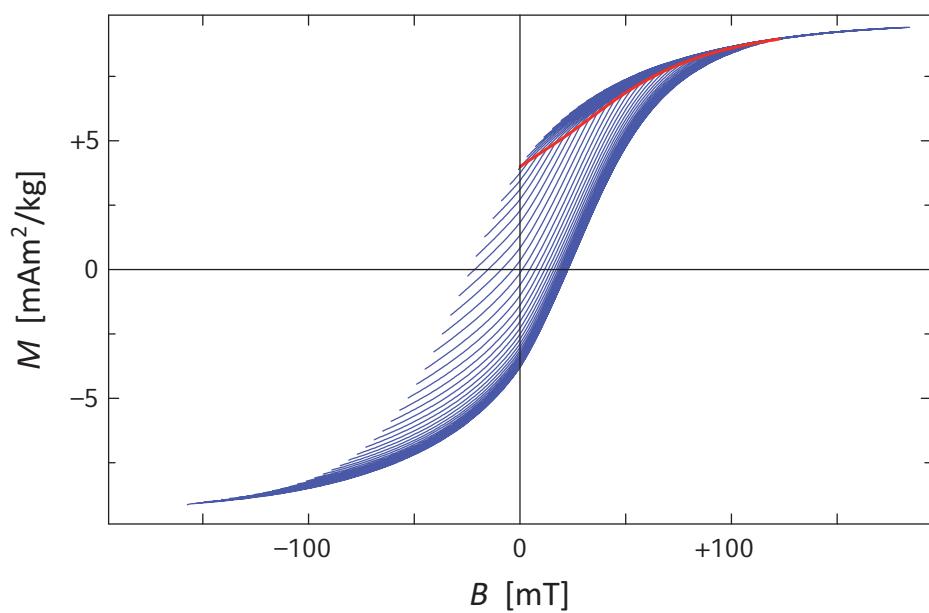


## VARIFORC User Manual

### Chapter 3:

## Import FORC measurements

---





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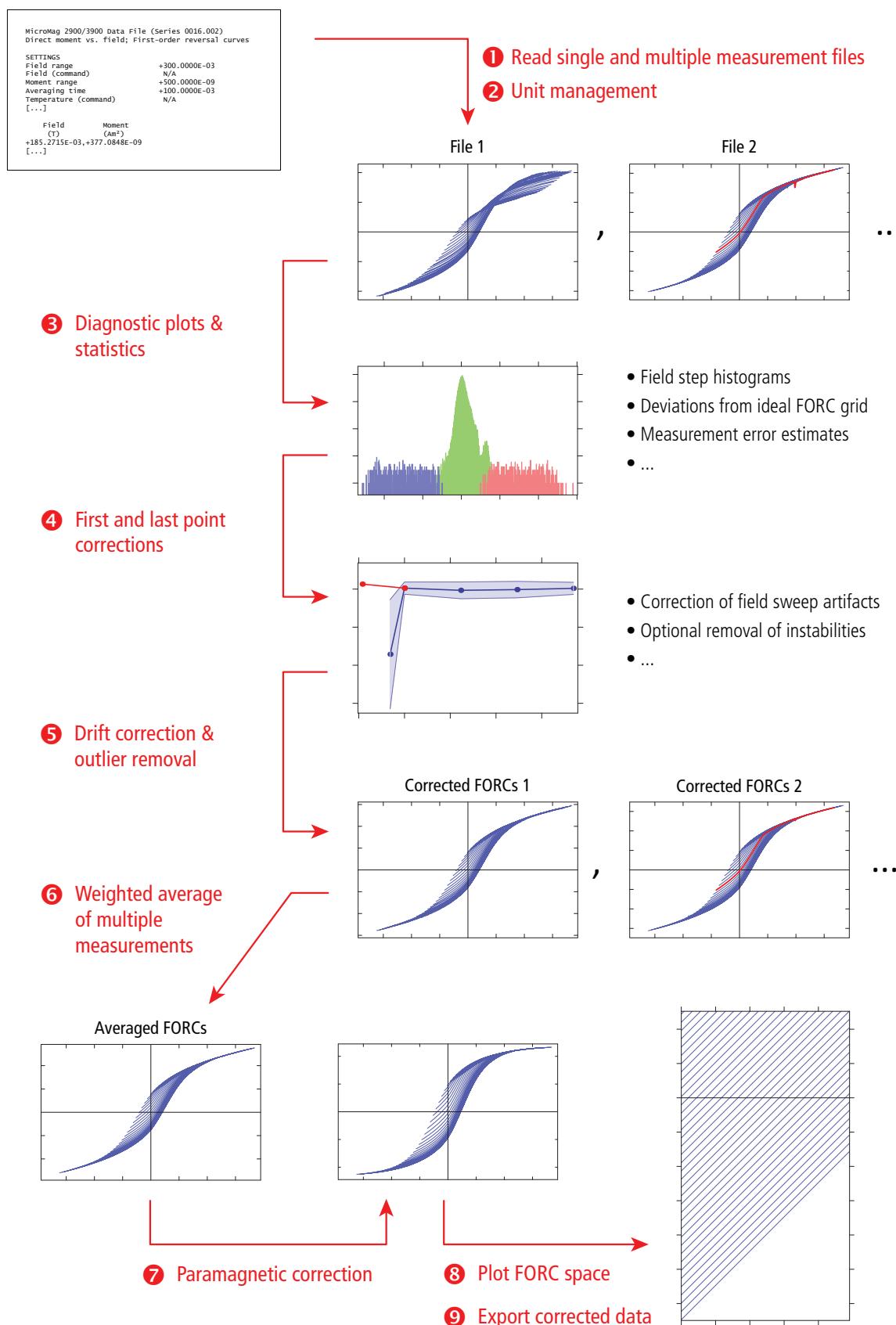
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### 3.1 ImportFORC highlights

ImportFORC is a module of the VARIFORC package that serves as first processing step for importing FORC measurements. This module imports a single set or multiples sets of raw FORC measurements, performs a series of corrections, and exports FORC data that are ready for further processing with other modules of the VARIFORC package. Like other VARIFORC modules, ImportFORC is controlled by user-defined options stored in a special parameter file that can be used for batch processing. The ImportFORC workflow (Fig. 3.1) is based on the following processing steps, with unique features highlighted in *cursive*.

- 1) Read single or *multiple* sets of FORC measurements performed according to the protocol described in Pike et al. [1999]. Accepts measurement files with *any column format and arbitrary header/footer lines* (e.g. all MicroMag™ formats).
- 2) *Offer an integrated unit management system for unit conversion and normalization by sample volume, mass, and area.*
- 3) Check the FORC measurement grid and *provides diagnostic plots of measurement quality parameters.*
- 4) *Correct possible problems with first and last measurement points related to field sweeping.*
- 5) Perform drift correction, and *removes outliers and measurement instabilities within individual curves.*
- 6) *Handle multiple measurements (e.g. of weak samples), calculating averaged curves to be used for further processing.*
- 7) *For better representation of FORC measurements with very weak ferrimagnetic contributions, a paramagnetic correction can be optionally performed using an approach-to-saturation law [Fabian, 2006]. High-field susceptibility estimates obtained from independent hysteresis measurements to higher fields can be used as well.*
- 8) *Plot the measured FORC space for better choice of further processing options with other VARIFORC modules.*
- 9) *Calculate an equivalent FORC set by subtracting the lower hysteresis branch from all curves. This set of curves is preferentially used instead of FORCs for further processing of samples featuring zero-coercivity contributions. Both sets of curves are exported and can be used for calculating FORC diagrams with CalculateFORC.*

Use this manual to learn about ImportFORC, and see the quick VARIFORC guide for a short summary and option reference.

**Fig. 3.1:** Graphical representation of the typical ImportFORC workflow.

### 3.2 Using ImportFORC

Like all VARIFORC modules, ImportFORC runs on a Wolfram Mathematica® or PlayerPro® notebook. A starting copy of this notebook is provided with the VARIFORC installation package under:

```
VARIFORC_Install/Modules/ImportFORC/VARIFORC_ImportFORC.cdf
```

You can copy this file to a different folder for your convenience. The notebook stores all processing steps and graphical results; therefore, it is best renamed and saved with reference to the processed FORC data. The default notebook provided with the installation package is a .cdf file (computable document format) that works with both Wolfram Mathematica® and PlayerPro®. The content of a .cdf notebook cannot be modified with Player Pro®, but existing commands can be evaluated and results saved without restrictions. The .cdf notebook can be saved as a regular notebook (.nb) with Wolfram Mathematica®.

ImportFORC notebooks begin with the following command line:

```
Get[FileNameJoin[{\$HomeDirectory, "VARIFORC", "VARIFORC_ImportFORC_code.txt"}]]
```

which uploads ImportFORC to the computation kernel. This line, as any other command in Mathematica® notebooks, is executed by placing the cursor on it and pressing the keys **SHIFT** and **ENTER** at the same time. A copyright message will appear below this line, confirming that ImportFORC has been uploaded successfully.

ImportFORC is then called by the command line

```
VARIFORC`ImportFORC
```

to be executed by pressing the keys **SHIFT** and **ENTER** at the same time. At this point, ImportFORC starts a system dialog for:

- 1) uploading a parameter file that contains user-defined processing options,
- 2) uploading a single measurement file or multiple measurement files stored in a common directory, and
- 3) choosing output files where results are stored.

The notebook appearance upon performing these steps is shown in [Fig. 3.2](#).

Files required by steps 1) and 2) should be ready *before* ImportFORC is started. If you want to process several FORC measurement sets of the same sample and calculate an average, place all measurement files in the same directory. The parameter file is an unformatted text file containing all processing options to be used by ImportFORC. You can find a template of this file with generically valid options in the VARIFORC installation package under:

```
VARIFORC_Install/Modules/ImportFORC/Default_VARIFORC_ImportFORC_Parameters.txt
```

You may copy this file to a directory hosting all VARIFORC processing files related to given FORC measurements.

**1** Upload source codes

```
In[1]:= Get[$HomeDirectory, "VARIFORC", "VARIFORC_ImportFORC_code.txt"]]

Function VARIFORC`ImportFORC for importing FORC measurements.
[VARIFORC package v1.0 for Wolfram Mathematica and Mathematica Player Pro.
© 2014 by Ramon Egli. All rights reserved.]
```

If used for scientific publications and presentations please cite as follows:  
Egli, R. (2013). VARIFORC: An optimized protocol for calculating non-regular first-order reversal curve (FORC) diagrams. *Global and Planetary Change* 110, 302-320.  
<http://dx.doi.org/10.1016/j.gloplacha.2013.08.003>

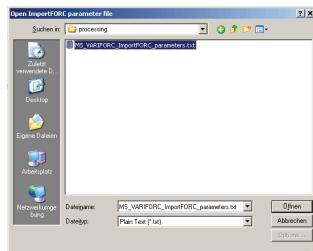
**2** Call ImportFORC

```
In[2]:= VARIFORC`ImportFORC
```

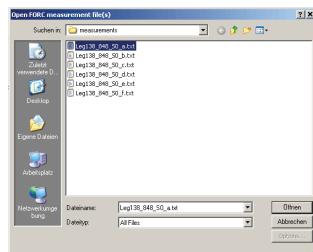
**3** Read auxiliary files

Initialization...

**4** Upload parameters file



**5** Upload measurement file(s)



**6** Define output file(s)



**7** Begin processing

Read parameter file...

```
Input parameters from C:/.../Example/ImportFORC_Parameters.txt:
INPUT 01. Field and magnetization column numbers .....; 1, 2
INPUT 02. FORC saturation field .....; Automatic
INPUT 03. Field slew rate .....; Automatic
INPUT 04. Averaging time of FORC measurements .....; Automatic
INPUT 05. Pause at FORC reversal field .....; Automatic
INPUT 06. Pause at FORC calibration field .....; Automatic
INPUT 07. Pause at FORC saturation field .....; Automatic
INPUT 08. Correction options for first FORC points .....; None, None
INPUT 09. Correction options for last FORC points .....; None, None
INPUT 10. FORC smoothing factor for error calculation .....; 3
INPUT 11. Smoothing factor for drift calculation .....; 3
INPUT 12. Lower limits for outlier detection/replacement .....; 2, 3
INPUT 13. Clipping limit of residuals color scale .....; 3
INPUT 14. FORC plotting options .....; Automatic
INPUT 15. Field units and calibration .....; T, 1, T
INPUT 16. Normalization factor(s) and unit .....; 27.2, mg
INPUT 17. Magnetization units and calibration .....; Am2, 1, mAm2/kg
INPUT 18. High-field limit for paramagnetic correction .....; 0.11
INPUT 19. High-field susceptibility .....; Automatic
INPUT 20. Approach-to-saturation exponent .....; 2.
INPUT 21. Number of last FORCs used for lower branch subtraction ..; 9.
```

**Fig. 3.2:** Initialization of the ImportFORC notebook.

Options in the parameter file can be modified with a text editor, according to your processing requirements (see [section 3.4](#) and the VARIFORC quick guide). Measurement file upload and output file naming are explained in [section 3.3](#).

After completing file upload and saving dialogs, ImportFORC proceeds autonomously until the end, without requesting any further action by the user. The processing status is continuously updated by progress messages, e.g.

Import parameters uploaded successfully.

warning messages, e.g.

**INPUT 05: Multiple entries for the averaging time have been found in the file header.**

error messages, e.g.

**No ImportFORC parameter file has been chosen. Program aborted.**

summary tables, e.g.

**Summary of parameters found in the file header:**

INPUT 02. Saturation field .....: 0.3  
INPUT 03. Field slew rate .....: 0.1  
INPUT 04. Averaging time .....: 0.1  
INPUT 05. Pause at reversal field ..: 0.5  
INPUT 06. Pause at calibration field: 0.5  
INPUT 07. Pause at saturation field : 0.2

and diagnostic plots as well as plots of final results. ImportFORC ends with the following message containing the total computation time:

**PROGRAM END. Total computation time 2m 11s.**

You can save the notebook file with all messages and generated plots for your records and re-use it. Plots can be selected and saved as graphics or image files.

ImportFORC error messages usually produce a program abort. If one of these messages appears, an error was encountered either in the VARIFORC installation, e.g.:

**INSTALLATION ERROR.  
File C:\...\VARIFORC\VARIFORC\_ImportFORC\_ProtocolNames.txt is damaged! Program Aborted. [2]  
Please replace this file before using VARIFORC\_Import (see user manual).**

or in the imported files, e.g.:

**INPUT 01: Field and measurement columns must be different. Program aborted.**

Error messages contain hints about the encountered problem. Installation errors are always produced by damaged source files (e.g. by accidental editing). In this case, VARIFORC should be re-installed according to the instructions of Chapter 2. Error messages that mention the parameter file or begin with INPUT... are generated by incorrect option specifications (see [section 3.5](#) for acceptable options), or by a corrupted file format. In the latter case, generate a new parameter file from

the original copy provided with the installation package. Error messages related to measurement files are produced either by FORC protocol parameters that are not found in the file header (see section 3.5 for solutions), or by an unrecognized or corrupted measurement file format.

- Acceptable FORC measurement file formats are based on FORC files produced by Micro Mag™ magnetometers. A detailed format description is given in section 3.6.
- ImportFORC recognizes a variety of measurement file formats, including all those generated by different generations of Micro Mag™ magnetometers. Since release 3.02, it is possible to import FORC measurements generated by protocols that do not include calibration measurements, as long as the remaining points of the measurement protocols match those of classic FORC measurements.
- Older MicroMag™ FORC files sometimes contain erroneously placed empty lines that signal the beginning of a new curve that does not exist. In this case, ImportFORC produces an error message reporting the line where this problem was encountered. You can correct this problem by eliminating the reported empty lines (see section 3.6).

- Large parts of the ImportFORC code are dedicated to error handling in order to avoid crashes and incorrect results. Although VARIFORC has been extensively tested, the occurrence of unexpected errors cannot be completely excluded. Such errors might generate a cascade of other errors and/or a program crash.
- Unexpected errors likely cause Mathematica® notebooks to freeze. In this case, the Mathematica® Kernel should be forcefully terminated as described in Chapter 2.

- 💡 All information concerning ImportFORC runs is stored in the Mathematica® notebook. You can save the notebook with its content for your records.
- 💡 Open only one Mathematica® notebook at the time.
- 💡 In order to avoid excessive memory usage, process a single dataset in each notebook.
- 💡 The time required to process 450 high-resolution FORCs (~162'000 measurements) with a 2 GHz dual core processor is <2 minutes.

### 3.3 ImportFORC file management

VARIFORC has a modular structure, so that each module performs specific operations by reading data stored in measurement files or files containing processed data, and exporting results to one or more files that can be used by other VARIFORC modules. ImportFORC deals with the first steps of data processing by reading:

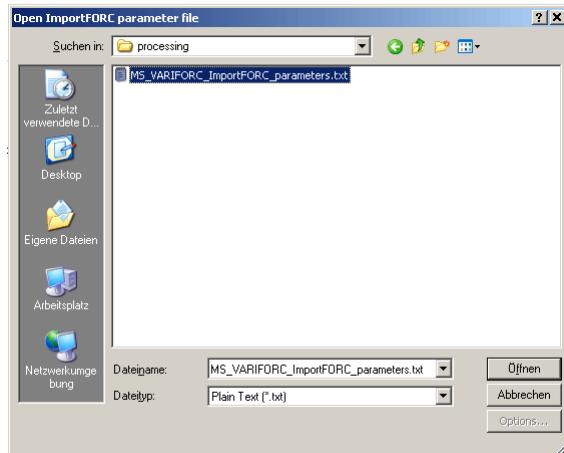
- 1) A text file containing user-defined processing parameters
- 2) A single FORC measurement file or several FORC measurement files stored in a common directory.

Results, in form of corrected FORC measurements with and without subtracted lower hysteresis branch, as well as a hysteresis loop derived from FORC measurements, are exported to three files with same user-defined name root.

ImportFORC calls the file dialog of your operating system in order to let you upload and export files, as described in the following.

#### 3.3.1 Parameter file upload

The parameter file is uploaded through the following dialog window:



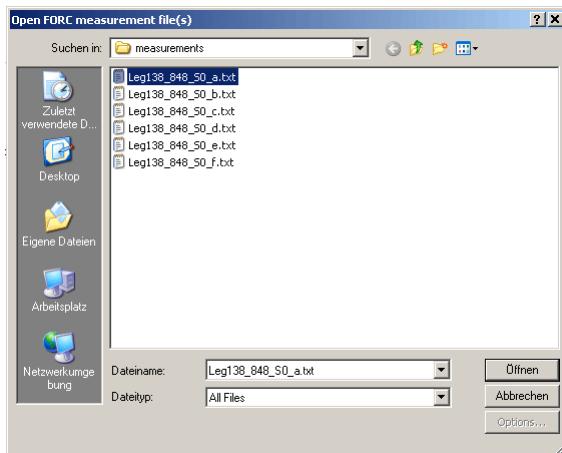
whose appearance depends on your operating system. ImportFORC automatically selects file names ending with `_ImportFORC_parameters.txt`, which is default for all ImportFORC parameter files. It is strongly recommended to keep this file name ending, so to avoid confusion with parameter files of other VARIFORC modules. The first part of the file name can be related to the sample being processed, e.g.:

```
/.../Sample01_ImportFORC_parameters.txt
```

If you do not find the parameter file in the expected directory, remove file name and file type filters in the dialog window, so that all files will be displayed.

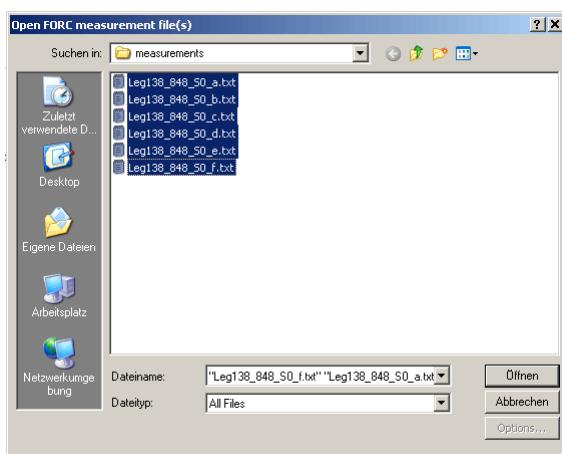
### 3.3.2 Measurement file(s) upload

A single measurement file is uploaded through the following dialog window:



whose detailed appearance depends on your operating system. Be careful to choose a single, unedited FORC measurement file.

In order to increase the signal-to-noise ratio, weak specimens can be measured several times and averaged with ImportFORC. In this case, all FORC measurements of the same specimen should be stored in a common directory. You can upload several measurement files at once by selecting them in the dialog window, e.g.:

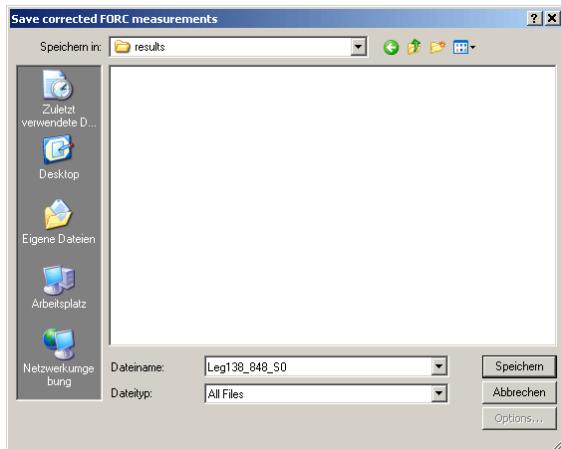


- Multiple measurements should be performed with exactly the same FORC protocol on the same specimen, or on different specimens of the same material. Measurements obtained with different measurements cannot be combined.
- You can combine FORC data obtained from different FORC protocols using the VARIFORC function LinearCombineFORC (see Chapter 7).

- In case of multiple specimen measurements requiring different normalizations (e.g. specimen masses), label measurement files so that their alphabetical sorting is unambiguous, for example by adding a measurement number with trailing zeroes to a common file name root (e.g. Spec01.txt, Spec02.txt, etc.). Normalization factors taken from the parameter file will be applied to the alphabetically sorted measurement files (see INPUT 16 in chapter 3.5).

### 3.3.3 Output file naming

A root name for all output files created by ImportFORC is entered through the following file saving dialog:



whose detailed appearance depends on your operating system. A file name taken from the chosen measurement file is proposed. Adopt this name or type a different name, without extension, which will be used as a common root for defining output file names by addition of the extension \_CorrectedMeasurements\_VARIFORC.frc for corrected (and averaged) FORC measurements, \_CorrectedMeasurementDifferences\_VARIFORC.frc for the same corrected measurements after subtraction of the lower hysteresis branch, and \_CorrectedMeasurements\_Hysteresis.hys for the hysteresis loop derived from corrected FORC measurements. In the example shown with the above dialog box, following files will be produced by ImportFORC:

```
/..../Leg138_848_s0_CorrectedMeasurements_VARIFORC.frc  
/..../Leg138_848_s0_CorrectedMeasurementDifferences_VARIFORC.frc  
/..../Leg138_848_s0_CorrectedMeasurements_Hysteresis_VARIFORC.frc
```

Output file names can also be chosen by clicking on an existing measurement file. In this case, the system will ask if you want to overwrite the existing file. Click "OK" to proceed. Measurement files are not overwritten because of the added extensions.

### 3.3.4 Folder organization

Because of the relatively large number of files produced by VARIFORC modules, VARIFORC input and output files are best organized in folders, depending on the purpose of FORC processing. The most suited folder structure depends on the purpose of FORC measurements. If FORC measurements are used to characterize individual samples, each with different FORC protocols and processing requirements, you might create a folder system for each sample. For example, folders related to a sample named `spec01` could be:

`/.../spec01/measurements/`

for storing one or more measurements,

`/.../spec01/processing/`

for storing VARIFORC notebooks (e.g. `Spec01_ImportFORC.nb`) and parameter files (e.g. `Spec01_VARIFORC_ImportFORC_parameters.txt`), and

`/.../spec01/results/`

for storing processing results (e.g. `Spec01_CorrectedMeasurements_VARIFORC.frc`). ImportFORC will remember these directories, which are automatically opened during the next run. If you use ImportFORC for the first time, or VARIFORC system files have been damaged, the following message appears

`Directory log file C:\...\VARIFORC_ImportFORC_Directories.txt is incomplete!  
VARIFORC_ImportFORC continues with default directories and creates a new log file.`

and default starting directories will be opened.

If systematic measurements of several samples are performed with the same FORC protocol, you might keep the folder structure discussed above and use just one parameter file for all samples (e.g. `MyProtocol_VARIFORC_ImportFORC_parameters.txt`).

### 3.4 Editing ImportFORC options

ImportFORC is controlled by 21 parameters that are uploaded from a parameter file ending with `_VARIFORC_ImportFORC_Parameters.txt`. This is an editable text file with a template provided with the installation package (see [Section 3.2](#)). This template contains universal parameters that define a minimal standard processing procedure that can be used with practically any type of FORC measurements. You can copy this file to any folder, e.g. the same folder containing the FORC data and/or the ImportFORC Mathematica® notebook, and use it as is. Nevertheless, in order to exploit all ImportFORC capabilities and define correct units, you should adapt these parameters to your requirements. For this purpose, open the ImportFORC parameter file with a text editor. You will see a table similar to the following example:

```
Input parameters for package VARIFORC_ImportFORC; (version 2.04).

INPUT 01. Field and magnetization column numbers .....; 1, 2
INPUT 02. FORC saturation field .....; Automatic
INPUT 03. Field slew rate .....; Automatic
INPUT 04. Averaging time of FORC measurements .....; Automatic
INPUT 05. Pause at FORC reversal field .....; Automatic
INPUT 06. Pause at FORC calibration field .....; Automatic
INPUT 07. Pause at FORC saturation field .....; Automatic
INPUT 08. Correction options for first FORC points .....; None, None
INPUT 09. Correction options for last FORC points .....; None, None
INPUT 10. FORC smoothing factor for error calculation .....; 3
INPUT 11. Smoothing factor for drift calculation .....; 5
INPUT 12. Lower limits for outlier detection/replacement .....; 3, 3
INPUT 13. Maximum amplitude of the residuals color scale .....; 3
INPUT 14. FORC plotting options .....; Automatic
INPUT 15. Field units and calibration .....; T, 1, T
INPUT 16. Normalization factor(s) and unit .....; 27.2, mg
INPUT 17. Magnetization units and calibration .....; Am2, 1, mAm2/kg
INPUT 18. High-field limit for paramagnetic correction .....; Automatic
INPUT 19. High-field susceptibility .....; Automatic
INPUT 20. Approach-to-saturation exponent .....; 2.
INPUT 21. Options for lower hysteresis branch subtraction .....; Hysteresis
```

Each line of this table (except for the first one) consists of a parameter option description (e.g. INPUT 03. Field slew rate) followed by the corresponding parameter value or option specification (e.g. Automatic). Parameters and option specifications are separated from their descriptions by a semicolon (;). Multiple parameters in the same row (e.g. a list of normalization factors) are always separated by a colon (:) with or without a single space after it.

You can define your own set of parameters according to the guidelines given in [section 3.5](#) and save the parameter file with an appropriated name related to its usage context. The file structure should never be altered and the file must be saved as .txt without conversion to other formats (MS Word, Rich Text, etc.).

**Example 1:** If you routinely perform identical high-resolution FORC measurements of sediment samples, you can store the parameter file as `Sediment_highres_VARIFORC_ImportFORC_Parameters.txt`, and recall this file every time you import one of these measurements with ImportFORC.

**Example 2:** Processing parameters to be used only for importing FORC measurements from `File_1.frc` can be stored in a parameter file named `File_1_VARIFORC_ImportFORC_Parameters.txt`.

- Always save import parameters as unformatted text files. If you use a text processor such as Microsoft Word, do not forget to save as text (`.txt`) only. Formatted text files are not recognized by ImportFORC.
- Do not change the table structure of the parameter file; in particular, do not add new lines. Multiple parameters representing the same input (e.g. `INPUT 15 Field units` and `calibration`) must be entered as a single line.
- Acceptable parameter formats are explained in detail in section 3.5. Incorrect or unrecognized formats generate error messages with reference to the corresponding input line (e.g. `INPUT 01`).

The following suggestions help you with an efficient management of ImportFORC processing options:

- 💡 Several input parameters can be set to automatic options, letting ImportFORC choose optimal values. Use automatic options if possible, unless you have specific processing requirements. For your convenience, the parameter file provided with the installation package is already based on automatic options whenever possible. The only parameter options you should change for a first meaningful ImportFORC run are the measurement and output units specified with `INPUT 15`, `INPUT 16`, and `INPUT 17`.
- 💡 Use consistent FORC protocols for your measurements, so that only few import parameter files are required. For example, all magnetofossil-bearing sediments can be measured with the same protocol and imported with the same options. Once the import parameters for a given type of FORC measurements have been defined, you can import measurements without any further input.

 If you have generated an invalid parameter file and you do not know how to restore the proper format, create a new file starting from the template provided with the installation package. For this reason, never overwrite templates in the installation package.

### 3.5 Full references to ImportFORC options

All ImportFORC parameter options are described in this section. You can refer to the VARIFORC quick guide for a compact summary.

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INPUT 11. FORC smoothing factor for drift calculation .....	3-37
INPUT 12. Lower limits for outlier detection/replacement .....	3-40
INPUT 13. Maximum amplitude of the residuals color scale .....	3-44
INPUT 14. FORC plotting options .....	3-45
INPUT 15. Field units and calibration .....	3-47
INPUT 16. Normalization factor(s) and unit .....	3-50
INPUT 17. Magnetization units and calibration .....	3-53
INPUT 18. High-field limit for paramagnetic correction .....	3-57
INPUT 19. High-field model constraint .....	3-61
INPUT 20. Approach-to-saturation exponent .....	3-63
INPUT 21. Calculation of FORC differences .....	3-65

## INPUT 01. Field and magnetization column numbers

INPUT 01 is a pair of positive integers indicating column numbers in FORC measurement file(s), which contains field and magnetization measurements, respectively. In all Micro Mag™ measurement files, field measurements are listed in the first column and magnetization measurements in the second column (Fig. 3.3), so that:

```
INPUT 01. Field and magnetization column numbers ....; 1, 2
```

Obviously, field and magnetization measurements cannot be indicated by the same column number.

```
MicroMag 2900/3900 Data File (Series 0016.002)
Direct moment vs. field; First-order reversal curves

INSTRUMENT
Configuration
Temperature control          AGM
None
[...]

SAMPLE
Mass
Volume
Demagnetizing factor        N/A
N/A
N/A

SETTINGS
Field range                 +300.0000E-03
Field (command)             N/A
Moment range                +500.0000E-09
Averaging time              +100.0000E-03
Temperature (command)       N/A
[...]

      Field           Moment
      (T)            (Am²)
+185.2715E-03,+377.0848E-09
+63.06715E-03,+252.6374E-09
+185.2725E-03,+376.9744E-09
+62.52715E-03,+252.2460E-09
+63.04827E-03,+252.9036E-09
+63.51750E-03,+253.2440E-09
+185.2722E-03,+376.9242E-09
+62.06688E-03,+251.1520E-09
+62.62683E-03,+252.2208E-09
+63.13141E-03,+252.7866E-09
+63.57060E-03,+253.2059E-09
+64.06388E-03,+254.0941E-09
[...]
```

**Fig. 3.3:** Excerpt of a MicroMag™ FORC measurement file. In this example, field and magnetization columns are labeled and units are specified explicitly. In older MicroMag™ measurement file formats, measurements are stored as unlabeled columns and units are specified in the file header. Additional columns (not shown here) are used to store environmental parameters such as temperature. In MicroMag™ measurement files, these columns always occur to the right of field and magnetization columns.

- 💡 If you have doubts about the meaning of columns in FORC measurement files, open them with a text editor. Columns are usually labeled.
- 💡 ImportFORC does not recognize column labels, due to practically unlimited labeling combinations and lack of a universal data format.

### INPUT 02-07. FORC protocol parameters

INPUT 02 to INPUT 07 represent parameters of the FORC measurement protocol, which are needed for proper drift correction. They have the following meanings:

- INPUT 02: FORC saturation field ( $H_{sat}$ ). This is the field applied before each curve is measured with the purpose of saturating the sample.
- INPUT 03: Field slew rate ( $SlewRate$ ). This is the maximum rate at which the field is changed, in (field unit)/(time unit). The default setting of MicroMag™ magnetometers is 1 T/s.
- INPUT 04: Averaging time of FORC measurements (Averaging time). This is the time required to perform a single measurement. Typical averaging times on MicroMag™ magnetometers are comprised between 0.1 and 0.5 s. Long averaging times are used for measuring weak samples in order to increase the signal-to-noise ratio.
- INPUT 05: Pause at FORC reversal field ( $PauseNtl$  or  $PauseRvrs$ ). Each FORC begins at the so-called reversal field. Once this field is set, the instrument can be paused in order to let the applied field stabilize and the viscous magnetization decay. This pause is usually comprised between 0 and 1 s.
- INPUT 06: Pause at FORC calibration field ( $PauseCal$ ). Additional measurements are performed in the so-called calibration field. The instrument can be paused before taking calibration measurements for stabilizing applied field and magnetization. This pause is usually comprised between 0 and 1 s.
- INPUT 07: Pause at FORC saturation field ( $PauseSat$ ). This is the time during which the sample is maintained in the saturation field specified by INPUT 02. The pause is usually comprised between 0 and 1 s.

These parameters are usually specified in the header lines of the FORC measurement file and labeled accordingly (see [section 3.6](#)). FORC protocol parameters in a MicroMag™ file header are highlighted in red in [Fig. 3.4](#).

ImportFORC automatically recognizes all FORC protocol parameters in current measurement files produced by MicroMag™ magnetometers. Therefore, you can set each input parameter to Automatic when importing MicroMag™ files, i.e:

```
INPUT 02. FORC saturation field (in original field units) ...; Automatic  
INPUT 03. Field slew rate .....; Automatic  
INPUT 04. Averaging time of FORC measurements .....; Automatic  
INPUT 05. Pause at FORC reversal field .....; Automatic  
INPUT 06. Pause at FORC calibration field .....; Automatic  
INPUT 07. Pause at FORC saturation field .....; Automatic
```

```

MicroMag 2900/3900 Data File (Series 0016.002)
Direct moment vs. field; First-order reversal curves

INSTRUMENT
Configuration AGM
Temperature control None
[...]

SAMPLE
Mass N/A
Volume N/A
Demagnetizing factor N/A

SETTINGS
Field range +300.0000E-03
Field (command) N/A
Moment range +500.0000E-09
Averaging time +100.0000E-03
Temperature (command) N/A
[...]
[...]

SCRIPT
Averaging time +100.0000E-03
Hb1 -40.0000E-03
Hb2 +60.0000E-03
Hc1 0.000000E+00
Hc2 +120.0000E-03
Hc1 +186.0645E-03
HNcr +503.4330E-06
HSat +300.0000E-03
NForc 450
PauseCal +500.0000E-03
PauseRvrs1 +500.0000E-03
PauseSat +200.0000E-03
SlewRate +100.0000E-03
Smoothing 5
Includes hysteresis loop? No
Includes Ms(H)? No
Number of segments 900
Number of data 9999

Field Moment
(T) (Am2)
+185.2715E-03 , +377.0848E-09
[...]

```

**Fig. 3.4:** Excerpt of a MicroMag™ FORC measurement file. FORC protocol parameters are highlighted in red.

Older MicroMag™ measurement files do not contain a file header with explicitly labeled FORC protocol parameters. In this case, you should retrieve these parameters from the file header, if there is one, or from your notes and enter them manually, e.g.:

```

INPUT 02. FORC saturation field (in original field units) ...; 0.3
INPUT 03. Field slew rate .....; 0.1
INPUT 04. Averaging time of FORC measurements .....; 0.1
INPUT 05. Pause at FORC reversal field .....; 0.5
INPUT 06. Pause at FORC calibration field .....; 0.5
INPUT 07. Pause at FORC saturation field .....; 0.2

```

In this case, FORC protocol parameters must be expressed with original time, field, and magnetization units of the measurements, regardless of later unit conversions you might have chosen. For example, if the original field unit was Oe, the saturation field (INPUT 02) should be entered with its value expressed in Oe, even if you have chosen to convert Oe in mT for later processing steps.

When FORC protocol parameters are set to Automatic, ImportFORC looks for corresponding values in the measurement file header, assuming that they are labeled by certain short names (e.g. Hsat for the saturation field) which are stored in a specific installation file. ImportFORC comes with a predefined list of short names used in known versions of MicroMag™ measurement files. These short names might change with future measurement file formats, in which case the list of short names needs to be updated according to the instructions reported below. If ImportFORC does not find a FORC protocol parameter, it produces a warning message and continues after assuming a default value.

- 💡 FORC protocol parameters are used by ImportFORC only for reconstructing the timing of FORC measurements for drift correction. Therefore, if these parameters cannot be retrieved from measurement files and any related information is lost, default values can be entered without affecting the drift correction too negatively. The saturation field should be larger than all measurement fields. All pauses can be set to zero and the averaging time to any value between 0.1 and 0.3 s.
- 💡 If FORC protocol parameters set to Automatic are not found in the measurement file header, ImportFORC replaces them with default parameters as specified in Table 3.1. In such cases, you can keep the default parameters or perform a new ImportFORC run with FORC protocol parameters specified explicitly in the parameter file.
- 💡 If FORC protocol parameters cannot be retrieved automatically from the measurement file, it is always advisable to check possible format updates as explained below.

### *Adding new FORC protocol names*

Short names of FORC protocol parameters used in various generations of MicroMag™ measurement files are stored in a VARIFORC system file located in the root directory of the installed VARIFORC package, i.e.

```
C:/.../VARIFORC/VARIFORC_ImportFORC_ProtocolNames.txt
```

The location of this directory is shown during VARIFORC installation with the `VARIFORC_Install.cdf` Mathematica® notebook (see Chapter 2). If you did not save the notebook after installation, open it from the installation package and evaluate the command line

```
$UserBaseDirectory
```

which gives you the full path of the installed VARIFORC package.

The system file `VARIFORC_ImportFORC_ProtocolNames.txt` contains the following table:

FORC protocol names to be recognized automatically by `VARIFORC_ImportFORC`; (version 1.0).

```
PARAMETER 01. Saturation field .....; HSat
PARAMETER 02. Field slew rate .....; SlewRate
PARAMETER 03. Measurement averaging time .; Averaging time
PARAMETER 04. Pause at reversal field ....; PauseNt1, PauseRvrs1
PARAMETER 05. Pause at calibration .....; PauseCal
PARAMETER 06. Pause at saturation .....; PauseSat
```

which has the same structure as all parameter tables used by VARIFORC. Each row, except the first one, is composed by a parameter description (e.g. PARAMETER 01. Saturation field), followed by a list of one or more short names expected in the header of measurement files (e.g. HSat for the saturation filed). For example, PARAMETER 04 (pause at reversal field) has already two short names for measurement files produced by two different versions of the MicroMag™ FORC control software.

If a new file format with different parameter names has been introduced since VARIFORC release, you can update ImportFORC by adding new short names in `VARIFORC_ImportFORC_ProtocolNames.txt`.

**Example:** Assume that the measurement averaging time (PARAMETER 03) is called AvgTime in measurement files produced by a new version of the MicroMag™ FORC measuring software. In order to make ImportFORC automatically read the averaging time, add the new name to the corresponding line of the parameter table, i.e.:

```
PARAMETER 03. Measurement averaging time .; Averaging time, AvgTime
```

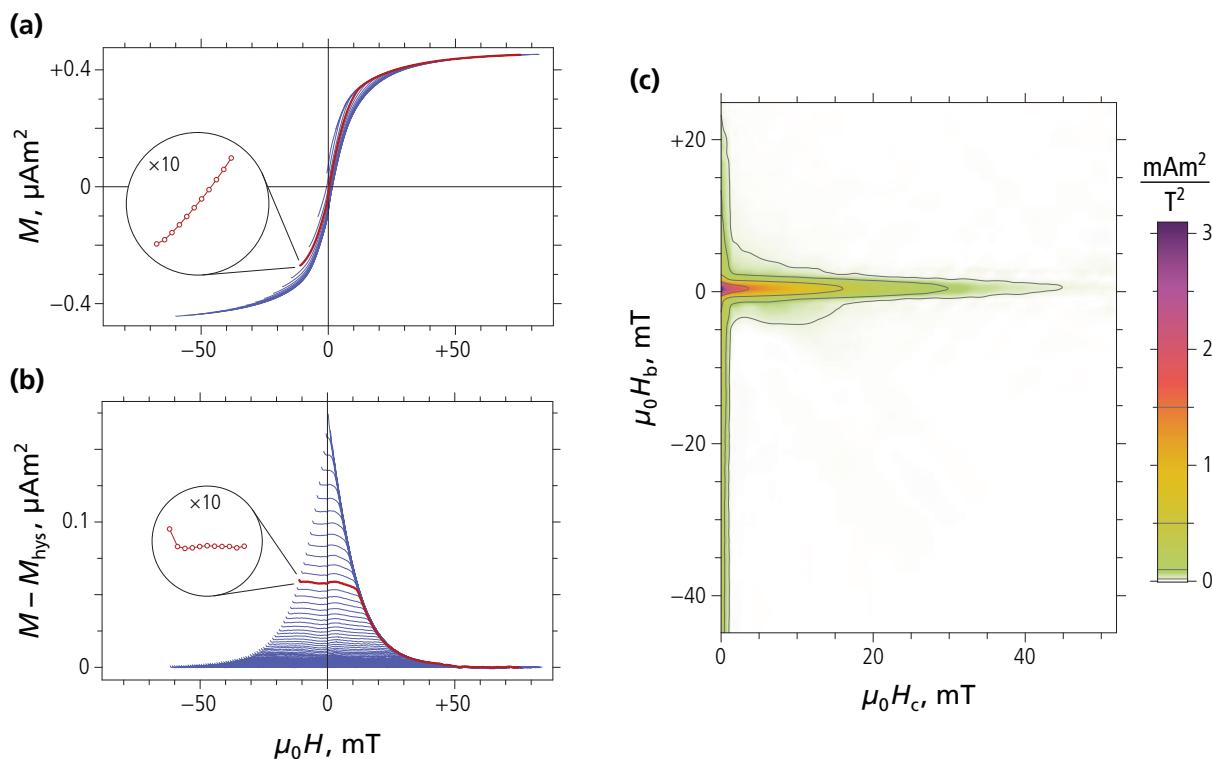
For this purpose you can use any text editor, but remember to store the modified file as text file without formatting. After this change has been performed, ImportFORC is immediately able to import the averaging time from new measurement files.

**Table 3.1:** FORC protocol parameters with currently used short names, as well as typical values used in FORC protocols and default values used by ImportFORC if not otherwise specified.

Parameter	Short names	Typical values	Default values
Saturation field $H_{\text{sat}}$	Hsat	close to saturation	$1.5 \times H_{\text{cal}}$
Field slew rate	SlewRate	0.1-1 T/s	$H_{\text{cal}}/(1 \text{ second})$
Measurement averaging time	Averaging time	0.1-0.3 s	0.1 s
Pause at reversal field	PauseNtl, PauseRvrsl	0-1 s	0
Pause at calibration	PauseCal	0-1 s	0
Pause at saturation	PauseSat	0-1 s	0

### INPUT 08. Correction options for first FORC points (updated)

INPUT 08 provides options for correcting artifacts occurring with the first measurement point of each FORC when measurements are performed while the applied field is continuously changed (so-called *sweep mode*). Measurement artifacts arise from the difficulty of controlling the sudden field sweep change needed after the field has decreased from positive saturation to the reversal field, in order to increase it again while measuring the magnetization. For this reason, the first FORC point is measured in a magnetic field that differs from the expected value and the measurement itself might be affected by a systematic error due to unwanted interactions between electromagnet and magnetic moment measurements. Systematic first point measurement errors produce a vertical ridge in the resulting FORC diagram, which extends over the whole measurement range. This ridge is a pure instrumental artifact (Fig. 3.5), which shall not to be confused with the similar signature of magnetic viscosity [Pike *et al.*, 2001].



**Fig. 3.5:** Example of anomalous first-point FORC measurements of dispersed magnetosomes (see the downloadable example “Dispersed magnetosomes”) obtained with a MicroMag™ system. **(a)** Drift-corrected measurements (blue, every 12<sup>th</sup> curve shown for clarity). A single curve is highlighted in red, with its first 11 points shown in the magnified insert. **(b)** Same as (a), after the lower hysteresis branch has been subtracted from all measurements (blue, every 3<sup>rd</sup> curve shown for clarity), as part of the standard ImportFORC output. Anomalous first point measurements are now clearly recognizable. **(c)** FORC diagram calculated from the data in (b) with the VARIFORC module CalculateFORC. The vertical ridge extending over the whole lower quadrant, far beyond the coercivity range of this sample, is an artifact produced by anomalous first-point measurements.

In order to eliminate possible artifacts affecting the first measurement point of each curve, INPUT 08 offers the possibility to correct the corresponding field and magnetization values. If you have no reason to suspect problems with first points, for instance in case of measurements performed in settled fields, you can avoid first-point corrections by setting:

```
INPUT 08. Correction options for first FORC points .....; None, None
```

where the parameter pair `None, None` means that the measured field (first `None`) and magnetization (second `None`) corresponding to the first point in each FORC are left unchanged ([Fig. 3.6a](#)).

The first point field measurement is corrected by replacing the first `None` with a positive number  $r$ , so that the new field value is given by the field of the next measurement point minus  $r$  times the mean field step  $\delta H$  of measurements. Choose  $r = 1$  in order to obtain a regular grid of field values, i.e.:

```
INPUT 08. Correction options for first FORC points .....; 1, None
```

For example, a FORC with successive measurement fields 0.10, 0.12, 0.13, 0.14, ..., in which the first field step is 0.02 instead of 0.01, is corrected so, that the new list of field values is 0.11, 0.12, 0.13, 0.14, ... The first magnetization measurement, on the other hand, is left unchanged ([Fig. 3.6b](#)).

If first-point magnetization measurements are not trusted, set the second parameter to `Automatic` in order to correct them, i.e.:

```
INPUT 08. Correction options for first FORC points .....; None, Automatic
```

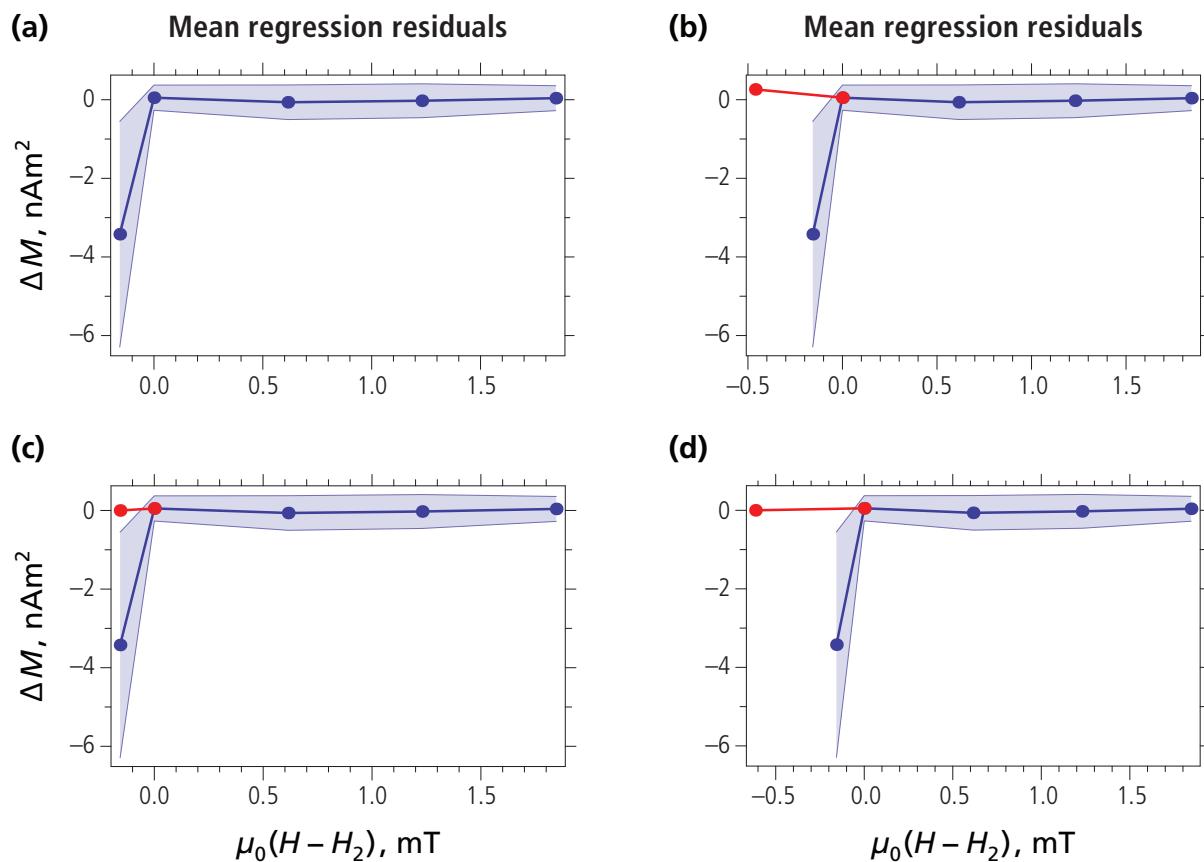
In this case, a new magnetization value is calculated for the first point by extrapolating the second-order polynomial trend defined by the next measurement points in each FORC ([Fig. 3.6c](#)). This option can also be used to intentionally discard magnetic viscosity effects and other special effects occurring at field reversals. The number `SF+1` of measurement points used to define the polynomial trend is controlled by the smoothing factor `SF` entered with INPUT 10, which is used for error calculation purposes.

Finally, you can decide to correct field *and* magnetization values of the first measurement point in order to obtain regular magnetization curves on a regular grid of fields, i.e.:

```
INPUT 08. Correction options for first FORC points .....; 1, Automatic
```

([Fig. 3.6d](#)).

ImportFORC provides diagnostic tools for the identification of first-point measurement artifacts, in form of plots similar to [Fig. 3.6](#). When processing FORC measurements without previous knowledge about the necessity of correcting first-point measurements, it is recommended to perform a preliminary ImportFORC run without corrections (i.e. INPUT 08 is set to `None, None`). After inspecting the diagnostic plots produced by this first run (e.g. [Fig. 3.6a](#)), desired corrections are introduced with a second ImportFORC run (e.g. [Fig. 3.6b-d](#)), after proper modification of INPUT 08 parameters.



**Fig. 3.6:** Examples of ImportFORC first-point corrections of FORC measurements obtained with an old MicroMag™ system (see the downloadable example “Magnetospirillum 1”). Plots represent mean differences (dots) of the first 5 points of all FORCs from trends defined by second-order polynomial regression. The standard deviation of all differences is represented by the shaded area. Corrected first-point measurements are represented in red. (a) Original data without corrections (i.e. INPUT 08 is None, None). The first field step is 0.15 mT instead of 0.63 mT. (b) First-point correction obtained by setting the first field step to 75% of the mean field step while the magnetization value is left unchanged (i.e. INPUT 08 is 0.75, None). (c) First-point correction obtained by replacing the first magnetization measurement with the extrapolation of the second-order polynomial trend defined by the next 4 points (i.e. INPUT 08 is None, Automatic). (d) Same as (c), after correcting the first field step by setting it equal to the mean field step (i.e. INPUT 08 is 1, Automatic).

First-point corrections are of paramount importance for the correct evaluation of magnetization changes occurring in proximity of reversal fields, such as those associated with magnetic viscosity, as shown in Fig. 3.7. In cases where a first point correction is required, measurements should be performed with sufficiently small field steps, so that extrapolation of magnetization curves to the reversal field is meaningful.

Sometimes, the second point of each curve is also affected by minor measurement artifacts. In this case, it is possible to correct the first two points by adding the number of points to be corrected (maximum 2) in INPUT 08, e.g.

INPUT 08. Correction options for first FORC points .....; None, Automatic, 2

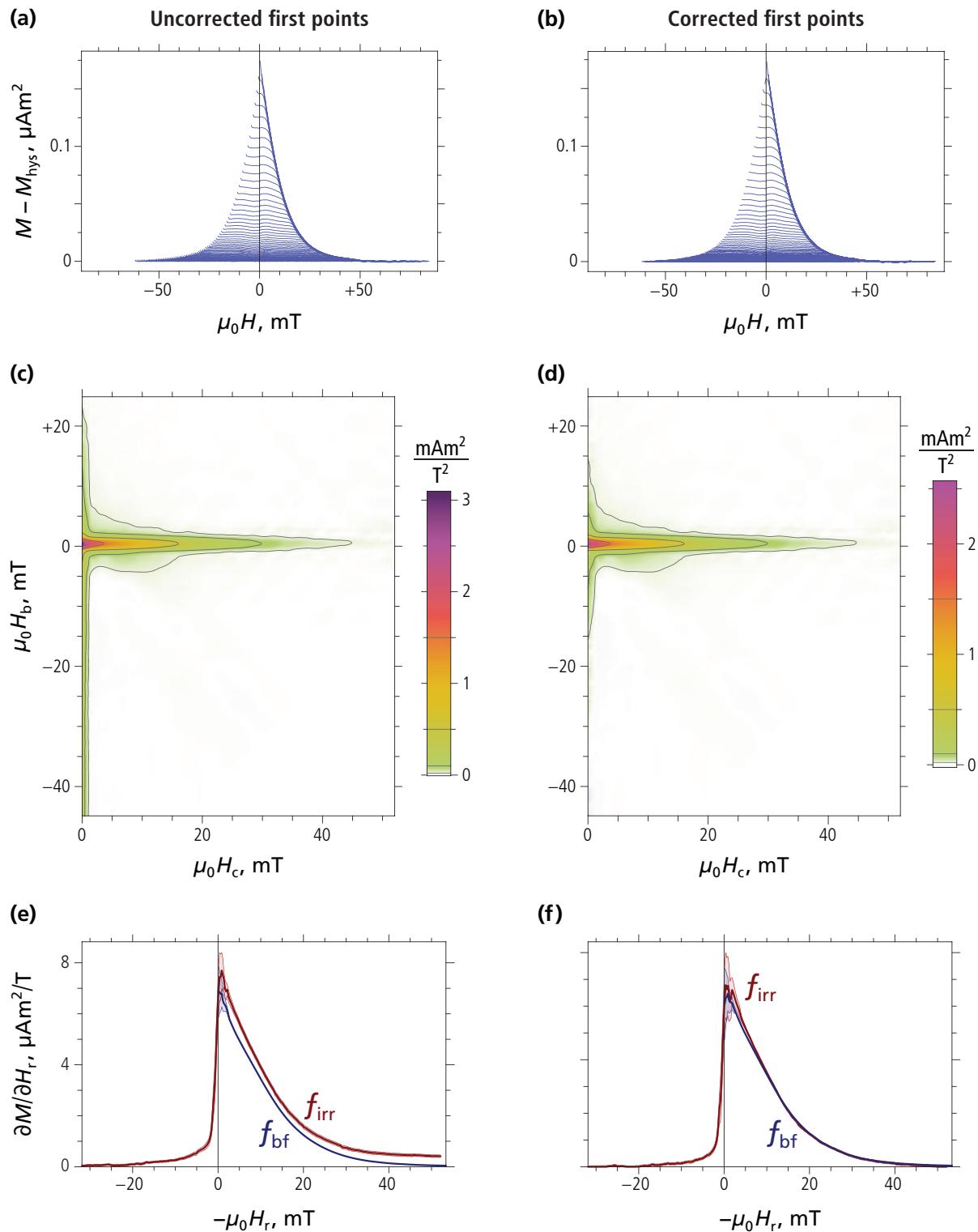
In this case, high-resolution measurements are mandatory, because polynomial extrapolation is extended over two field steps.



The effective magnetometer performance at field reversals can be checked by measuring a paramagnetic standard. In this case, first-point anomalies represent measurement artifacts. This test is highly recommended when investigating magnetization processes occurring during field reversals (e.g. magnetic viscosity).

- First-point measurements can lie above the trend defined by following measurements because of viscous magnetization contributions [Pike *et al.*, 2001]; however, only for reversal field amplitudes not exceeding the saturation field of the specimen (i.e. the field at which the two branches of a major hysteresis loop merge).
- Automatic correction of first-point magnetizations is performed by extrapolating the trend defined by a certain number of next points with a second-order polynomial. The number of next points taken into consideration for this purpose is equal to the smoothing factor used for error calculations (INPUT 10) plus 1. This ensures that the linear trend is defined over a number of points that supports sufficient noise suppression over the smallest possible field range. The examples of Fig. 3.6 were obtained with a smoothing factor of 3, so that 3+1 points are plotted in addition to the first one.

**Fig. 3.7** (front page): First-point correction example based on high-resolution FORC measurements of dispersed magnetosomes (see the downloadable example “Dispersed magnetosomes”). The left and right plot columns correspond to measurements without and with first-point correction, respectively. **(a-b)** Drift-corrected FORC measurement differences (blue, every 3<sup>rd</sup> curve shown for clarity), obtained by subtracting the lower hysteresis branch from all measurements. The curve envelope coincides with the irreversible component of the hysteresis loop. Notice the anomalous measurements at the beginning of each curve in (a). **(c-d)** FORC diagrams obtained with the VARIFORC module CalculateFORC on the basis of measurements shown in (a-b). Anomalous first-point measurements produce a vertical ridge in (c), which extends beyond the maximum coercivity range of the sample. The ridge amplitude is constant over  $H_b < 0$ . The FORC diagram obtained from corrected data (d) shows the real extent of the vertical ridge produced by magnetic viscosity. (Continues on front page)

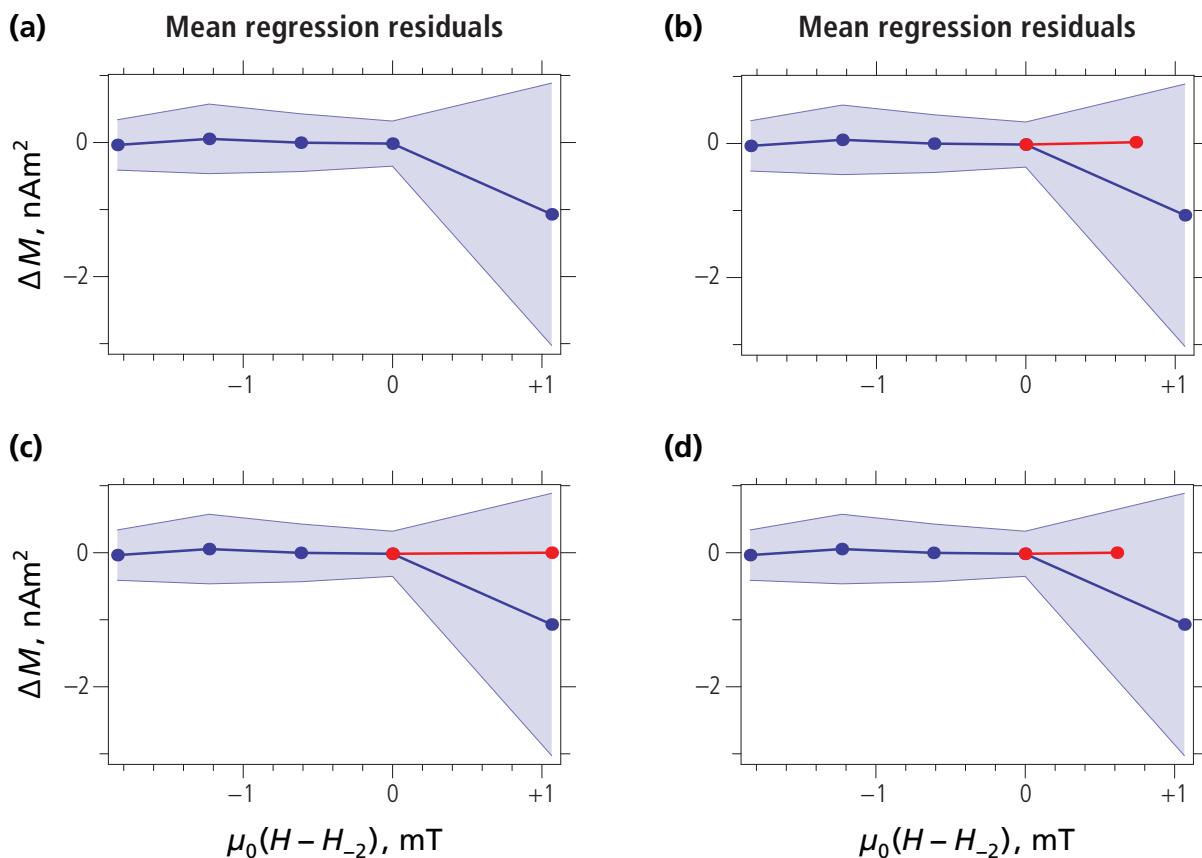


**Fig. 3.7 (continued): (e-f)** Coercivity distributions  $f_{\text{bf}}$  (blue) and  $f_{\text{irr}}$  (red) corresponding to the first derivative of the backfield demagnetization curve and the irreversible component of the upper hysteresis branch, respectively, as deduced from FORC measurements. The vertical ridge produced by anomalous first-point measurements provides a constant background to  $f_{\text{irr}}$  in (e), preventing its decay to zero at high coercivities. This problem does not occur with coercivity distributions (f) obtained from first-point-corrected FORC data.

**INPUT 09. Correction options for last FORC points (updated)**

INPUT 09 is defined by a pair of parameters used to correct possible problems occurring with the last measurement point in each FORC. INPUT 09 works exactly as INPUT 08 (see previous section), except for the fact that it applies to the last measurement of each FORC.

As for the case of first-point corrections, ImportFORC provides diagnostic plots for identifying possible measurement artifacts (e.g. Fig. 3.8).



**Fig. 3.8:** Examples of ImportFORC last-point corrections of FORC measurements obtained with an old Micro Mag™ system (see the downloadable example “Magnetospirillum 1”). Plots represent mean differences (dots) of the last 5 points of all FORCs from trends defined by second-order polynomial regression. The standard deviation of all differences is represented by the shaded area. Corrected last-point measurements are represented in red. **(a)** Original data without corrections (i.e. INPUT 09 is None, None). The first field step is 1.05 mT instead of 0.63 mT. **(b)** Last-point correction obtained by setting the last field step to 120% of the mean field step while the magnetization value is left unchanged (i.e. INPUT 09 is 1.2, None). **(c)** Last-point correction obtained by replacing the first magnetization measurement with the extrapolation of the second-order polynomial trend defined by the previous 4 points (i.e. INPUT 09 is None, Automatic). **(d)** Same as (c), after correcting the last field step by setting it equal to the mean field step (i.e. INPUT 08 is 1, Automatic).

In analogy with first-point corrections, it is possible to correct the last two points of each curve by adding the number of points to be corrected (maximum 2) in INPUT 09, e.g.

INPUT 09. Correction options for first FORC points .....; None, Automatic, 2

In this case, high-resolution measurements are mandatory, because polynomial extrapolation is extended over two field steps.

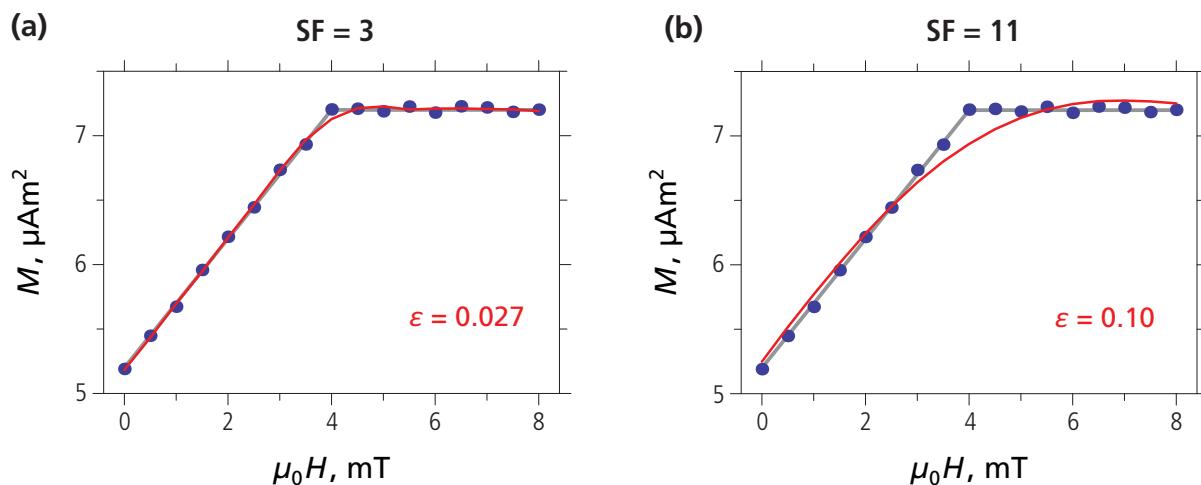
- First-point measurements can lie above the trend defined by following measurements because of viscous magnetization contributions [Pike *et al.*, 2001]. On the other hand, deviations of last-point measurements from a continuous trend is always attributable to measurements artifacts.
- Last-point measurements artifacts, if not corrected, can produce instabilities at the upper and right edges of FORC diagrams extending over the whole measurement range.

### INPUT 10. FORC smoothing factor for error calculations

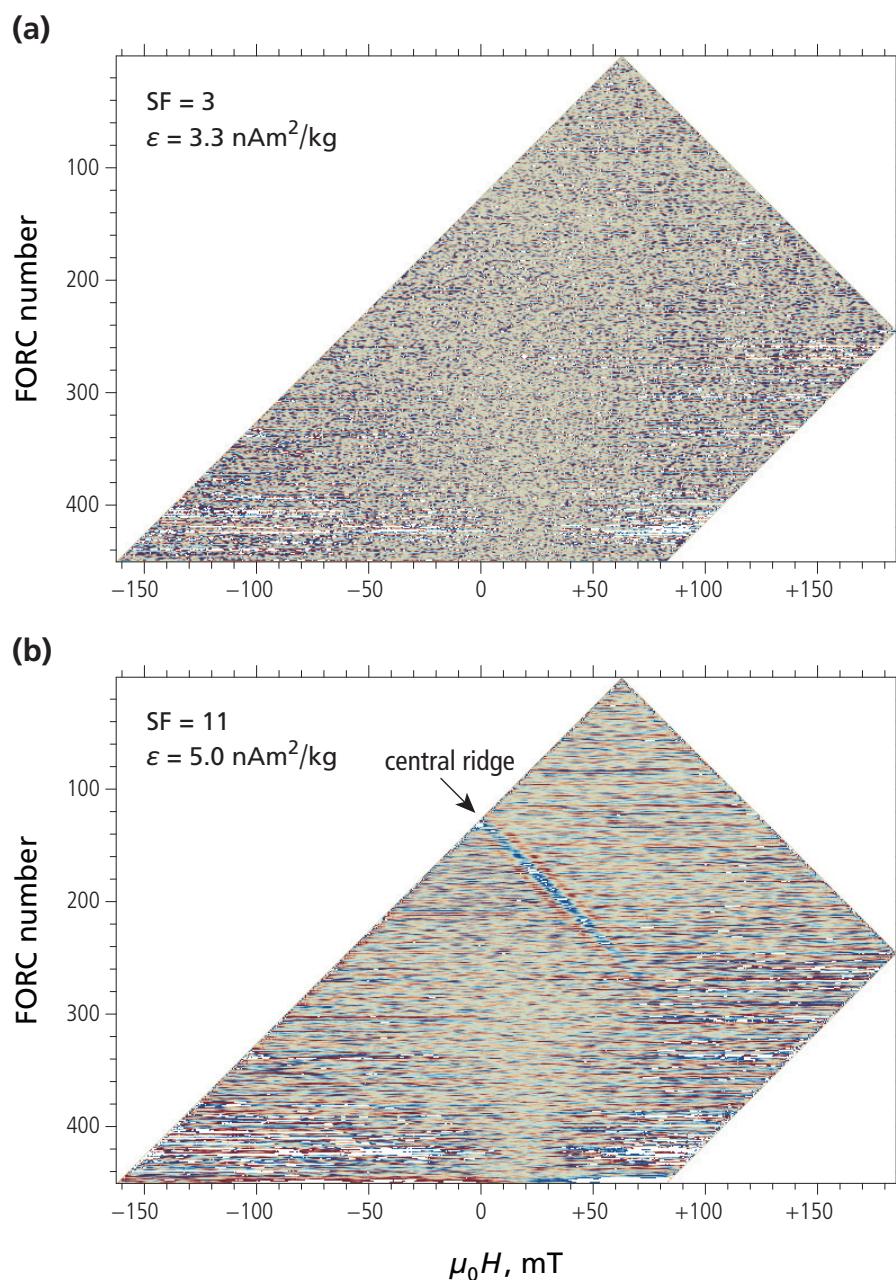
Measurement error estimates are used by ImportFORC for removing outliers and weighting multiple FORC measurements according to their quality. An empirical error estimate is obtained on the basis of polynomial regression residuals over intervals containing  $2SF + 1$  points, where the positive integer  $SF > 0$  is a so-called smoothing factor entered with INPUT 10. The smoothing factor is to be chosen so, that groups of  $2SF + 1$  consecutive FORC measurements can be fitted by a third-order polynomial without appreciable fitting errors. In this case, regression residuals can be identified with measurement errors. Typical smoothing factors are comprised between 3 and 5, e.g.:

```
INPUT 10. FORC smoothing factor for error calculation ....; 3
```

Usually,  $SF = 3$  is a sufficiently small smoothing factor to be used with most demanding FORC measurements containing sharp changes in slope associated with the so-called central ridge (Fig. 3.9a). In such cases, larger smoothing factors cannot resolve sharp details, introducing misfits that are interpreted as measurement errors (Fig. 3.9b). Such misfits are easily recognizable on regression residual maps generated automatically by ImportFORC (Fig. 3.10), where they appear as localized high-amplitude patterns. A correct choice of INPUT 10 is obtained by increasing SF in successive ImportFORC runs, until large misfits begin to be recognizable on the residuals map. An exact optimization of INPUT 10 is not necessary, because outlier detection and measurement quality evaluation perform satisfactory over a wide range of smoothing factors.



**Fig. 3.9:** Polynomial regression on synthetic FORC data examples featuring a sharp slope change typical of samples containing non-interacting single-domain magnetic particles. Gray lines represent noise-free curves to which Gaussian errors with standard deviation  $\epsilon = 0.02$  have been added in order to obtain simulated measurements (dots). Smoothed curves obtained with cubic polynomial regression over  $2SF + 1$  points are shown in red. **(a)** Results for  $SF = 3$ . The measurement error estimated from regression residuals ( $\epsilon = 0.027$ ) is close to the true value and the smoothed curve does not deviate significantly from measurements. **(b)** Results for  $SF = 11$ . The measurement error estimated from regression residuals ( $\epsilon = 0.10$ ) is much larger than the true value, as excessive smoothing produced significant deviations from measurements.

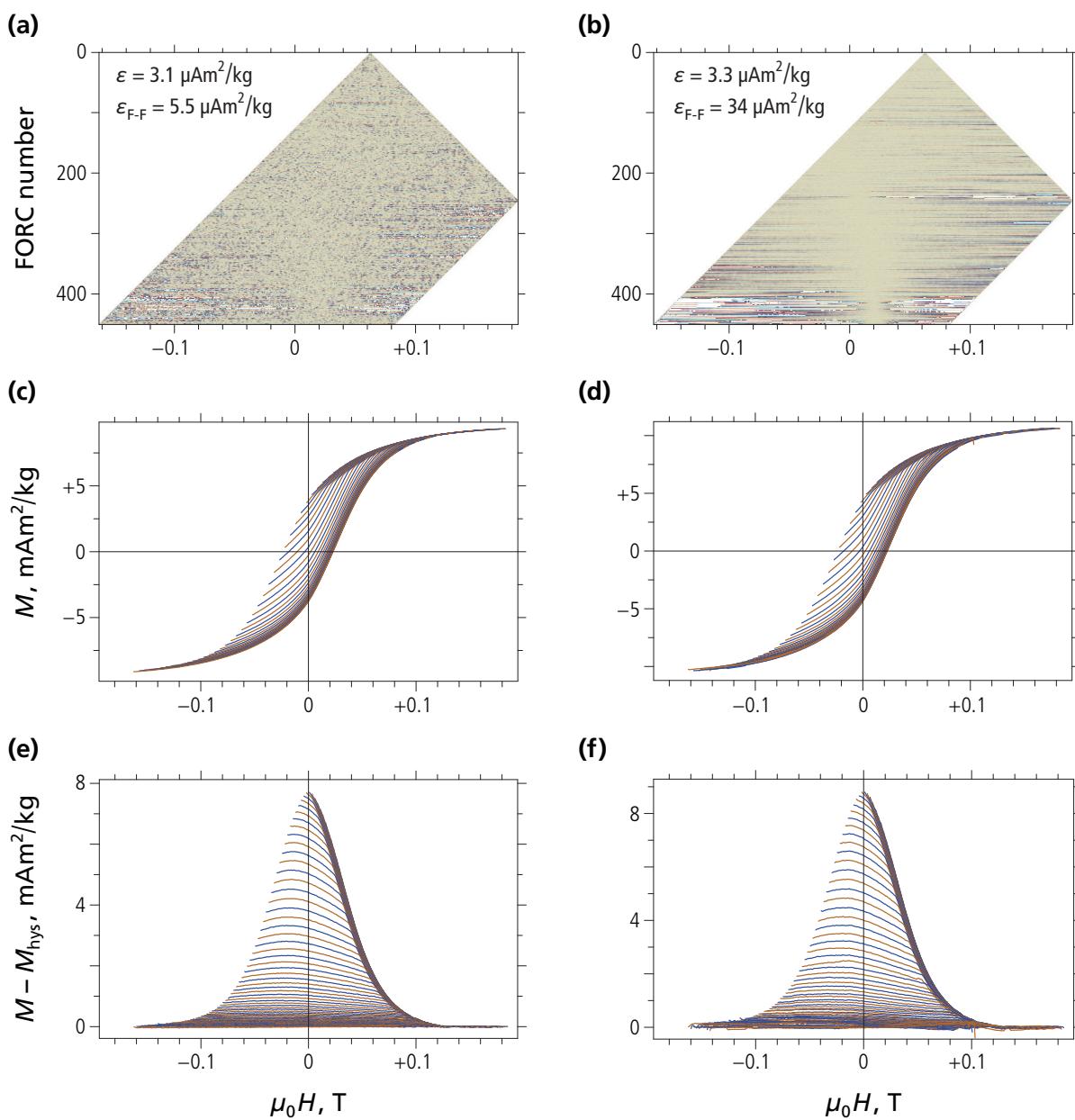


**Fig. 3.10:** Polynomial regression residuals as plotted by ImportFORC on processing FORC measurements of a pelagic carbonate (see the downloadable example “pelagic carbonate”). Each pixel of the color maps represents the difference between an actual measurement and its smoothed counterpart obtained by third-order polynomial regression over  $2SF + 1$  points on the same curve (horizontal pixel lines), where SF is the smoothing factor given by INPUT 10. **(a)** Correct SF choices (e.g. SF = 3) produce a residuals pattern that reflects pure measurement noise. In this case, measurement errors increase at large field amplitudes. Individual FORCs affected by transient disturbances are clearly recognizable as horizontal stripes with large residuals. White gaps indicate measurements that have been identified as outliers. **(b)** Large misfits start to appear with excessively large SF values (e.g. SF = 11), in this case over the so-called central ridge, where regression residuals overestimate true measurement errors. Nevertheless, similar groups of measurements are identified as outliers (white pixels) in (a) and (b), demonstrating that a precise SF optimization is not required by ImportFORC.

In the limit case represented by  $SF = 1$ , groups of  $2SF + 1 = 3$  points are always exactly fitted by third-order polynomials, yielding no regression residuals. Therefore, realistic measurement error estimates are obtained only with  $SF > 2$ .

The importance of measurement error estimates for optimal processing of multiple FORC measurements can be appreciated with the example of multiple FORC measurements of a pelagic carbonate specimen with a saturation moment of only  $0.27 \mu\text{Am}^2$ , obtained with a MicroMag™ AGM. Two FORC sets among a total of 6 repeated measurements are shown in Fig. 3.11. The first set reflect ideal conditions yielding very stable measurements with an estimated standard error  $\varepsilon = 84 \text{ pAm}^2$  within individual curves and  $\varepsilon_{F-F} = 150 \text{ pAm}^2$  between different (drift-corrected) curves. For comparison, the nominal sensitivity of a MicroMag™ 2900 AGM is  $\sim 30 \mu\text{Am}^2$  at 0.1 s averaging time. The second set of measurements shown in Fig. 3.11 is characterized by a similar standard error within individual curves ( $\varepsilon = 90 \text{ pAm}^2$ ); however, short-term instabilities of unknown origin increase the standard error between curves by almost an order of magnitude ( $\varepsilon_{F-F} = 925 \text{ pAm}^2$ ). These instabilities appear as horizontal stripes with large-amplitudes on residuals plots produced by ImportFORC (Fig. 3.11b). Even after drift correction and outlier removal, the quality of corrected FORC data remains visibly worse than that of the first set of measurements.

If multiple FORC measurements are averaged, best noise suppression is achieved by weighting each set of measurements with the squared inverse of the corresponding standard errors. Such weighted averages are calculated by ImportFORC on the basis of the estimated standard errors  $\varepsilon_{F-F}$  between curves. In the abovementioned example, six sets of FORC measurements (with first two shown in Fig. 3.11) yielded the following values of  $\varepsilon_{F-F}$ :  $5.5, 34, 7.1, 26, 20, 35 \text{ pAm}^2$ , with corresponding weight factors of  $0.56, 0.014, 0.35, 0.026, 0.042, 0.014$ . A total weight of only  $\sim 10\%$  is assigned to unstable FORC sets (#2, #4, #5, and #6). The estimated standard error of the weighted average ( $\varepsilon_{F-F} = 110 \text{ pAm}^2$ ) is  $\sim 2.4$  times smaller than that of a simple arithmetic mean, demonstrating the importance of a proper measurement error handling as performed by ImportFORC. In this context, the choice of a smoothing factor via INPUT 10 is not particularly critical. With the abovementioned example, replacing  $SF = 3$  with  $SF = 4$  changes the weight factors and the estimated standard errors by  $< 15\%$ .



**Fig. 3.11:** ImportFORC analysis of two sets of FORC measurements of the same pelagic carbonate specimen (see the downloadable example “pelagic carbonate”) The two FORC sets have been measured with a Micro Mag™ AGM under the same conditions. **(a-b)** Maps of polynomial regression residuals (colored pixels) as a function of the applied field and the FORC number, obtained with SF = 3. Individual curves are represented by horizontal pixel lines. White gaps correspond to measurements that have been identified as outliers. Mean standard errors are given within individual curves ( $\varepsilon$ ) and between different curves ( $\varepsilon_{F-F}$ ). Notice the strong horizontal striping in (b), which reflects much larger values of  $\varepsilon_{F-F}$ , due to short-term measurement instabilities of unknown origin. **(c-d)** Plots of corrected FORC measurements, as produced by v1.01 of Import FORC. Every 10<sup>th</sup> curve is shown for clarity. Contrary to what could be expected from regression residual plots in (a-b), differences between the two sets of measurements are barely visible. **(e-f)** Same as (c-d), after subtracting the lower hysteresis branch from each curve. Quality differences between the two sets of measurements are now clearly distinguishable, especially for lower curves, where regression residuals were particularly large.

- Smoothing factors comprised between 3 and 5 are usually appropriated for processing high-resolution FORC measurements.
- Residuals produced by excessive smoothing feature amplitude variations that correlate with the FORC diagram. For example, maximum residual amplitudes might occur in proximity of the central ridge (e.g. Fig. 3.10b), in which case SF must be decreased.
- Horizontal stripes with large-amplitude residuals reflect measurement instabilities of individual FORC curves and should not be taken into consideration when choosing the smoothing factor.

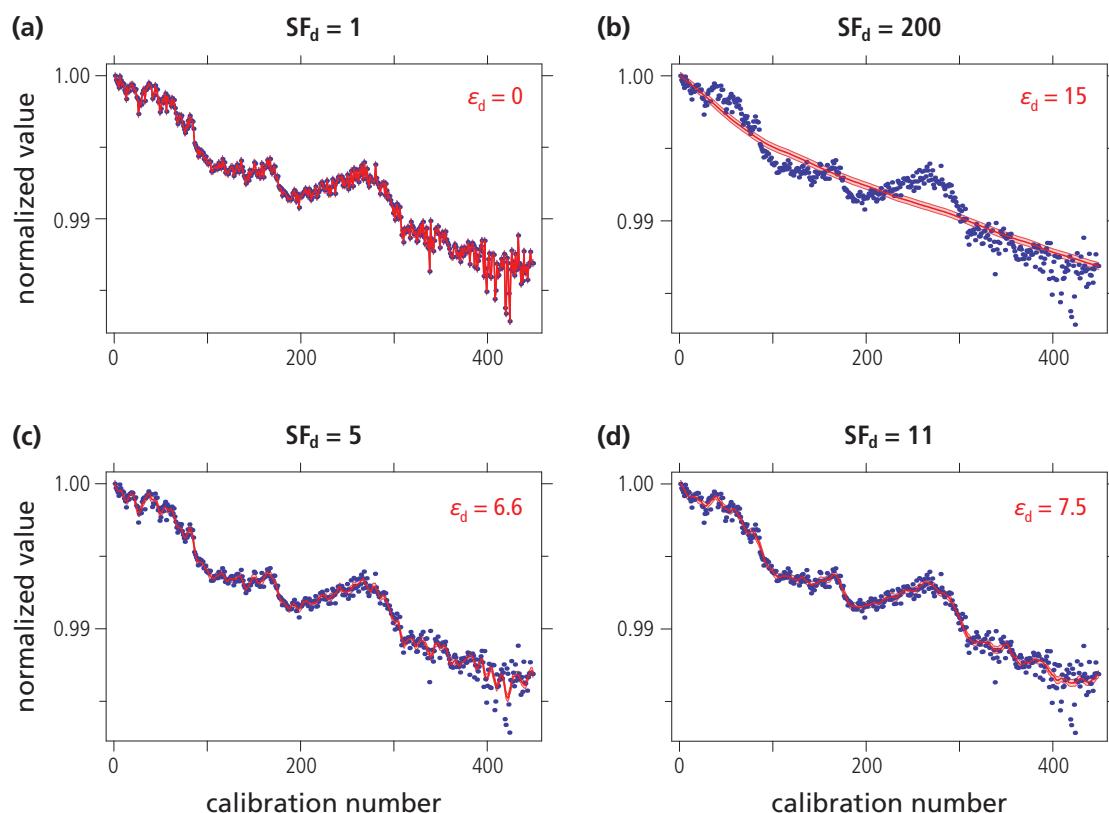
- 💡 The smoothing factor used by ImportFORC should not be confused with the smoothing factor underlying FORC diagram calculations. Within ImportFORC, the smoothing factor serves only for the purpose of estimating measurement errors and remove outliers. Therefore, it does not affect FORC processing beyond the weights used for averaging multiple measurement (see below).
- 💡 An option for removing measurement outliers during FORC diagram calculation is provided by CalculateFORC. However, there are good reasons for removing such outliers already with ImportFORC: In case of multiple measurements, ImportFORC checks each FORC set individually before merging all measurements into a single set, so that averaging is not degraded by outliers. Furthermore, corrected FORC measurements produced by ImportFORC are themselves a valuable source of information besides processed FORC diagrams.

### INPUT 11. FORC smoothing factor for drift calculation

INPUT 11 is a smoothing factor used by ImportFORC for suppressing the measurement noise of calibration measurements. It has the same meaning as the smoothing factor given with INPUT 10 and operates over temporal changes of calibration values. Accordingly, INPUT 11 is a positive integer  $SF_d$ , e.g.:

```
INPUT 11. Smoothing factor for drift calculation ....; 3
```

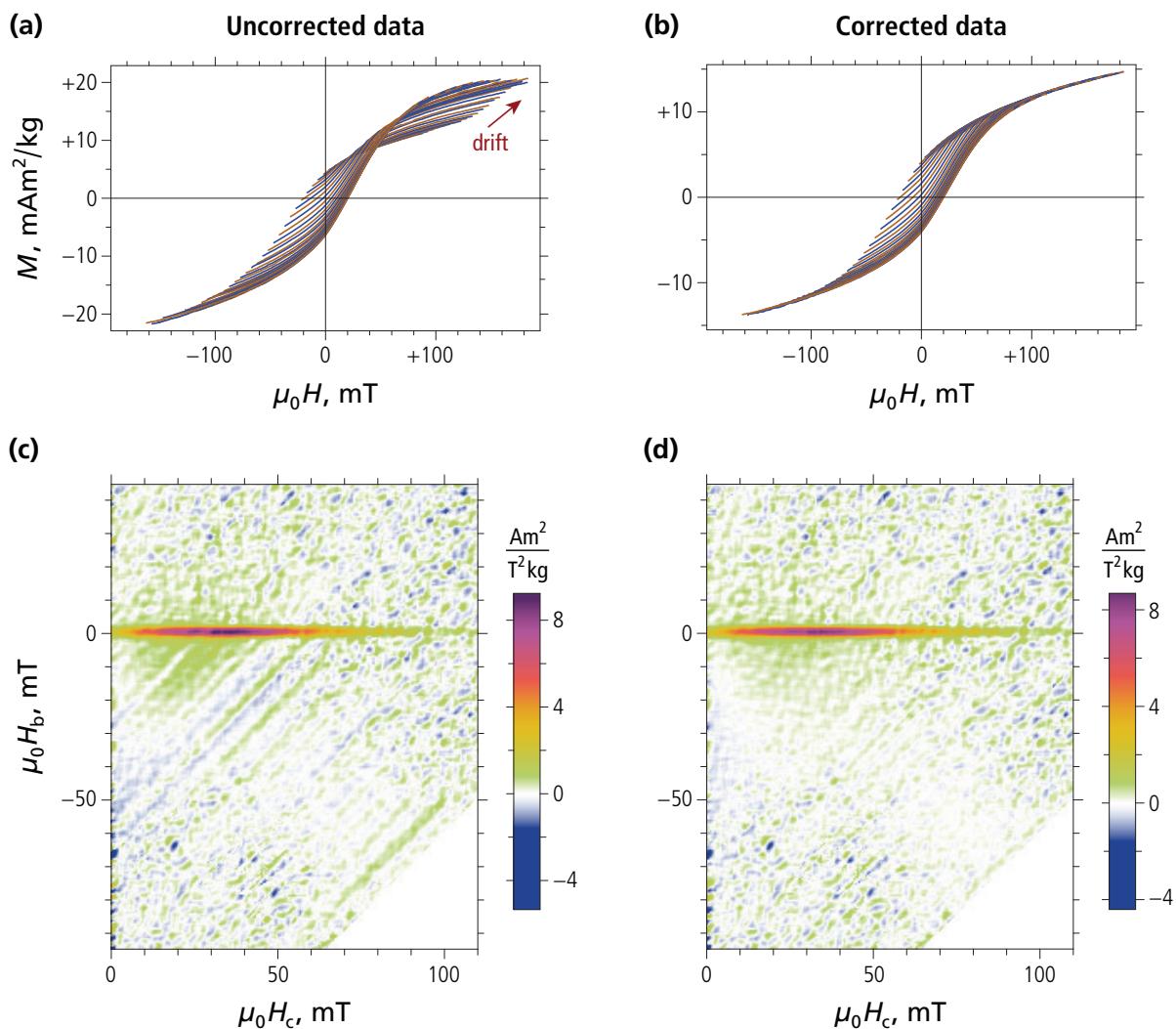
such that cubic polynomial regression is performed over intervals containing  $2SF_d + 1$  calibration measurements. Calibration measurements are taken in the same applied field before each FORC is measured. Any temporal change of such measurements represents a drift that is corrected by ImportFORC. Because calibration measurements are affected by measurement errors as other measurements do, a polynomial regression with smoothing factor SF is used for noise reduction. The resulting smoothed calibration curve defines a continuous drift that is removed from all FORC measurements (Fig. 3.12).



**Fig. 3.12:** Calibration measurements of a pelagic carbonate (see the downloadable example “pelagic carbonate”) before (dots) and after (red line with  $\pm 1$  standard deviation confidence interval) smoothing with given  $SF_d$ . (a) The smoothed curve produced with  $SF_d = 1$  coincides with original measurements and noise is not removed. (b) Excessive smoothing ( $SF_d = 200$ ) captures the general trend, but eliminates drift-related fluctuations. (c-d) Examples of reasonable smoothing factors producing regression residuals similar to those of FORC measurements ( $\epsilon = 5.5$ ).

Regular drifts, which are characterized by a smooth change of calibration measurements over time, do not affect the *local* properties of the measured curves, which are particularly relevant for FORC calculations. Therefore, correction of a regular drift produces only very marginal FORC diagram improvements. On the other hand, transient disturbances produce irregular drifts, which are characterized by sudden “jumps” of calibration values and corresponding gaps between successive curves (e.g. Fig. 3.13a). Irregular drift is a widespread characteristic of FORC measurements, especially if small field steps and long integration times are used, often degrading the quality of FORC diagrams significantly (Fig. 3.13c). If the drift rate does not change significantly during the time required to measure individual curves, drift correction can effectively remove or drastically reduce drift-related artifacts (Fig. 3.13d). In all cases, drift correction improves the graphical representation of FORC measurements (Fig. 3.13b).

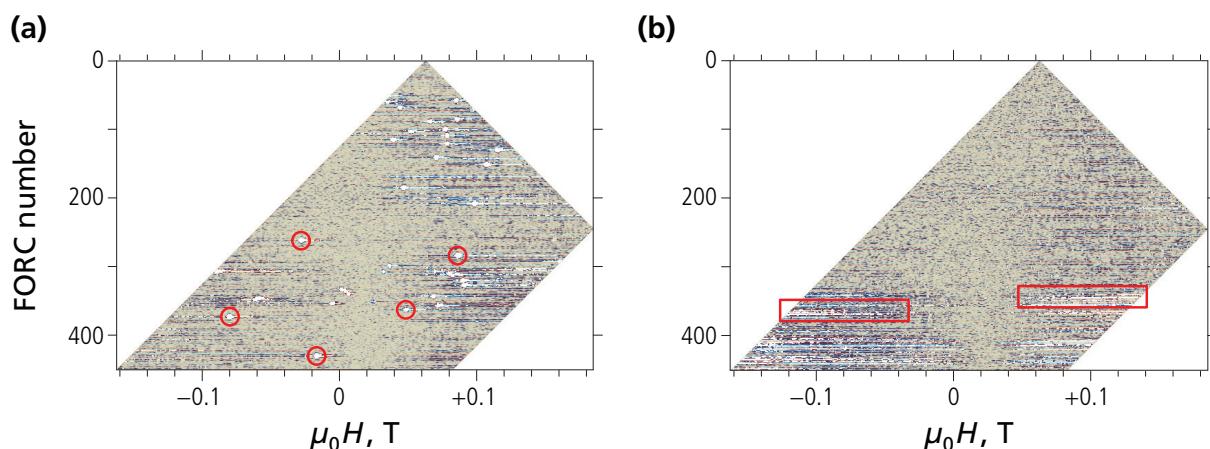
- 💡 As reasonable initial guess for INPUT 11 you can enter the same smoothing factor used for the FORC measurements (INPUT 10).
- 💡 If INPUT 11 is correctly chosen, the estimated standard error between consecutive FORCs (reported as “inter-FORC standard error” by ImportFORC) is of the same order of magnitude as the estimated standard error of calibration measurements.
- 💡 The quality of FORC diagram is greatly affected by sudden changes of the drift rate (irregular drift). Therefore, the smoothing factor  $SF_d$  of drift correction must be small enough for polynomial regression to reproduce all non-random changes of calibration measurements (e.g. Fig. 3.12c).



**Fig. 3.13:** Drift correction example based on high-resolution FORC measurements of a pelagic carbonate (see the downloadable example “pelagic carbonate”). **(a)** Uncorrected FORC measurements. Every 10<sup>th</sup> curve is shown for clarity. In this example, regular drift is characterized by a systematic increase of the apparent FORC amplitude (arrow) as measurements proceed with curves beginning at decreasing reversal fields. Rapid increments and decrements of the drift rate, on the other hand, produce visible gaps between consecutive curves and overlaps, respectively. These irregularities are particularly evident near positive saturation. **(b)** Drift-corrected FORC measurements, obtained by setting  $SF_d = 3$  with INPUT 11. **(c-d)** FORC diagrams obtained from original (c) and drift-corrected (d) FORC measurements. In both cases, the same processing options (i.e. a constant smoothing factor of 5) and color scales have been used. Drift-related errors appear in (c) as diagonal stripes crossing the FORC space. Each stripe corresponds to a sudden change of the drift rate. Such features are almost completely absent in (d).

### INPUT 12. Lower limits for outlier detection/replacement

Electromagnetic or mechanical measurement disturbances produce anomalous measurements that appear as outliers in regression residuals plots (Fig. 3.14a). Sometimes, these disturbances last over several measurements, producing instabilities that alter significant parts of individual curves (Fig. 3.14b). Such instabilities degrade the quality of FORC diagrams also over nearby domains covered by undisturbed measurements, up to the size of regression regions used during FORC processing.



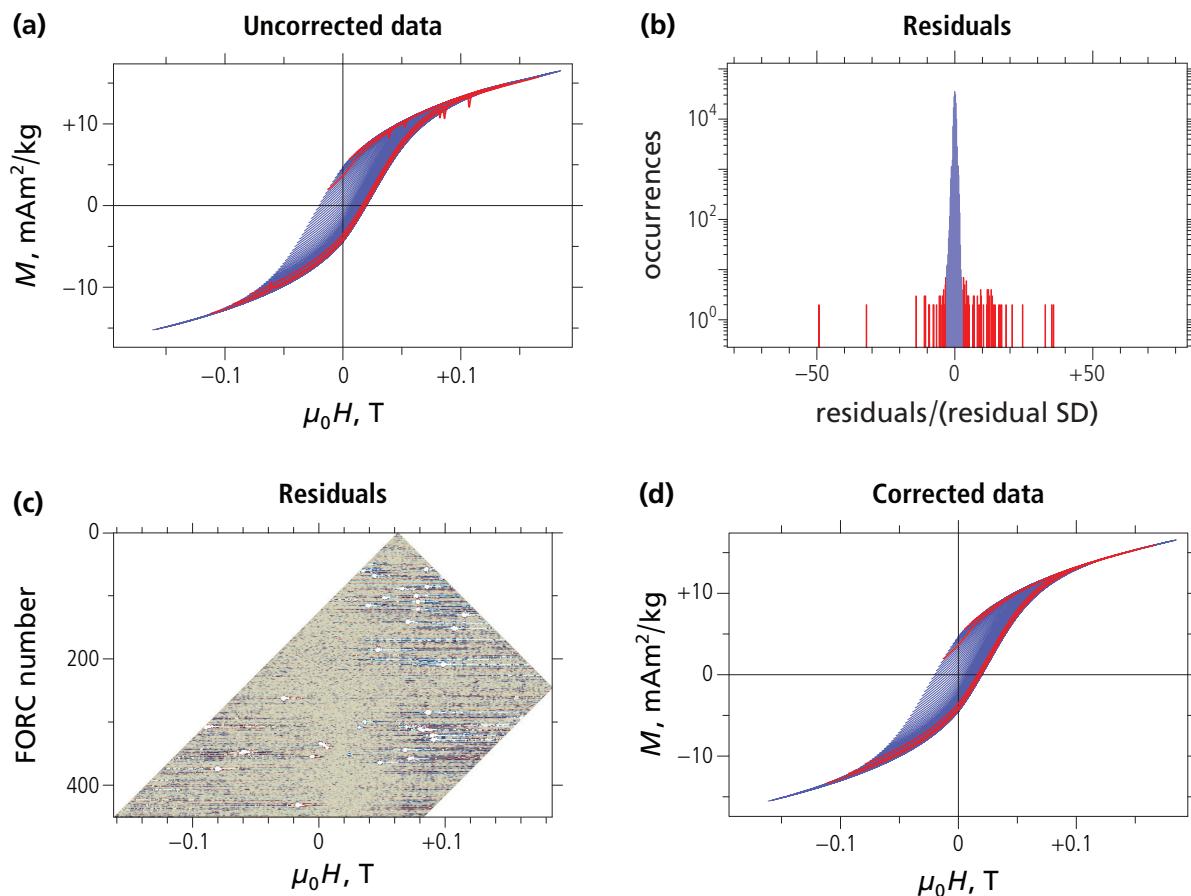
**Fig. 3.14:** Polynomial regression residuals for two MicroMag™ AGM measurements of the same pelagic carbonate specimen (see the downloadable example “pelagic carbonate”). The color scale runs from blue (negative) to red (positive). Each pixel row corresponds to a single curve. Outliers exceeding the color scale range appear as white pixels. In (a), residuals contain isolated outliers (some are highlighted by red circles). In (b), parts of individual curves are characterized by measurement instabilities with large residuals (horizontal stripes, some highlighted by red rectangles).

ImportFORC can identify and remove isolated outliers, as well as whole unstable curves, and replace them with measurements extrapolated from neighbor curves. This operation is performed on the basis of cubic polynomial regression of FORC measurements using the smoothing factor SF defined with INPUT 10. Regression residuals of undisturbed measurements are described by a statistical distribution with standard deviation  $\varepsilon$ , which reflects the random nature of measurement errors (Fig. 3.15). So-called *outliers* are defined as measurements producing regression residuals with amplitudes exceeding a user-defined threshold  $r_1 = \lambda_1 \varepsilon$ , which is expressed as given multiple  $\lambda_1$  of the residual standard deviation  $\varepsilon$ . The parameter  $\lambda_1 > 0$  represents the first entry of INPUT 12, and ensures that all measurements with residual amplitudes  $> \lambda_1 \varepsilon$  are excluded from error calculations. An additional threshold  $r_2 = \lambda_2 \varepsilon$  is defined by the second entry  $\lambda_2$  of INPUT 12, and represents the limit above which measurements with residual amplitudes  $> \lambda_2 \varepsilon$  are replaced by extrapolations obtained from neighbor points.

INPUT 12 consists of a pair of positive standard deviation multipliers  $\lambda_1, \lambda_2$  with  $\lambda_2 \geq \lambda_1$ , e.g.:

INPUT 12. Lower limits for outlier detection/replacement ....; 2, 3

for  $\lambda_1=2$  and  $\lambda_2=3$ . The standard deviation multipliers can be any positive number  $\geq 1$ ; however, statistical considerations restrict the range of meaningful values that should be entered with INPUT 12 to numbers  $\geq 2$ .



**Fig. 3.15:** Outlier identification example based on MicroMag™ AGM measurements of a pelagic carbonate sample (see the downloadable example “pelagic carbonate”). **(a)** Original FORC measurements with curves affected by spikes highlighted in red. **(b)** Histogram of polynomial regression residuals normalized by their standard deviation  $\varepsilon$ . Residual amplitudes  $>3\varepsilon$  are highlighted in red. Even if they represent a vanishing fraction of all FORC measurements (notice the logarithmic scale of counts), they degrade the quality of FORC processing results. **(c)** Regression residuals as a function of applied field and FORC number (same as Fig. 3.14a), where outlier amplitudes  $>3\varepsilon$  are represented by white pixels. Isolated spikes are clearly recognizable. Outliers are replaced by extrapolation of neighbor curves. **(d)** Corrected FORC measurements with removed outliers. INPUT 12 parameters used for this example were 2, 3 (i.e. residual amplitudes  $>2\varepsilon$  are ignored in error calculations, and measurements corresponding to residual amplitudes  $>3\varepsilon$  are replaced by extrapolated values).

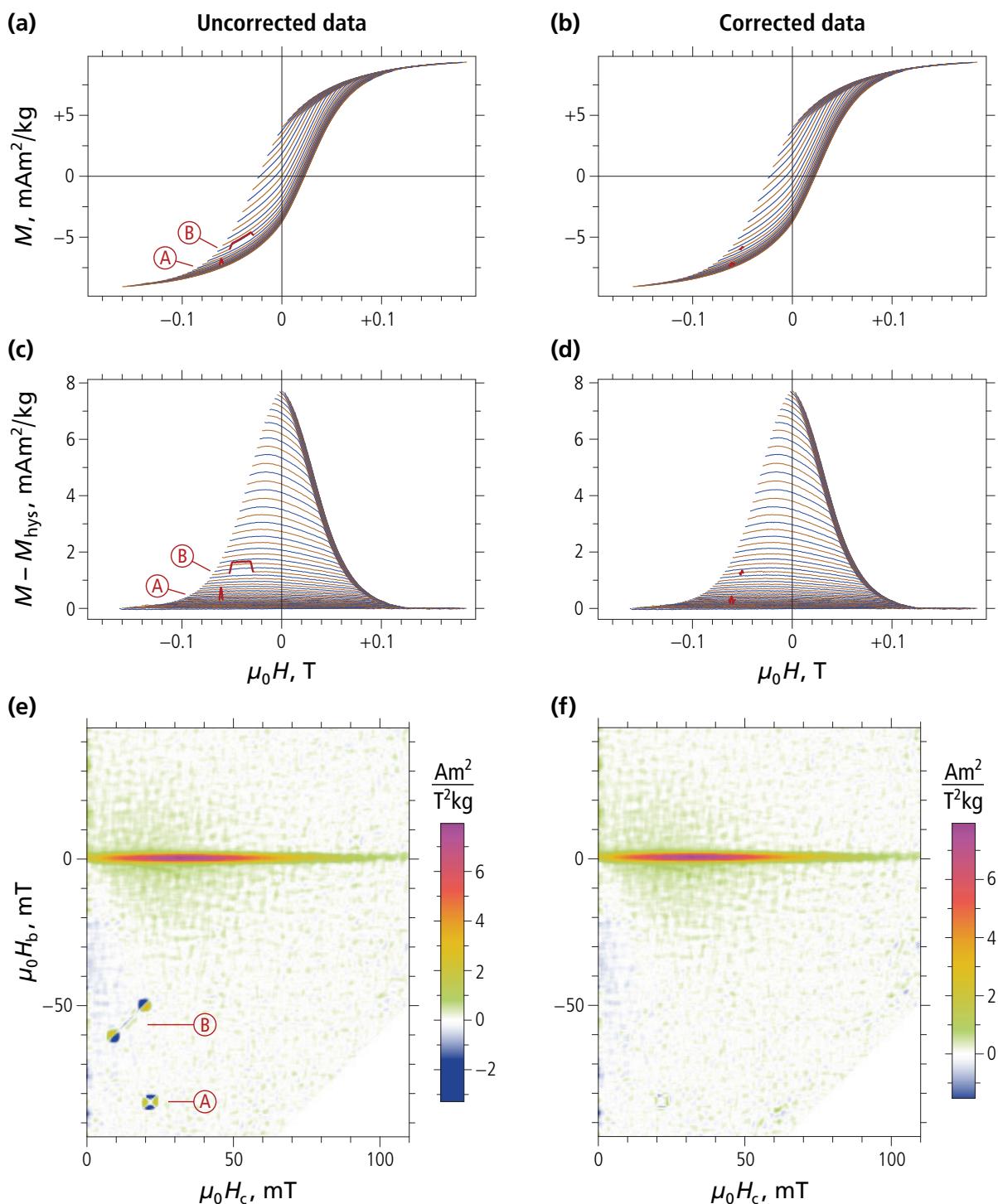
If measurement errors are described by a Gaussian probability function with standard deviation  $\varepsilon$ ,  $\sim 32\%$  of all error amplitudes exceed  $\varepsilon$ ,  $\sim 4.6\%$  of all errors amplitudes exceed  $2\varepsilon$ ,  $\sim 1.2\%$  of all error amplitudes exceed  $2.5\varepsilon$ , and only  $\sim 0.3\%$  of all error amplitudes exceed  $3\varepsilon$ . Because outliers are rare events by definition,  $\lambda_1$ ,  $\lambda_2$  should always be  $\geq 2$ . All measurements are taken into consideration without outlier removal if a very large value of  $\lambda_2$  (e.g. 100) is entered.

The effect of outlier removal on FORC processing is shown in Fig. 3.16 for two common types of measurement disturbances, i.e. a single incorrect point and a group of vertically shifted points.

- 💡 Outlier identification and exclusion is suppressed by choosing  $\lambda_1, \lambda_2 \gg 1$  (e.g. INPUT 12 is 50, 50). In this case, all measurements are considered equally valid.
- 💡 Outliers can be excluded only from error calculations by choosing  $\lambda_2 \gg 1$  (e.g. INPUT 12 is 2, 50).
- 💡 The same outliers are excluded from error and FORC calculations by choosing  $\lambda_1 = \lambda_2$  (e.g. INPUT 12 is 2.5, 2.5). This is the recommended default choice.

- The smaller is  $\lambda_2$ , the more measurements have to be replaced by extrapolation, the higher is the risk of introducing extrapolation artifacts. The amount of replaced points can be seen in residuals plots produced by ImportFORC (e.g. white pixels in Fig. 3.14). Check that such points are sufficiently isolated and surrounded by regular measurements.

**Fig. 3.16** (front page): Outlier correction example based on MicroMag™ AGM measurements of a pelagic carbonate sample (see the downloadable example “pelagic carbonate”). (a) Original FORC measurements with two measurement disturbances added for demonstration purposes: an isolated spike (A) and a group of offset points (B), both highlighted in red, as sometimes seen in real measurements. (b) Same as (a), after outlier correction with  $\lambda_1 = \lambda_2 = 3$  (i.e. INPUT 12 is set to 3, 3).



**Fig. 3.16 (continued):** (c-d) Uncorrected and corrected measurements after subtraction of the lower hysteresis branch. The replacement of anomalous points with values extrapolated from regular measurements is clearly visible (red curve segments). (e-f) FORC diagrams obtained with CalculateFORC from the uncorrected and corrected measurements shown in (a-b). According to the definition of FORC function as mixed derivative of measured curves with respect to  $H_r$  and  $H$ , a line of shifted points within a single curve (labeled as B in (a) and (c)), produces two FORC diagram anomalies corresponding to the beginning and the end of the shifted measurements, where both  $M/H_r$  and  $M/H$  are very large.

### INPUT 13. Maximum amplitude of the residuals color scale

As discussed with INPUT 12, measurement errors are estimated by analyzing polynomial regression residuals. These residuals are plotted on a two-dimensional map of the measured FORC space (Fig. 3.17), with a color scale ranging from blue (negative values) to red (positive values) through gray (zero). The color scale is usually dominated by few outliers, so that most residuals appear in gray, unless the range of residual amplitudes covered by the color scale is limited. This limit is entered with INPUT 13 as multiple of the standard deviation  $\varepsilon$  of the regression residuals, in analogy to INPUT 12. For example,

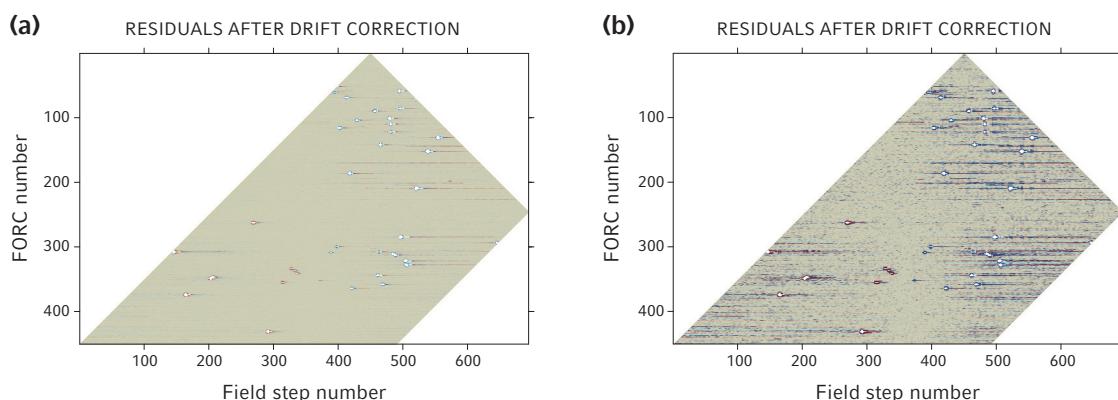
```
INPUT 13. Maximum amplitude of the residuals color scale .....; 3
```

means that regression residuals with amplitudes  $>3\varepsilon$  are plotted with the same saturated blue or red color, depending on their sign. On the other hand, regression residual amplitudes exceeding the replacement limit set by INPUT 12 are plotted as white pixels. If the color scale extension coincides with the replacement limit of set by INPUT 12, e.g.:

```
INPUT 12. Lower limits for outlier detection/replacement ....; 2, 3
```

```
INPUT 13. Clipping limit for color scale of residuals .....; 3
```

all residuals below the replacement limit are represented with a regular color scale. This is the recommended choice for INPUT 13.



**Fig. 3.17:** Regression residuals of MicroMag™ AGM measurement of a pelagic carbonate sample (see the downloadable example “pelagic carbonate”). The measurements contain isolated disturbances of unknown origin, which are shown in Fig. 3.15. The outlier replacement limit (INPUT 12) is 15 for both plots, and residuals in excess of this limit are represented by white pixels. On the other hand, the color scale amplitude (INPUT 13) is 15 in (a) and 3 in (b). Residual details are visible only in (b), because the color scale extends only over “regular” measurement residuals comprised between  $\pm 3$  standard deviations.



Choose a color scale clipping limit (INPUT 13) of 2-3 for best visualization of regression residuals.

#### INPUT 14. FORC plotting options

ImportFORC plots each set of imported FORC measurements before drift correction, as well as the corrected measurements. Because the number of measured curves is usually  $>100$ , and even  $>400$  for high-resolution measurements, individual curves might be fully undistinguishable on such plots. Therefore, the number of plotted curves can be reduced according to criteria specified with INPUT 14. The simplest choice for INPUT 14 is:

```
INPUT 14. FORC plotting options ....; Automatic
```

in which case the number of plotted curves is reduced to about 100. This gives reasonable results if the hysteresis loop is sufficiently opened. Less curves should be plotted in case of materials characterized by almost closed hysteresis loops, as for many geological samples (Fig. 3.18a), while more curves should be plotted in case of materials characterized by squared hysteresis loops (Fig. 3.18b).

In many cases, best results are obtained by specifying the number of plotted curves explicitly. For example,

```
INPUT 14. FORC plotting options ....; 200
```

attempts to plot 200 curves by skipping a certain number of curves between plotted ones. On the other hand,

```
INPUT 14. FORC plotting options ....; All
```

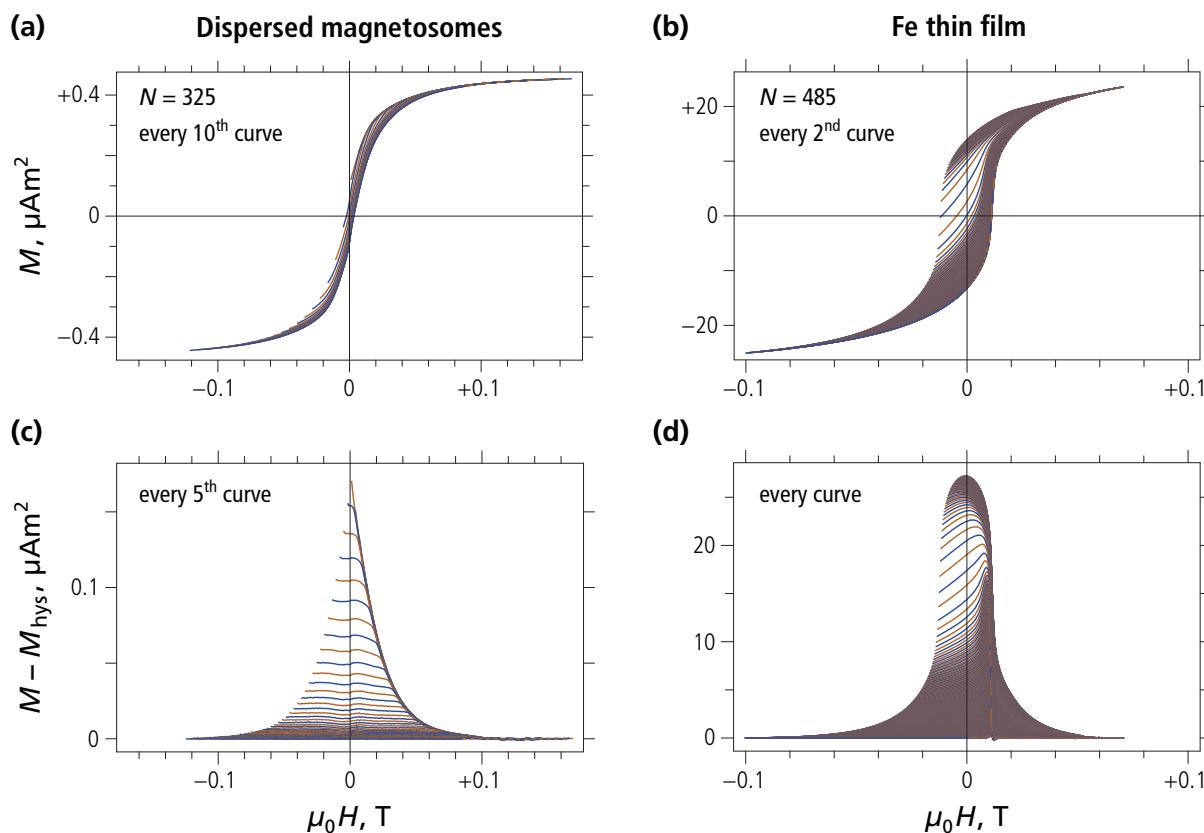
is used to plot all curves.

FORC plots can be controlled even more precisely by defining INPUT 14 as a couple of positive integers. In this case, the first integer represents the number of the first curve to be plotted; while the second integer specifies every how many curves one is plotted. For example,

```
INPUT 14. FORC plotting options ....; 5, 10
```

tells ImportFORC that the first curve to be plotted is the 5<sup>th</sup> one, and that every 10<sup>th</sup> curve is plotted from the 5<sup>th</sup> on.

- 💡 100 is a reasonable number of curves to be plotted as first trial, and is used when INPUT 14 is set to Automatic.
- 💡 The first FORCs are always very short and appear practically as single points. Therefore they are best skipped, as done by ImportFORC if INPUT 14 is set to Automatic or is defined by a single number. The number of skipped initial curves is specified explicitly if INPUT 14 is defined by a pair of integers.



**Fig. 3.18:** FORC plotting examples based on measurements of (a) magnetosomes dispersed in a clay matrix (see the downloadable example “dispersed magnetosomes”), and (b) a Fe thin field. The two examples are representative for materials with moderately closed hysteresis loops (as most geological samples), and very rectangular hysteresis loops, respectively. Even if similar numbers  $N$  of curves have been measured, curve spacing is very different in the two cases. In order to avoid excessive crowding, the number of plotted curves has been reduced by (a) a factor 10 (i.e. INPUT 13 is set to 32 or to 10, 10), and by (b) a factor 2 (i.e. INPUT 13 is set to 242 or to 2, 2). (c-d) Measurement differences obtained by subtracting the lower hysteresis branch from the curves in (a-b). Because curve spacing is always larger in this kind of measurement representation, ImportFORC automatically doubles the number of plotted curves with respect to the case of original measurements.

## INPUT 15. Field units and calibration

INPUT 15 controls the field unit management of ImportFORC and determines which field unit is used in all steps of FORC processing. INPUT 15 consists of three comma-separated entries. The first entry sets the unit of magnetic field measurements stored in the measurement file. Usually, the field unit is reported in the file header or as column label. Older measurement files produced by MicroMag™ magnetometers might indicate field and magnetization units as "SI", "hybrid SI" and "CGS", in which case the field unit is T ("SI" or "hybrid SI") or Oe ("CGS"). The third and last entry of INPUT 15 sets the output field unit that will be used for plotting and exporting FORC data, as well as for any subsequent processing with VARIFORC modules. The second entry of INPUT 15 is a positive number representing a field calibration factor. Usually, magnetometers are properly calibrated, in which case the calibration factor to be entered is 1. If field measurements were not calibrated correctly, the calibration factor is positive number by which all field measurements must be multiplied in order to obtain correct values.

For example, the following parameters for INPUT 15:

```
INPUT 15. Field units and calibration .....; oe, 1, t
```

are entered if the measurement file contains calibrated field measurements in Oe (Oesterd), which should be converted into Tesla (T). ImportFORC recognizes all S.I. and C.G.S. field units, as well as power-of-ten unit multipliers (e.g. 1e-3 T) and S.I. prefixes (e.g. mT). Valid S.I. prefixes and unit abbreviations are listed in [Table 3.2](#) and [Table 3.3](#), respectively.

S.I. field units specified with INPUT 15 can refer to the magnetic field  $H$  (A/m), as well as the magnetic induction  $B = \mu_0 H$  (T) associated with the magnetic field  $H$  in air. The second option is widespread, whereby  $B$  is often interchanged with  $H$ .

**Table 3.2:** S.I. prefixes and multipliers recognized by ImportFORC, with corresponding abbreviations accepted in INPUT 15. Prefixes can precede units directly (e.g. mT, but also m T), while numeric multipliers must be separated from the corresponding unit by an empty space (e.g. 1e-3 T).

SI prefix	Symbol	Factor	Abbreviation for INPUT 15
Femto	f	$10^{-15}$	f, 1e-15, 1E-15, 10^-15
Pico	p	$10^{-12}$	p, 1e-12, 1E-12, 10^-12
Nano	n	$10^{-9}$	n, 1e-9, 1E-9, 10^-9, 1e-09, 1E-09, 10^-09
Micro	μ	$10^{-6}$	μ, micro, 1e-6, 1E-6, 10^-6, ...
Milli	m	$10^{-3}$	m, 1e-3, 1E-3, 10^-3, 1e-03, 1E-03, 10^-03
Kilo	k	$10^{+3}$	k, 1e3, 1E3, 10^3, 1e+3, ..., 1e03
Mega	M	$10^{+6}$	M, 1e6, 1E6, 10^6, 1e+6, ..., 1e06

**Table 3.3:** Field units recognized by ImportFORC and corresponding abbreviations to be used with INPUT 15.

Unit name	Symbol	INPUT 15	Conversion to S.I.	Conversion to C.G.S.
<i>S.I. unit for H</i> A/m	A/m	A/m, A m <sup>-1</sup> , A m <sup>-1</sup>	1 A/m = $4\pi \times 10^{-7}$ T	1 A/m = $4\pi \times 10^{-3}$ Oe
<i>S.I. unit for B</i> Tesla	T	T	1 T = $10^7 / (4\pi)$ A/m	1 T = $10^4$ Oe
<i>C.G.S. units</i>				
Oesterd	Oe	Oe	1 Oe = $10^{-4}$ T	1 Oe = 1 G
Gauss	G	G	1 G = $10^{-4}$ T	1 G = 1 Oe

Field unit and SI prefix specifications with INPUT 15 are based on intuitive rules described in the following:

- 1) S.I. prefixes and unit multipliers always precede the unit name (e.g. mT and not Tm).
- 2) S.I. prefixes can be entered with their official symbol (e.g. m, μ, n), according to [Table 3.2](#), or as corresponding multipliers (e.g. 1e-3, 1e-6, 1e-9). The S.I. prefix “micro” can be entered as symbol (i.e. μ) or by its full name (i.e. micro).
- 3) Unit multipliers must be powers of 10. Multipliers that do not correspond to S.I. prefixes can be entered as well (e.g. 1e-4, 1e-5).
- 4) Unit multipliers can be entered as full numbers (e.g. 0.01, 100) and with scientific notation (e.g. 1e3, 1E3, 1e+3, 1E+3, 1e03, 1E03, 1e+03, 1E+03, 10^3).
- 5) An empty space between unit multipliers and units is mandatory (e.g. 1e-3 T, and not 1e-3T), while it is not necessary between S.I. prefixes and units (e.g. μT, microT, and also μ T, micro T).
- 6) Fundamental unit names are given by their abbreviation according to [Table 3.3](#) (e.g. T, Oe). Composite units are entered as sequence of fundamental units followed by their exponent and separated by an empty space in case of multiplication and by a slash (/) in case of division (e.g. A/m, A m<sup>-1</sup>, A m<sup>-1</sup>).

If the output unit specified in INPUT 15 differs from the original unit, ImportFORC automatically performs a unit conversion according to [Table 3.3](#), so that all results are expressed in output units, taking also S.I. prefixes and unit multipliers into account. For example, the following two definitions of INPUT 15:

```
INPUT 15. Field units and calibration .....; oe, 1, mt
INPUT 15. Field units and calibration .....; oe, 1, 1e-3 T
```

produce the same unit transformation according to which 1000 Oe are converted to 100 mT.

- 💡 For best appearance of FORC plots produced by ImportFORC, choose appropriate S.I. prefixes that avoid very large numbers. For example, if FORC measurements are performed over a field range of  $\pm 0.3$  T, best output units are T (e.g. plot ticks every 0.1 T), mT (e.g. plot ticks every 100 mT), and kOe (e.g. plot ticks every 1 kOe).
- 💡 Non-S.I. unit multipliers (e.g. 0.1, 10, 100) can be used but are not recommended.

## INPUT 16. Normalization factor(s) and unit

INPUT 16 is used to normalize measured magnetic moments, and convert them into magnetization values. Magnetometers always measure magnetic dipole moments; therefore, the primary unit of FORC measurements is that of a magnetic moment (S.I.: Am<sup>2</sup>, C.G.S.: emu). Magnetizations are obtained by dividing the magnetic moment by specimen volume (volume magnetization; S.I.: A/m, C.G.S.: emu/cm<sup>3</sup>) or mass (mass magnetization; S.I.: Am<sup>2</sup>/kg, C.G.S.: emu/g). ImportFORC can also deal with surface magnetizations (S.I.: A, C.G.S.: emu/cm<sup>2</sup>), which are most appropriated when dealing with thin films. Volume magnetizations, on the other hand, are best suited to the characterization of pure magnetic materials, and mass magnetizations are best used with heterogeneous materials (e.g. geologic samples).

If measured magnetic moments should be converted into magnetizations, INPUT 16 is used for entering the required normalization factor (e.g. specimen volume, mass, or surface), followed by its unit. The normalization factor is separated from its unit by a comma. For example,

```
INPUT 16. Normalization factor(s) and unit ....; 27.2, mg
```

converts the magnetic moment of a specimen with a mass of 27.2 mg into a mass magnetization. Output magnetizations will be expressed according to original unit of measurements (see INPUT 17) and the normalization unit entered with INPUT 16. Normalization is avoided by entering

```
INPUT 16. Normalization factor(s) and unit ....; 1, none
```

where *none* is the name used for a pure number without unit. In this case, all results are expressed with the same type of unit used for the measurements (e.g. magnetic moments).

As with INPUT 15, S.I. prefixes and unit multipliers can be used. For example, the following INPUT 16 specifications

```
INPUT 16. Normalization factor(s) and unit ....; 27.2, mg
INPUT 16. Normalization factor(s) and unit ....; 0.0272, g
INPUT 16. Normalization factor(s) and unit ....; 27.2, 1e-3 g
INPUT 16. Normalization factor(s) and unit ....; 27.2, 1e-6 kg
```

are equivalent and correspond to normalization with a specimen mass of 27.2 mg. Accepted S.I. and C.G.S. units for mass, volume, and area are listed in [Table 3.4](#), and valid S.I. prefixes are given in [Table 3.2](#). Notice that cm is the C.G.S. unit of length, where “c” is part of the unit name rather than the prefix corresponding to 10<sup>-2</sup>. Accordingly, 1 cm<sup>3</sup> corresponds to 10<sup>-6</sup> m<sup>3</sup>, and not to 0.01 m<sup>3</sup>. Masses, volumes, and areas can be entered with any unit listed in [Table 3.4](#), regardless of measurement units: for example a volume in cm<sup>3</sup> can be used for normalizing a magnetic moment in Am<sup>2</sup>. ImportFORC performs all unit conversions required to obtain a consistent S.I. or C.G.S. output unit as specified by INPUT 17.

**Table 3.4:** Volume, area, and mass units recognized by ImportFORC and corresponding abbreviations accepted with INPUT 16.

Unit name	Symbol	INPUT 16	Conversions
Volume m <sup>3</sup>	m <sup>3</sup> cm <sup>3</sup>	m3, m^3 cm3, cm^3	1 cm <sup>3</sup> = 10 <sup>-6</sup> m <sup>3</sup>
Area m <sup>2</sup>	m <sup>2</sup> cm <sup>2</sup>	m2, m^2 cm2, cm^2	1 cm <sup>2</sup> = 10 <sup>-4</sup> m <sup>2</sup>
Mass kg	kg g mg	kg, 1e3 g, ... g mg, 1e-3 g, ...	1 kg = 10 <sup>3</sup> g 1 mg = 10 <sup>-3</sup> g

ImportFORC support the processing of multiple FORC measurements of the same specimen or different specimens of the same material. In the latter case, measurements have to be normalized individually by specimen mass, volume, or area. For this purpose, a series of normalization factors corresponding to the alphabetically sorted measurement files can be entered with INPUT 16. For example, if specimen 1, specimen 2, and specimen 3 have masses of 22.1, 27.2, and 25.4 mg, respectively, and corresponding measurements have been saved as spec2.txt, spec1.txt, and spec3.txt, respectively, INPUT 16 is given by:

```
INPUT 16. Normalization factor(s) and unit ....; 27.2, 22.1, 25.4, mg
```

where individual masses, as well as the final unit, are separated by commas. If a single normalization factor is entered, ImportFORC assumes that multiple measurements of the same specimen have been performed and normalize all dataset by the same factor. If several normalization factors are entered, their total number must coincide with that of uploaded measurement files; otherwise the program is terminated after producing the following error message:

```
Number of normalization factors does not coincide with number of measurement files
[INPUT 16]. Program aborted.
```

- Caution should be used when processing multiple specimen measurements in order to avoid normalization errors. Normalization factors in INPUT 16 are automatically allocated to measurement files sorted by their name. Therefore, all measurement files should be named so, that alphabetical sorting is absolutely unambiguous.

- File sorting ambiguities, are best avoided by combining a common name with a progressive number, e.g. spec1.txt, spec2.txt. If you import more than 9 files, be careful to use trailing zeroes, e.g. spec01.txt, spec02.txt, etc.
- Normalization factors of multiple measurements must share the same unit.
- File naming is irrelevant in case of multiple measurements of the same specimen, because only a single normalization factor is required.

- 💡 The unit management of ImportFORC helps defining correct FORC units that are used in subsequent processing steps. Quantitative analysis of FORC diagrams is possible only within a consistent unit system. For this reason, measurement units should be properly normalized.
- 💡 The ImportFORC unit management is disabled if the measurement and/or output magnetization units are set to `none` (see INPUT 17). In this case, arbitrary conversions between unrecognized or incorrect units can be performed through the normalization factor.
- 💡 MicroMag™ magnetometers use proper magnetic moment or magnetization units, which are fully compatible with the ImportFORC unit management. On the other hand, improper measurements units based on default specimen volumes or masses (e.g. A/m, assuming a specimen volume of 10 cm<sup>3</sup>) can be corrected through a unitless normalization. For example, measurements in A/m of a specimen with a real mass of 1 g, based on a default volume of 10 cm<sup>3</sup>, can be converted to a proper mass magnetization in Am<sup>2</sup>/kg by entering 100, none with INPUT 16 (the normalization factor is obtained by multiplying A/m with 10 cm<sup>3</sup> = 10<sup>-5</sup> m<sup>3</sup> and dividing the result by 1 g = 10<sup>-3</sup> kg, which is equivalent to multiplying by 10<sup>-2</sup> or dividing by 100).

### INPUT 17. Magnetization units and calibration

INPUT 17 determines the output magnetization unit that will be used by all VARIFORC modules. It is given by three entries separated by commas. The first entry is the unit of magnetic moment measurements stored in the measurement file. Usually, the magnetic moment unit is reported in the file header or as column label. Older measurement files produced by MicroMag™ magnetometers might refer to field and magnetization units as "SI", "hybrid SI" and "CGS", in which case magnetic moment unit is Am<sup>2</sup> ("SI" or "hybrid SI") or emu ("CGS"). The third and last entry of INPUT 17 is the output magnetization unit used for plotting and exporting FORC data, as well as for any subsequent processing with other VARIFORC modules. The second entry of INPUT 17 is a positive number representing a calibration factor for magnetic moment measurements. Usually, measurements are correctly calibrated if proper specimen mounting and centering procedures are used, in which case you enter 1 as calibration factor. If measurements were not calibrated correctly (for example because of bad centering), a correction (calibration) factor can be entered. This factor is the positive number with which all magnetic moment measurements must be multiplied in order to obtain correctly calibrated values.

For example, the following INPUT 17 parameters are entered:

```
INPUT 17. Magnetization units and calibration .....; emu, 1, Am2/kg
```

if the measurement file contains calibrated magnetic moment measurements in emu that should be converted into a mass magnetization expressed in Am<sup>2</sup>/kg. If the output unit is a different physical quantity with respect to the original unit (e.g. magnetic moment and mass magnetization), unit conversion requires a proper normalization to be entered with INPUT 16 (e.g. the specimen mass). Incompatible combinations of magnetization and normalization units entered with INPUT 16 and INPUT 17 (e.g. Am<sup>2</sup> to be converted to Am<sup>2</sup>/kg by normalization with 1 cm<sup>3</sup>) will terminate ImportFORC with the following error message:

Incompatible output magnetization unit! Program aborted.

On the other hand, different unit systems (i.e. S.I. and C.G.S.) can be always be combined.

ImportFORC recognizes S.I. and C.G.S. magnetic moment and magnetization units, as well as unit multipliers (e.g. 1e-3 Am<sup>2</sup>) and S.I. prefixes (e.g. mAm<sup>2</sup>). Valid S.I. prefixes and magnetic units are listed in [Table 3.2](#) and [Table 3.5](#), respectively.

- ImportFORC checks the consistency between measurement units and output units through the specifications given with INPUT 16 and INPUT 17. Inconsistent specifications are not accepted unless the measurement and/or magnetization unit is labeled as **none**. In this case, the unit management is disabled and normalization is performed using the numerical factor entered with INPUT 16, without further conversions. All unit factors and S.I. prefixes preceding a unit labeled as **none** are ignored.

**Table 3.5:** Magnetization units recognized by ImportFORC and corresponding abbreviations accepted with INPUT 17.

Unit name	Symbol	INPUT 17	Conversions
<i>Magnetic moment</i> Am <sup>2</sup> emu	Am <sup>2</sup> emu	Am2, A m2, A m <sup>2</sup> emu	1 Am <sup>2</sup> =10 <sup>3</sup> emu 1 emu=10 <sup>-3</sup> Am <sup>2</sup>
<i>Volume magnetization</i> A/m emu/cm <sup>3</sup>	A/m emu/cm <sup>3</sup>	A/m, A m <sup>-1</sup> , A m <sup>-1</sup> emu/cm <sup>3</sup> , emu cm <sup>-3</sup> , ...	1 A/m=10 <sup>-3</sup> emu/cm <sup>3</sup> 1 emu/cm <sup>3</sup> =10 <sup>3</sup> A/m
<i>Volume magnetization</i> A/m emu/cm <sup>3</sup>	A/m emu/cm <sup>3</sup>	A/m, A m <sup>-1</sup> , A m <sup>-1</sup> emu/cm <sup>3</sup> , emu cm <sup>-3</sup> , ...	1 A/m=10 <sup>-3</sup> emu/cm <sup>3</sup> 1 emu/cm <sup>3</sup> =10 <sup>3</sup> A/m
<i>Surface magnetization</i> A emu/cm <sup>2</sup>	A emu/cm <sup>2</sup>	A emu/cm <sup>2</sup> , emu cm <sup>-2</sup> , ...	1 A=0.1 emu/cm <sup>2</sup> 1 emu/cm <sup>2</sup> =10 A
<i>Mass magnetization</i> Am <sup>2</sup> /kg emu/g	Am <sup>2</sup> /kg emu/g	Am2/kg, A m <sup>2</sup> kg <sup>-1</sup> , ... emu/g, emu g <sup>-1</sup> , ...	1 Am <sup>2</sup> /kg=1 emu/g 1 emu/g=1 Am <sup>2</sup> /kg

**Example 1:** The measurement unit is emu, and FORC processing results should be expressed in mAm<sup>2</sup>/kg. In this case, the specimen mass (e.g. 0.1 g) is required for normalization. Accordingly, INPUT 16 will be given by 0.1, g, and INPUT 17 by emu, 1, mAm<sup>2</sup>/kg. Measurements will be converted to mAm<sup>2</sup>/kg by multiplication with 10<sup>4</sup> (1 emu=10<sup>-3</sup> Am<sup>2</sup>, Am<sup>2</sup> are converted to Am<sup>2</sup>/kg by division with 10<sup>-4</sup> kg, and 1 Am<sup>2</sup>/kg=10<sup>3</sup> mAm<sup>2</sup>/kg ).

**Example 2:** The measurement unit is emu, and FORC processing results should be expressed in μAm<sup>2</sup>. Normalization is not required, because both units correspond to magnetic moments. Accordingly, INPUT 16 will be given by 1, none, and INPUT 17 by emu, 1, micro Am<sup>2</sup>. Measurements will be converted to μAm<sup>2</sup> by multiplication with a factor 10<sup>-3</sup> (1 emu=10<sup>-3</sup> Am<sup>2</sup>, and 1 Am<sup>2</sup>=10<sup>-6</sup> μAm<sup>2</sup> ).

**Example 3:** The measurement unit is A/m, based on a default specimen volume of 1 cm<sup>3</sup>. The real specimen has a mass of 0.1 g and FORC processing results should be expressed in mAm<sup>2</sup>/kg. In this case, measurement units are inconsistent and the ImportFORC unit management is disabled by entering INPUT 17 as none, 1, mAm<sup>2</sup>/kg. The proper unit conversion factor (i.e. 10) must be calculated manually and entered with INPUT 16 as 10, none (the measured magnetic moment in Am<sup>2</sup> is obtained by multiplying measurements with 1 cm<sup>3</sup>=10<sup>-6</sup> m<sup>3</sup>, Am<sup>2</sup> are then normalized by 10<sup>-4</sup> kg, and 1 Am<sup>2</sup>/kg=10<sup>3</sup> mAm<sup>2</sup>/kg ).

The unit management of ImportFORC is essential for later FORC processing steps, especially at the stage where coercivity distributions and magnetizations are derived from FORC data. In this case, magnetization, coercivity, and FORC units must be properly matched. S.I. and C.G.S. magnetization, coercivity distribution, and FORC diagram units managed by VARIFORC modules are listed in [Table 3.6](#).

- Output units defined with ImportFORC are used in all subsequent FORC processing steps without further conversions. For example, magnetic moments in  $\mu\text{Am}^2$  and fields in mT define a coercivity distribution in  $(\mu\text{Am}^2)/(m\text{T})$  which is equivalent to  $\text{mA}\text{m}^2/\text{T}$ .
- Hybrid output field and magnetization units (e.g. magnetization in  $\text{Am}^2/\text{kg}$  and field in Oe) can be used, but such combinations are not recommended, because resulting FORC diagrams and coercivity distributions will be expressed by an inconsistent mixture of S.I. and C.G.S. units. A warning message is produced in this case.

**Tab. 3.6:** Magnetization, coercivity distribution, and FORC diagram units. Only S.I.- and C.G.S.-consistent units are listed. Units followed by (H) and by (B) refer to magnetic fields expressed in A/m and in T, respectively. “linear” and “log” coercivity distributions refer to coercivity distributions calculated for linear and logarithmic field scales, respectively.

Magnetization Coercivity distribution (log)	Coercivity distribution (linear)	FORC diagram
<i>Magnetic moment</i> $\text{Am}^2$ emu	<i>Magnetic moment/field</i> $\text{m}^3$ (H) or $\text{Am}^2/\text{T}$ (B) emu/Oe	<i>Magnetic moment/(field)<sup>2</sup></i> $\text{m}^4/\text{A}$ (H) or $\text{Am}^2/\text{T}^2$ (B) emu/Oe <sup>2</sup>
<i>Volume magnetization</i> $\text{A}/\text{m}$ $\text{emu}/\text{cm}^3$	<i>Magnetization/field</i> — (H) or $\text{A}/(\text{Tm})$ (B) emu/(cm <sup>3</sup> Oe)	<i>Magnetization/(field)<sup>2</sup></i> $\text{m}/\text{A}$ (H) or $\text{A}/(\text{T}^2\text{m})$ (B) emu/(cm <sup>3</sup> Oe <sup>2</sup> )
<i>Surface magnetization</i> $\text{A}$ $\text{emu}/\text{cm}^2$	<i>Magnetization/field</i> $\text{m}$ (H) or $\text{A}/\text{T}$ (B) emu/(cm <sup>2</sup> Oe)	<i>Magnetization/(field)<sup>2</sup></i> $\text{m}^2/\text{A}$ (H) or $\text{A}/\text{T}^2$ (B) emu/(cm <sup>2</sup> Oe <sup>2</sup> )
<i>Mass magnetization</i> $\text{Am}^2/\text{kg}$ emu/g	<i>Magnetization/field</i> $\text{m}^3/\text{kg}$ (H) or $\text{Am}^2/(\text{kg T})$ (B) emu/(g Oe)	<i>Magnetization/(field)<sup>2</sup></i> $\text{m}^4/(\text{kg A})$ (H) or $\text{Am}^2/(\text{kg T}^2)$ (B) emu/(g Oe <sup>2</sup> )

**Example 1:** Output units “mT” for the magnetic field and “ $\mu\text{Am}^2/\text{kg}$ ” for the mass magnetization produce coercivity distributions expressed in  $\text{mAm}^2/(\text{kg T})$ , and FORC diagrams expressed in  $\text{Am}^2/(\text{kg T}^2)$ .

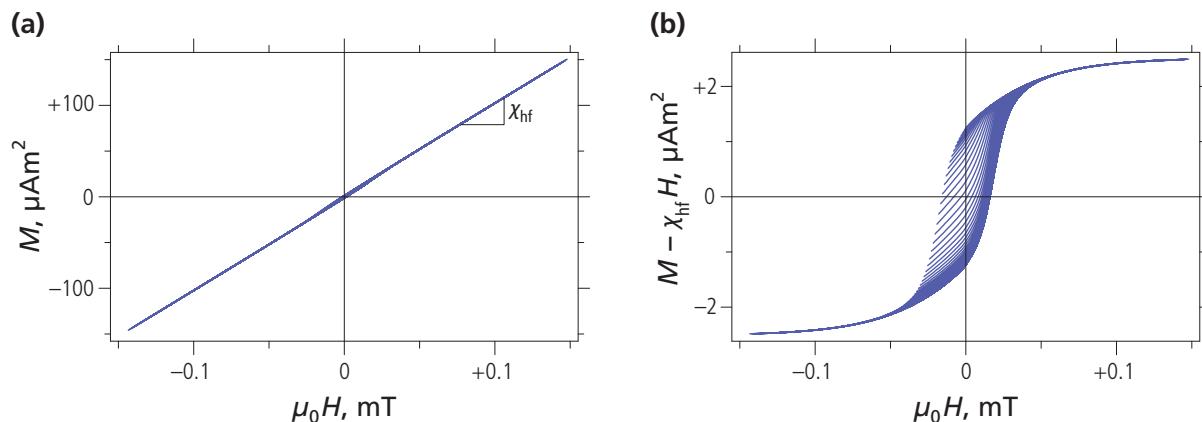
**Example 2:** Output units “kOe” for the magnetic field and “ $\text{Am}^2/\text{kg}$ ” for the mass magnetization produce coercivity distributions expressed in  $\text{mAm}^2/(\text{kg Oe})$ , and FORC diagrams expressed in  $\mu\text{Am}^2/(\text{kg Oe}^2)$ . Such hybrid S.I. and C.G.S. units are inconsistent and should be avoided.

- 💡 For best appearance in plots and compact export files, choose appropriate SI prefixes that avoid very small magnetization values. For example, if the saturation magnetization is  $5 \times 10^{-3} \text{ Am}^2/\text{kg}$ , the most appropriated output unit is  $\text{mAm}^2/\text{kg}$ . If the specimen coercivity is of the order of 10 mT, as commonly the case for magnetite, the order of magnitudes of coercivity distribution and FORC diagram amplitudes will be  $\sim 1 \text{ Am}^2/(\text{kg T})$  and  $\sim 100 \text{ Am}^2/(\text{kg T}^2)$ .
- 💡 Non-SI unit multipliers (e.g. 0.1, 10, 100) are possible but not recommended.
- 💡 Quantitative analysis of FORC diagrams is possible only with proper unit handling.
- 💡 The ImportFORC unit management is disabled if the input and/or output magnetization units are set to none.

### INPUT 18. High-field limit for paramagnetic correction

FORC measurements of geologic samples are often dominated by a field-proportional magnetization  $M_{\text{hf}} = \chi_{\text{hf}} H$  due to the high-field susceptibility  $\chi_{\text{hf}}$  of dia-, para-, and antiferromagnetic minerals. This magnetization does not contribute to the FORC diagram and is therefore irrelevant to FORC processing. However, subtraction of  $M_{\text{hf}}$  in what is called a *paramagnetic correction* is necessary for the calculation of the saturation magnetization  $M_s$ , and useful for a better representation of FORC measurements (Fig. 3.19).

Proper paramagnetic corrections require measurements to extend well into the saturation range of hysteresis (i.e. where the two branches are perfectly overlapped). This condition is rarely met by FORC measurement protocols, whose aim is to cover the field range where most irreversible magnetization processes occur. Nevertheless, ImportFORC offers the possibility to perform this correction with available measurements through options entered with INPUT 18, INPUT 19, and INPUT 20.



**Fig. 3.19:** Example of paramagnetic correction applied to FORC measurements dominated by a large high-field susceptibility. **(a)** Original measurements where ferrimagnetic contributions are barely distinguishable. The slope of all curves over the saturation range coincides with the high-field susceptibility  $\chi_{\text{hf}}$ . **(b)** Same measurements after subtraction of  $M_{\text{hf}} = \chi_{\text{hf}} H$ . The single-domain nature of ferrimagnetic contributions is now clearly visible.

- Paramagnetic corrections involve the subtraction of the same (linear) magnetization curve  $M_{\text{hf}} = \chi_{\text{hf}} H$  from all measurements and do therefore not affect FORC processing.
- In some cases, FORC measurements extend well enough into the saturation range of hysteresis (e.g. Fig. 3.19), so that reliable estimates of the saturation magnetization can be obtained.

A paramagnetic corrections is not performed upon choosing the following option

`INPUT 18. High-field limit for paramagnetic correction ....; None`

In this case, the related input parameters INPUT 19 and INPUT 20 will be ignored. Otherwise, INPUT 18 represents the lower limit  $H_s$  of the so-called *saturation range*  $|H| > H_s$  of hysteresis. This range is used to estimate the high-field susceptibility required for the paramagnetic correction. The simplest way of choosing this range is by the automatic option

`INPUT 18. High-field limit for paramagnetic correction ....; Automatic`

in which case ImportFORC identifies  $H_s$  with 80% of the largest field amplitude used for FORC measurements. A similar criterion is used by the MicroMag™ control software for default paramagnetic correction of hysteresis loops. Alternatively, you can enter the high-field limit explicitly, e.g.

`INPUT 18. High-field limit for paramagnetic correction ....; 0.1`

for the example of Fig. 3.19a, where the saturation is assumed to begin above 0.1 mT. Explicit high-field limits must be expressed in output field units. Because the hysteresis properties are usually unknown before FORC processing is started, a preliminary ImportFORC run with INPUT 18 set to Automatic is recommended before entering explicit limits. If the chosen high-field limit exceeds the measurement range, the following warning message

`WARNING: Measurements do not extend over sufficiently large fields, as required  
by INPUT 18! A paramagnetic correction will not be performed.`

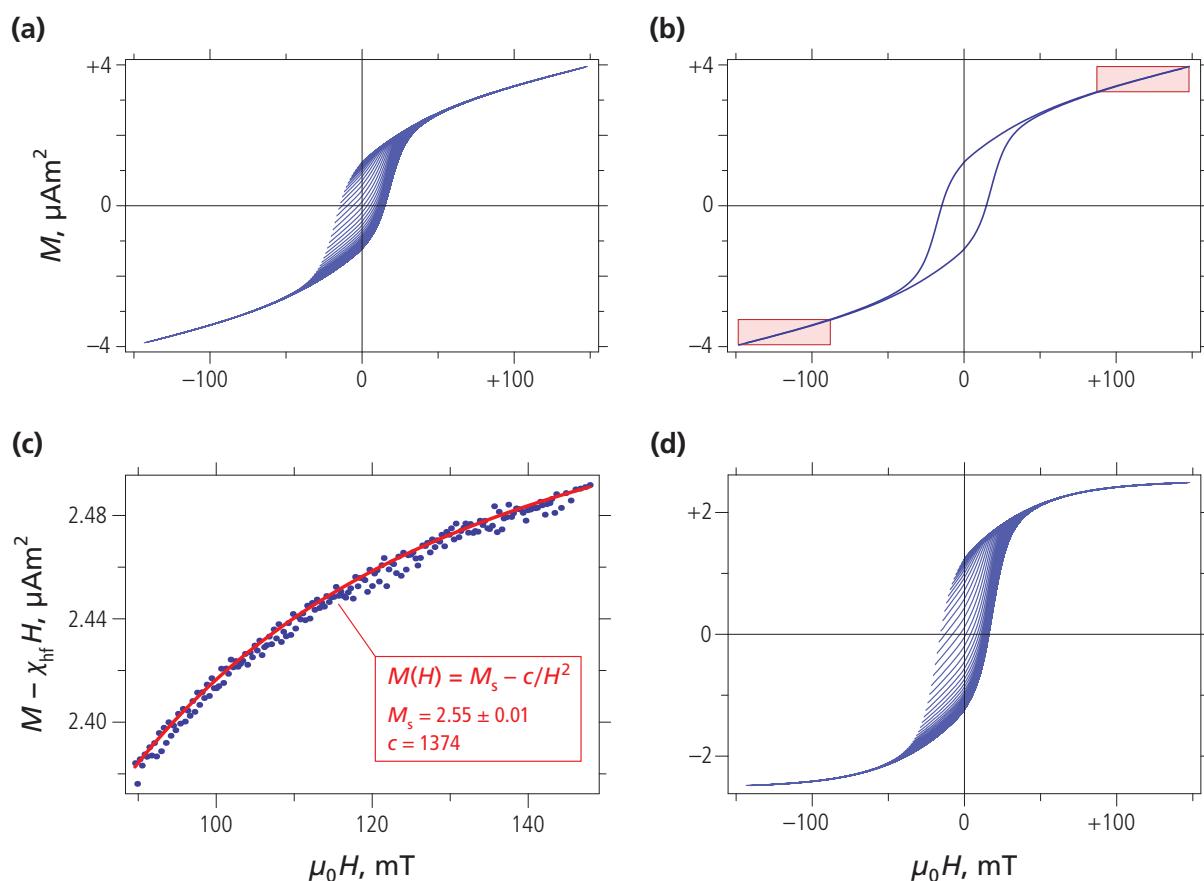
warns that ImportFORC will not perform a paramagnetic correction.

After choosing Automatic or an explicit numeric value for INPUT 18, the paramagnetic correction is performed in two steps. First, a hysteresis loop is calculated from FORC measurements by selecting the first and last measurement points of each curve (e.g. Fig. 3.20a-b). The saturation range of this loop is represented by measurements performed in fields  $H < H_s$  and  $H > H_s$ . A single curve  $M_{\text{sat}}(H)$  representing the saturation range of hysteresis (e.g. Fig. 3.20c) is obtained by converting negative values over  $H < H_s$  into positive ones by inversion symmetry, i.e.  $M(H) = -M(-H)$ . Once  $M_{\text{sat}}$  has been calculated, measurement points on this curve are fitted with a so-called *approach-to-saturation law*

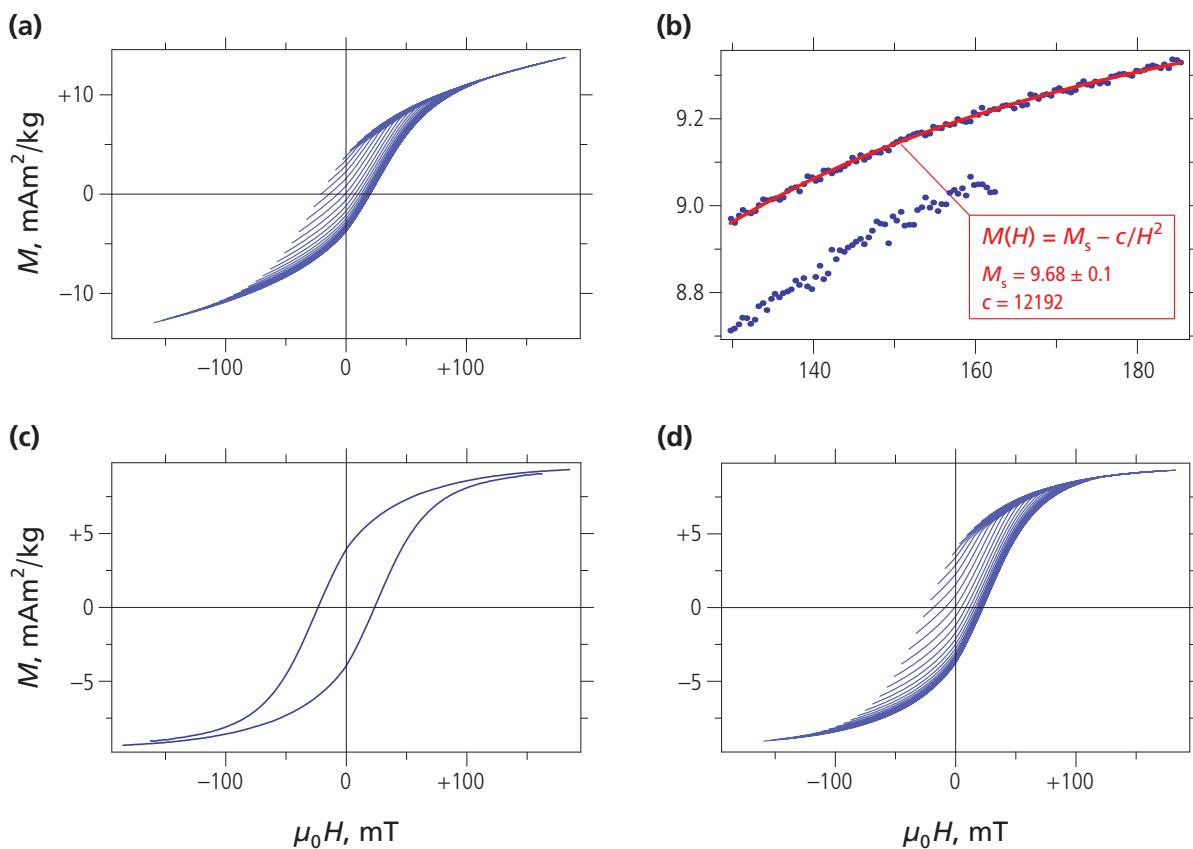
$$M_{\text{sat}}(H) = M_s - cH^{-\beta} + \chi_{\text{hf}}H \quad (3.1)$$

where  $M_s$  is the spontaneous magnetization of the ferrimagnetic component of hysteresis,  $c$  is a constant,  $\beta$  a positive exponent usually comprised between 1 and 2, and  $\chi_{\text{hf}}$  the high-field susceptibility [Fabian, 2006]. The term  $cH^{-\beta}$  in eq. (3.1) describes how fast the ferrimagnetic contribution is saturated by the applied field. Minimization of least-squares residuals provides estimates of the unknown parameters  $M_s$ ,  $\chi_{\text{hf}}$ ,  $\beta$  and  $c$ . These parameters are strongly correlated, so that reliable estimates can be obtained only if measurements extend far into the saturation range.

Otherwise, additional assumptions controlled by INPUT 19 and INPUT 20 are needed to constrain the solution. For example,  $\beta=2$  has been assumed in the example of Fig. 3.20, because this value is appropriate for single-domain particles. Once the unknown parameters of eq. (3.1) have been determined, paramagnetic correction is performed by subtracting  $M_{\text{hf}} = \chi_{\text{hf}} H$  from all FORC measurements. If FORC measurements do not cover the whole range of irreversible magnetization processes, the hysteresis loop reconstructed from FORC measurements is not a major one (e.g. Fig. 3.21). Paramagnetic corrections based on such loops are not very reliable, although reasonable estimates of  $M_s$  and  $\chi_{\text{hf}}$  can often be obtained with known values of  $\beta$ .



**Fig. 3.20:** Paramagnetic correction of FORC measurements of cultured magnetotactic bacteria (see the downloadable example “Magnetospirillum 1”), as generated by ImportFORC with minor editorial modifications. **(a)** Drift -corrected FORC measurements. A paramagnetic contribution  $M = \chi_{\text{hf}} H$  with  $\chi_{\text{hf}} = 0.01$   $\text{mAm}^2/\text{T}$  has been added numerically to the raw data for demonstration purposes. **(b)** Hysteresis loop derived from the FORC measurements in (a). The saturation range defined by INPUT 18 has been highlighted by the shaded rectangles ( $H > 90$  mT and  $H < -90$  mT) **(c)** Saturation range measurements (dots) selected by the shaded rectangles in (a), after application of inversion symmetry for negative values and subtraction of  $M_{\text{hf}} = \chi_{\text{hf}} H$ , with  $\chi_{\text{hf}} = 0.010016$   $\text{mAm}^2/\text{T}$  obtained from a least-squares fit with eq. (3.1) (red line). **(d)** Ferrimagnetic component of the FORC measurements, obtained by subtracting  $M_{\text{hf}} = \chi_{\text{hf}} H$  from the measurements shown in (a).



**Fig. 3.21:** Paramagnetic correction of FORC measurements of a pelagic carbonate (see the downloadable example “pelagic carbonate”), as generated by ImportFORC with minor editorial modifications. **(a)** Drift-corrected FORC measurements. **(b)** Saturation range of the hysteresis loop derived from FORC measurements, obtained by setting a high-field limit of 130 mT with INPUT 18. The upper and lower hysteresis branches do not merge because the positive saturation imposed by the FORC measurement protocol as initial condition for each curve is not reached in the maximum measurement field. The red line is a least-squares fit with eq. (3.1), which gives  $\chi_{hf} = 24.4 \text{ } \mu\text{Am}^2/(\text{kg T})$ . The magnetization  $M_{hf} = \chi_{hf} H$  associated with high-field susceptibility has been subtracted from all data shown in this plot. **(c)** Ferrimagnetic hysteresis derived from FORC measurements after paramagnetic correction. **(d)** Ferrimagnetic component of the FORC measurements, obtained by subtracting  $M_{hf} = \chi_{hf} H$  from the measurements shown in (a).

💡 Although FORC measurements do usually not extend over the large fields required for complete saturation, the approach used by ImportFORC is very effective and often provides superior results with respect to more widespread paramagnetic corrections based on a simple linear approximation  $M_{sat}(H) = M_s + \chi_{hf} H$  of the saturation range.

### INPUT 19. High-field model constraint

INPUT 19 is relevant only if a paramagnetic correction of FORC data is performed (i.e. INPUT 18 is not set to None). Paramagnetic corrections are based on the subtraction of a field-proportional magnetization  $M_{hf} = \chi_{hf} H$  from all measurements, where the proportionality constant  $\chi_{hf}$  is the high-field susceptibility, so that the corrected measurements converge to the saturation magnetization  $M_s$  in large fields. Because  $\chi_{hf}$  and  $M_s$  are generally not known a-priori,

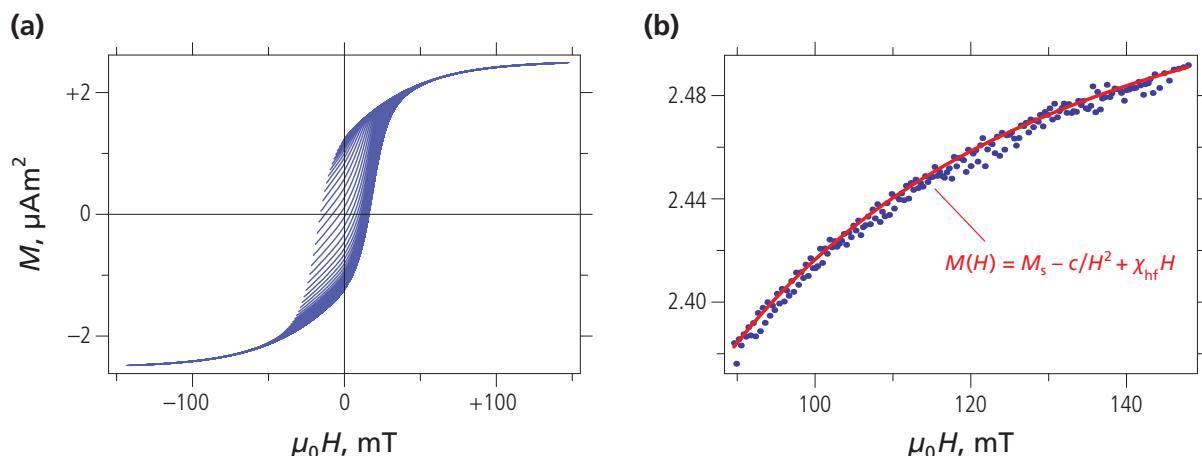
```
INPUT 19. High-field model constraint ....; None
```

is used for letting ImportFORC obtain an estimate of these parameters from FORC data over the saturation range specified by INPUT 18. In order to ensure compatibility with previous VARIFORC versions, Automatic can be entered instead of None. If  $\chi_{hf}$  or  $M_s$  are known from independent hysteresis measurements over large fields, the paramagnetic correction of FORC measurements is much better constrained by entering an explicit value of  $\chi_{hf}$  or  $M_s$  with INPUT 19. Both parameters must be expressed with the proper unit: this is the *output magnetization unit* for  $M_s$ , and *(output magnetization unit)/(output field unit)* for  $\chi_{hf}$ , where output field and magnetization units have been defined with INPUT 15 and INPUT 17, respectively. For example,  $\chi_{hf}$  for the FORC measurements shown in Fig. 3.22 coincides with the diamagnetic susceptibility  $\chi = -0.128 \times 10^{-6} \text{ Am}^2/\text{T}$  of the sample holder. Given the output units mT and  $\mu\text{Am}^2$  in the example of Fig. 3.22, the correct specification of  $\chi_{hf}$  is

```
INPUT 19. High-field susceptibility ....; -1.28e-4 xhf
```

because  $0.128 \times 10^{-6} \text{ Am}^2/\text{T} = 0.128 \mu\text{Am}^2/\text{T} = 0.128 \times 10^{-3} \mu\text{Am}^2/\text{mT}$ . The type of parameter entered with INPUT 19 is specified by adding Xhf or Ms after the numerical value entered for  $\chi_{hf}$  or  $M_s$ , respectively. If no specification is given, the numerical value is assumed to represent  $\chi_{hf}$ .

High-field model constraints are particularly useful when a very precise correction is needed for FORC measurements that do not reach sufficiently large fields for a meaningful application of the approach-to-saturation model. In this case,  $M_s$  is best taken from a separated hysteresis measurements. FORC diagrams are insensitive to paramagnetic corrections, because the same magnetization curve  $M_{hf} = \chi_{hf} H$  is subtracted from all measurements. However, a paramagnetic correction might be required to obtain a meaningful plot of FORC measurements in case of specimens with very closed hysteresis loops (e.g. because of very small ferrimagnetic contributions or multidomain properties). A paramagnetic correction is also required when correcting FORC measurements from a mean internal field originating in the ferrimagnetic components, such as through exchange coupling. In this case, non-ferrimagnetic contributions to the FORC measurements need to be removed before processing them with CalculateFORC.



**Fig. 3.22:** Paramagnetic correction of FORC measurements of cultured magnetotactic bacteria (see the downloadable example “Magnetospirillum 1”). **(a)** Drift-corrected FORC measurements. **(b)** Saturation range of the hysteresis loop deduced from the FORC measurements in (a) after application of inversion symmetry for negative values. The red line is a least-squares fit obtained with the approach-to-saturation model of eq. (3.1).

- Usually,  $\chi_{hf}$  is derived from hysteresis measurements to maximum available fields, so that correct units to use for INPUT 19 are automatically obtained if hysteresis is processed with the same field and magnetization units of the FORC data. Otherwise, the correct unit for  $\chi_{hf}$  is obtained with field and magnetization unit conversions given in Tables 3.3 and 3.5.
- If  $\chi_{hf}$  is derived from susceptibility values expressed in C.G.S., the correct value to be entered with INPUT 19 is obtained by multiplying  $\chi_{hf}$  with a factor  $4\pi$ .

💡 If the specimen is known to have a negligible high-field susceptibility, set INPUT 19 to 0 in order to obtain more reliable  $M_s$ -estimates.

## INPUT 20. Approach-to-saturation exponent

INPUT 20 is relevant only if a paramagnetic correction of FORC data is performed (i.e. INPUT 18 is not set to None). In this case, INPUT 20 can be used to constrain the exponent  $\beta$  in the approach-to-saturation law expressed by eq. (3.1). This exponent is usually a number comprised between 1 and 2, depending on the nature of magnetization processes occurring near saturation [Fabian, 2006]. For example, magnetic moment rotation in single-domain particles is characterized by  $\beta = 1$ , while domain wall unpinning in multidomain particles gives a much “harder” saturation approach characterized by  $\beta \rightarrow 1$ .

If the nature of magnetization carriers is known – for instance by analogy with other samples – the expected value of  $\beta$  can be entered with INPUT 20 in order to obtain a constrained fit yielding more reliable values of  $M_s$  and  $\chi_{hf}$ . For instance,

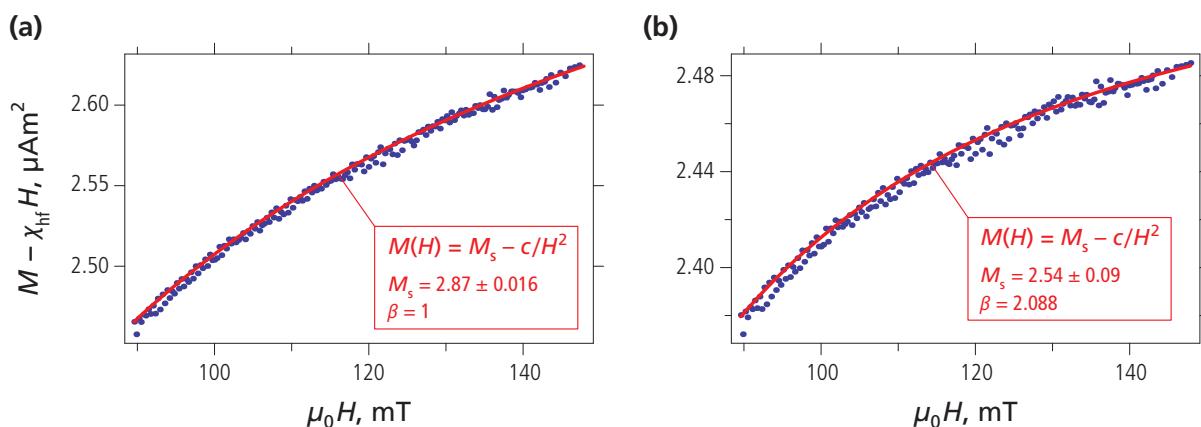
```
INPUT 20. Approach-to-saturation exponent ....; 2
```

was used to process the examples of Fig. 3.21 and Fig. 3.22, because both materials are known to contain exclusively or mainly single-domain magnetic particles.

On the other hand,

```
INPUT 20. Approach-to-saturation exponent ....; Automatic
```

is used to let ImportFORC find an exponent  $1 \leq \beta \leq 2$  that best fits FORC data in the saturation range chosen with INPUT 18 (Fig. 3.23). This option, however, should be adopted only if FORC measurements extend well into the saturation range, or if an explicit high-field susceptibility value has been entered with INPUT 19, in order to avoid excessively unstable results.

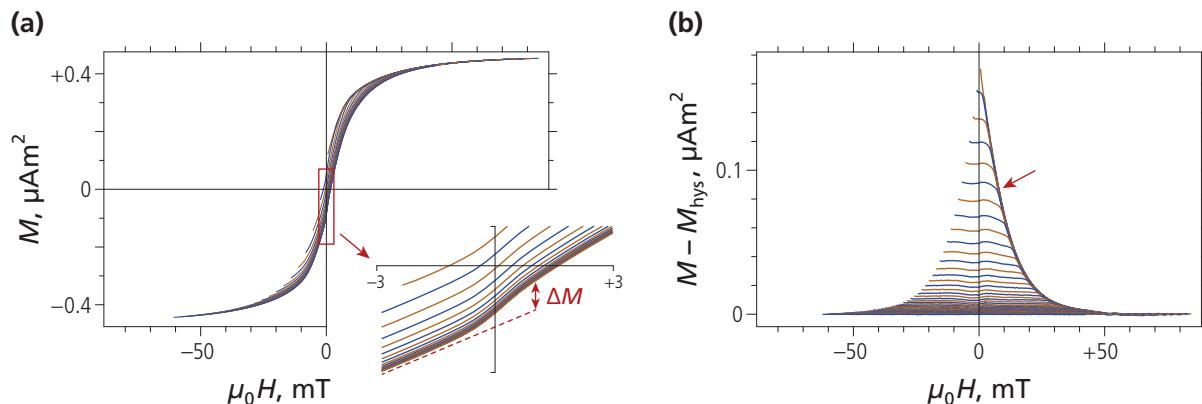


**Fig. 3.23:** Paramagnetic correction of FORC measurements on cultured magnetotactic bacteria (see the downloadable example “Magnetospirillum 1”). Dots represent the hysteresis loop reconstructed from FORC measurements and the red line is the best-fit approach-to-saturation model, both after subtraction of the high-field susceptibility contribution  $M = \chi_{hf}H$ . **(a)** Results obtained by setting  $\beta = 1$  with INPUT 20. **(b)** Unconstrained model (i.e. INPUT 20 was set to Automatic). In this case, model results almost coincide with the ideal case of single-domain particles with  $\beta = 2$ . Notice the different  $M_s$ -estimates in (a) and (b).

- 💡 In general, larger  $M_s$ -estimates are obtained with smaller values of  $\beta$  and vice-versa.
- 💡 If a series of similar samples is processed (e.g. volcanic glasses from the same eruption, sediments from the same core), consistent paramagnetic corrections are obtained by specifying the same saturation range (by INPUT 18) and by constraining the approach-to-saturation exponent to a common value (by INPUT 20) valid for all samples.

### INPUT 21. Calculation of FORC differences

Typical FORC measurement protocols are based on the measurement of at least  $\sim 100$  curves, which fill the area enclosed by the major hysteresis loop. In most cases, this area is very small, so that few details can be recognized in direct plots of measurements (e.g. Fig. 3.24a). Given the fact that only differences between measured curves matter for the calculation of FORC diagrams, an effective way of enhancing measurement details consists in plotting all curves after subtraction of the lower hysteresis branch (Fig. 3.24b). This procedure makes details visible, which are otherwise “compressed” in the area enclosed by the hysteresis loop. For example, the central ridge becomes clearly visible as a series of sharp kinks in the measured curves. Furthermore, the use of FORC measurement differences eliminates FORC processing problems related to particular features that are common to all curves, such as the relatively sharp magnetization increase occurring at  $H = 0$  in Fig. 3.24a.



**Fig. 3.24:** (a) FORC measurements of magnetosomes dispersed in clay (see the downloadable example “dispersed magnetosomes”). A relatively sharp magnetization increase  $\Delta M = 0.04 \mu\text{Am}^2$  around  $H = 0$  is clearly recognizable in the enlarged plot of the region enclosed by the red rectangle. This feature is common to all curves starting at  $H_r < 0$ , and is produced by moment switching of single-domain particles with almost zero coercivity. It occurs within  $\pm 1$  mT from  $H = 0$ , over only 5 measurement points, and poses a problem for FORC processing, because second-order polynomial regression cannot reproduce the sigmoidal curve shape over  $\geq 5$  points corresponding to smoothing factors  $\geq 2$ . This and other features, such as the central ridge, are not recognizable in plots that cover the whole measurement range, because all curves are enclosed in the small opening of the major hysteresis loops. (b) Same measurements as in (a), after subtracting the lower hysteresis branch reconstructed from FORC measurements. These curves define the same FORC diagram as the original measurements in (a), as it is the case for any addition/subtraction of the same curve to all measurements. The curves envelope corresponds to the difference between upper and lower hysteresis branches, also known as the irreversible component of hysteresis [Fabian and von Dobeneck, 1997]. The sharp magnetization increase around  $H = 0$  has been eliminated, because it is a common feature of all curves, including the hysteresis branches. Detailed differences between the curves are now clearly visible. For example, the central ridge – a typical FORC signature of non-interacting single-domain particle – is recognizable as a series of sharp kinks occurring along the right limit of the curve envelope (arrow).

ImportFORC plots and exports modified curves

$$M^*(H_r, H) = M(H_r, H) - M_{\text{hys}}^-(H) \quad (3.2)$$

obtained by subtracting the lower branch  $M_{\text{hys}}^-$  of the major hysteresis loop from all measurements. Because  $M_{\text{hys}}^-$  does not depend on the reversal field  $H_r$ , it does not contribute to the FORC function so that FORC diagrams calculated from the original measurements  $M$  and from the modified curves  $M^*$  are identical as long as polynomial regression is able to fit these curves correctly. The envelope of all  $M^*$ -curves is given by

$$M^*(H_r, H = H_r) - M_{\text{hys}}^-(H) = M_{\text{hys}}^+(H) - M_{\text{hys}}^-(H) \quad (3.3)$$

and coincides with the difference between upper and lower hysteresis branch, also known as the irreversible component of hysteresis [Fabian and von Dobeneck, 1997].

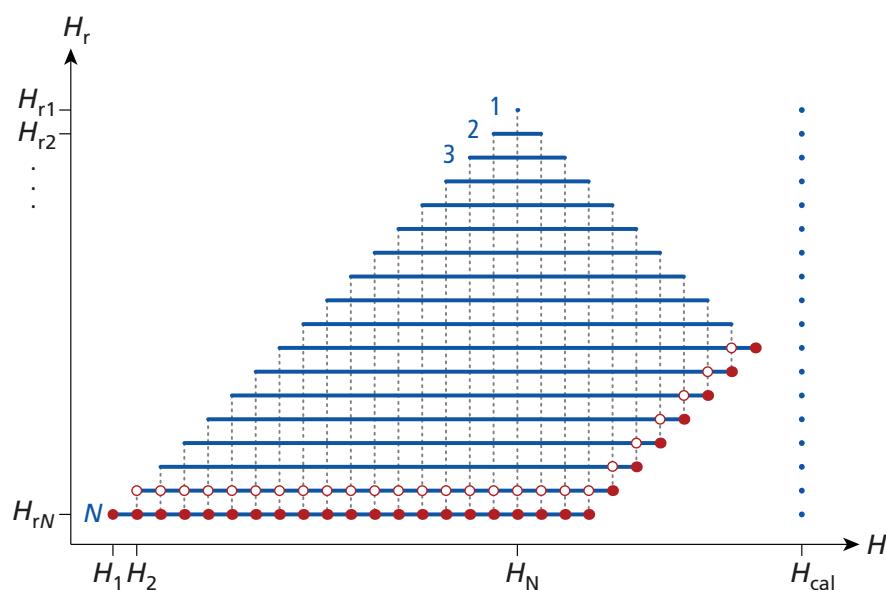
ImportFORC can use two methods for estimating the lower hysteresis branch and subtract it from the FORC measurements, which can be chosen with INPUT 21. The simplest method consists in taking a given number of last FORC curves as an approximation of the lower hysteresis branch, e.g.

INPUT 21. Options for lower hysteresis branch subtraction .....; FORC,4

for the four last curves. In this case, ImportFORC assumes that the whole range of irreversible magnetization processes is covered by the FORC protocol, so that last curves, which start at most negative reversal fields, coincide with the lower branch of the major hysteresis loop. Furthermore, all curves end in the saturation range of hysteresis, so that the whole lower limit of the measured FORC space (Fig. 3.25) can be used to reconstruct the lower hysteresis branch. If more than one curve is chosen with INPUT 21, the second-last FORC and the second-last points of all curves, as well as the third-last curves/points and so on, are taken into consideration for the calculation of  $M_{\text{hys}}^-$ . In this case, measurements corresponding to the same  $H$ -values will be averaged, enabling to reduce the error of  $M_{\text{hys}}^-$  being added to the other measurements (Table 3.7).

**Tab. 3.7:** Number of last curves used to reconstruct the lower hysteresis branch, error of reconstructed hysteresis branch in % of the measurement error, and additional error introduced by subtracting the lower hysteresis branch from all measurements.

INPUT 21	Error of reconstructed hysteresis	Additional error on FORC measurements with subtracted hysteresis
1	100%	41%
2	71%	22%
4	50%	12%
9	33%	5%



**Fig. 3.25:** Representation of the measured FORC space as function of the reversal field  $H_r$  and the applied field  $H$ . Each curve is a horizontal line starting at  $H = H_r$ , followed by a calibration measurement (dot) in the field  $H_{cal}$ . Measurements proceed from the most positive reversal field  $H_{r1}$  (top) to the last reversal field  $H_{rN}$  (bottom). The lower edge of the measured space (highlighted by red dots) defines the lower hysteresis branch reconstructed from FORC measurements if INPUT 21 is set to 1. Additional lines of points (e.g. red circles) are averaged for the reconstruction of the lower hysteresis branch if INPUT 21 is set to a number  $> 1$ .

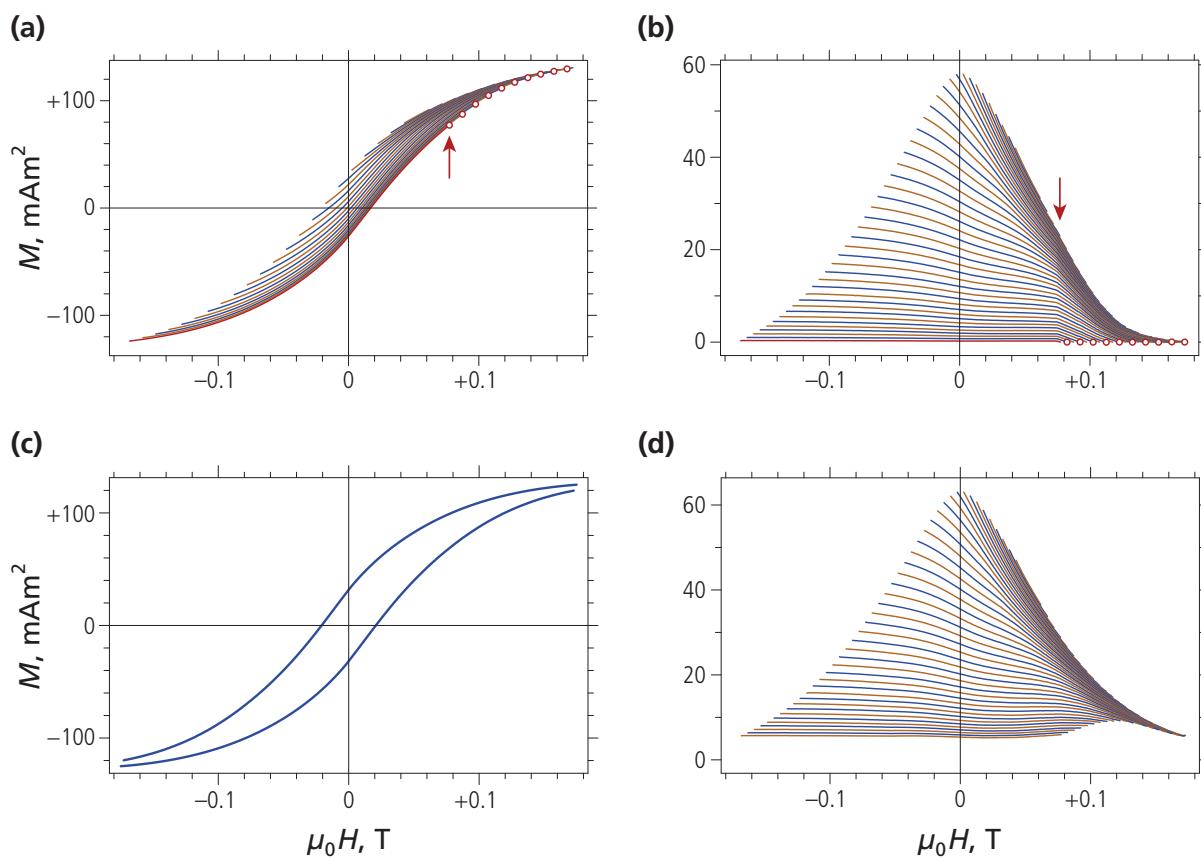
Lower hysteresis branch subtraction is performed in a correct manner only if the last curves specified by INPUT 21 starts from negative saturation, where the two hysteresis branches fully overlap. If this is not the case, a kink will occur for  $M_{hys}^-$  at the place where the last curve ends and is extrapolated with last points of previous curves. This kink is transferred to all curves upon subtraction of  $M_{hys}^-$  (Fig. 3.26b), introducing unwanted artifacts. This problem is overcome by the second option offered by ImportFORC, i.e.

INPUT 21. options for lower hysteresis branch subtraction .....; Hysteresis

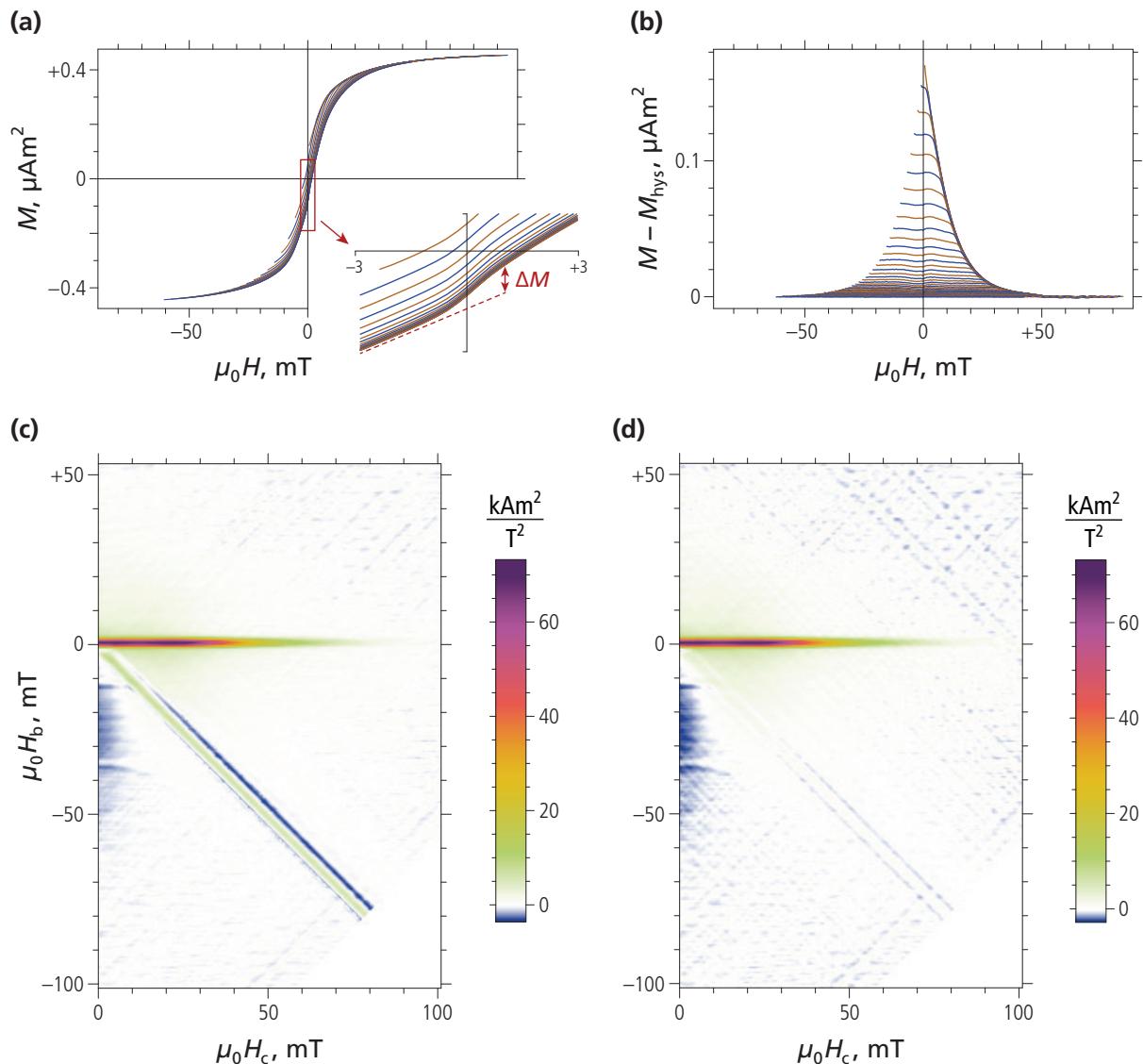
In this case, the lower hysteresis branch is reconstructed using the first and last measurement points of all curves, and assuming an inversion symmetry between the two branches of the hysteresis loop. In this way, a larger range of fields can be exploited, avoiding artifacts in positive fields beyond the last measurement point of the last curve (Fig. 3.26c). The use of this option is recommended in case of heavily unsaturated curves.

As mentioned above, the use of drift-corrected data (e.g. Fig. 3.24a) or drift-corrected differences (e.g. Fig. 3.24b) for the calculation of FORC diagrams is fully equivalent, as long as polynomial regression is able to fit the data correctly. The choice one particular dataset becomes relevant as soon as the measured curves contain features that cannot be fitted correctly by polynomial regression. If

such features are common to all curves, as in the example of Fig. 3.27, the calculation of FORC differences will eliminate them, so that the FORC diagram is conveniently calculated using such differences, instead of direct measurements. The VARIFORC package CalculateFORC enables this choice on the basis of drift-corrected measurements and measurement differences exported by ImportFORC. Measurement differences contain a slightly larger measurement noise (Table 3.7), depending on the option chosen with INPUT 21, and should therefore be used instead of direct measurements only in case of documented processing problems, and if additional artifacts are not introduced when subtracting the lower hysteresis branch.



**Fig. 3.26:** (a) FORC measurements of a sediment sample from Mono Lake (California, U.S.A.). Every 20<sup>th</sup> curve is shown for clarity. All curves are unsaturated, so that the envelope of all curves does not coincide with the major hysteresis loop. Red line and points represent the lower hysteresis branch reconstructed from the last curve(s) when INPUT 21 is set to FORC , 1. Because last curve does not start from negative saturation, a kink occurs where that lower hysteresis branch starts to be defined by the last measurement point of previous curves (arrow). (b) FORC measurements after subtraction of the reconstructed lower hysteresis branch. The arrow marks the point where the kink in the reconstructed lower hysteresis branch is transmitted to the measured curves. (c) Hysteresis loop reconstructed from the envelope of all FORC measurements (i.e. first and last measurements of each curve). (d) FORC measurement differences obtained by subtracting the lower branch of the reconstructed loop shown in (c) upon setting INPUT 21 to Hysteresis. Because the reconstructed hysteresis loop is free of artifacts, kinks do not appear in FORC difference curves, unlike in(b).



**Fig. 3.27:** Example of complete FORC processing of magnetosomes dispersed in clay (see the downloadable example “dispersed magnetosomes”). **(a)** Drift-corrected measurements. Every 10<sup>th</sup> curve is shown for clarity. A relatively sharp magnetization increase around  $H=0$  is clearly recognizable in the enlarged plot of the region enclosed by the red rectangle. **(b)** Same measurements as in (a), after subtracting the lower hysteresis branch reconstructed from FORC measurements. Every 5<sup>th</sup> curve is shown for clarity. The sharp magnetization increase around  $H=0$  has been eliminated, because it is a common feature of all curves, including the hysteresis branches. **(c)** FORC diagram obtained from measurements in (a) with CalculateFORC and a smoothing factor SF = 8. The diagonal ridge is a processing artifact caused by polynomial regression misfits at  $H=0$ . Second-order polynomial fitting over  $2SF+1=17$  points is unable to reproduce the sigmoid shape of curves responsible for the magnetization increase  $\Delta M$  over only 5 points. **(d)** FORC diagram obtained from measurement differences in (b), and same processing parameters as in (c). Processing artifacts along  $H=0$  are now completely absent, because the magnetization increase  $\Delta M$  over  $H=0$  has been removed from the processed curves. The FORC diagrams in (c) and (d) are otherwise identical.

- 💡 FORC measurement differences plotted by ImportFORC as part of its standard output reveal details that are not recognizable in plots of the original measurements. Such details include possible measurement problems (e.g. uncorrected outliers and instabilities), lack of saturation, as well as specific fingerprints such as magnetic viscosity (i.e. magnetization decay over the first points of each curve) and the central ridge (i.e. slope discontinuity at  $H = H_r$ ).
- 💡 Features that are common to all measurement curves and do not contribute to the FORC diagram (e.g. the general hysteresis shape and sharp magnetization increases near  $H = 0$ ) are automatically removed from measurement differences. Therefore, FORC processing problems related to these features are solved by using measurement differences instead of direct measurements as basis for the calculation of FORC diagrams.

- The calculation of FORC measurement differences enhances measurement noise slightly (Table 3.7). Therefore, the calculation of FORC diagrams should be based on direct measurements, unless evident processing problems are encountered.
- FORC measurement differences obtained from strongly unsaturated curves should be considered with caution, since they might contain artifacts (e.g. Fig. 3.26b). In this case, INPUT 21 should be set to [Hysteresis](#).

### 3.6 FORC measurement formats

ImportFORC reads FORC measurements saved with formats developed for MicroMag™ magnetometers. These formats varied slightly over the years, and recent versions are similar to the excerpt shown in Fig. 3.28.

```

MicroMag 2900/3900 Data File (Series 0016.002)
Direct moment vs. field; First-order reversal curves

INSTRUMENT
Configuration AGM
Temperature control None
[...]

SAMPLE
Mass N/A
Volume N/A
Demagnetizing factor N/A

SETTINGS
Field range +300.0000E-03
Field (command) N/A
Moment range +500.0000E-09
Averaging time +100.0000E-03
Temperature (command) N/A
[...]
[...]

SCRIPT
Averaging time +100.0000E-03
Hb1 -40.00000E-03
Hb2 +60.00000E-03
Hc1 0.000000E+00
Hc2 +120.0000E-03
Hcal +186.0645E-03
HNcr +503.4330E-06
HSat +300.0000E-03
NForc 450
PauseCal +500.0000E-03
PauseRvrs1 +500.0000E-03
PauseSat +200.0000E-03
SlewRate +100.0000E-03
Smoothing 5
Includes hysteresis loop? No
Includes Msi(H)? No
Number of segments 900
Number of data 9999

      Field          Moment
      (T)            (Am2)
+185.2715E-03,+377.0848E-09 (calibration measurement #1)
+63.06715E-03,+252.6374E-09 (FORC #1: 1 point)
+185.2725E-03,+376.9744E-09 (calibration measurement #2)
+62.52715E-03,+252.2460E-09 (FORC #2: 3 points)
+63.04827E-03,+252.9036E-09
+63.51750E-03,+253.2440E-09
+185.2722E-03,+376.9242E-09 (calibration measurement #3)
+62.06688E-03,+251.1520E-09 (FORC #3: 5 points)
+62.62683E-03,+252.2208E-09
+63.13141E-03,+252.7866E-09
+63.57060E-03,+253.2059E-09
+64.06388E-03,+254.0941E-09
[...]

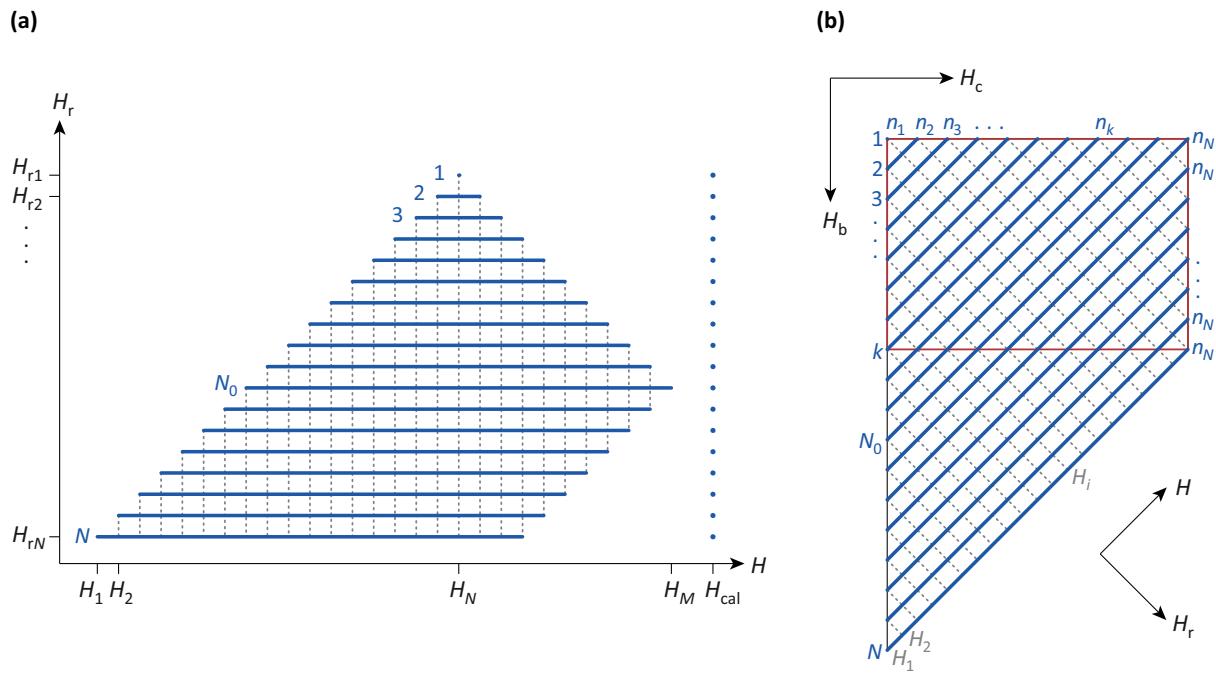
```

**Fig. 3.28:** Excerpt of a MicroMag™ FORC measurement file. Comments not belonging to the original file are given in blue.

MicroMag™ measurement files are composed of a header containing measurement and FORC protocol parameters, followed by two or three columns of comma-separated measurement values. The first and second columns contain field and magnetization measurements, respectively. A third column with temperature measurements is optionally available. Data are arranged in blocks separated by empty lines. Each block represents either single or multiple calibration measurements, or FORC measurements. Calibration measurements are easily identified by the fact that they are all performed in the same field. Each FORC is preceded by a calibration measurement block. Therefore, the dataset begins with a calibration measurement block, followed by the first FORC block, another calibration measurement block, the second FORC block, and so on. Calibration blocks consist usually of a single measurement performed in the calibration field. With some older protocols, calibration measurements were performed three times in a row, so that each calibration block contains three measurements.

ImportFORC reads FORC measurement files using the smallest possible set of assumptions, so that it is quite insensitive to small format changes. For example, it does not assume that the file header ends at a given line number, or that FORC protocol parameters are stored at a given place in the file header. Moreover, some flexibility is also granted to the FORC protocol. For example, calibration measurements can be measured a single time or repeatedly. In the latter case, multiple calibration measurements are averaged by ImportFORC. Calibration measurements can be performed indifferently before or after each FORC. The FORC protocol structure recognized by ImportFORC is shown in Fig. 3.29, and consists of a series of  $N$  curves starting at regularly spaced reversal fields  $H_{r1}, H_{r2}, \dots, H_{rN}$ . Curves starting at a reversal field  $H_{rk}$  are measured at regularly spaced fields  $H_{k1} = H_{rk}$ ,  $H_{k2} = H_{rk} + \delta H$ , etc., so that reversal and measurement fields form a regular grid with mesh size  $\delta H$ . (Fig. 3.29a). The boundaries of this grid are defined so, that the same grid, when plotted in transformed FORC coordinates  $H_c = (H - H_r)/2$  and  $H_b = (H + H_r)/2$ , encloses a rectangular region (red rectangle in Fig. 3.29b) coinciding with the intended FORC diagram range. The  $H_c$ - and  $H_b$ -limits of this region, along with measurement timing (i.e. averaging time and pauses at saturation, calibration, and reversal) and the number  $N$  of measured curves, are reported in the file header as part of the FORC measuring protocol. ImportFORC checks the integrity of FORC data according to the characteristics described above, and exports a set of corrected measurements with same structure and FORC coordinates.

Contrary to other FORC processing software, the VARIFORC module CalculateFORC can calculate FORC diagrams over any region enclosing the measurements, also beyond of the red rectangle in Fig. 3.19b, thereby making an optimized use of all measurements. This is possible because non-zero FORC amplitudes are intrinsically included in the area covered by measurements, if the reversal fields range from positive to negative saturation (see FORC tutorial in Chapter 7).



**Fig. 3.29:** FORC measurements structure according to the protocol described in Pike *et al.* [1999], which is used with MicroMag<sup>TM</sup> magnetometers. **(a)** Measured FORC trajectories (blue) in  $(H, H_r)$ -coordinates, where  $H_r$  is the reversal field and  $H$  the measuring field. Reversal and measuring fields form a regularly spaced grid (dashed lines). Calibration measurements are performed in a calibration field  $H_{cal}$  larger than measurement fields. **(b)** Same FORC trajectories as in (a), plotted in the transformed coordinates  $H_c = (H - H_r)/2$  and  $H_b = (H + H_r)/2$  used to plot FORC diagrams. The number of measurement points in each FORC (i.e.  $n_1, n_2, \dots, n_N$ ) is chosen so, that measurements include a rectangular region (red) defined by the FORC measuring protocol as  $[H_{c,\min}, H_{c,\max}]$  and  $[H_{b,\min}, H_{b,\max}]$ .  $N_0$  is the number corresponding to the first FORC that reaches full length with  $n_N$  measurement points.

The number of measurement points in each curve is determined by the measurement protocol shown in Fig. 3.29. This number increases in steps of two from the first curve ( $n_1$  points) to curve  $N_0$  ( $n_N$  points), and remains constant for all successive curves. ImportFORC verifies the integrity of FORC data by checking the number of points in each curve and the regularity of the field steps  $\delta H$ . Because calibration and FORC measurement sequences are delimited by empty lines, addition or removal of such lines makes the dataset unreadable. In this case, ImportFORC produces an error message reporting the first block number where an unexpected number of measurements has been encountered, e.g.:

```
Unexpected number of measurements in block 125 (lines 13481-13511) or
block 126 (lines 13513-13514)
```

Whenever such a message is encountered, check the measurement file over the indicated range of lines and remove additional empty lines or introduce them if they are missing. This problem is sometimes encountered when processing FORC measurements produced with older MicroMag<sup>TM</sup>

systems, because of additional empty lines erroneously introduced during file writing. These problems do not occur with modern system, unless the measurement file has been damaged.

## 3.7 Formats of data exported by ImportFORC

ImportFORC exports three files containing corrected FORC measurements (`_CorrectedMeasurements_VARIFORC.frc`), corrected FORC measurements with subtracted lower hysteresis branch (`_CorrectedMeasurementDifferences_VARIFORC.frc`), and the upper branch of the hysteresis loop derived from FORC measurements (`_CorrectedMeasurements_Hysteresis.frc`). These files are required by other VARIFORC modules for further processing. They also provide a data source for other applications, and contain useful summary information. The files are produced with a specific format that is explained in the following.

### 3.7.1 Corrected FORC measurements

Corrected FORC measurements are exported to a file with the structure shown in Fig. 3.30. The file header contains summary information about the FORC protocol and data structure, followed by corrected measurements listed in a comma-separated two-column format with no empty lines. The beginning of the data section is univocally located by the title line “Corrected measurements”, regardless of the actual row number. Information blocks in the file header begin with a title (e.g. “Field and magnetization units”), followed by comma-separated parameter lists. Empty lines are used to separate blocks. Line widths are unlimited and might therefore be wrapped by some text editors. The content of blocks is explained in the following.

#### Block 1: File title

The first line contains the file title “VARIFORC v1.0 ...”, where “...” represents the type of FORC data (i.e. “corrected FORC measurements” or “corrected FORC measurements with subtracted lower branch”).

#### Block 2: Source files

This block, entitled “Normalization unit and factors for listed source files”, contains a list of file names that have been used as data source for creating the corrected measurements. The first element listed in this block is the unit of the factors used to normalize original measurements (e.g. a mass unit for converting magnetic moment measurements into mass magnetizations). The next elements build a list of file names, preceded by corresponding normalization factors. Corrected FORC measurements correspond to weighted averages of measurements stored in the listed files, normalized by corresponding factors. If the file was generated by the VARIFORC module Linear CombineFORC, instead of ImportFORC, the block is titled “Linear combination factors for listed source files”, and contains a list of corrected FORC measurement files preceded by corresponding linear combination factors.

VARIFORC v2.0 corrected FORC measurements with subtracted lower hysteresis branch.

## Normalization unit and factors for listed source files

FORC protocol parameters (number of FORCs, number of first curve with maximum length, ...)  
450,246.0.0005015553545586107,0.0005775312123660717

## List of FORC lengths

## Field and magnetization units

T, mAm<sup>2</sup>/kg

Saturation remanence with standard error, saturation magnetization with standard error, ...  
3.897134730097964, 0.0006913444803027636, 9.758817813285226, 0.06385782357290273

## List of measurement fields

-0.1617138,-0.16120645,-0.1607005333333334,-0.160195125,-0.15970128,-0.159191683333333333,09490909091,-0.1340956267857143,-0.13359350175438597,-0.1330929672413793,-0.13259939830508567,-0.10847863271028038,-0.1079761416666666,-0.10747017706422018,-0.106967728181818,-0.05,-0.08388822615384615,-0.08338558006369427,-0.08289215158227849,-0.08238489704402516,-0.07,-0.058778346213592236,-0.058267884830917875,-0.05776502860576923,-0.057261055789473686,-0.5927047244096,-0.03418277776470588,-0.0336834774609375,-0.033186525097276265,-0.0326864196063,-0.010603214370860927,-0.010109700330033004,-0.009606078,-0.009104070062295083,-0.0086012980991805157592,0.013485220628571428,0.013984884387464386,0.0144867622727272,0.01498738055386165413534,0.03855942695,0.03906023591022444,0.03956034674129354,0.04005652672456570.0636420734375,0.06415329109619687,0.06465470076233183,0.06515420213483146,0.0656542569819734633507854,0.09021020073684212,0.09071210005291006,0.09121114672872341,0.091705213262032367,0.1162578583333334,0.11675374124087591,0.11725932720588235,0.11775624407407406,0.11822093022,0.14282268058823527,0.1433227958333335,0.14381790481927711,0.14431893719512195,0.140625,0.16984658548387097,0.1703406183333333,0.17084127068965518,0.17134316964285715,0.1

High-field susceptibility used for paramagnetic correction and standard error

22.141976945193424,0.019617235224985742

## Corrected measurements

0.06306701607457865 , 7.835310398629668  
0.06252723606194903 , 7.8364236710604676  
0.06305379983050963 , 7.842617919309848  
0.0635178823128684 , 7.847200398144448  
0.06206771825143699 , 7.812787643767485  
0.06262809844566078 , 7.8273601457606485  
0.06313261129110728 , 7.839264110392458  
0.06357648320526406 , 7.8481123884505815  
0.0640641715369791 , 7.863644067102313  
0.061514626718234725 , 7.783128178091891  
0.06213234155527458 , 7.8132923793899565  
0.0626291348871504 , 7.819848189095403  
0.06313106028367986 , 7.842413712772066  
0.06363701318087826 , 7.852781680104314  
0.06406868791307928 , 7.867015265508586  
0.06453595994828823 , 7.8731780068194395  
0.06104891480875077 , 7.777082403993943  
0.0616322302738682 , 7.791243030124716  
0.062131909001764 , 7.807502208448721  
0.06262858649746564 , 7.819440297103064  
0.06313003939674772 , 7.831369479171681  
0.06363736563518753 , 7.848945860523038  
0.06414828240652111 , 7.869734464099178  
0.06156282056862655 , 7.88528266388651

**Fig. 3.30:** Example of corrected FORC measurement file produced by ImportFORC. Information blocks begins with a title (highlighted in blue), followed by a list of parameters. FORC data begin after “Corrected measurements” and do not contain empty lines.

### Block 3: FORC protocol parameters

This block, entitled “FORC protocol parameters”, contains all information required for reconstructing the FORC protocol (see [section 3.6](#) for a detailed description of this protocol). The first parameter is the number  $N$  of FORCs, the second parameter is the number  $N_0$  corresponding to the first FORC with full length, the third parameter is the mean field step size  $\delta H$ , and the last parameter is the mean size of first steps.

### Block 4: List of FORC lengths

This block, entitled “List of FORC lengths”, is a list  $n_1, n_2, \dots, n_N$  of total numbers of measurement points contained in each curve. This list is used to reconstruct individual FORC curves from corrected measurements listed in the last block.

### Block 5: Field and magnetization units

This block, entitled “Field and magnetization units”, contains the field and magnetization units of corrected FORC measurements. Units can be preceded by S.I. prefixes or numerical unit multipliers (see [section 3.5](#)). All field and magnetization values reported in the file are given with these units.

### Block 6: Hysteresis parameters

This block, entitled “Saturation remanence with standard error, saturation magnetization with standard error, coercive field with standard error, maximum derivative field, derivative width”, contains a list of hysteresis parameters deduced from FORC measurements; in order of appearance as in the block title: saturation remanence  $M_{rs}$ , standard error of  $M_{rs}$ , saturation magnetization  $M_s$ , standard error of  $M_s$ , coercive field  $H_c$ , standard error of  $H_c$ , field for which the first derivative of the lower hysteresis branch is maximal, field interval over which the first derivative of the lower hysteresis branch decreases from its maximum by 50%. Depending on the chosen ImportFORC options,  $M_s$  might not have been calculated, in which case its value and the corresponding standard error are replaced by “None” entries. Remanence measurements required for calculating  $M_{rs}$  are not always available, for example in case of FORC sets extending only over positive  $H_b$ -values. If remanence measurements are lacking,  $M_{rs}$  and its standard error are set to “None”. The last two parameters are used by certain FORC processing options of CalculateFORC. Parameters reported in this block are purely informative, and do not affect FORC processing.

### Block 7: List of measurement fields

This block, entitled “List of measurement fields”, contains the full list of mean measurement fields, sorted in ascending order.

### Block 8: High-field susceptibility used for paramagnetic correction

This block, entitled “High-field susceptibility used for paramagnetic correction and standard error”, contains the high-field susceptibility  $\chi_{hf}$  estimated from hysteresis data obtained from FORC measurements or a corresponding default value entered with INPUT 19. Depending on the chosen ImportFORC options,  $\chi_{hf}$  might not have been calculated.

### Block 9: Corrected FORC measurements

This block, entitled “Corrected measurements”, contains the corrected FORC measurements in a comma-separated, two-column format, where the first column contains the measured fields and the second column the corresponding corrected magnetization values. There are no empty lines separating individual curves. FORCs can be reconstructed from this dataset using the list of FORC lengths reported in the file header. If FORC data should be imported with third-party software, consider that the beginning of this block is set by the block title, and not by a fixed line number. This enables future VARIFORC releases to extend the file header with lines containing additional information. These will always be added after the block containing a list of measurement fields (block 8), so that already existing blocks continue to occupy the same positions.

#### 3.7.2 Hysteresis loop reconstructed from FORC measurements

The upper branch of the hysteresis loop reconstructed from FORC measurements is exported to a file with the structure shown in Fig. 3.31. The file header contains summary information and is followed by field and magnetization values of the upper hysteresis branch, listed in a comma-separated two-column format with no empty lines. The beginning of the data section is univocally located by the title line “Upper hysteresis branch”, regardless of the actual row number. Information blocks in the file header begin with a title (e.g. “Field and magnetization units”), followed by comma-separated parameter lists. Empty lines are used to separate different blocks. Line widths are unlimited and might be wrapped by some text editors. The information blocks coincide with blocks 1, 2, 5, 6, and 8 of the corrected FORC measurement files (see section 3.7.1) and are followed by a last block containing data that define the upper hysteresis branch reconstructed from FORC measurements.

A paramagnetic correction has been performed if a numerical value of  $M_s$  is given in block 4. If hysteresis data should be imported with third-party software, consider that the beginning of this block is set by the block title, and not by a fixed line number. This enables future VARIFORC releases to extend the file header with lines containing additional information. These will be eventually added after the hysteresis parameter block (block 4), so that already existing blocks continue to occupy the same positions.

VARIFORC v1.0 corrected hysteresis deduced from FORC measurements.

Normalization unit and factors for listed source files

mg,27.2,E:\...\Leg138\_848\_S0\_a.txt, 27.2,E:\...\Leg138\_848\_S0\_b.txt, ...

Field and magnetization units

T,mAm<sup>2</sup>/kg

Saturation remanence with standard error, saturation magnetization with standard error, ..  
3.897134730097964,0.0006913444803027636,9.758817813285226,0.06385782357290273

Upper hysteresis branch

-0.16232408474463628,-13.154719464316324  
-0.16178280088289992,-13.13226640818062  
-0.1613337375263111,-13.135492348377696  
-0.16078771356969176,-13.111816097517703  
-0.16032490131204238,-13.11112104260856  
-0.15977335225062048,-13.094304926199003  
-0.15932531793699814,-13.095983868474956  
-0.15878418543051126,-13.046335795860093  
-0.15832906053224696,-13.042994463488345  
-0.15778342044726537,-13.017299359023637  
-0.15731728668090875,-13.036461153150336  
-0.15677189900145264,-12.99883157714917  
-0.15631009215475886,-12.976350132748891  
-0.15577044996889572,-12.950667984427854  
-0.1553208067999018,-12.928403353509728  
-0.1547776853554144,-12.92784067281246  
-0.15431373513788957,-12.912595945508496  
-0.15377268953882112,-12.899563836955382  
-0.1533229714133827,-12.886559492168852  
-0.15278123522764575,-12.858934210343133  
-0.15231887335448815,-12.84033713417023  
-0.1517797183021377,-12.814279809021563  
-0.1512096237642564,-12.79123150624227  
-0.15076497032532635,-12.79912552338344  
-0.150214803735362,-12.771026777281484  
-0.14975739262630652,-12.765255442284033  
-0.14921250718316287,-12.715183007633527  
-0.1487609670699618,-12.726963025551886  
-0.14821120809801552,-12.702395112619795  
-0.1477554961358207,-12.697096841166083  
-0.14720920967884024,-12.681798198076093  
-0.14675858024458,-12.639920224741433  
-0.14621435750002637,-12.622170809787564  
-0.14574307522537633,-12.611218508198307  
-0.14519412651488428,-12.611098601803146  
-0.14474403025379703,-12.59291614523676  
-0.14420395411354045,-12.572707051645855  
-0.1437425599072006,-12.52674340875875  
-0.14320324745743443,-12.518347852080256  
-0.14274300677157417,-12.494552003736892  
-0.1421994605794279,-12.499351015087905  
-0.14173996277738568,-12.456540832641641  
-0.14119397663018157,-12.429218030627473  
-0.1407439017327419,-12.454887674917087  
-0.14020822003319888,-12.404218086392895  
-0.13973761003429,-12.372725288266341  
-0.1391939335677145,-12.362873157893322  
...

**Fig. 3.31:** Example of hysteresis file produced by ImportFORC. Information blocks begins with a title (highlighted in blue), followed by a list of parameters. Hysteresis data begin after “Corrected measurements” and do not contain empty lines.

### 3.8 Literature

Fabian, K. (2006). Approach to saturation analysis of hysteresis measurements in rock magnetism and evidence for stress dominated magnetic anisotropy in young mid-ocean ridge basalt, *Physics of the Earth and Planetary Interiors* 154, 299-307.

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Pike, C.R., A.P. Roberts, and K.L. Verosub (1999). Characterizing interactions in fine magnetic particle systems using first order reversal curves, *Journal of Applied Physics* 85, 6660-6667.

Pike, C.R., A.P. Roberts, and K.L. Verosub (2001). First-order reversal curve diagrams and thermal relaxation effects in magnetic particles, *Geophysical Journal International* 145, 721-730.