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# A FAIR road to a bioAFM databank

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**The 2020s are characterized by the proliferation of artificial intelligence (AI), a development that, while not novel, has been propelled by the recent accessibility of vast quantities of data. To pursue this avenue, it is of the utmost importance to create high-quality, open databanks. A number of biophysical communities are concurrently engaged in the development of their respective databanks and databases. In this commentary, we aim to direct attention toward the initial efforts to establish a high-quality databank with atomic force microscopy (AFM) data: bioAFM-DB. There are encouraging signs within the community suggesting a shift toward depositing AFM data in public repositories. This commentary outlines the current state of this endeavor, its challenges, and potential courses of action.**

Databanks are repositories that gather and store scientific data, thereby enabling the development of databases that facilitate the organization and retrieval of this data. Public repositories have existed for more than 50 years, long before the advent of "Big Data." One of the oldest repositories in the molecular biology field is the Protein Data Bank (PDB), which emerged from a handful of crystallographers in 1971.[1] Databanks evolve based on available computational infrastructure and changes in the global needs of the research community. Currently, the Registry of Research Data Repositories (re3data.org) contains over 3,300 repository sites[Suppl. ref 1], some of which are related to "Microscopy". For instance, the registry includes extensions of the PDB, such as the Nucleic Acid Knowledgebase;[2] specialized resources, such as the Yeast Resource Center Public Image Repository[3] and the Brain Image Library;[4] and general image repositories, such as the Image Data Resource,[5] and the BioImage Archive.[6] Some microscopy-related repositories manage electron microscopy (EM) data, such as the Electron Microscopy Data Bank,[7] which stores electron density maps, and the Electron Microscopy Public Image Archive,[8] which provides raw images and 3D cryo-EM maps.

Currently, there is no repository for scanning probe microscopy (SPM). SPM is a family of microscopy techniques[Suppl. ref 2] derived from the scanning tunneling microscope (STM), which was developed in the early 1980s[Suppl. ref 3]. A prevalent member of the SPM family, atomic force microscopy (AFM)[9] was developed in 1986 and has become widespread in both material and biological sciences[Suppl. ref 4]. AFM detects a sample surface with a sharp probe integrated at the end of a flexible cantilever, which allows a spatial topographic map to be obtained at nanoscale resolution and physical properties to be measured[Suppl. ref 5]. Key benefits of using AFM in life science applications over other types of microscopies include the ability to image biological samples in physiological buffer conditions (i.e., in liquid and at a controlled temperature) and an exceptional signal-to-noise ratio, which enables imaging individual molecules with sub-nanometer resolution in topography[Suppl. ref 6]. Moreover, AFM allows probing physical properties of biological samples, including active biomolecules, proteins, nucleic acids, biomaterials, living cells and tissues, and obtain stiffness, adhesion or viscosity maps[Suppl. ref 7]. Development of faster scanning AFM technologies has allowed imaging of biological processes and

biomolecular dynamics down to sub-nanometer spatial and sub-second temporal resolutions[Suppl. ref 8]. In this commentary, we advocate for establishing a path towards the creation of a bioAFM databank (bioAFM-DB) and the development of its associated databases.

Is now the right time to develop a repository for AFM data? We believe so because AFM has reached a level of maturity and use that was not the case 20 years ago[Suppl. ref 9]. Specifically, in the last 10 years, among the average yearly 9000 published articles containing “Atomic Force Microscop*” topics, only 9.2% contained AFM, or its explicit name, in their titles, indicating that it has become a routine biophysical tool. Other signs of maturity include the availability of high-quality, free and open-source software for handling AFM data, such as WsXM[Suppl. ref 10], Gwyddion[Suppl. ref 11], AtomicJ[Suppl. ref 12], FiberApp[Suppl. ref 13], SmarTrace[Suppl. ref 14], Nanite[Suppl. ref 15], Topostats[Suppl. ref 16], AutoSmarTrace[Suppl. ref 17], dForce2.0[Suppl. ref 18], PyFMLab[Suppl. ref 19], NanoLocz[Suppl. ref 20], CellMAP[Suppl. ref 21], and a growing population of AFM analysis scripts at GitHub[Suppl. ref 22, ref 23]. Furthermore, there is a continuous increase in applications using AFM data in structural biology such as AFM-Assembly[Suppl. ref 24], BioAFMViewer[Suppl. ref 25], Trace_y[Suppl. ref 26], and recently with high-speed AFM films such as tools based on rigid-body fitting[Suppl. ref 27, ref 28] and flexible fitting[Suppl. ref 29, ref 30] via normal mode analysis NMFF-AFM[Suppl. ref 31], NanoLocz[Suppl. ref 20], BioAFMViewer 5.0[Suppl. ref 32], and AFMFit[Suppl. ref 33]. Another incentive for the timing of an AFM data repository is the recent ambition of research institutions and funding agencies to encourage researchers to find, access, interoperate, and reuse scientific data.

Both the USA National Science Foundation (NSF) and the National Institutes of Health (NIH) mandate data sharing as a core expectation of federally funded research. In 2016, the European Commission established the FAIR Data Principles, FAIR being an acronym for Findable, Accessible, Interoperable, and Reusable.[10] These principles establish guidelines that go beyond the common practice of including statements such as "data is available upon request" in publications. The FAIR principles aim at correcting shortcomings in data availability, including missing or incomplete data descriptors, rigid or non-standardized file formats, a lack of data organization and validation, and low persistence of data

over time[Suppl. ref 34]. The FAIR principle acknowledges the effort involved in producing data and the global economy surrounding data access and storage within the research community. The importance of data archiving has been extensively discussed[10,11,Suppl. ref 35]. Multiple scientific fields are progressing in the FAIR definition of their data such as NMR-based metabolomics data[Suppl. ref 36], optical tweezers[12] and biomolecular simulations.[13] The benefits of data archiving include physical access to raw data,[14] which is often different from the processed data found in the supplementary materials of published articles. Data archiving fosters reproducibility in research, conserves taxpayer resources by eliminating redundant research, and maintains public confidence in science. Undoubtedly, the most significant benefit of publicly accessible data is accelerating scientific discoveries by building on available data beyond its original purpose. A paradigmatic example of this is the above mentioned PDB, whose founders may not have anticipated successful reutilization of their data in the prediction tools like AlphaFold2[Suppl. ref 37] and RoseTTAFold[Suppl. ref 38] when depositing their experimentally determined X-ray structures. We, as researchers developing and applying AFM to biological and biomolecular systems co-signing this commentary, agree on the importance of distributing AFM data and support this effort.

AFM data sharing would require a certain level of standardization regarding data acquisition, storage and annotation. Several proactive standardization actions should be mentioned. As early as 2010, the issue of AFM data management was raised within a European network on applications of atomic force microscopy to nanomedicine and life sciences (COST Action TD1002). This Action proposed a Standardized Nanomechanical Atomic force microscopy Procedure (SNAP) that improved reproducibility of elasticity measurements[Suppl. ref 39]. Earlier round-robin experiments pointed towards similar standardized calibration of AFM cantilevers[Suppl. ref 40]. The SNAP approach was further improved during the Marie Skłodowska-Curie Innovative Training Network Phys2BioMed, by including sample preparation and data analysis standardized routines[Suppl. ref 41]. Also developed during the Phys2BioMed, effort in standardization continued with a tentative definition of a common text-based AFM universal file format[Suppl. ref 19, ref 42]. Additional efforts include the establishment of a dataset of simulated-AFM images of small organic molecules[Suppl. ref 43] or the recent development of a structural biology-

compatible file format for AFM[Suppl. ref 44]. In short, an AFM databank should store the experimental raw AFM data, its accompanying metadata and its related processing steps to improve the reproducibility in this field.

Therefore, why does an AFM databank not already exist? The daunting procedural tasks required for developing a strategy to deposit AFM data in a public repository may answer this question. One major hurdle in creating an AFM databank is the wide variety of samples and associated preparation protocols as well as heterogeneity of data types. AFM crosses a range of fields, from physics and chemistry to biology. There is an enormous number of sample types, ranging from mineral materials to biological tissues, from hard to soft specimens, and from conductive to insulating surfaces. This variety of samples correlates with a wide range of measurement modes, from topographic images to force measurements. There is also the possibility of datasets from AFM systems coupled, for example, to optical microscopes[Suppl. ref 45] or infrared[Suppl. ref 46] and Raman[Suppl. ref 47] spectroscopies. Thus, defining the minimum metadata for all these types of samples and information requires a significant effort. Furthermore, there are several AFM instrument manufacturers, including laboratories building their own instruments, each with several models and various levels of historical legacy in their data formats. The FAIR principles cannot be applied to these proprietary formats; therefore, most data from AFM instruments cannot be stored in a database without prior conversion and without a reading tool that ensures interoperability (as found in AFMReader[Suppl. ref 48], for instance). Another issue raised by the community concerns data quality, as there are no clear definitions of what constitutes good and bad topographic images or force-distance curves. This issue requires an open discussion among the AFM communities.

In retrospect, a possible reluctance to distribute AFM data may originate from a lack of understanding of how and for what "others" who did not produce the data might use it. For instance, a particular group may want to test its developed data processing tools on AFM data from other laboratories. For that, multiple images or force-distance curves of different quality (good, fair, or poor) would be

needed. It is, however, unusual that a scientific publication necessitates the deposition of “poor quality” AFM data. A clear advantage of a databank should be the deposition of complete datasets, rather than a couple of images or force curves included in published works.

To fulfill the FAIR principle, the bioAFM data repository must adhere to the following constraints:

1) A robust infrastructure is required to upload, store and distribute the data (FA).

2) A specific ontology should be agreed upon to prepare the minimum informative metadata, both human and computer readable (I).

3) Deposited data should contain the minimum information necessary to reproduce and analyze the data; including functional/dedicated open software (IR).

4) Data quality must be appropriately annotated (FIR)

Where do we stand now? Fortunately, the maturity of the AFM field means that this project does not have to start from scratch. A group of volunteers has started working on this AFM metadata. The group officially met before and during the AFM data symposium, which was held alongside the 15th AFMBioMed conference, in Barcelona in April 2025, and advanced in dividing the metadata into subsections: sample, cantilever, experimental conditions, recording parameters and data. The European Bioinformatics Institute (EBI) of EMBL generously oversees these preliminary metadata efforts and is committed to following the development process for the potential integration of the AFM database into the EBI. The EBI's contribution is invaluable to our community because it provides the necessary infrastructure for data deposition, finding, access, dissemination, and visualization. One clear benefit of collaborating with the EBI is its expertise in providing time-based data access through appropriate release.

The development of a databank is an ambitious long-term project. While the initial design strategies should be as broad as possible, it is impractical to start the project with every type of AFM data. The

project will progress in steps to grow into a full-scale repository. Following the positioning of the EBI in the field of life sciences, the "bio" side of the databank will develop first, and the immediate focus will target three AFM data types: topography, spectroscopy, and nanomechanics. Volunteers are welcome and encouraged to join this initiative by contacting the corresponding authors, and contribution not only from academia but also from the industrial sector will be essential. In addition to the minimal metadata required for deposition, two major topics need further discussion:

1) What constitutes a dataset or a databank entry?

Several questions arise: which of the experimentally recorded data should be stored in the database? Should the data be linked to a scientific publication? Can large datasets be stored as a single entry? Should all recorded data be deposited or just the relevant data used in the associated publication? Let us take the example of AFM topography. Depending on the experimental imaging mode, several kinds of data are recorded simultaneously, also known as channels (deflection, height, amplitude error, phase signal). Most often with AFM height images, if we ignore the trace and retrace measurements, only a single channel (height) is used. Should it be the only deposited data? Should the accompanying measurements and calibrations be also deposited? How to handle the tip convolution effect in AFM topography? All these details will be discussed and evaluated during the course of establishing this databank and its underlying databases. There is nevertheless a topic of importance for initial deposition in the databank: reference datasets (images, pulling, indenting). These datasets are especially important for standardization efforts in research and in metrology. They should allow for poor-quality, noisy, and diverse AFM measurements of realistic AFM data, which may be valuable for developers of novel AFM data processing tools. In the era of artificial intelligence and machine-learning, the need for extremely large, diverse, and accurately annotated datasets has become even more pressing[Suppl. ref 9]. Training robust models requires not only raw data but also high-quality ground-truth labels, which are scarce, labor-intensive to generate, and often inconsistent across laboratories. As a starting point, since many journals have policies that require data deposition, the initial data

deposited in the repository could likely be that included in submitted manuscripts. However, there is plenty of room for discussion.

2) Defining the architecture and format of the AFM data files in the repository to allow conversion from a proprietary format to the open repository's format and their import/export tools.

Although any specific data format can be deposited in a databank, a lack of a common format will reduce the effectiveness of AFM data dissemination, both inside and outside the AFM community. It highlights the particular role of file conversion and reading software tools, such as those from Gwyddion [Suppl. ref 11], afmformats [Suppl. ref 15], Topostats[Suppl. ref 16], AFMReader[Suppl. ref 48], NanoLocz[Suppl. ref 20] and PyFMReader[Suppl. ref 19]. The development of an integrative AFM file format has already begun, as demonstrated by the Universal Spectroscopic and Imaging Data (USID) format developed at the Oak Ridge National Laboratory[Suppl. ref 49] or the UFF mentioned above[Suppl. ref 19]. A possible starting point is to deposit raw AFM data and include a tool for exporting and downloading raw data to transform it into manageable data, as AFMReader does. Once again, as a community, it will be important to reach an agreement about a common AFM data exchange file format.

Our ultimate goal is to promote a unified platform, in the spirit of the PDB,[1] to all AFM communities. We will have fulfilled part of our goals if we reach the following three objectives: 1) Disseminate bioAFM data in various biological fields beyond the laboratories that produce it; 2) Improve user education on using bioAFM data, particularly regarding the associated pitfalls; 3) Increase the integration of bioAFM data into other biophysical pipelines, such as integrated structural biology for AFM topography. This platform will include an online AFM data deposition mechanism, appropriate validation of depositions, and a referencing key, such as an entry code or digital object identifier (DOI). In a second stage, improvements will involve interlinking with other databases such as MBDB,[14] MechanoPro-DB[Suppl. ref 50], MechanoBase[Suppl. ref 51]. A possible starting point could be the BioStudies system at EBI.[15] The bioAFM databank will be established through a governance framework that

defines usage policies and the ethical implications of using open data. We anticipate reaching a significant milestone in this active development process at a symposium organized alongside the next AFMBioMed conference, in Brno, in 2027.

**The development of bioAFM-DB and its related databases is poised to address open questions across diverse fields—from single-molecule conformations and molecular binding mechanisms to the mechanics of aging, and diseases. By making AFM findings accessible to broader scientific communities, bioAFM-DB will enable cross-validation of experimental data with other microscopies (such as EM and super-resolution) and biophysical tools (including optical tweezers and nanoindenters), as well as with computational models. This integration will further establish bioAFM as a standard tool in biophysics and exemplifies the transformative potential of merging biophysics and data science, driving knowledge forward through a multidisciplinary approach.**

**References:**


1. Berman, H.M., Kleywegt, G.J., Nakamura, H. & Markley, J.L. The Protein Data Bank at 40: reflecting on the past to prepare for the future. *Structure* **20**, 391-396 (2012).
2. Lawson, C.L., Berman, H.M., Chen, L., Vallat, B. & Zirbel, C.L. The Nucleic Acid Knowledgebase: a new portal for 3D structural information about nucleic acids. *Nucleic Acids Res.* **52**, D245-D254 (2024).
3. Riffle, M. & Davis, T.N. The Yeast Resource Center Public Image Repository: A large database of fluorescence microscopy images. *BMC Bioinformatics* **11**, 263 (2010).
4. Kenney, M. et al. The Brain Image Library: A community-contributed microscopy resource for neuroscientists. *Sci. Data* **11**, 1212 (2024).
5. Williams, E. et al. The Image Data Resource: A bioimage data integration and publication platform. *Nat. Methods* **14**, 775-781 (2017).
6. Hartley, M. et al. The BioImage archive - Building a home for life-sciences microscopy data. *J. Mol. Biol.* **434**, 167505 (2022).
7. The wwPDB Consortium EMDB-the Electron Microscopy Data Bank. *Nucleic Acids Res.* **52**, D456-D465 (2024).
8. Iudin, A. et al. EMPIAR: the Electron Microscopy Public Image Archive. *Nucleic Acids Res.* **51**, D1503-D1511 (2023).
9. Binnig, G., Quate, C.F. & Gerber, C. Atomic force microscope. *Phys. Rev. Lett.* **56**, 930-933 (1986).
10. Wilkinson, M.D. et al. The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* **3**, 160018 (2016).
11. Roche, D.G. et al. Troubleshooting public data archiving: suggestions to increase participation. *PLoS Biol.* **12**, e1001779 (2014).
12. Halma, M.T.J. et al. FAIR data for optical tweezers experiments. *Biophys. J.* **124**, 1255-1272 (2025).
13. Amaro, R.E. et al. The need to implement FAIR principles in biomolecular simulations. *Nat. Methods* **22**, 641-645 (2025).
14. Agerschou, E.D. et al. Molecular Biophysics Database (MBDB) makes raw measurements findable and reusable. *Eur. Biophys. J.* (2025).
15. McEntyre, J., Sarkans, U. & Brazma, A. The BioStudies database. *Mol. Syst. Biol.* **11**, 847 (2015).

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**Supplementary references:**

1. Pampel, H. et al. re3data - Indexing the global research data repository landscape since 2012. *Sci. Data* **10**, 571 (2023).
2. Bian, K. et al. Scanning probe microscopy. *Nat. Rev. Meth. Primers* **1** (2021).
3. Binnig, G., Rohrer, H., Gerber, C. & Weibel, E. Surface studies by scanning tunneling microscopy. *Phys. Rev. Lett.* **49**, 57 - 61 (1982).
4. Lang, H.P., Hegner, M., Meyer, E. & Gerber, C. Nanomechanics from atomic resolution to molecular recognition based on atomic force microscopy technology. *Nanotechnology* **13**, R29-R36 (2002).
5. Marti, O. et al. Scanning probe microscopy of biological samples and other surfaces. *J. Microsc.* **152**, 803-809 (1988).
6. Engel, A. & Muller, D.J. Observing single biomolecules at work with the atomic force microscope. *Nat. Struct. Biol.* **7**, 715-718 (2000).
7. Krieg, M. et al. Atomic force microscopy-based mechanobiology. *Nat Rev Phys* **1**, 41-57 (2019).
8. Heath, G.R. & Scheuring, S. High-speed AFM height spectroscopy reveals micros-dynamics of unlabeled biomolecules. *Nat. Commun.* **9**, 4983 (2018).
9. Thomas-Chemin, O. et al. Advancing high-throughput cellular atomic force microscopy with automation and artificial intelligence. *ACS Nano* **19**, 5045-5062 (2025).
10. Horcas, I. et al. WSXM: a software for scanning probe microscopy and a tool for nanotechnology. *Rev. Sci. Instrum.* **78**, 013705 (2007).
11. Nečas, D. & Klapetek, P. Gwyddion: an open-source software for SPM data analysis. *Cent. Eur. J. Phys.* **10**, 181-188 (2012).
12. Hermanowicz, P., Sarna, M., Burda, K. & Gabrys, H. AtomicJ: An open source software for analysis of force curves. *Rev. Sci. Instrum.* **85**, 063703 (2014).
13. Usov, I. & Mezzenga, R. FiberApp: An open-source software for tracking and analyzing polymers, filaments, biomacromolecules, and fibrous objects. *Macromolecules* **48**, 1269-1280 (2015).
14. Rezaei, N., Lyons, A. & Forde, N.R. Environmentally controlled curvature of single collagen proteins. *Biophys. J.* **115**, 1457-1469 (2018).
15. Muller, P. et al. nanite: using machine learning to assess the quality of atomic force microscopy-enabled nano-indentation data. *BMC Bioinformatics* **20**, 465 (2019).
16. Beton, J.G. et al. TopoStats - A program for automated tracing of biomolecules from AFM images. *Methods* **193**, 68-79 (2021).
17. Schneider, M., Al-Shaer, A. & Forde, N.R. AutoSmarTrace: Automated chain tracing and flexibility analysis of biological filaments. *Biophys. J.* **120**, 2599-2608 (2021).
18. Gisbert, V.G. & Garcia, R. Insights and guidelines to interpret forces and deformations at the nanoscale by using a tapping mode AFM simulator: dForce 2.0. *Soft Matter.* **19**, 5857-5868 (2023).
19. López-Alonso, J. et al. PyFMLab: Open-source software for atomic force microscopy microrheology data analysis. *Open Res. Europe* **3**, 187 (2024).
20. Heath, G.R., Micklethwaite, E. & Storer, T.M. NanoLocz: Image analysis platform for AFM, high-speed AFM, and localization AFM. *Small Meth.* (2024).
21. Allard, A. et al. CellMAP: an open-source software tool to batch-process cell topography and stiffness maps collected with an atomic force microscope. *BMC Bioinformatics* **26**, 38 (2025).
22. Kabanov, D. (https://github.com/DaniilKabanov/CardioScripts; 2025).
23. Efremov, Y. (https://github.com/yu-efremov/ViscoIndent; 2020).
24. Trinh, M.-H. et al. Computational reconstruction of multidomain proteins using atomic force microscopy data. *Structure* **20**, 113-120 (2012).

25. Amyot, R. & Flechsig, H. BioAFMviewer: An interactive interface for simulated AFM scanning of biomolecular structures and dynamics. *PLoS Comput. Biol.* **16**, e1008444 (2020).
26. Xue, W.F. Trace_y: Software algorithms for structural analysis of individual helical filaments by three-dimensional contact point reconstruction atomic force microscopy. *Structure* **33**, 363-371 e362 (2025).
27. Niina, T., Matsunaga, Y. & Takada, S. Rigid-body fitting to atomic force microscopy images for inferring probe shape and biomolecular structure. *PLoS Comput. Biol.* **17**, e1009215 (2021).
28. Ogane, T. et al. Development of hidden Markov modeling method for molecular orientations and structure estimation from high-speed atomic force microscopy time-series images. *PLoS Comput. Biol.* **18**, e1010384 (2022).
29. Niina, T., Fuchigami, S. & Takada, S. Flexible fitting of biomolecular structures to atomic force microscopy images via biased molecular simulations. *J. Chem. Theory Comput.* **16**, 1349-1358 (2020).
30. Dasgupta, B., Miyashita, O. & Tama, F. Reconstruction of low-resolution molecular structures from simulated atomic force microscopy images. *Biochim. Biophys. Acta* **1864**, 129420 (2020).
31. Wu, X., Miyashita, O. & Tama, F. Modeling conformational transitions of biomolecules from atomic force microscopy images using normal mode analysis. *J. Phys. Chem. B* **128**, 9363-9372 (2024).
32. Amyot, R. et al. Flexible fitting to infer atomistic-precision models of large-amplitude conformational dynamics in biomolecules from high-speed atomic force microscopy imaging. *ACS Nano* **19**, 34065–34079 (2025).
33. Vuillemot, R., Pellequer, J.-L. & Grudinin, S. Deciphering conformational dynamics in AFM data using fast nonlinear NMA and FFT-based search with AFMfit. *Commun. Biol.* **8**, 1381 (2025).
34. Kratz, J. & Strasser, C. Data publication consensus and controversies. *F1000Res.* **3**, 94 (2014).
35. Roche, D.G., Kruuk, L.E., Lanfear, R. & Binning, S.A. Public data archiving in ecology and evolution: How well are we doing? *PLoS Biol.* **13**, e1002295 (2015).
36. Gouveia, G.J. et al. Perspective: use and reuse of NMR-based metabolomics data: what works and what remains challenging. *Metabolomics* **20**, 41 (2024).
37. Jumper, J. et al. Highly accurate protein structure prediction with AlphaFold. *Nature* **596**, 583-589 (2021).
38. Baek, M. et al. Accurate prediction of protein structures and interactions using a three-track neural network. *Science* **373**, 871-876 (2021).
39. Schillers, H. et al. Standardized Nanomechanical Atomic force microscopy Procedure (SNAP) for measuring soft and biological samples. *Sci. Rep.* **7**, 5117 (2017).
40. te Riet, J. et al. Interlaboratory round robin on cantilever calibration for AFM force spectroscopy. *Ultramicroscopy* **111**, 1659-1669 (2011).
41. Perez-Dominguez, S. et al. Reliable, standardized measurements for cell mechanical properties. *Nanoscale* **15**, 16371-16380 (2023).
42. Phys2BioMed (https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5d9018fb2&appId=PPGMS; 2020).
43. Carracedo-Cosme, J., Romero-Muniz, C., Pou, P. & Perez, R. QUAM-AFM: A free database for molecular identification by atomic force microscopy. *J. Chem. Inf. Model.* **62**, 1214-1223 (2022).
44. Jiang, Y., Wang, Z. & Scheuring, S. A structural biology compatible file format for atomic force microscopy. *Nat. Commun.* **16**, 1671 (2025).
45. Ludwig, T., Kirmse, R., Poole, K. & Schwarz, U.S. Probing cellular microenvironments and tissue remodeling by atomic force microscopy. *Pflugers Arch.* **456**, 29-49 (2008).
46. Dazzi, A. et al. AFM-IR: combining atomic force microscopy and infrared spectroscopy for nanoscale chemical characterization. *Appl. Spectrosc.* **66**, 1365-1384 (2012).
47. Stöckle, R.M., Suh, Y.D., Deckert, V. & Zenobi, R. Nanoscale chemical analysis by tip-enhanced Raman spectroscopy. *Chem. Phys. Lett.* **318**, 131-136 (2000).

48. Whittle, S., Shephard, N. & TopoStats Team (https://github.com/AFM-SPM/AFMReader/; 2025).
49. Somnath, S. et al. USID and Pycroscopy - Open frameworks for storing and analyzing spectroscopic and imaging data. *arXiv* (2019).
50. Mesbah, I., Habermann, B. & Rico, F. MechanoProDB: a web-based database for exploring the mechanical properties of proteins. *Database* **2024**, baae047 (2024).
51. Xiong, Y. et al. MechanoBase: a comprehensive database for the mechanics of tissues and cells. *Database* **2024**, baae040 (2024).