Source of 150 TEM images containing biogenic magnetite grains for training and validation.

|  |  |
| --- | --- |
| **Image index number** | **Image source** |
| 0 | Bazylinski & Frankel, 2004 |
| 1-5, 7 | Chang et al., 2016 |
| 6, 31, 51-64 | Zhang et al., 2021 |
| 8-16 | Channell et al., 2013 |
| 17-19 | He & Pan, 2020 |
| 20, 22-24 | Kopp et al., 2009 |
| 21 | Housen & Moskowitz, 2005 |
| 25-27 | Kopp et al., 2007 |
| 28-30, 32 | Lascu and Plank, 2013 |
| 33-34 | Usui et al., 2017 |
| 35-38 | Usui & Yamazaki, 2021 |
| 39-40 | Yamazaki et al., 2020 |
| 41-44 | Yamazaki et al., 2019 |
| 45-48 | Yamazaki & Horiuchi, 2016 |
| 49-50 | Yamazaki, 2012 |
| 65-103, 112 | Experimental data produced in our group |
| 104 | Hanzlik et al., 2002 |
| 105 | Kopp et al., 2006 |
| 106 | Zhou et al. 2010 |
| 107, 141, 142, 149 | Prozorov et al., 2007 |
| 108 | Amor et al., 2015 |
| 109 | Chang et al., 2012 |
| 110 | Dunin-Borkowski et al., 1998 |
| 111 | Mao et al., 2014 |
| 113 | Meldrum et al., 1993b |
| 114 | Kobayashi et al., 2006 |
| 115 | Abraçado et al., 2010 |
| 116, 123, 146 | Devouard et al., 1998 |
| 117 | Hanzlik et al., 1996 |
| 118 | Frankel et al., 1979 |
| 119 | Fischer et al., 2011 |
| 120, 138 | Lang & Shuler, 2006 |
| 121 | Pósfai et al., 2006 |
| 122 | Xiang et al., 2007 |
| 124 | Moskowitz et al., 2008 |
| 125, 131, 134 | Staniland et al., 2009 |
| 126 | Alphandéry et al., 2009 |
| 127 | Bauerlein, 2003 |
| 128, 130 | Lefèvre et al., 2011 |
| 129 | Faivre & Schüler, 2008 |
| 132-133 | Busigny et al., 2021 |
| 135-137 | Liu et al., 2020 |
| 139, 145 | Meldrum et al., 1993a |
| 140 | Li & Pan, 2012 |
| 143 | Li et al., 2009 |
| 144 | Pan et al., 2009 |
| 147 | Timko et al., 2009 |
| 148 | Popa et al., 2009 |

**References for Supporting Information**

Abraçado, L. G., Abreu, F., Keim, C. N., Campos, A. P. C., Lins, U., & Farina, M. (2011). Magnetosome chain superstructure in uncultured magnetotactic bacteria.*Physical Biology, 7*(4), 046016–046016. <https://doi.org/10.1088/1478-3975/7/4/046016>

Alphandéry, E., Ding, Y., Ngo, A. T., Wang, Z. L., Wu, L. F., & Pileni, M. P. (2009). Assemblies of aligned magnetotactic bacteria and extracted magnetosomes: What is the main factor responsible for the magnetic anisotropy?*ACS Nano, 3*(6), 1539–1547. <https://doi.org/10.1021/nn900289n>

Amor, M., Busigny, V., Durand-Dubief, M., Tharaud, M., Ona-Nguema, G., Gélabert, A., Alphandéry, E., Menguy, N., Benedetti, M. F., Chebbi, I., & Guyot, F. (2015). Chemical signature of magnetotactic bacteria.*Proceedings of the National Academy of Sciences, 112*(6), 1699–1703. <https://doi.org/10.1073/pnas.1414112112>

Bauerlein, E. (2003). Biomineralization of unicellular organisms: An unusual membrane biochemistry for the production of inorganic nano- and microstructures.*Angewandte Chemie (International Ed.), 42*(6), 614–641. <https://doi.org/10.1002/anie.200390176>

Bazylinski, D. A., & Frankel, R. B. (2004). Magnetosome formation in prokaryotes. *Nature Reviews Microbiology, 2*(3), 217–230. <https://doi.org/10.1038/nrmicro842>

Busigny, V., Mathon, F. P., Jézéquel, D., Bidaud, C. C., Viollier, E., Bardoux, G., Bourrand, J., Benzerara, K., Duprat, E., Menguy, N., Monteil, C. L., & Lefevre, C. T. (2021). Mass collection of magnetotactic bacteria from the permanently stratified ferruginous Lake Pavin, France.*Environmental Microbiology, 24*(2), 721–736. <https://doi.org/10.1111/1462-2920.15458>

Chang, L., Heslop, D., Roberts, A. P., Rey, D., & Mohamed, K. J. (2016). Discrimination of biogenic and detrital magnetite through a double Verwey transition temperature.*Journal of Geophysical Research: Solid Earth, 121*(1), 3–14. <https://doi.org/10.1002/2015JB012485>

Chang, L., Roberts, A. P., Williams, W., Fitz Gerald, J. D., Larrasoana, J. C., Jovane, L., & Muxworthy, A. R. (2012). Giant magnetofossils and hyperthermal events.*Earth and Planetary Science Letters, 351-352*, 258–269. <https://doi.org/10.1016/j.epsl.2012.07.031>

Channell, J. E. T., Hodell, D. A., Margari, V., Skinner, L. C., Tzedakis, P. C., & Kesler, M. S. (2013). Biogenic magnetite, detrital hematite, and relative paleointensity in Quaternary sediments from the southwest Iberian margin.*Earth and Planetary Science Letters, 376*, 99–109. <https://doi.org/10.1016/j.epsl.2013.06.026>

Devouard, B., Posfai, M., Hua, X., Bazylinski, D. A., Frankel, R. B., & Buseck, P. R. (1998). Magnetite from magnetotactic bacteria: size distributions and twinning.*The American Mineralogist, 83*(11-12), 1387–1398. <https://doi.org/10.2138/am-1998-11-1228>

Dunin-Borkowski, R. E., McCartney, M. R., Frankel, R. B., Bazylinski, D. A., Pósfai, M., & Buseck, P. R. (1998). Magnetic microstructure of magnetotactic bacteria by electron holography.*Science, 282*(5395), 1868–1870. <https://doi.org/10.1126/science.282.5395.1868>

Faivre, D., & Schüler, D. (2008). Magnetotactic bacteria and magnetosomes.*Chemical Reviews, 108*(11), 4875–4898. <https://doi.org/10.1021/cr078258w>

Fischer, A., Schmitz, M., Aichmayer, B., Fratzl, P., & Faivre, D. (2011). Structural purity of magnetite nanoparticles in magnetotactic bacteria.*Journal of the Royal Society Interface, 8*(60), 1011–1018. <https://doi.org/10.1098/rsif.2010.0576>

Frankel, R. B., Blakemore, R. P., & Wolfe, R. S. (1979). Magnetite in freshwater magnetotactic bacteria.*Science, 203*(4387), 1355–1356. <https://doi.org/10.1126/science.203.4387.1355>

Hanzlik, M., Winklhofer, M., & Petersen, N. (1996). Spatial arrangement of chains of magnetosomes in magnetotactic bacteria.*Earth and Planetary Science Letters, 145*(1-4), 125–134. <https://doi.org/10.1016/S0012-821X(96)00191-4>

Hanzlik, M., Winklhofer, M., & Petersen, N. (2002). Pulsed-field-remanence measurements on individual magnetotactic bacteria.*Journal of Magnetism and Magnetic Materials, 248*(2), 258–267. <https://doi.org/10.1016/S0304-8853(02)00353-0>

He, K., & Pan, Y. (2020). Magnetofossil abundance and diversity as paleoenvironmental proxies: A case study from southwest Iberian margin sediments.*Geophysical Research Letters, 47*, e2020GL087165. <https://doi.org/10.1029/2020GL087165>

Housen, B. A., & Moskowitz, B. M. (2006). Depth distribution of magnetofossils in near-surface sediments from the Blake/Bahama outer ridge, western north Atlantic Ocean, determined by low-temperature magnetism.*Journal of Geophysical Research, 111*, G01005. <https://doi.org/10.1029/2005JG000068>

Kobayashi, A., Kirschvink, J. L., Nash, C. Z., Kopp, R. E., Sauer, D. A., Bertani, L. E., Voorhout, W. F., & Taguchi, T. (2006). Experimental observation of magnetosome chain collapse in magnetotactic bacteria: sedimentological, paleomagnetic, and evolutionary implications.*Earth and Planetary Science Letters, 245*(3-4), 538–550. <https://doi.org/10.1016/j.epsl.2006.03.041>

Kopp, R. E., Nash, C. Z., Kobayashi, A., Weiss, B. P., Bazylinski, D. A., & Kirschvink, J. L. (2006). Ferromagnetic resonance spectroscopy for assessment of magnetic anisotropy and magnetostatic interactions: A case study of mutant magnetotactic bacteria.*Journal of Geophysical Research, 111*, B12S25. <https://doi.org/10.1029/2006JB004529>

Kopp, R. E., Raub, T. D., Schumann, D., Vali, H., Smirnov, A. V., & Kirschvink, J. L. (2007). Magnetofossil spike during the Paleocene-Eocene thermal maximum: Ferromagnetic resonance, rock magnetic, and electron microscopy evidence from Ancora, New Jersey, United States.*Paleoceanography, 22*, PA4103. <https://doi.org/10.1029/2007PA001473>

Kopp, R. E., Schumann, D., Raub, T. D., Powars, D. S., Godfrey, L. V., Swanson-Hysell, N. L., Maloof, A. C., & Vali, H. (2009). An Appalachian Amazon? Magnetofossil evidence for the development of a tropical river-like system in the mid-Atlantic United States during the Paleocene-Eocene thermal maximum. *Paleoceanography, 24*, PA4211. <https://doi.org/10.1029/2009PA001783>

Lang, C., & Schüler, D. (2006). Biogenic nanoparticles: Production, characterization, and application of bacterial magnetosomes.*Journal of Physics: Condensed Matter, 18*(38), S2815–S2828. <https://doi.org/10.1088/0953-8984/18/38/S19>

Lascu, I., & Plank, C. (2013). A new dimension to sediment magnetism: charting the spatial variability of magnetic properties across lake basins.*Global and Planetary Change, 110*, 340–349. <https://doi.org/10.1016/j.gloplacha.2013.03.013>

Lecun, Y., Bottou, L., Bengio, Y., & Haffner, P. (1998). Gradient-based learning applied to document recognition. *Proceedings of the IEEE, 86*(11), 2278–2324. <https://doi.org/10.1109/5.726791>

Lefèvre, C. T., Posfai, M., Abreu, F., Lins, U., Frankel, R. B., & Bazylinski, D. A. (2011). Morphological features of elongated-anisotropic magnetosome crystals in magnetotactic bacteria of the nitrospirae phylum and the deltaproteobacteria class.*Earth and Planetary Science Letters, 312*(1-2), 194–200. <https://doi.org/10.1016/j.epsl.2011.10.003>

Li, J., & Pan, Y. (2012). Environmental factors affect magnetite magnetosome synthesis in magnetospirillum magneticum AMB-1: Implications for biologically controlled mineralization. *Geomicrobiology Journal, 29*(4), 362–373. <https://doi.org/10.1080/01490451.2011.565401>

Li, J., Pan, Y., Chen, G., Liu, Q., Tian, L., & Lin, W. (2009). Magnetite magnetosome and fragmental chain formation of Magnetospirillum magneticum AMB-1: Transmission electron microscopy and magnetic observations.*Geophysical Journal International, 177*(1), 33–42. <https://doi.org/10.1111/j.1365-246X.2009.04043.x>

Liu, P., Liu, Y., Zhao, X., Roberts, A. P., Zhang, H., Zheng, Y., Wang, F., Wang, L., Menguy, N., Pan, Y., & Li, J. (2021). Diverse phylogeny and morphology of magnetite biomineralized by magnetotactic cocci.*Environmental Microbiology, 23*(2), 1115–1129. <https://doi.org/10.1111/1462-2920.15254>

Mao, X., Egli, R., Petersen, N., Hanzlik, M., & Liu, X. (2014). Magneto-chemotaxis in sediment: First insights.*PloS One, 9*(7), e102810. <https://doi.org/10.1371/journal.pone.0102810>

Meldrum, F. C., Mann, S., Heywood, B. R., Frankel, R. B., & Bazylinski, D. A. (1993). Electron microscopy study of magnetosomes in a cultured coccoid magnetotactic bacterium.*Proceedings of the Royal Society: Biological Sciences, 251*(1332), 231–236. <https://doi.org/10.1098/rspb.1993.0034>

Meldrum, F. C., Mann, S., Heywood, B. R., Frankel, R. B., & Bazylinski, D. A. (1993). Electron microscopy study of magnetosomes in two cultured vibrioid magnetotactic bacteria.*Proceedings of the Royal Society: Biological Sciences, 251*(1332), 237–242. <https://doi.org/10.1098/rspb.1993.0035>

Moskowitz, B. M., Bazylinski, D. A., Egli, R., Frankel, R. B., & Edwards, K. J. (2008). Magnetic properties of marine magnetotactic bacteria in a seasonally stratified coastal pond (Salt Pond, MA, USA).*Geophysical Journal International, 174*(1), 75–92. <https://doi.org/10.1111/j.1365-246X.2008.03789.x>

Pan, Y., Lin, W., Tian, L., Zhu, R., & Petersen, N. (2009). Combined approaches for characterization of an uncultivated magnetotactic coccus from lake Miyun near Beijing.*Geomicrobiology Journal, 26*(5), 313–320. <https://doi.org/10.1080/01490450902748633>

Popa, R., Fang, W., Nealson, K. H., Souza-Egipsy, V., Berqú, T. S., Banerje, S. K., & Penn, L. R. (2009). Effect of oxidative stress on the growth of magnetic particles in magnetospirillum magneticum.*International Microbiology, 12*(1), 49–57. <https://doi.org/10.2436/20.1501.01.81>

Pósfai, M., Kasama, T., & Dunin-Borkowski, R. E. (2006). Characterization of bacterial magnetic nanostructures using high-resolution transmission electron microscopy and off-axis electron holography. *Magnetoreception and magnetosomes in bacteria* (pp. 197-225). Springer Berlin Heidelberg. <https://doi.org/10.1007/7171_044>

Prozorov, R., Prozorov, T., Mallapragada, S. K., Narasimhan, B., Williams, T. J., & Bazylinski, D. A. (2007). Magnetic irreversibility and the Verwey transition in nanocrystalline bacterial magnetite.*Physical Review B, Condensed Matter and Materials Physics, 76*(5). <https://doi.org/10.1103/PhysRevB.76.054406>

Ronneberger, O., Fischer, P., & Brox, T. (2015). U-net: Convolutional networks for biomedical image segmentation. *Medical image computing and computer-assisted intervention – MICCAI 2015* (pp. 234–241). Springer International Publishing. <https://doi.org/10.1007/978-3-319-24574-4_28>

Staniland, S., Williams, W., Telling, N., Van Der Laan, G., Harrison, A., & Ward, B. (2008). Controlled cobalt doping of magnetosomes in vivo.*Nature Nanotechnology, 3*(3), 158–162. <https://doi.org/10.1038/nnano.2008.35>

Timko, M., Dzarova, A., Kovac, J., Skumiel, A., Józefczak, A., Hornowski, T., Gojżewski, H., Zavisova, V., Koneracka, M., Sprincova, A., Strbak, O., Kopcansky, P., & Tomasovicova, N. (2009). Magnetic properties and heating effect in bacterial magnetic nanoparticles.*Journal of Magnetism and Magnetic Materials, 321*(10), 1521–1524. <https://doi.org/10.1016/j.jmmm.2009.02.077>

Usui, Y., & Yamazaki, T. (2021). Non-chained, non-interacting, stable single-domain magnetite octahedra in deep-sea red clay: A new type of magnetofossil? *Geochemistry, Geophysics, Geosystems, 22*, e2021GC009770. https://doi.org/10.1029/2021GC009770

Usui, Y., Yamazaki, T., & Saitoh, M. (2017). Changing abundance of magnetofossil morphologies in pelagic red clay around minamitorishima, Western North Pacific.*Geochemistry, Geophysics, Geosystems, 18*(12), 4558–4572. <https://doi.org/10.1002/2017GC007127>

Xiang, L., Wei, J., Jianbo, S., Guili, W., Feng, G., & Ying, L. (2007). Purified and sterilized magnetosomes from magnetospirillum gryphiswaldense MSR‐1 were not toxic to mouse fibroblasts in vitro.*Letters in Applied Microbiology, 45*(1), 75–81. <https://doi.org/10.1111/j.1472-765X.2007.02143.x>

Yamazaki, T. (2012). Paleoposition of the Intertropical Convergence Zone in the eastern Pacific inferred from glacial‐interglacial changes in terrigenous and biogenic magnetic mineral fractions. *Geology, 40*(2), 151–154. <https://doi.org/10.1130/g32646.1>

Yamazaki, T., Fu, W., Shimono, T., & Usui, Y. (2020). Unmixing biogenic and terrigenous magnetic mineral components in red clay of the Pacific Ocean using principal component analyses of first-order reversal curve diagrams and paleoenvironmental implications.*Earth, Planets, and Space, 72*(120), 1–15. <https://doi.org/10.1186/s40623-020-01248-5>

Yamazaki, T., & Horiuchi, K. (2016). Precessional control on ocean productivity in the Western Pacific warm pool for the last 400 kyr: Insight from biogenic magnetite.*Geochemistry, Geophysics, Geosystems, 17*(11), 4399–4412. <https://doi.org/10.1002/2016GC006446>

Yamazaki, T., Suzuki, Y., Kouduka, M., & Kawamura, N. (2019). Dependence of bacterial magnetosome morphology on chemical conditions in deep-sea sediments.*Earth and Planetary Science Letters, 513*, 135–143. <https://doi.org/10.1016/j.epsl.2019.02.015>

Zhang, Q., Liu, Q., Roberts, A. P., Yu, J., Liu, Y., & Li, J. (2021). Magnetotactic bacterial activity in the North Pacific Ocean and its relationship to Asian dust inputs and primary productivity since 8.0 Ma. *Geophysical Research Letters*, 48, e2021GL094687. https://doi.org/10.1029/2021GL094687

Zhou, K., Pan, H., Yue, H., Xiao, T., & Wu, L. (2010). Architecture of flagellar apparatus of marine magnetotactic cocci from Qingdao. *Marine Sciences, 34*(12), 88–92. (In Chinese)