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An open-source, QGIS-based solution for digital geological mapping: GEOL-QMAPS

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ABSTRACT

Digital geological mapping has experienced significant growth over the past three decades due to the advent of commercial geographical information systems, advances in global positioning systems, and the availability of portable hand-held devices, such as mobile personal computers (PCs), smartphones, and tablets. Numerous software packages have been developed to collect, combine, organise, visualise, publish, and share field data with enhanced spatial accuracy and minimal post-field processing. However, many of these tools are not open-source or are not made available to the geoscientific community, remaining specific to given mapping projects or organisations.

In this contribution we introduce GEOL-QMAPS, an open-source, QGIS-based solution promoting digital geological mapping in a harmonised, comprehensive and flexible way. It can be used in the field with a tablet PC or *via* the QGIS-based QField app on iOS or Android mobile devices, enabling synchronisation with desktop QGIS and the creation of field databases. Designed as a general solution, the GEOL-QMAPS solution consists of a QGIS field data entry template and a custom QGIS plugin, both available on free-access online repositories. The plugin allows for the adaptation of dictionaries (i.e., lists of attributes describing geological features), initially set to international nomenclatures, to the guidelines of different mapping projects. The solution also facilitates the loading and consultation of relevant legacy geodatasets (*e.g.,* preexisting field data, geochemical, geophysical maps or punctual datasets). A fact map, created from field data collected across the Archean Sula-Kangari greenstone belt in Sierra Leone, demonstrates the solution's advantages in terms of post-field processing and raw field data sharing.

1. Introduction

Geological mapping traditionally relies on reporting geological information within a specific area, such as the distribution of lithological units and the presence and extent of tectonic structures at a given spatial resolution, to infer their arrangement at depth and what they reveal about the local geological record (Maltman, 2012; Barnes and Lisle, 2013). Field data collection can be performed in various natural environments, on foot or using other forms of transport, and requires minimal equipment: paper, a topographic or aerial photographic base map, compass-clinometers, notebooks, clipboards, and pencils. These requirements have remained largely unchanged since the production of the first country-scale geological map over two centuries ago (Smith, 1801). However, advances in digital technologies, such as global positioning systems (GPS), geographical information systems (GIS), and portable hand-held devices for data collection, have led to the emergence of numerous digital mapping tools in the past thirty years.

The introduction of tablet personal computers (PCs) and mobile GIS software-based, personal digital assistants has been crucial in the widespread adoption of digital geological mapping (DGM). These tools enable collaborative data collection and editing in the field, as well as synchronisation with desktop GIS to populate shared, harmonised databases with limited post-field processing (Brodaric, 1997; Briner et al., 1999; Brimhall et al., 2001; Akciz et al., 2002; Howard, 2002; De Donatis and Bruciatelli, 2006; Howard et al., 2009). They are flexible and allow for the optimisation of details mapped, even in remote areas (Clegg et al., 2006). This is especially true for recent models of tablets and smartphones, which feature many sensors and adequate

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hardware-software capabilities to support various, accurate GIS-based field data collection apps (De Donatis et al., 2018; Lee et al., 2018; Yeon, 2021). Recent mobile device-supported DGM solutions even allow the integration of microscopic-scale, lab-based data (*e.g.,* thin section microphotographs) with structural and lithological field data to track complex geological relationships (*e.g.,* StraboSpot data system; Walker et al., 2019; Duncan et al., 2021). These technological advances have led to increased use of GIS and DGM tools for fieldwork preparation and data collection, marking a new era in fieldwork teaching (Marra et al., 2017).

However, there is a lack of consistency in digital field data, as GIS-based DGM tools have predominantly been developed as collaborative tools for standardised data collection within single organisations or projects (*e.g.,* Soller, 1999, 2000; Brimhall et al., 2001; André and Antunes, 2004; Leslie et al., 2014; Jordan and Napier, 2016; Galluzzi, 2019; Gencarelli et al., 2022). Only a few, such as the one implemented by Gencarelli et al. (2022), are based on open-source GIS softwares and apps like QGIS (QGIS, 2024) and the related QField app available on iOS or Android (QField - Efficient field work built for QGIS, 2024). Additionally, the code for these field data entry tools is rarely available online or is only accessible on request from the corresponding author (*e.g.,* Gencarelli et al., 2022), limiting their use by other geologists.

While developing digital mapping tools specific to a project or organisation may seem practical, as it allows for the design of templates tailored to specific needs and protects intellectual property, it limits the ability of geologists to compile, share, and reuse data from different projects. The StraboSpot DGM tool (Walker et al., 2019) is an exception, being an open-source solution supported by FAIR data principles (findability, accessibility, interoperability, reusability; Wilkinson et al., 2016). However, StraboSpot is a standalone software, and transferring data to another GIS software requires exporting in an appropriate format, uploading and redefining symbologies.

There is, therefore, a need for a free, open-source, GIS-based DGM solution that supports both online and offline fieldwork and provides straightforward control over available data. QGIS and QField appear to be the optimal software-app combination to meet these requirements. It is essential to predefine a field data entry template that accommodates a wide range of geological observations using established nomenclatures. This can be achieved by creating custom field data layers in QGIS with dictionaries and constraints. The DGM solution should also allow for customisation of the field database design and symbology to align with various guidelines and support the import and harmonisation of legacy data. Distributed field teams should be able to compile their data into a master field database, which can be achieved through in-house QGIS plugin tools.

Leveraging QGIS's capabilities, its extensive plugin support, and the recent development of the QField app, we therefore introduce **GEOL-QMAPS**, a **Q**GIS-based, digital **geol**ogical **map**ping **s**olution that fulfils these specifications. It includes a ready-to-use QGIS project template with numerous custom field data layers and a related custom QGIS plugin. Although GEOL-QMAPS was initially developed for the stage 4 of the West African eXploration Initiative project (WAXI4, 2024), it is in no way hard-wired to the West African region and can be considered as a general solution adaptable to any mapping guidelines.

We will describe the structure of the QGIS project template and the architecture of the implemented field database, provide guidance on how to get started and implement the solution prior to and during fieldwork, and highlight the advantages of GEOL-QMAPS as a comprehensive and flexible DGM solution. To illustrate its use, we will discuss a fact map featuring field data collected across the Archean Sula-Kangari greenstone belt in Sierra Leone.

2. Advantages of digital over traditional geological mapping

This section presents an overview of why DGM is poised to surpass traditional mapping, if it has not already done so. The advantages of DGM over paper-based maps are two-fold.

2.1. Publication and sharing of raw field data

Fact maps are designed to provide an unbiased representation of observations and measurements, focusing on raw, objective data such as outcrop locations and descriptions, the extent, orientation, and kinematics of structures, mineral occurrences or sampling points. Ideally, these data and their geological interpretation, concerning elements such as subsurface unit distribution, stratigraphic relationships, and the presence of large-scale faults and folds, should be consistent among different geologists working under similar conditions with comparable skill sets. However, this scenario is highly unusual. Geological maps typically result from the interpretation of sparse, spatially non-uniform data collected using sampling strategies (Jones et al., 2004) that vary from project to project, often led by geologists with differing expertise.

Sampling strategy depends on factors such as terrain accessibility, topography, exposure quality, the mapper's knowledge of the area and their mapping experience, available time, and weather conditions. These factors can change over time or between projects, resulting in the collection of different raw field datasets. It has been demonstrated that different geologists will produce varied maps of the same area based on different field observation datasets (Sturkell et al., 2008). Consequently, the sampling strategy and the mapper's expertise critically influence geological interpretation. Therefore, it is essential for geologists to distinguish clearly between raw data and the inferences drawn from them, ensuring both are reported accurately and separated (Ramsay and Huber, 1987).

Despite this importance, fact maps are rarely published explicitly alongside traditional, interpreted maps. GIS-assisted DGM techniques now facilitate the collection, publication, and sharing of georeferenced raw field data, as well as field photographs and other background information (*e.g.,* geophysical data, satellite imagery, digital elevation model) related to the studied area (Jones et al., 2004). These data can be easily reused in subsequent field campaigns (McCaffrey et al., 2005).

2.2. Accurate georeferencing of field data with limited scale restriction

Since the widespread adoption of GIS in the 1980s, it has become an essential tool in Earth sciences and other fields for data organisation, visualisation, search, combination, analysis, and prediction (Jones et al., 2004). Field data previously recorded in notebooks and on paper maps are now systematically digitised to build extensive, searchable geodatabases. However, if field data are not accurately spatially located when initially recorded (*e.g.,* due to missing or misreported coordinates or an unknown coordinate reference system), the resulting digital dataset will be erroneous and/or incomplete, compromising interpretation accuracy. For paper maps, although guidelines exist to assist with GIS digitisation (Erharter et al., 2023; also available as an online supplement to Schmalfuss et al., 2023), the accuracy of the digital map cannot exceed that of the original map, which depends on its scale and quality. The advent of portable hand-held devices and the increased spatial accuracy of GPS triggered the revolution in DGM (Jones et al., 2004; McCaffrey et al., 2005). Geologists can now collect GPS-located numeric field data with spatial accuracy up to 1 m, depending on signal quality. This capability allows for detailed data collection in specific areas without being constrained by map scale. Such precision may be crucial for understanding the regional context but might be unattainable with paper maps due to scale limitations.

3. A new QGIS-based general solution for harmonised, digital geological mapping

3.1. Use of QGIS software and QField application

The GEOL-QMAPS field data entry template and custom plugin have been designed using free and open-source tools, namely QGIS software (version 3.36.01 Maidenhead; QGIS, 2024), the QGIS-based QField application (version 3.3.11 Darién; QField - Efficient field work built for QGIS, 2024) and the QFieldSync plugin for QGIS (version 4.10.1). QGIS is one of the most popular free geospatial software available and is part of the Open-Source Geospatial Foundation (OSGeo). The extensive integration of new tools through plugin development and the growing community of users and developers may eventually make it the primary geospatial tool for Earth and planetary science studies (Rosas-Chavoya et al., 2022). The QFieldSync plugin facilitates the use of QGIS projects with the QField application, enabling the collection of structured and georeferenced field data on Android and iOS mobile devices. It also allows for the synchronisation of data in QGIS and the compilation of a GIS field geodatabase. The use of the plugin is essential for collecting field data unless using tablet PCs. The development of QField for mobile devices has made the QGIS-QField combination a very convenient tool for collecting new field data and consulting, visualising, and modifying GIS databases directly in the field. QField has seen increasing use in geosciences and other fields since its release in 2019 (*e.g.,* Iandelli et al., 2021; Gencarelli et al., 2022; De Donatis and Pappafico, 2023).

Fig. 1 illustrates the procedure for using GEOL-QMAPS from the office to the field, using both QGIS and QField tools. A step-by-step guide for loading the initial QGIS project onto mobile devices and synchronising newly entered data back into the QGIS project is detailed in the how-to guide included with the QGIS project template on the Zenodo repository. Note that QFieldCloud, released by the developers of the QField app, provides an alternative online method for synchronising and merging data collected in QField within online storage (QFieldCloud - Seamless fieldwork, 2024). However, annual fees apply for full access to cloud functionalities. Another option is to run a local copy of QFieldCloud (available at https://github.com/opengisch/qfieldcloud) on a private server or virtual machine.

3.2. Structure of the template

The GEOL-QMAPS QGIS project with the field data entry template is available online as an archive file in a Zenodo repository (Perret, 2024). The current version is 3.0.13, resulting from progressive upgrades based on feedback from beta-testers at the University of Western Australia, Australia, University of Lorraine, France and Félix Houphouët-Boigny University, Ivory Coast.

The archive file contains a main folder with the QGIS project file, relevant field data entry files and database folders, a log file, and how-to guides. As shown in Table 1, the QGIS project folder architecture is designed to facilitate various aspects of GIS use for fieldwork (Wagtendonk and De Jeu, 2007; Marra et al., 2017):

- *consultation of existing raster or vector geodatabases to prepare fieldwork or while mapping:* existing field data, georeferenced geological or geophysical maps, geochronological or geochemical datasets, elevation data, satellite imagery, exploration or mining data, etc., may be stored in the repository. The main folder contains several sub-folders where relevant geodata can be sorted by theme. For example, the main folder includes an “11. ORTHOPHOTOGRAPHY-SATELLITE IMAGERY” sub-folder with an extract of ©Google Satellite imagery centred on Africa (spatial resolution of 5 km), which is used as a base map in the blank QGIS project. Sub-folder names match the group names where related layers should be loaded in the QGIS project (Fig. 2). Additional sub-folders can be created to store existing GIS datasets that should be loaded into matching groups in the QGIS project,
- *collection of new field data* (see sub-section 3.3)*:* The “0. FIELD DATA” folder contains one CURRENT MISSION geopackage with all empty field data entry layers. Sample and field photographs should be stored in the “DCIM” sub-folder. There is also a CURRENT MISSION + CSV FILES. qlr layer style definition file to open related data sources and bring in all related style information and group architecture displayed in the QGIS mapping project template (Fig. 2). The CSV FILES group uploaded this way contains dictionaries used in dropdown lists for filling field data entry forms, which can be edited using a custom QGIS plugin (see below),
- *management and processing of collected data during or post-fieldwork:* a custom plugin for QGIS has been developed at the University of Western Australia to assist with critical GIS operations at different

Table 1
Structure of the QGIS mapping project template folder stored in the GEOL-QMAPS archive file available for download online (v3.0.13; Perret, 2024). Note that the 1. EXISTING FIELD DATABASE folder at Level 3, not shown in the Table, contains a COMPILATION.gpkg file and an EXISTING FIELD DATABASE.qlr Layer Definition file, similar to those in the 0. FIELD DATA folder, to facilitate compilation and import from legacy data using the custom GEOL-QMAPS QGIS plugin.

GEOL-QMAPS_v3.0.13 archive file			
Level 1	Level 2	Level 3	*CURRENT MISSION + CSV FILES.qlr file loaded in QGIS: group architecture*
archive folder	QGIS TEMPLATE folder	0. FIELD DATA folder	
QGIS TEMPLATE	0. FIELD DATA *Contains the field data layers*	CURRENT MISSION + CSV FILES.qlr *Layer Definition file to upload empty field data layers and dictionaries in QGIS*	STOPS-SAMPLING-PHOTOGRAPHS-COMMENTS *Record of stop points, sampling, photographs, and additional comments*
GEOL-QMAPS_ v3.0.13_Tutorial. pdf (with and without notes) *How-to guides* List of updates of the different releases.docx *Log file*	1. GPS-LOCALITIES OF INTEREST to 11. ORTHOPHOTOGRAPHY-SATELLITE IMAGERY *Sub-folders where to store and sort relevant geodata loaded in the QGIS project* 99. COMMAND FILES-PLUGIN *Files required for the custom QGIS plugin* WAXI4 - Mission ID - Date.qgz *QGIS mapping project template*	CURRENT MISSION.gpkg *Contains empty field data layers* DCIM *Default repository for field and sampling photographs loaded in related field data layers*	STRUCTURES (LINEAR and PLANAR) *Record of structural information, e.g., punctual measurements, extent of linear or polygonal structural features, etc …* LITHOLOGY *Record of lithological information, e.g., nature of outcrops, contacts and extent of different lithological units, etc …* GEOPHYSICAL MEASUREMENTS *Record of magnetic susceptibility measurements* CSV FILES *Contains dictionaries for dropdown lists in field data entry forms*

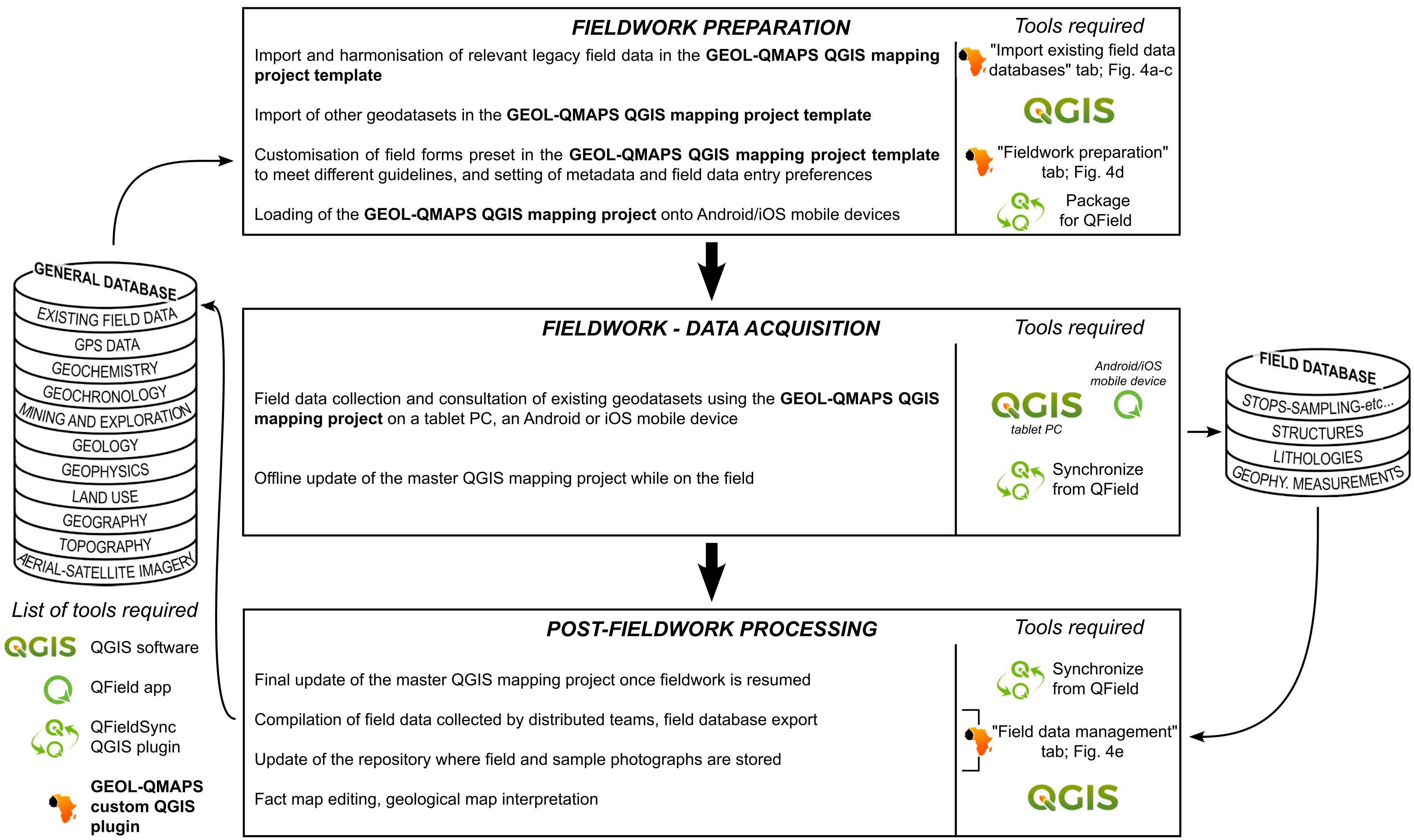

Fig. 1. Flowchart illustrating the process from fieldwork preparation and field data acquisition to field database compilation and further use, using the GEOL-QMAPS solution. Logos of QGIS software, QField app, and QFieldSync QGIS plugin are from the QGIS and QField websites (QField - Efficient field work built for QGIS, 2024; QGIS, 2024). Note that the procedure for online updating of the master QGIS mapping project *via* QFieldCloud, by subscribing to it or creating a copy on a virtual machine, is not shown in the figure.

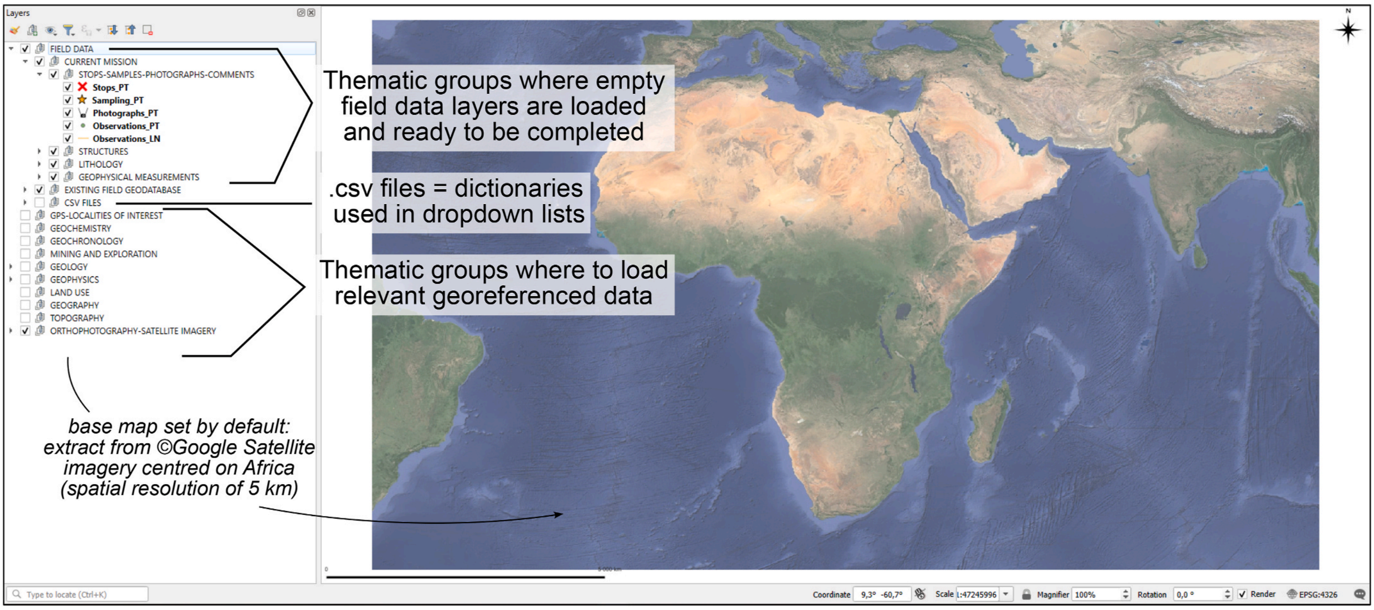

Fig. 2. Annotated screenshot of the QGIS window illustrating the tree architecture of the GEOL-QMAPS field data entry template. Note how it replicates the folder organisation of the QGIS template archive file (Table 1; Perret, 2024) to facilitate geodatabase management. Styles, including labels, symbols, and attribute forms, are preset to facilitate field data collection.

stages of the fieldwork process, including field database management (plugin code available at https://github.com/swaxi/WAXI_QF; see sub-section 4.2). During fieldwork, regularly updating field geodatabases can significantly aid in adjusting the ongoing fieldwork campaign.

The final steps of DGM, namely (i) data analysis, curation and map editing and (ii) post-fieldwork analyses such as modelling, can then be supported by desktop GIS (Fig. 1; Karssenberg et al., 2001; Jones et al., 2004). The custom QGIS plugin also facilitates certain operations to simplify pre- and post-field data transfer and processing (see sub-section 4.2).

3.3. Collectable field data

The detailed list of layers contained in the field data geopackage and their attributes, *i.e.,* the information that can be provided for each new entity, is available in Supplementary Material 1. Layer names are straightforward and clearly indicate the nature of the geoinformation supported by the corresponding form. The layer name suffix denotes the typology of vector entities that can be entered: "_PT" for points, "_LN" for lines and "_PG" for polygons. Field data are divided into four groups:

- 0. STOPS-SAMPLING-PHOTOGRAPHS-COMMENTS: this group contains field data layers for entering stop and sampling points, photographs, and providing additional comments as point or line features. Pictures of samples and field photographs are stored in a DCIM sub-folder,
- 1. STRUCTURES: this group contains field data layers for entering structural information, such as punctual measurements of orientation and description of linear features (*e.g.,* fold axes and lineations), or planar features, (*e.g.,* bedding, schistosity-cleavage, shear zones-faults, fractures, mineral veins and dikes), as well as the extent of these structural features and deformed areas,
- 2. LITHOLOGY: contains field data layers for entering lithological information for supergene, sedimentary, volcanoclastic, igneous extrusive or intrusive, and metamorphic rocks, including the nature of observed rocks, contacts between units, extent of units, *etc*,
- 3. GEOPHYSICAL MEASUREMENTS: currently, only magnetic susceptibilty measurements can be entered, with the possibility of providing details about the analysed rock.

3.4. Future maintenance of the GEOL-QMAPS solution

The first author of this contribution will be responsible for maintaining and updating the GEOL-QMAPS solution to ensure compatibility with new versions of QGIS, keeping it available to the public. Future releases of GEOL-QMAPS will aim to incorporate modifications based on user feedback and advancements in QField, enhancing the digital mapping experience to be more comprehensive and user-friendly. Upgrades will primarily focus on the comprehensiveness of the field data layers and their attribute forms, as well as the clarity of the how-to guides. Suggestions made to the corresponding author of this contribution that would facilitate field execution will be considered.

The QGIS field data entry template is open-source, allowing experienced users to modify it as needed to create different templates without starting from scratch. Less experienced users can provide feedback and requests for changes to the template's architecture to the corresponding author. All requests will be considered, provided they do not contradict the majority opinion. Users can also customise the template to meet different mapping guidelines by modifying the predefined dictionaries for field data entry (see sub-section 4.2.2).

4. Insights

4.1. A comprehensive, harmonised, standardised digital mapping tool

4.1.1. Specifications of the GEOL-QMAPS solution

The GEOL-QMAPS DGM solution has been designed to adhere to international nomenclature standards for field data reporting and to facilitate data harmonisation among different users, thereby reducing post-field processing. Attribute forms are crafted to be as comprehensive and user-friendly as possible, employing several tabs to guide users through the description of geological features in an effective and thorough manner (Fig. 3). They refer to state-of-the-art nomenclatures and methods for describing geological information, making this DGM tool a versatile solution applicable to any mapping project. This includes

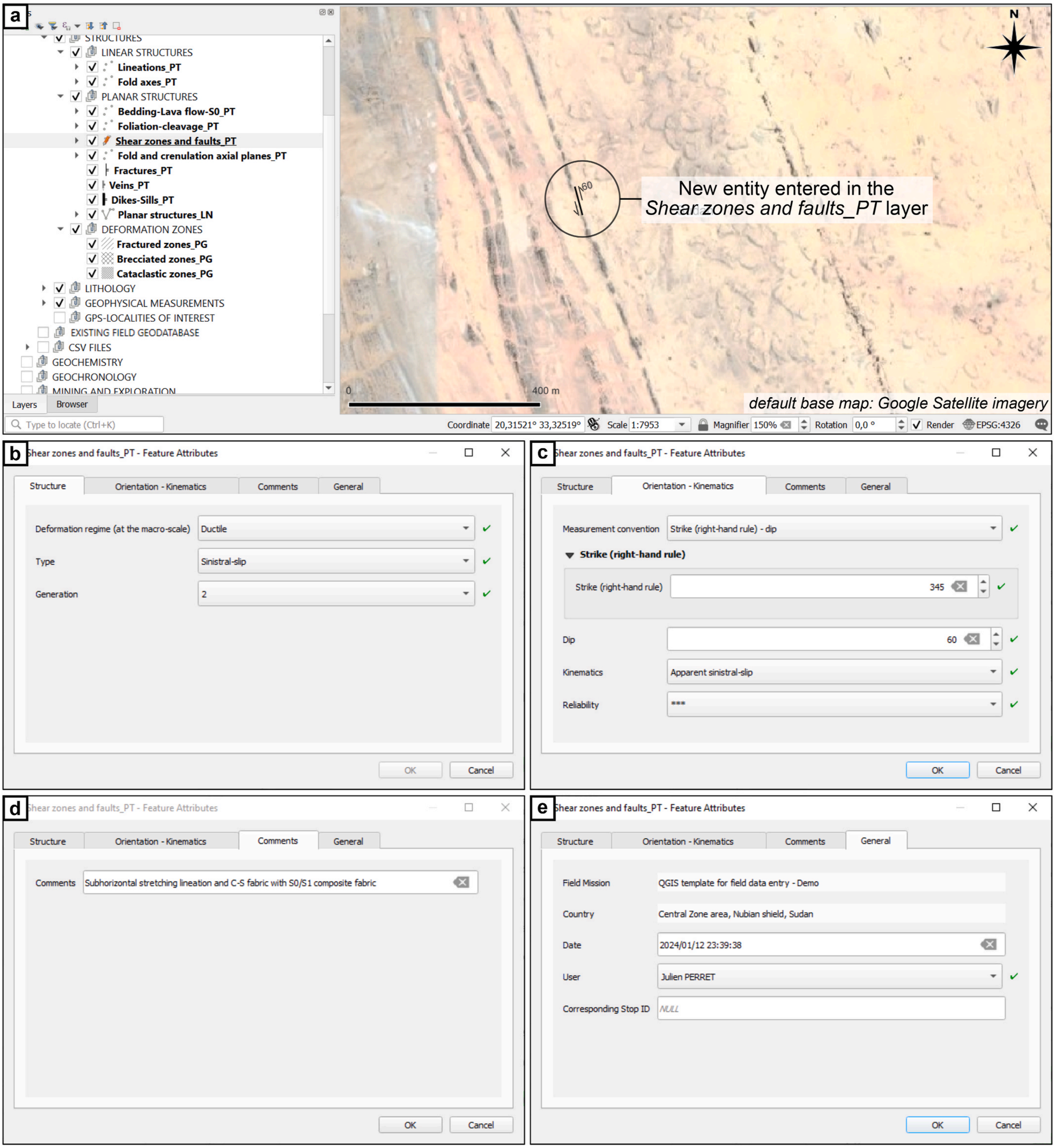

Fig. 3. Example of map rendering (**a**) and related filling of attribute form tabs (**b-e**) for the entry of a new entity in the *Shear zones and faults_PT* layer. The shear zone orientation measurement was originatelly collected during fieldwork at the Central Zone gold deposit, Block 15, Sudanese Nubian shield (Perret, 2021; Perret et al., 2021). **a** Conventional symbols are used to represent structures (*e.g.,* a sinistral shear zone). **b** *Structure tab:* provides information about the deformation regime and additional kinematics information. **c** *Orientation tab*: note the dropdown list to switch from strike and dip to dip-dip direction nomenclature for reporting orientation. There is a reliability attribute enabling the weighting of the confidence level in the measurement made. **d** *Comments tab:* this tab and related attribute is the same for every field data layer implemented and enables the provision of any additional information about the data entry. It may notably help with identifying what is missing in the current forms. **e** *General tab:* provides metadata useful for further data compilation. Attributes are automatically filled, except for the User attribute, which may be modified or set to a relevant default value. Adding new users to the related dropdown list and modifying the Field Mission and Country attribute values are handled by the custom QGIS plugin related to the QGIS mapping project (https://github.com/swaxi/WAXI_QF). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

reporting the orientation of planar and linear structures, such as right-hand rule strike-dip or dip-dip direction and trend (also known as azimuth or plunging direction) and plunge (*e.g.,* Allmendinger, 2015; Lisle, 2020), rock names, textures, and modal composition in the case of igneous-(derived) rocks (Irvine and Baragar, 1971; Streckeisen, 1974, 1976, 1980; Le Bas and Streckeisen, 1991; McPhie et al., 1993; Le Maitre et al., 2005) or mineral abbreviations (Siivola and Schmid, 2007; Whitney and Evans, 2010).

Where possible, we have implemented dropdown lists, stored as. csv files (Supplementary Material 1), from which users must select one or several values to complete attribute fields. This is critical for optimising data entry and limiting discrepancies in data collection over time and between different users. It also facilitates data sharing and integration in projects involving multiple organisations (*e.g.,* WAXI4, 2024) and between projects led by a single organisation.

Additionally, symbols and labels for the different data layers have been set in the most explicit manner possible and adhere to broadly accepted symbology when appropriate (*e.g.,* structural symbols; Fig. 3a). This proves helpful for subsequent post-field fact map editing in QGIS and data sharing.

4.1.2. Comparison with existing digital geological mapping solutions

Among the existing solutions for digital geological mapping, the StraboSpot data system (Walker et al., 2019; Duncan et al., 2021) offers possibilities most similar to GEOL-QMAPS. It is free, open-source, and allows users to collect a wide range of geoscientific data in the field, known as *spots*, on both iOS and Android mobile devices. It also employs controlled vocabularies developed by the geoscientific community, facilitating standardised data collection and enhancing data findability. StraboSpot has several advantages over GEOL-QMAPS, such as (i) the ability for users to make their data public, making large collections of raw field data available online, (ii) its interoperability with applications such as Stereonet or StraboTools and (iii) the use of a graph database approach that supports the integration of multi-scale, field- and lab-based observations. However, transferring data from StraboSpot to another GIS software requires exporting it in an appropriate format, uploading it, and redefining symbologies, whereas GEOL-QMAPS is already GIS-based, facilitating data transfer to other GIS users. In our view, while StraboSpot is an excellent tool for building and sharing databases of field- and lab-based, multi-scale observations, GEOL-QMAPS represents a robust alternative for traditional geological mapping using digital devices and straightforward post-fieldwork GIS data management (see sub-section 4.2.3).

4.2. From fieldwork preparation to post-field processing: a responsive digital mapping tool

Despite the GEOL-QMAPS mapping template offering field data forms aligned with conventional nomenclatures, its design is flexible enough to meet any mapping project guidelines and facilitate database management and consultation. We have implemented a custom QGIS plugin to support critical GIS operations related to these topics through a user-friendly interface accessible to a broad audience, including novices in GIS (Fig. 4). The QGIS plugin window is divided into tabs displaying different functionalities. The last tab provides general information and is not described further.

4.2.1. Harmonising existing field datasets with the current mapping project architecture

The first tab ("Import existing field databases") is dedicated to reformatting existing lithological and structural databases according to the architecture of the mapping project template (Fig. 4a-c). This is crucial for post-field compilation with newly collected field data and for the visualisation and consultation of all data within a single frame of reference. The four-step process relies on the similarity between field names and entered values in imported databases concerning names of field data layers and available values for field form completion in the provided template. Uploading and processing of the legacy database relate to Step 1 (Fig. 4a). Processing involves applying an arbitrary threshold to a similarity score calculated by the *fuzzywuzzy* string-matching library (https://github.com/seatgeek/fuzzywuzzy), after constructing a thesaurus of similar terms. The latter approach is exemplified in Joshi et al. (2021). To allow user-supervised validation of the proposed indexing of fields and values during Step 2, the user can check and correct mismatches and, if necessary, discard values or columns from the existing field database being processed (different sub-tabs for column names, rock names, and structural data; Fig. 4b and c). A colour code assists in identifying potential mismatches (Fig. 4b). Step 3 enables the generation of output QGIS layers once data import is validated. The final step is optional and allows for merging any output QGIS layer into a single layer that may store data imported from different sources (Fig. 4a-c).

4.2.2. Field work preparation: update of field forms and metadata, and field data entry preferences settings

The second tab ("Fieldwork preparation") addresses metadata updates related to the current mapping project (*e.g.,* mapping project ID and location attributes; Fig. 3e and 4d). A tool allows the setting of a new default value for the 'User' field in a given or all field data layers. If not already present, the value is added to the related dictionary. This can improve efficiency during field data entry as the user does not need to edit the related field for at least the first entity entered in each layer. It is also possible to set the preferred method for entering stop data points (*i.e.,* with or without auto-increment of Stop ID numbers).

The conventions used in the QGIS project template to describe any lithological or structural features follow international standards but can be easily modified to match other mapping guidelines *via* a tool available in the second tab of the custom QGIS plugin window. This tool enables the user to easily update all .csv files and customise dropdown lists in any field data entry form accordingly. This is particularly useful for mine-scale mapping, where local rock names are often employed. In such cases, the user may wish to edit the dictionary listing rock names using the custom QGIS plugin and set symbols for each name in QGIS desktop prior to collecting field data. This can be easily done by following QGIS documentation (https://docs.qgis.org/testing/en/docs/user_manual/working_with_vector/vector_properties.html#symbology-properties). With appropriate pre-field preparation, GEOL-QMAPS can thus be considered a solution applicable on a scale larger than the West African region, for which it was initially developed.

Finally the user can clip a large database to a specific geographic zone to reduce the amount of data transferred to the mobile device. The newly updated field data can be merged back into the main database in the next tab.

4.2.3. Field data management: from data combination to early processing

The third tab ("Field data management") allows users to merge datasets or projects, and export layers by themes, *e.g.,* merging all lithology-related point layers, which is useful for field database implementation (Fig. 4e). The overall data collection and processing rely on the open-source QGIS software and compatible apps or plugins. This makes it easy to share parts of or complete field databases with industrial, governmental, or academic partners immediately after fieldwork completion, with minimal time spent on database building. Additionally, it is possible to merge field data acquired from different projects led by one or multiple organisations, provided they followed the same template architecture (if modified from the default one), with minimal geodata management.

Such extensive databases can be particularly useful for further numerical field data processing to assess the reliability of different interpretative models (Jones et al., 2004). Note that other tasks, such as clustering field data based on a neighboring distance threshold or updating the repository where field and sample photographs (displayed

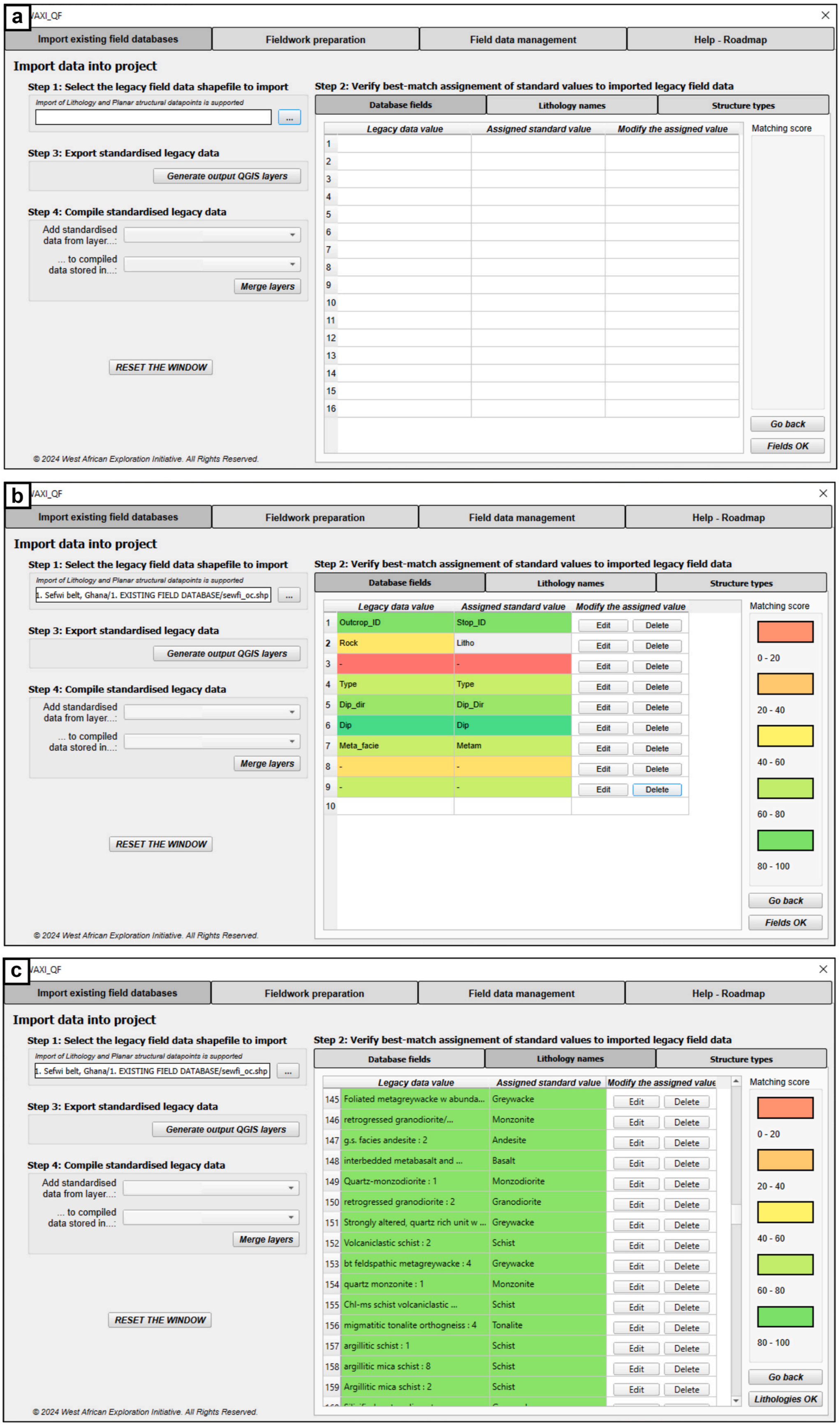

Fig. 4. Annotated screenshots of the different tabs of the custom plugin window opened in the QGIS environment. **a-c** The "Import existing field databases" tab provides a multiple-step, semi-automated process to harmonise and import existing field data following the architecture of the field data layers available in the QGIS template. Raw data are stored in a legacy field for each layer. **d** The "Fieldwork preparation" tab provides tools for project customisation, *i.e.,* clipping of existing

databases to a region of interest, editing dictionaries for field completion in the different data entry forms, modification of the 'User' default value for one or every field data layer, updating of mapping project metadata, setting preferences for stop data point entry, and export of a custom layer definition style for field data layers and dictionaries if they have been modified to match different mapping guidelines. **e** The "Field data management" tab provides tools to merge projects or layers, export data, and set preferences for early data visualisation and processing on QGIS, *i.e.,* data merging and export, setting preferences for stereographic projection of punctual structural measurements relying on another custom plugin available at https://github.com/swaxi/qgis-stereonet, updating the repository where field and sample photographs loaded in the QGIS project are stored.

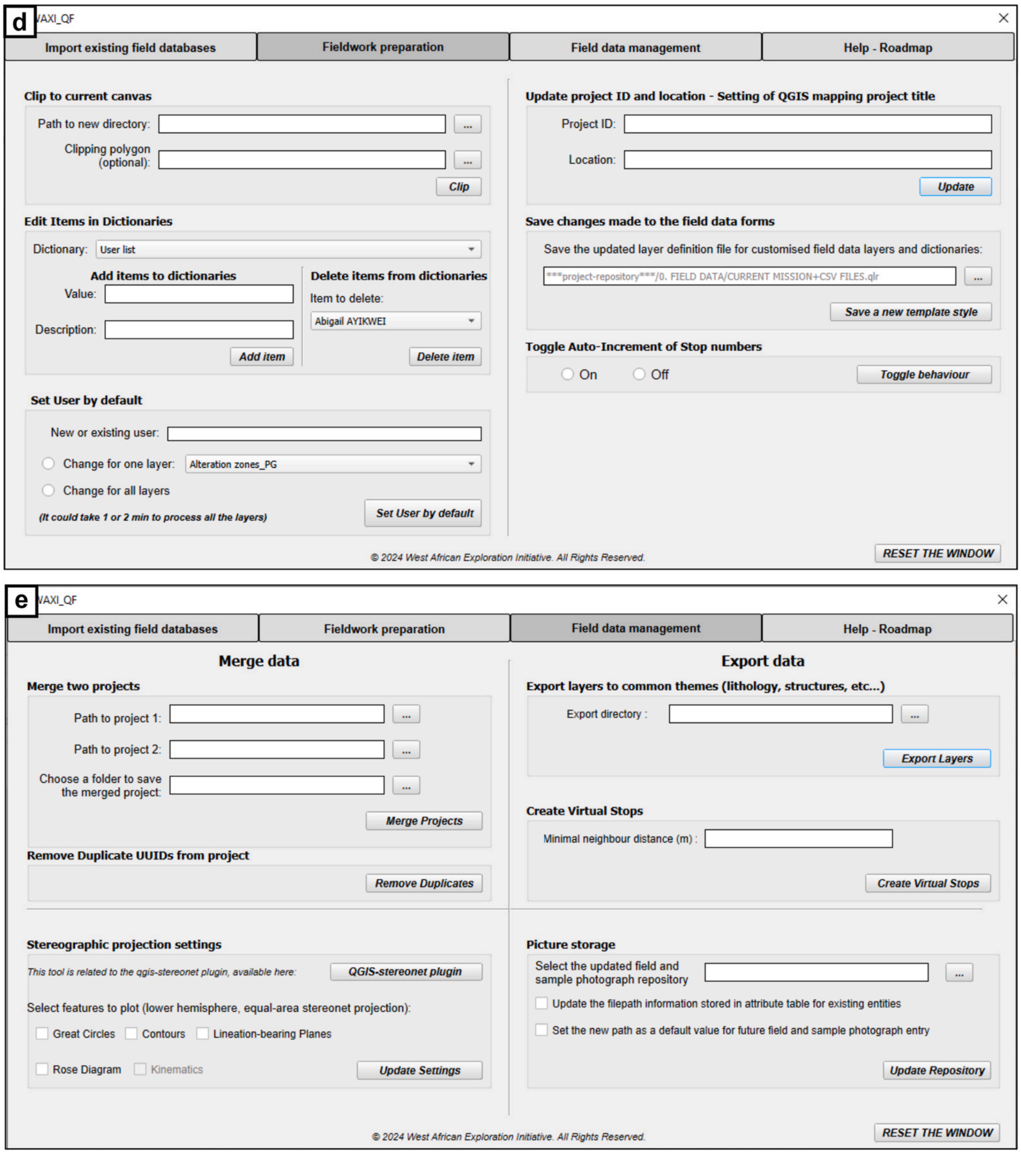

Fig. 4. (*continued*).

as map tips in the QGIS project) are stored, are managed by the QGIS plugin. A final functionality aims at setting preferences for stereographic projection of point structural measurements, using another custom plugin available at https://github.com/swaxi/qgis-stereonet. Tools available in this tab therefore assist in initiating post-field data visualisation, interpretation and management, with minimal processing time.

Note that these tools work with data compatible with, or acquired using the GEOL-QMAPS solution. To utilise these tools with legacy field data collected using other mapping softwares, the data must first be harmonised and imported into a GEOL-QMAPS QGIS project using the "Import existing field databases" tool provided by the custom QGIS plugin (see sub-section 4.2.1).

4.3. *Case study: field data collection across the Sula-Kangari greenstone belt, Sierra Leone*

Field data were collected across the Archean Sula-Kangari greenstone belt, Sierra Leone, using the proposed QGIS template and the QField app (Fig. 5), as part of the WAXI4 research programme. This study ultimately aims to reappraise the lithostratigraphic and tectonic evolution recorded in the area. Current knowledge of the regional geology primarily relies on pioneering work conducted by the British Geological Survey (*e.g.,* Wilson and Marmo, 1958; Marmo, 1962; MacFarlane et al., 1981), research from the 1980s and 1990s (*e.g.,* Morel, 1979; Umeji, 1983; Rollinson, 1999), and the 1:250,000-scale geological map of Sierra Leone (Geological Survey of Sierra Leone, 2004). The use of the QGIS-based DGM introduced in this contribution has proven relevant in three aspects detailed below.

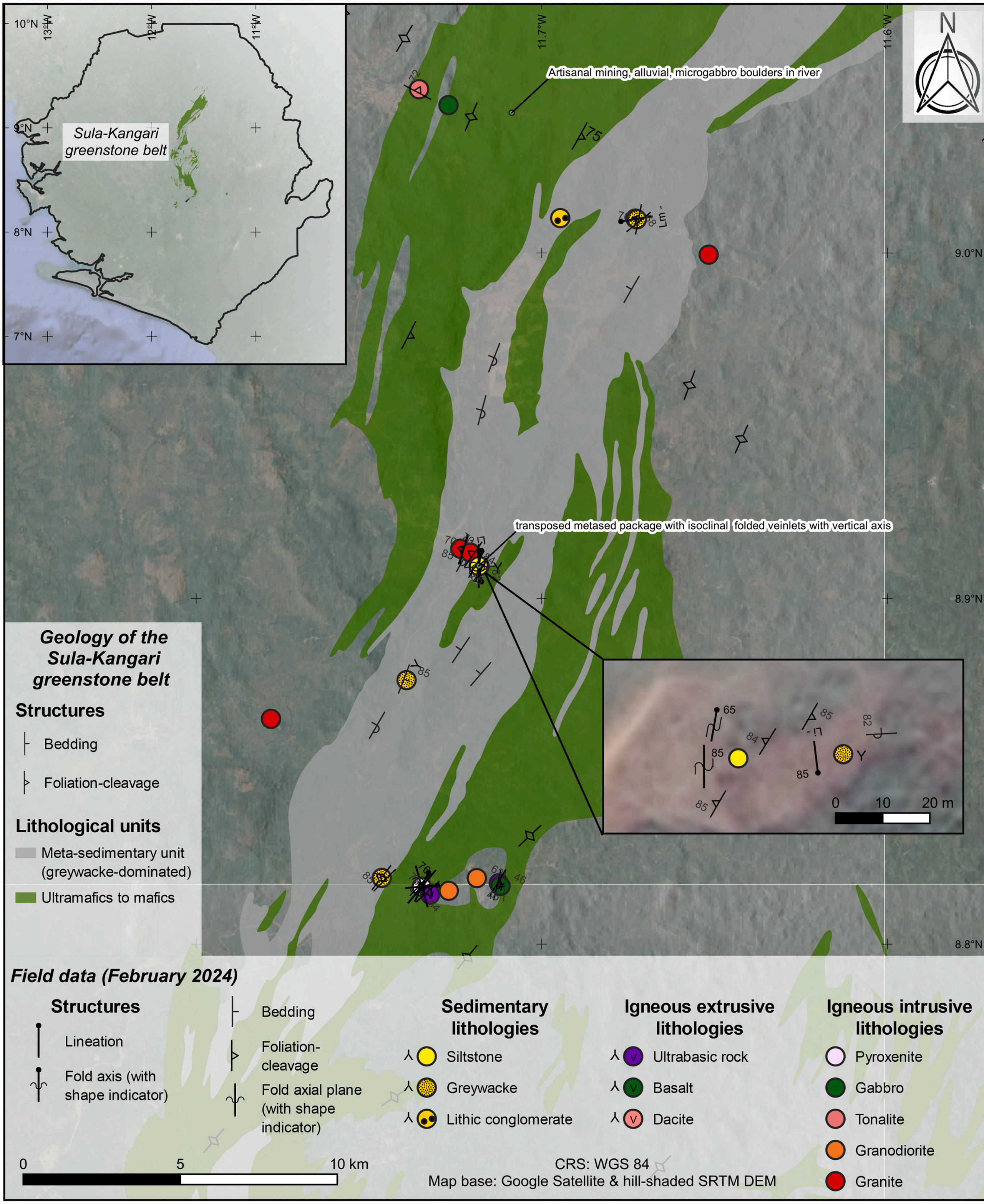

Fig. 5. Fact map edited on QGIS displaying field data collected across the Archean Sula-Kangari greenstone belt using GEOL-QMAPS (Perret, 2024). The background geology of the Sula-Kangari greenstone belt is from the digital geological map of Sierra Leone (Geological Survey of Sierra Leone, 2004).

Loading the country-scale geological map in QGIS as vector files and maps georeferenced according to the references mentioned above enabled the creation of a digital geodatabase available for consultation on QField during fieldwork (see background layers in Fig. 5). Additional satellite imagery, land use shapefiles, and DEM rasters were also loaded to aid navigation in the field.

Structural measurements added using the field data entry template are represented using international symbology, facilitating their comparison with existing field datasets at a glance while in the field. New measurements across the Sula-Kangari greenstone belt confirm that subvertical, N- to NNE-striking fabrics control its structural framework and that the meta-sedimentary to mafic series are mostly overturned. Data collected also reveal an additional degree of complexity, with description of steep, isoclinal folding visible at the outcrop scale (see inset in Fig. 5). Although such a pattern has been described at different places in the Sula Mountains and Kangari Hills (Wilson and Marmo, 1958; Marmo, 1962), the related structural data are not present on the regional map, likely due to misreporting or filtering of the dataset to fit the 1:250,000 scale of representation. This underscores the importance of editing and sharing fact maps with all raw data collected, which is easily achievable during QGIS post-field processing of data collected using the designed DGM template (Fig. 5).

Moreover, first-order insights into the lithostratigraphic record across the Sula-Kangari greenstone belt are readily apparent from the fact map. Despite poor exposure quality in such a tropical environment, visited outcrops confirm the predominance of meta-sediments and mafic to ultramafic rocks, intruded by ante-to syn-tectonic and post-tectonic granitoids, and the overall spatial distribution of these units (Fig. 5; Wilson and Marmo, 1958; Marmo, 1962; MacFarlane et al., 1981; Umeji, 1983; Rollinson, 1999). Data collected at this scale suggest that it should be possible to map more precisely the distribution of sub-units at the belt scale. Coupling georeferenced, raw field data (lithology data points and systematic magnetic susceptibility measurements) with recent, high-resolution, airborne magnetic and radiometric images (Archer, 2019; Anderson and Lahai, 2021) would be particularly useful, similar to what has been done elsewhere in West Africa (*e.g.,* Metelka et al., 2011). Since there is no further need for field data georeferencing, post-field processing and data integration will be faster.

5. Conclusions

This contribution introduces GEOL-QMAPS, an open-source, QGIS-based, geological mapping solution designed to facilitate fieldwork preparation, field data collection and field database management. It can be run in the field using a tablet PC or the QGIS-based QField app on iOS or Android mobile devices. The system provides an integrated workflow for mapping entirely within QGIS or QField, eliminating the need to switch between different mapping platforms.

GEOL-QMAPS has been designed as a general solution adaptable to any mapping guidelines. The QGIS mapping project consists of a combination of field forms with dropdown lists and symbols adhering to widespread nomenclatures for geological classification and lithological-structural descriptions. It ensures global harmonisation of data entered by different users and the use of similar symbology, which critically limits the time required for post-field processing of the field database and raw data sharing (*e.g.,* fact map editing). Although the dictionaries are tailored to the West African context, they are easily modified to align with other organisations' data standards, thanks to the use of an open-source custom QGIS plugin. The latter also facilitates pre- and post-field management of the geodatabase. GEOL-QMAPS could therefore be beneficial for industry and geological survey mapping programmes, as well as in field camp classes.

In contrast to most existing GIS modules designed to collect, combine, organise, visualise, publish, and/or share field data, the GEOL-QMAPS mapping module and the related custom QGIS plugin are open-source and available online (Perret, 2024; https://github.com/swaxi/WAXI_QF, respectively). Both the mapping module and the plugin are still under active development, which means that further upgrades will be released to make it the most user-friendly, collaborative, digital geological mapping tool possible.

CRediT authorship contribution statement

Julien Perret: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Conceptualization. **Mark W. Jessell:** Writing – review & editing, Validation, Software, Project administration, Funding acquisition, Conceptualization. **Eliott Bétend:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Julien Perret reports financial support was provided by Amira International Ltd. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The GEOL-QMAPS QGIS template related to this article is available online on a Zenodo repository (hyperlink in the web version of this article).The custom QGIS plugin related to the template is available online on a GitHub repository (hyperlink in the web version of this article).

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Appendix A. Supplementary Material 1

Supplementary data to this article can be found online at https://doi.org/10.1016/j.acags.2024.100197.

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