol Micr*, **66**, 3142-3149.

Canganella, F., Jones, W.J., Gambacorta, A. & Antranikian, G. (1998). *Thermococcus guaymasensis sp. nov. and Thermococcus aggregans sp. nov., two novel thermophilic archaea isolated from the Guaymas Basin hydrothermal vent site*. *Int J Syst Evol Micr*, **48**, 1181-1185

Chan, P.P., Cozen, A.E. & Lowe, T.M. (2013). *Reclassification of Thermoproteus neutrophilus Stetter and Zillig 1989 as Pyrobaculum neutrophilum comb. nov. based on phylogenetic analysis*. *Int J Syst Evol Micr*, **63**, 751-754.

Chen, Z., Yu, H., Li, L., Hu, S. & Dong, X. (2012). *The genome and transcriptome of a newly described psychrophilic archaeon, Methanolobus psychrophilus R 15, reveal its cold adaptive characteristics*. *Env MicrobiolRep*, **4**, 633-641.

Cuzin, N., Ouattara, A.S., Labat, M. & Garcia, J.L. (2001). *Methanobacterium congolense sp. nov., from a methanogenic fermentation of cassava peel*. *Int J Syst Evol Micr*, **51**, 489-493.

Dalmasso, C., Oger, P., Selva, G., Courtine, D., L'Haridon, S., Garlaschelli, A., Roussel, E., Miyazaki, J., Reveillaud, J., Jebbar, M. &Takai, K. (2016). *Thermococcus piezophilus sp. nov., a novel hyperthermophilic and piezophilic archaeon with a broad pressure range for growth, isolated from a deepest hydrothermal vent at the Mid-Cayman Rise*. *Syst Appl Microbiol*, **39**, 440-444.

Dominova, I.N., Kublanov, I.V., Podosokorskaya, O.A., Derbikova, K.S., Patrushev, M.V. & Toshchakov, S.V. (2013). *Complete genomic sequence of "Thermofilum adornatus" strain 1910bT, a hyperthermophilic anaerobic organotrophic crenarchaeon*. *Genome Announce*, **1**, e00726-13.

Dopson, M., Baker-Austin, C., Hind, A., Bowman, J.P. & Bond, P.L. (2004). *Characterization of Ferroplasma isolates and Ferroplasma acidarmanus sp. nov., extreme acidophiles from acid mine drainage and industrial bioleaching environments*. *Appl Environ Microbio.*, **70**, 2079-2088.

Elberson, M.A. & Sowers, K.R. (1997). *Isolation of an aceticlastic strain of Methanosarcina siciliae from marine canyon sediments and emendation of the species description for Methanosarcina siciliae*. *Int J Syst Evol Micr*, **47**, 1258-1261.

Erauso, G., Reysenbach, A.L., Godfroy, A., Meunier, J.R., Crump, B., Partensky, F., Baross, J.A., Marteinsson, V., Barbier, G., Pace, N.R. & Prieur, D. (1993). *Pyrococcus abyssi sp. nov., a new hyperthermophilic archaeon isolated from a deep-sea hydrothermal vent. Arch Microbiol*, **160**, 338-349.

Ferrari, A., Brusa, T., Rutili, A., Canzi, E. & Biavati, B. (1994). *Isolation and characterization of Methanobrevibacter oralis sp. nov*. *Curr Microbiol*, **29**, 7-12.

Fiala, G., & Stetter, K. O. (1986). *Pyrococcus furiosus sp. nov. represents a novel genus of marine heterotrophic archaebacteria growing optimally at 100 C*. *Arch Microbiol*, **145**, 56-61.

Fiala, G., Stetter, K. O., Jannasch, H. W., Langworthy, T. A., & Madon, J. (1986). *Staphylothermus marinus sp. nov. represents a novel genus of extremely thermophilic submarine heterotrophic archaebacteria growing up to 98 C*. *Syst Appl Microbiol*, 8, 106-113.

Franzmann, P. D., Springer, N., Ludwig, W., De Macario, E. C., & Rohde, M. (1992). *A methanogenic archaeon from Ace Lake, Antarctica: Methanococcoides burtonii sp. nov. Syst Appl Microbiol*, **15**, 573-581.

Golyshina, O.V., Lünsdorf, H., Kublanov, I.V., Goldenstein, N.I., Hinrichs, K.U. & Golyshin, P.N. (2016). *The novel extremely acidophilic, cell-wall-deficient archaeon Cuniculiplasma divulgatum gen. nov., sp. nov. represents a new family, Cuniculiplasmataceae fam. nov., of the order Thermoplasmatales*. *Int J Syst Evol Micr*, **66**, 332.

Golyshina, O.V., Pivovarova, T.A., Karavaiko, G.I., Kondratéva, T.F., Moore, E.R., Abraham, W.R., Lünsdorf, H., Timmis, K.N., Yakimov, M.M. & Golyshin, P.N. (2000). *Ferroplasma acidiphilum gen. nov., sp. nov., an acidophilic, autotrophic, ferrous-iron-oxidizing, cell-wall-lacking, mesophilic member of the Ferroplasmaceae fam. nov., comprising a distinct lineage of the Archaea Int J Syst Evol Micr*, **50**, 997-1006.

Golyshina, O.V., Yakimov, M.M., Lünsdorf, H., Ferrer, M., Nimtz, M., Timmis, K.N., Wray, V., Tindall, B.J. & Golyshin, P.N. (2009). *Acidiplasma aeolicum gen. nov., sp. nov., a euryarchaeon of the family Ferroplasmaceae isolated from a hydrothermal pool, and transfer of Ferroplasma cupricumulans to Acidiplasma cupricumulans comb. nov*.

González, J.M., Kato, C. & Horikoshi, K. (1995). *Thermococcus peptonophilus sp. nov., a fast-growing, extremely thermophilic archaebacterium isolated from deep-sea hydrothermal vents. Arch Microbiol*, **164**, 159-164.

González, J.M., Masuchi, Y., Robb, F.T., Ammerman, J.W., Maeder, D.L., Yanagibayashi, M., Tamaoka, J. & Kato, C. (1998). *Pyrococcus horikoshii sp. nov., a hyperthermophilic archaeon isolated from a hydrothermal vent at the Okinawa Trough*. *Extremophiles*, **2**, 123-130.

Hensley, S.A., Jung, J.H., Park, C.S. & Holden, J.F. (2014). *Thermococcus paralvinellae sp. nov. and Thermococcus cleftensis sp. nov. of hyperthermophilic heterotrophs from deep-sea hydrothermal vents*. *Int J Sys Evol Micr*, **64***,* 3655-3659.

Huber, G., Spinnler, C., Gambacorta, A. & Stetter, K.O. (1989). *Metallosphaera sedula gen, and sp. nov. represents a new genus of aerobic, metal-mobilizing, thermoacidophilic archaebacteria*. *Syst Appl Microbiol*, **12,** 38-47.

Huber, H., Burggraf, S., Mayer, T., Wyschkony, I., Rachel, R. & Stetter, K.O. (2000). *Ignicoccus gen. nov., a novel genus of hyperthermophilic, chemolithoautotrophic Archaea, represented by two new species, Ignicoccus islandicus sp nov and Ignicoccus pacificus sp nov. and Ignicoccus pacificus sp. nov. Int J Syst Evol Micr*, **50**, 2093-2100.

Huber, R., Kristjansson, J.K. & Stetter, K.O. (1987). *Pyrobaculum gen. nov., a new genus of neutrophilic, rod-shaped archaebacteria from continental solfataras growing optimally at 100 C. Arch Microbiol*, **149**, 95-101.

Huber, R., Sacher, M., Vollmann, A., Huber, H. & Rose, D. (2000). *Respiration of arsenate and selenate by hyperthermophilic archaea*. *Syst Appl Microbiol*, **23,** 305-314.

Huber, R., Stöhr, J., Hohenhaus, S., Rachel, R., Burggraf, S., Jannasch, H.W. & Stetter, K.O. (1995). *Thermococcus chitonophagus sp. nov., a novel, chitin-degrading, hyperthermophilic archaeum from a deep-sea hydrothermal vent environment*. *Arch Microbiol*, **164,** 255-264.

Huser, B.A., Wuhrmann, K. and Zehnder, A.J. (1982). *Methanothrix soehngenii gen. nov. sp. nov., a new acetotrophic non-hydrogen-oxidizing methane bacterium*. *Arch Microbiol*, **132**, 1-9.

Itoh, T., Suzuki, K., Sanchez, P.C. & Nakase, T. (2003). Caldisphaera lagunensis gen. nov., sp. nov., a novel thermoacidophilic crenarchaeote isolated from a hot spring at Mt Maquiling, Philippines. *Int J Syst Evol Micr*, ***53,*** 1149-1154.

Itoh, T., Suzuki, K.I. & Nakase, T. (2002). *Vulcanisaeta distributa gen. nov., sp. nov., and Vulcanisaeta souniana sp. nov., novel hyperthermophilic, rod-shaped crenarchaeotes isolated from hot springs in Japan*. *Int J Syst Evol Micr*, **52,** 1097-1104.

Itoh, T., Suzuki, K.I., Sanchez, P.C. & Nakase, T. (1999). *Caldivirga maquilingensis gen. nov., sp. nov., a new genus of rod-shaped crenarchaeote isolated from a hot spring in the Philippines*. *Int J Syst Evol Micr*, **49,** 1157-1163.

Jahn, U., Hohn, M.J., Kronner, M., Näther, D.J., Burghardt, T., Rachel, R., Stetter, K.O. & Huber, H., 2007. *Ignicoccus hospitalis sp. nov., the host of 'Nanoarchaeum equitans'*. *Int J Syst Evol Micr*,**57,** .803-808.

Jeanthon, C., L'haridon, S., Reysenbach, A.L., Corre, E., Vernet, M., Messner, P., Sleytr, U.B. & Prieur, D. (1999). *Methanococcus vulcanius sp. nov., a novel hyperthermophilic methanogen isolated from East Pacific Rise, and identification of Methanococcus sp. DSM 4213Tas Methanococcus fervens sp. nov. Int J Syst Evol Micr*, **49,** 583-589.

Jeanthon, C., L'haridon, S., Reysenbach, A.L., Vernet, M., Messner, P., Sleytr, U.B. & Prieur, D., 1998. *Methanococcus infernus sp. nov., a novel hyperthermophilic lithotrophic methanogen isolated from a deep-sea hydrothermal vent*. *Int J Syst Evol Micr*, **48,** 913-919.

Jolivet, E., L'Haridon, S., Corre, E., Forterre, P. & Prieur, D. (2003). *Thermococcus gammatolerans sp. nov., a hyperthermophilic archaeon from a deep-sea hydrothermal vent that resists ionizing radiation*. *Int J Syst Evol Micr*, **53,** 847-851.

Jones, J.B. & Stadtman, T.C. (1977). *Methanococcus vannielii: culture and effects of selenium and tungsten on growth*. *J Bacteriol*, **130,** 1404.

Jones, W.J., Leigh, J.A., Mayer, F., Woese, C.R. & Wolfe, R.S. (1983*). Methanococcus jannaschii sp. nov., an extremely thermophilic methanogen from a submarine hydrothermal vent*. *Arch Microbiol*, **136,** 254-261.

Kadam, P.C. & Boone, D.R. (1995). *Physiological characterization and emended description of Methanolobus vulcani*. *Int J Syst Evol Micr*, **45,** 400-402.

Kendall, M.M., Liu, Y., Sieprawska-Lupa, M., Stetter, K.O., Whitman, W.B. & Boone, D.R. (2006). *Methanococcus aeolicus sp. nov., a mesophilic, methanogenic archaeon from shallow and deep marine sediments*. *Int J Syst Evol Micr*, **56,** 1525-1529.

Kern, T., Fischer, M.A., Deppenmeier, U., Schmitz, R.A. & Rother, M. (2016). *Methanosarcina flavescens sp. nov., a methanogenic archaeon isolated from a full-scale anaerobic digester*. *Int J Syst Evol Micr*, **66***,* 1533-1538.

Kochetkova, T.V., Kublanov, I.V., Toshchakov, S.V., Osburn, M.R., Novikov, A.A., Bonch-Osmolovskaya, E.A. & Perevalova, A.A. (2016). *Thermogladius calderae gen. nov., sp. nov., an anaerobic, hyperthermophilic crenarchaeote from a Kamchatka hot spring*. *Int J Syst Evol Micr*, **66**, 1407-1412.

König, H. & Stetter, K.O. (1982). *Isolation and characterization of Methanolobus tindarius, sp. nov., a coccoid methanogen growing only on methanol and methylamines*. *Zentralblatt für Bakteriologie Mikrobiologie und Hygiene: I. Abt. Originale C: Allgemeine, angewandte und ökologische Mikrobiologie*, **3,** 478-490.

Kotelnikova, S., Macario, A.J. & Pedersen, K. (1998). *Methanobacterium subterraneum sp. nov., a new alkaliphilic, eurythermic and halotolerant methanogen isolated from deep granitic groundwater*. *Int J Syst Evol Micr*, **48,** 357-367.

Kurr, M., Huber, R., König, H., Jannasch, H.W., Fricke, H., Trincone, A., Kristjansson, J.K. & Stetter, K.O. (1991). *Methanopyrus kandleri, gen. and sp. nov. represents a novel group of hyperthermophilic methanogens, growing at 110 C*. *Arch Microbiol*, **156,** 239-247.

L'Haridon, S., Corre, E., Guan, Y., Vinu, M., La Cono, V., Yakimov, M., Stingl, U., Toffin, L. & Jebbar, M. (2017). *Complete Genome Sequence of Methanohalophilus halophilus DSM 3094T, Isolated from a Cyanobacterial Mat and Bottom Deposits at Hamelin Pool, Shark Bay, Northwestern Australia*. *Genome Announc*, **5,** e01604-16.

Leadbetter, J.R. & Breznak, J.A. (1996). *Physiological ecology of Methanobrevibacter cuticularis sp. nov. and Methanobrevibacter curvatus sp. nov., isolated from the hindgut of the termite Reticulitermes flavipes*. *Appl Environ Microbiol*, **62,** 3620-3631.

Leadbetter, J.R., Crosby, L.D. & Breznak, J.A. (1998). *Methanobrevibacter filiformis sp. nov., a filamentous methanogen from termite hindguts*. *Arch Microbiol*, **169,** 287-292.

Lin, T. J., El Sebae, G., Jung, J. H., Jung, D. H., Park, C. S., & Holden, J. F. (2016). *Pyrodictium delaneyi sp. nov., a hyperthermophilic autotrophic archaeon that reduces Fe (III) oxide and nitrate*. *Int J Syst Evol Micr,* **66**, 3372.

Liu, L.J., You, X.Y., Guo, X., Liu, S.J. & Jiang, C.Y., (2011). *Metallosphaera cuprina sp. nov., an acidothermophilic, metal-mobilizing archaeon*. *Int J Syst Evol Micr*, **61**, 2395-2400.

Liu, Y., Boone, D.R., Sleat, R. & Mah, R.A. (1985). *Methanosarcina mazei LYC, a new methanogenic isolate which produces a disaggregating enzyme*. *Appl Environ Microbiol*, **49**, 608-613.

Lomans, B.P., Maas, R., Luderer, R., den Camp, H.J.O., Pol, A., van der Drift, C. and Vogels, G.D. (1999). *Isolation & characterization of Methanomethylovorans hollandica gen. nov., sp. nov., isolated from freshwater sediment, a methylotrophic methanogen able to grow on dimethyl sulfide and methanethiol*. *Appl Environ Microbiol*, **65**, 3641-3650.

Ma, K., Liu, X. & Dong, X. (2006). *Methanosaeta harundinacea sp. nov., a novel acetate-scavenging methanogen isolated from a UASB reactor*. *Int J Syst Evol Micr*, *56*(1), pp.127-131.

Maestrojuan, G.M. and Boone, D.R. (1991). *Characterization of Methanosarcina barkeri MST and 227, Methanosarcina mazei S-6T, and Methanosarcina vacuolata Z-761T*. *Int J Syst Evol Micr*, **41,** 267-274.

Marteinsson, V.T., Birrien, J.L., Reysenbach, A.L., Vernet, M., Marie, D., Gambacorta, A., Messner, P., Sleytr, U.B. & Prieur, D. (1999). *Thermococcus barophilus sp. nov., a new barophilic and hyperthermophilic archaeon isolated under high hydrostatic pressure from a deep-sea hydrothermal vent*. *Int J Syst Evol Micr*, **49**, 351-359.

Miller T.L & Lin C. *Description of Methanobrevibacter gottschalkii sp. nov., Methanobrevibacter thaueri sp. nov., Methanobrevibacter woesei sp. nov. and Methanobrevibacter wolinii sp. nov. Int J Syst Evol Micr.* **52,** *819–822*

Miller, T.L. & Wolin, M.J. (1985). *Methanosphaera stadtmaniae gen. nov., sp. nov.: a species that forms methane by reducing methanol with hydrogen. Arch Microbiol*, **141**, 116-122.

Miroshnichenko, M.L., Gongadze, G.M., Rainey, F.A., Kostyukova, A.S., Lysenko, A.M., Chernyh, N.A. & Bonch-Osmolovskaya, E.A. (1998). *Thermococcus gorgonarius sp. nov. and Thermococcus pacificus sp. nov.: heterotrophic extremely thermophilic archaea from New Zealand submarine hot vents*. *Int J Syst Evol Micr*, **48**, 23-29.

Miroshnichenko, M.L., Hippe, H., Stackebrandt, E., Kostrikina, N.A., Chernyh, N.A., Jeanthon, C., Nazina, T.N., Belyaev, S.S. & Bonch-Osmolovskaya, E.A. (2001). *Isolation and characterization of Thermococcus sibiricus sp. nov. from a Western Siberia high-temp*erature oil reservoir. *Extremophiles*, **5**, 85-91.

Miroshnichenko, M.L., Kostrikina, N.A., Chernyh, N.A., Pimenov, N.V., Tourova, T.P., Antipov, A.N., Spring, S., Stackebrandt, E. & Bonch-Osmolovskaya, E.A. (2003). *Caldithrix abyssi gen. nov., sp. nov., a nitrate-reducing, thermophilic, anaerobic bacterium isolated from a Mid-Atlantic Ridge hydrothermal vent, represents a novel bacterial lineage*. *Int J Syst Evol Micr*, **53**, 323-329.

Mochimaru, H., Tamaki, H., Hanada, S., Imachi, H., Nakamura, K., Sakata, S. & Kamagata, Y., 2009. *Methanolobus profundi sp. nov., a methylotrophic methanogen isolated from deep subsurface sediments in a natural gas field*. *Int J Syst Evol Micr*, **59**, 714-718.

Morii, H., Nishihara, M. & Koga, Y. (1983). *Isolation, characterization and physiology of a new formate-assimilable methanogenic strain (A2) of Methanobrevibacter arboriphilus*. *Agr Biol Chem Tokyo*, **47**, 2781-2789.

Nakagawa, S., Takai, K., Horikoshi, K. & Sako, Y. (2004). *Aeropyrum camini sp. nov., a strictly aerobic, hyperthermophilic archaeon from a deep-sea hydrothermal vent chimney*. *Int J Syst Evol Micr*, **54**, 329-335.

Neuner, A., Jannasch, H.W., Belkin, S. & Stetter, K.O. (1990). *Thermococcus litoralis sp. nov.: a new species of extremely thermophilic marine archaebacteria. Arch Microbiol*, **153**, 205-207.

Niederberger, T.D., Götz, D.K., McDonald, I.R., Ronimus, R.S. & Morgan, H.W. (2006). *Ignisphaera aggregans gen. nov., sp. nov., a novel hyperthermophilic crenarchaeote isolated from hot springs in Rotorua and Tokaanu, New Zealand*. *Archives of microbiology*, **56**, 965-971.

Oberto, J., Gaudin, M., Cossu, M., Gorlas, A., Slesarev, A., Marguet, E. & Forterre, P. (2014). *Genome sequence of a hyperthermophilic archaeon, Thermococcus nautili 30-1, that produces viral vesicles*. *Genome Announc.*, **2**, e00243-14.

Obraztsova, A. Y., Shipin, O. V., Bezrukova, L. V., & Belyaev, S. S. (1987). *Properties of the coccoidmethylotrophic methanogen, methanococcoides-euhalobius sp-nov*. *Microbiology*, **56**, 523-527.

Paterek, J.R. & Smith, P.H. (1988). *Methanohalophilus mahii gen. nov., sp. nov., a methylotrophic halophilic methanogen*. *Int J Syst Evol Micr*, **38**, 122-123.

Perevalova, A.A., Bidzhieva, S.K., Kublanov, I.V., Hinrichs, K.U., Liu, X.L., Mardanov, A.V., Lebedinsky, A.V. & Bonch-Osmolovskaya, E.A. (2010). *Fervidicoccus fontis gen. nov., sp. nov., an anaerobic, thermophilic crenarchaeote from terrestrial hot springs, and proposal of Fervidicoccaceae fam. nov. and Fervidicoccales ord. nov*. *Int J Syst Evol Micr*, **60**, 2082-2088.

Pikuta, E.V., Marsic, D., Itoh, T., Bej, A.K., Tang, J., Whitman, W.B., Ng, J.D., Garriott, O.K. & Hoover, R.B. (2007). *Thermococcus thioreducens sp. nov., a novel hyperthermophilic, obligately sulfur-reducing archaeon from a deep-sea hydrothermal vent*. *Int J Syst Evol Micr*, **57**, 1612-1618.

Preston, C.M., Wu, K.Y., Molinski, T.F. & DeLong, E.F. (1996). *A psychrophilic crenarchaeon inhabits a marine sponge: Cenarchaeum symbiosum gen. nov., sp. nov*. *Proc Natl Acad Sci USA*, **93**, 6241-6246.

Prokofeva, M.I., Kostrikina, N.A., Kolganova, T.V., Tourova, T.P., Lysenko, A.M., Lebedinsky, A.V. & Bonch-Osmolovskaya, E.A. (2009). *Isolation of the anaerobic thermoacidophilic crenarchaeote Acidilobus saccharovorans sp. nov. and proposal of Acidilobales ord. nov., including Acidilobaceae fam. nov. and Caldisphaeraceae fam. nov*. *Int J Syst Evol Micr*, **59**, 3116-3122.

Rea, S., Bowman, J.P., Popovski, S., Pimm, C. & Wright, A.D.G. (2007). *Methanobrevibacter millerae sp. nov. and Methanobrevibacter olleyae sp. nov., methanogens from the ovine and bovine rumen that can utilize formate for growth*. *Int J Syst Evol Micr*, **57**, 450-456.

Sako, Y., Nomura, N., Uchida, A., Ishida, Y., Morii, H., Koga, Y., Hoaki, T. & Maruyama, T. (1996). *Aeropyrum pernix gen. nov., sp. nov., a novel aerobic hyperthermophilic archaeon growing at temperatures up to 100 C*. *Int J Syst Evol Micr*, **46**, 1070-1077.

Sako, Y., Nunoura, T. & Uchida, A. (2001). *Pyrobaculum oguniense sp. nov., a novel facultatively aerobic and hyperthermophilic archaeon growing at up to 97 degrees C*. *Int J Syst Evol Micr*, **51**, 303-309.

Schleper, C., Pühler, G., Klenk, H.P. and Zillig, W. (1996). *Picrophilus oshimae and Picrophilus torridus fam. nov., gen. nov., sp. nov., two species of hyperacidophilic, thermophilic, heterotrophic, aerobic archaea*. *Int J Syst Evol Micr,* **46**, 814-816.

Segerer, A., Langworthy, T.A. & Stetter, K.O. (1988). *Thermoplasma acidophilum and Thermoplasma volcanium sp. nov. from solfatara fields*. *Syst Appl Microbiol*, **10**, 161-171.

Shimizu, S., Upadhye, R., Ishijima, Y., & Naganuma, T. (2011). *Methanosarcina horonobensis sp. nov., a methanogenic archaeon isolated from a deep subsurface Miocene formation*. *Int J Syst Evol Micr*, **61**, 2503-2507.

Simankova, M.V., Parshina, S.N., Tourova, T.P., Kolganova, T.V., Zehnder, A.J. & Nozhevnikova, A.N. (2001). *Methanosarcina lacustris sp. nov., a new psychrotolerant methanogenic archaeon from anoxic lake sediments*. *Syst Appl Microbiol*, **24**, 362-367.

Slobodkina, G.B., Lebedinsky, A.V., Chernyh, N.A., Bonch-Osmolovskaya, E.A. & Slobodkin, A.I. (2015). *Pyrobaculum ferrireducens sp. nov., a hyperthermophilic Fe (III)-, selenate-and arsenate-reducing crenarchaeon isolated from a hot spring Int J Syst Evol Micr*, **65**, 851-856.

Sorokin, D.Y., Merkel, A.Y., Abbas, B., Makarova, K.S., Rijpstra, W.I.C., Koenen, M., Damsté, J.S.S., Galinski, E.A., Koonin, E.V. & van Loosdrecht, M.C. (2018). *Methanonatronarchaeum thermophilum gen. nov., sp. nov. and'Candidatus Methanohalarchaeum thermophilum', extremely halo (natrono) philic methyl-reducing methanogens from hypersaline lakes comprising a new euryarchaeal class Methanonatronarchaeia classis nov*. *Int J Syst Evol Micr*, **68**, 2199-2208.

Sowers, K.R. & Ferry, J.G. (1983). *Isolation and characterization of a methylotrophic marine methanogen, Methanococcoides methylutens gen. nov., sp. nov*. *Appl Environ Microbiol*, **45**, 684-690.

Spring, S., Rachel, R., Lapidus, A., Davenport, K., Tice, H., Copeland, A., Cheng, J.F., Lucas, S., Chen, F., Nolan, M. & Bruce, D. (2010). *Complete genome sequence of Thermosphaera aggregans type strain (M11TL T)*. *Stand Genomic Sci*, **2**, 245.

Stetter, K.O., Thomm, M., Winter, J., Wildgruber, G., Huber, H., Zillig, W., Jané-Covic, D., König, H., Palm, P. & Wunderl, S. (1981). *Methanothermus fervidus, sp. nov., a novel extremely thermophilic methanogen isolated from an Icelandic hot spring*. *Zentralblatt für Bakteriologie Mikrobiologie und Hygiene: I. Abt. Originale C: Allgemeine, angewandte und ökologische Mikrobiologie*, **2**, 166-178.

Stewart, L.C., Jung, J.H., Kim, Y.T., Kwon, S.W., Park, C.S. & Holden, J.F. (2015). *Methanocaldococcus bathoardescens sp. nov., a hyperthermophilic methanogen isolated from a volcanically active deep-sea hydrothermal vent*. *Int J Syst Evol Micr*, **65**, 1280-1283.

Stieglmeier, M., Klingl, A., Alves, R.J., Rittmann, S.K.M., Melcher, M., Leisch, N. & Schleper, C. (2014). *Nitrososphaera viennensis gen. nov., sp. nov., an aerobic and mesophilic, ammonia-oxidizing archaeon from soil and a member of the archaeal phylum Thaumarchaeota*. *Int J Syst Evol Micr*, **64**, 2738.

Suzuki, T., Iwasaki, T., Uzawa, T., Hara, K., Nemoto, N., Kon, T., Ueki, T., Yamagishi, A. & Oshima, T. (2002). *Sulfolobus tokodaii sp. nov.(f. Sulfolobus sp. strain 7), a new member of the genus Sulfolobus isolated from Beppu Hot Springs, Japan*. *Extremophiles*, **6**, 39-44.

Takai, K., Inoue, A. & Horikoshi, K. (2002). *Methanothermococcus okinawensis sp. nov., a thermophilic, methane-producing archaeon isolated from a Western Pacific deep-sea hydrothermal vent system*. *Int J Syst Evol Micr*, **52**, 1089-1095.

Takai, K., Nealson, K.H. & Horikoshi, K. (2004). *Methanotorris formicicus sp. nov., a novel extremely thermophilic, methane-producing archaeon isolated from a black smoker chimney in the Central Indian Ridge*. *Int J Syst Evol Micr*, **54**, 1095-1100.

Takayanagi, S., Kawasaki, H., Sugimori, K., Yamada, T., Sugai, A., Ito, T., Yamasato, K. & Shioda, M. (1996). *Sulfolobus hakonensis sp. nov., a novel species of acidothermophilic archaeon. Int J Syst Evol Micr*, **46**, 377-382.

Toshchakov, S.V., Korzhenkov, A.A., Samarov, N.I., Mazunin, I.O., Mozhey, O.I., Shmyr, I.S., Derbikova, K.S., Taranov, E.A., Dominova, I.N., Bonch-Osmolovskaya, E.A. & Patrushev, M.V. (2015). *Complete genome sequence of and proposal of Thermofilum uzonense sp. nov. a novel hyperthermophilic crenarchaeon and emended description of the genus Thermofilum*. *Stand Genomic Sci*, **10**, 122.

Uemori, T., Ishino, Y., Doi, H., & Kato, I. (1995). *The hyperthermophilic archaeon Pyrodictium occultum has two alpha-like DNA polymerases*. *J Bacteriol*, **177**, 2164-2177.

Völkl, P., Huber, R., Drobner, E., Rachel, R., Burggraf, S., Trincone, A. & Stetter, K.O. (1993). *Pyrobaculum aerophilum sp. nov., a novel nitrate-reducing hyperthermophilic archaeum*. *Appl Environ Microbiol*, **59**, 2918-2926.

Wasserfallen, A., Nölling, J., Pfister, P., Reeve, J. & De Macario, E.C. (2000). *Phylogenetic analysis of 18 thermophilic Methanobacterium isolates supports the proposals to create a new genus, Methanothermobacter gen. nov., and to reclassify several isolates in three species, Methanothermobacter thermautotrophicus comb. nov., Methanothermobacter wolfeii comb. nov., and Methanothermobacter marburgensis sp. nov*. *Int J Syst Evol Micr*, **50**, 43-53.

Whitman, W.B., Shieh, J., Sohn, S., Caras, D.S. & Premachandran, U. (1986). *Isolation and characterization of 22 mesophilic methanococci*. *Syst Appl Microbiol*, **7**, 235-240.

Wirth, R., Chertkov, O., Held, B., Lapidus, A., Nolan, M., Lucas, S., Hammon, N., Deshpande, S., Cheng, J.F., Tapia, R. & Han, C. (2011). *Complete genome sequence of Desulfurococcus mucosus type strain (O7/1 T). Stand Genomic Sci*, **4**, 173.

Yoshida, N., Nakasato, M., Ohmura, N., Ando, A., Saiki, H., Ishii, M. & Igarashi, Y., 2006*. Acidianus manzaensis sp. nov., a novel thermoacidophilic archaeon growing autotrophically by the oxidation of H 2 with the reduction of Fe 3+. Curr Microbiol*, **53**, 406-411.

You, X.Y., Liu, C., Wang, S.Y., Jiang, C.Y., Shah, S.A., Prangishvili, D., She, Q., Liu, S.J. & Garrett, R.A. (2011). *Genomic analysis of Acidianus hospitalis W1 a host for studying crenarchaeal virus and plasmid life cycles*. *Extremophiles*, **15**, 487.

Zaparty, M., Esser, D., Gertig, S., Haferkamp, P., Kouril, T., Manica, A., Pham, T.K., Reimann, J., Schreiber, K., Sierocinski, P. & Teichmann, D. (2010). *"Hot standards" for the thermoacidophilic archaeon Sulfolobus solfataricus*. *Extremophiles*, **14**, 119.

Zeng, X., Zhang, X., Jiang, L., Alain, K., Jebbar, M. & Shao, Z. (2013). *Palaeococcus pacificus sp. nov., an archaeon from deep-sea hydrothermal sediment*. *Int J Syst Evol Micr*, **63**, 2155-2159.

Zhao, W., Zeng, X. & Xiao, X. (2015). *Thermococcus eurythermalis sp. nov., a conditional piezophilic, hyperthermophilic archaeon with a wide temperature range for growth, isolated from an oil-immersed chimney in the Guaymas Basin*. *Int J Syst Evol Micr*, **65**, 30-35.

Zhilina, T. N., & Zavarzin, G. A. (1987). *Methanohalobium evestigatus n. gen., n. sp.- An extremely halophilic methane-forming archebacterium(Methanohalobium evestigatus n. gen., n. sp.- Ekstremal'no-galofil'naia metanoobrazuiushchaia arkhebakteriia).* In *Akademiia Nauk SSSR, Doklady* (Vol. 293, No. 2, pp. 464-468).

Zhilina, T.N. & Zavarzin, G.A. (1987). *Methanosarcina vacuolata sp. nov., a vacuolated Methanosarcina*. *Int J Syst Evol Micr*, **37**, 281-283.

Zillig, W., Gierl, A., Schreiber, G., Wunderl, S., Janekovic, D., Stetter, K.O. & Klenk, H.P. (1983). *The archaebacterium Thermofilum pendens represents, a novel genus of the thermophilic, anaerobic sulfur respiring Thermoproteales*. *Syst Appl Microbiol*,, **4**, 79-87.

Zillig, W., Holz, I., Janekovic, D., Klenk, H.P., Imsel, E., Trent, J., Wunderl, S., Forjaz, V.H., Coutinho, R.& Ferreira, T. (1990). *Hyperthermus butylicus, a hyperthermophilic sulfur-reducing archaebacterium that ferments peptides*. *J Bacteriol*, **172**, 3959-3965.

Zillig, W., Kletzin, A., Schleper, C., Holz, I., Janekovic, D., Hain, J., Lanzendörfer, M. & Kristjansson, J.K. (1993). *Screening for Sulfolobales, their plasmids and their viruses in Icelandic solfataras*. *Syst Appl Microbiol*, **16**, 609-628.

Zinder, S.H., Sowers, K.R. & Ferry, J.G. (1985). *Methanosarcina thermophila sp. nov., a thermophilic, acetotrophic, methane-producing bacterium*. *Int J Syst Evol Micr,* **35**, 522-523.