# GEOSPHERE

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# Bringing sedimentology and stratigraphy into the StraboSpot data management system

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## ABSTRACT

The StraboSpot data system provides field-based geologists the ability to digitally collect, archive, query, and share data. Recent efforts have expanded this data system with the vocabulary, standards, and workflow utilized by the sedimentary geology community. A standardized vocabulary that honors typical workflows for collecting sedimentologic and stratigraphic field and laboratory data was developed through a series of focused workshops and vetted/refined through subsequent workshops and field trips. This new vocabulary was designed to fit within the underlying structure of StraboSpot and resulted in the expansion of the existing data structure. Although the map-based approach of StraboSpot did not fully conform to the workflow for sedimentary geologists, new functions were developed for the sedimentary community to facilitate descriptions, interpretations, and the plotting of measured sections to document stratigraphic position and relationships between data types. Consequently, a new modality was added to StraboSpot—Strat Mode—which now accommodates sedimentary workflows that enable users to document stratigraphic positions and relationships and automates construction of measured stratigraphic sections. Strat Mode facilitates data collection and co-location of multiple data types (e.g., descriptive observations, images, samples, and measurements) in geographic and stratigraphic coordinates across multiple scales, thus preserving spatial and stratigraphic relationships in the data structure. Incorporating these digital technologies will lead to better research communication in sedimentology through a common vocabulary, shared standards, and open data archiving and sharing.

## ■ INTRODUCTION

In an exciting age of evolving technology, geosciences will continue to be part of the ongoing digital revolution (Walker and Black, 2000; Whitmeyer et al., 2010; Mookerjee et al., 2015a; Chan et al., 2016; Walker et al., 2020; Walker, 2021). The Geoinformatics and EarthCube programs of the National Science Foundation (NSF) were designed in part to help the geoscience community

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develop digital tools to facilitate and enhance data collection, storage, and sharing (Gil et al., 2014). The StraboSpot data system, designed initially for the structural geology and tectonics communities (Walker and Tikoff, 2014; Tikoff et al., 2018; Walker et al., 2019a; Glazner and Walker, 2020), was one significant result of these efforts. During the development of the StraboSpot mobile application and website, it became clear that the overall approach would benefit field geology in general. For that reason, we sought to bring sedimentary geology into the StraboSpot framework. Additional communities studying igneous petrology, metamorphic petrology, and microstructures are also working on their own data vocabulary, standards, and workflow structure for expansion of StraboSpot (e.g., Newman et al., 2017; Ash et al., 2018; Tikoff et al., 2018). We report here on the efforts to involve the sedimentary geology community in building upon and tailoring the existing infrastructure of StraboSpot to accommodate the discipline's data collection and storage needs. Two significant challenges for field sedimentary geology are: (1) the highly variable and descriptive features that are commonly challenging to quantify and categorize, and (2) the high degree of ambiguity of some features that may require multiple steps and broader context to arrive at a possible interpretation (Chan et al., 2016). However, interactions with data scientists clearly showed there were indeed ways to overcome some of the hurdles through synergistic collaborations (Mookerjee et al., 2015b; Ash et al., 2018).

StraboSpot is an integrated field geology data system designed around the concept of organizing data with spots and tags (see list of terms and definitions in Table 1). A spot is an area of significance over which a set of observations is valid. Spots have a host of attributes, location information, and can be hierarchical or nested. Tags are conceptual groupings of spots that can link information regardless of spatial position (Walker et al., 2019a). StraboSpot is also built on a highly flexible and efficient graph database structure rather than a more traditional relational structure. The graph database stores attributes of spots (or nodes) and connections (or edges) between those spots. This design and structure work well for field data since individual field observations possess their own attributes, but their meaning and importance come from their geographic or hierarchical associations and connections. The ability to connect individual observations is critical for data storage and sharing as well as for data exploration and synthesis. Currently, StraboSpot is accessed via a web version and mobile app, each of which have slightly different appearances but

TABLE 1. SELECT STRABOSPOT TERMS AND DEFINITIONS

| Term | Definition* |
|---|---|
| Spot | An area of significance over which a set of observations is valid. |
| Point spot | Spot at a point/location that possesses geographic coordinates (when added to a map) or image coordinates (when added to an image basemap) and a radius of significance. |
| Line spot | Spot along a line through space (when added to a map) or on an image basemap with vertex coordinates that also possesses a buffer region of significance. |
| Polygon spot | Spot denoting an area with vertex coordinates. |
| Interval | Building block of a stratigraphic section within Strat Mode that possesses geographic coordinates, stratigraphic coordinates (top, bottom), and a grain size/composition attribute to plot on a stratigraphic column. |
| Strat Mode | New modality added to StraboSpot used to track and document stratigraphic position and relationships of sedimentary observations. The mode works as a one-dimensional stratigraphic thickness and attribute map. |
| Tags | Conceptual groupings of spots that can link information regardless of their spatial position. |
| Interval Type/Spot Sed Characteristics | Designation for any spot ("interval type" for intervals only) as a sedimentary "bed," "package of beds," "interbedded," "unexposed/covered," or "not measured." This designation handles ambiguity of sedimentary attributes and makes it possible to apply the spot concept. |
| *Modified after Walker et al. (2019a). | |

the same functionality and data structure (see instructions and help at https://www.strabospot.org/help; accessed May 2021).

In expanding the StraboSpot data system to include sedimentary geology observations, our objective was to develop discipline-specific functionality by engaging sedimentary geologists in:

(1) developing a community vocabulary (terminology, definitions, workflow, and attribute organization);

(2) implementing that vocabulary in the StraboSpot app to collect field data, create and interpret stratigraphic columns, search and query data, and store and share data;

(3) beta-testing the app; and

(4) launching the app to share with the community with the hope of eventual widespread adoption by sedimentary geologists.

The foundations and overall functionality of StraboSpot are described by Walker et al. (2019a). This paper details the development of StraboSpot for sedimentary geology, including background on sedimentary workflows and data types, new functionality in StraboSpot (Strat Mode), and a discussion of lessons learned and future possibilities. This application provides many research opportunities for the sedimentary community and a valuable teaching resource.
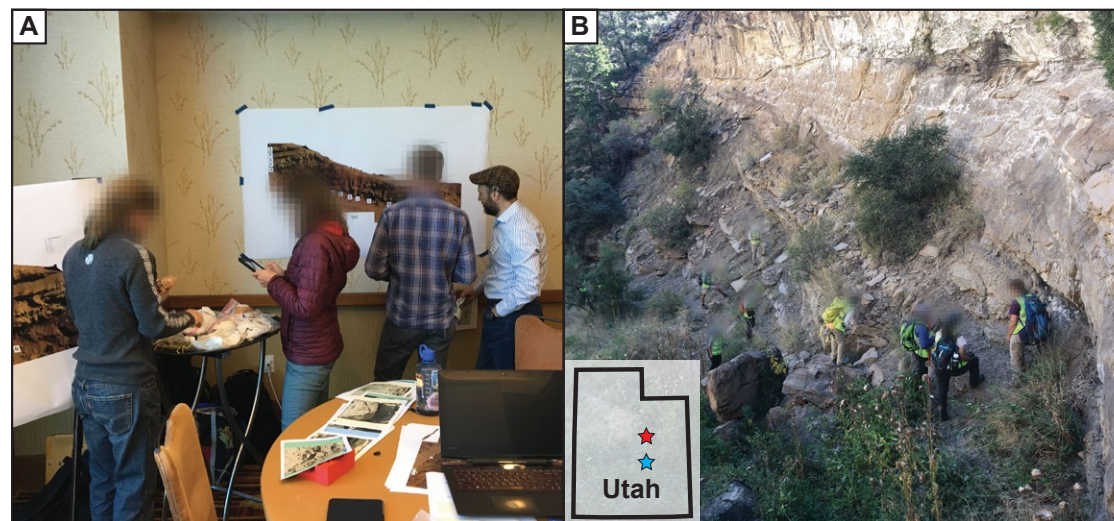
## ■ APPLICATION DEVELOPMENT

### Community Involvement

To develop a vocabulary that the sedimentary community would adopt, we held multiple workshops and meetings (Figs. 1A–1B) to solicit community input and feedback. Each workshop typically consisted of a range of subdiscipline experts, of whom ~40–60% were women, spanning scientists from early to advanced career stages and including both academic and industry representatives where possible. In addition to workshops, we solicited targeted feedback from pertinent experts for vocabulary clarifications/refinement as needed. Workshops aimed at the general sedimentology community were broadly advertised and open to anyone including students to professionals. Workshops were free and/or subsidized so that cost should not have been a barrier. Throughout the project, we communicated our efforts through multiple venues such as presentations, posters, town halls, and workshops at professional meetings (Chan et al., 2017, 2020; Newman et al., 2017; Walker et al., 2019b; Duncan et al., 2018, 2020).

### Vocabulary Development and Implementation

The main priority at the start of the project was to make detailed and integrated vocabulary lists (Tables 2A and 2B). Formal vocabulary is essential because the terms will be stored and searchable in the final repository or database management system. Community/participant feedback helped hone vocabulary and solidified workflows that would ultimately be included in the StraboSpot data structure; this vocabulary is programmed in as attributes of Spots. The resultant sedimentary (sed) vocabulary is organized in seven categories: 1. Sed Interval, 2. Sed Lithologies, 3. Sed Bedding, 4. Sed Structures, 5. Sed Diagenesis, 6. Sed Fossils, and 7. Sed Interpretations. Each of these categories contains subcategories and input fields organized into groups of similar attributes. Our approach was to provide a vocabulary that would cover most applications but not offer every possibility. A completely inclusive approach is burdensome to the user, who must interact with seemingly

Figure 1. Images are from StraboSpot Geological Society of America (GSA) short courses and workshops. (A) Participants used 3-D outcrop model posters and hand-samples to test StraboSpot vocabulary and function during the GSA 2018 Annual Meeting in Indianapolis, Indiana, USA. (B) Participants put StraboSpot to the test in a shoreface succession of the Sowbelly Parasequence, Spring Canyon Member of the Blackhawk Formation of central Utah, USA, during a post-GSA workshop in September 2019. Inset map shows the locations of the workshop field trip near Helper, Utah, (red star) and the San Rafael Swell (blue star).

TABLE 2A. SED TABS WITH CORRESPONDING SUBTABS

| Sed Lithologies | | Sed Structures | | Sed Interpretations | |
|---|---|---|---|---|---|
| Lithology | Siliciclastic Type | Physical | Cross Bedding Types | Process | Energy |
| | Dunham Classification | | Ripple Lamination Types | | Sediment Transport |
| | Other primary lithology | | Horizontal Bedding | | Fluidization |
| | Lithification & Color | | Deformation Structures | | Other Processes |
| Texture | Grain Size & Range | Bioturbation | Bioturbation Index | Environment | Clastic |
| | Dunham Range | Bedding Plane Structures | Bedding Plane Features | | Carbonates |
| | Sorting Rounding | | | Surfaces | Surface Attributes |
| | Shape | Pedogenic Structures | Paleosol Horizons | | Surface Interpretation |
| Composition | Minerals | | Paleosol Structures | Architecture | Description |
| | Dott & Folk/McBride | | Paleosol Classification | | Sequence Stratigraphy |
| | Carbonate Components | | | | Specific Environment Interpretations |
| | Matrix Composition | | | | |
| | Other Lithology Type | | | | |

TABLE 2B. SED TABS WITH NO SUBTABS

| Sed Bedding | Sed Diagenesis | Sed Fossils |
|---|---|---|
| Bed Geometry | Cement | Body: Invertebrate |
| Lower Contact Attributes | Veins | Body: Plant/Algae |
| Upper Contact Attributes | Fractures | Body: Vertebrate |
| Interbed Attributes | Nodules/Concretions | Trace |
| Package Attributes | Porosity Types | Biogenic Growth Structures |
| | Carbonate Desiccation & Dissolution | |

endless lists, and the length of data-input forms must be balanced with the available screen working space; this is especially true for the mobile app. To address these constraints, we included an "other" option for every category or grouping as well as designated fields to add optional user notes if a needed term is not in the vocabulary. As future needs evolve, user-defined tags can facilitate the recording and grouping of information that is not built into the existing vocabulary lists.

## Creation of the Strat Mode

While developing the vocabulary and its structure, we recognized that the map-based interface of StraboSpot, suitable for many areas of field geology, was insufficient for sedimentary geology data collection. Collecting stratigraphic data and documenting relationships of sedimentary attributes, where the stacking of successive packages in one location is a fundamental observation, must be carried out within a stratigraphic framework. As a result of this realization of community workflow, we developed a new data collection mode that forms the basis and framework for sedimentary data collection: Strat Mode.

## Testing

Testing was extensive, owing to the addition of Strat Mode and the complex vocabulary. We measured the effectiveness based on how sedimentary faculty viewed the program and how they envisioned students and novices would use it in the field. We had to answer such questions as, are the steps logical and intuitive? Is the vocabulary sufficiently complete? We held several indoor workshops as well as field workshops to test the new StraboSpot vocabulary and functionality.

Our September 2019 field workshop focused on testing the basic functionality of the StraboSpot app to digitally collect sedimentary field data (see Supplemental File A[1]). On the first day, teams of two to three participants used StraboSpot to measure and describe a stratigraphic section in the well-studied Sow Belly Parasequence of the Cretaceous Spring Canyon Member of the Blackhawk Formation (wave-dominated shoreface strata; Kamola and Van Wagoner, 1995) at Gentile Wash in the Book Cliffs of central Utah, USA (Fig. 1B). This team activity was a test to see how well the vocabulary and program functionality worked for collecting sedimentary field data and generating stratigraphic columns. The second day was spent measuring and describing a portion of the Jurassic Carmel Formation (mixed clastic-carbonate sequence) in the San Rafael Swell of central Utah. The third day focused on a discussion of any issues with workflow/vocabulary and getting feedback on how to simplify and streamline descriptive data collection functions (stratal attributes) and reviewing the more challenging interpretation functions (processes, depositional environments, and architecture). A major discussion point was how best to handle data collection and stratigraphic plotting of "interbedded" intervals.

Overall, field workshop participants were very enthusiastic about the potential of digital data systems. They liked the vocabulary standards, the ability to link annotated photographs and sketches to georeferenced localities and stratigraphic intervals, the potential for sharing data, and a searchable backend data management archive. Participants did, however, express concerns about hardware difficulties under outdoor field conditions, awkward interface problems, and data backups. We addressed these issues in changes to the StraboSpot application.

We conducted both pre- and post-workshop surveys of the participants (see Supplemental File A). The participants indicated they were inclined to use StraboSpot in both teaching and research applications particularly with versatile and customizable options. Some of the most encouraging post-workshop survey results were: >75% felt it was a positive field experience, and 100% were enthusiastic about the potential of StraboSpot. Participants consider the strength of StraboSpot to be the way it can facilitate quick drafting of a measured stratigraphic section and its capacity to import and link photos to any part of the section. The application also allows for georeferencing of observations, and it has functionality for sketching. Participants felt it worked well for overall data management and sharing. They further cited the strong aspects for teaching: appropriate uniform vocabulary and immediate visualization of stratigraphic sections to facilitate rapid feedback to students.

## Releasing StraboSpot for Sedimentary Geology

Initially, we planned to release the app and share it and the website with the sedimentary community at the Geological Society of America (GSA) 2020 Annual Meeting in Montreal. However, the COVID-19 pandemic led us to change plans and accelerate the release. Instead, we ran a webinar/teaching session online in June 2020 to take advantage of the fact that many geoscientists had to change their plans and were no longer conducting summer field work. This shift also meant that the application was released prior to the academic year so that faculty could incorporate it as part of instructional plan development. We were able to utilize sedimentary and geologic community listserves and social media to announce the free online webinar course composed of three sessions (1.5 h each) spread over one week.

Through the workshop, we shared the sedimentary capabilities of StraboSpot with over 100 registered faculty, students, and professionals (including some international participants). The use of a virtual videoconferencing platform with screen sharing allowed us to present the following sessions (in order): basic introduction and instruction, StraboSpot stratigraphy case study examples, and examples of the individual participant sections that were created during the week. To provide synchronous and asynchronous support, we offered help sessions via videoconferencing and a shared Google Doc to log questions. The shared Google Doc seemed to be the preferred mode for asking questions across any time zone, but it required timely staff monitoring and input. Recordings of the sessions are available at https://www.youtube.com/playlist?list=PL3jEmSMv6rzGBTHSo0Z8zphZPAE9qaY0Z.

We received many positive responses and very useful feedback in a post-workshop survey (Supplemental File B [see footnote 1]). Of the 43 post-survey respondents, 100% felt the virtual workshop adequately introduced them to StraboSpot. Participants expressed approval of many strong aspects of the app and cited the georeferencing of data as critical. Many reported that they would use the app in teaching upper-level undergraduate sedimentology and stratigraphy courses.

Some of the most limiting factors that directly and indirectly affect the use of the StraboSpot program are related to hardware issues. Concerns include the limited amount of readable space on tablets/mobile devices, the precision and accuracy of the device compass/accelerometer, difficulties with seeing the screen in sunlight, and battery-life limitations. As with any digital data, it is critical to make sure data are uploaded and backed up to safe, accessible sites (whether cloud-based or stored locally on a device).

## ■ SEDIMENTARY APPROACH

Like many field-based disciplines, field sedimentology and stratigraphy deal with complex and heterogeneous data types that range from grain- to basin-scales. Compounding the complexity is the need to record sedimentological data within a stratigraphic context and framework; this challenge required the creation of Strat Mode within StraboSpot. Although workflows vary based on study purpose and scale, outcrop/core availability, and even personal preference, there are still general attributes of sedimentary data and workflows that guided the development of sedimentary options in StraboSpot.

Before describing how these options in StraboSpot work, we discuss unique aspects of sedimentary field data collection that are not shared by other subdisciplines.

## Sedimentary Field Workflows

Although highly variable in purpose, scope, scale, and implementation, there are numerous commonalities in workflows outlined in standard textbooks on sedimentary geology (e.g., Stow, 2011; Nichols, 2009; Tucker, 2011; Boggs, 2012). Most studies start with broad-scale observations of an outcrop; noting gross characteristics and first-order lithological attributes allows the sedimentary geologist to focus on analysis of key areas and to decide if and where to measure a section (Fig. 2A). The second step is for the sedimentary geologist to determine attributes for the outcrop as a whole for reconnaissance-level work or to measure a section at the bed to interval level for detailed research. Third, the sedimentary geologist documents relationships and contacts between intervals and the overall bed and package geometries (Figs. 2B–2C). Finally, once the data have been collected and the measured section is drafted, the sedimentary geologist then can interpret the succession. Interpretations span scales from individual beds and groupings of units to lithofacies, architectural elements, and depositional environments of whole sedimentary packages. Specific workflow steps, the types of data collected, and the interpretation of the succession are heavily dependent on the individual user's expertise and goals. Determination of workflow steps must also incorporate study emphasis/questions, level of detail needed to test hypotheses, available time, and any



Figure 2. Field sed/strat workflow example shows: (A) outcrop photo of complex fluvial/alluvial strata of the Cretaceous Baseline Formation of southern Nevada; (B) annotated photo marking the bed boundaries (bold lines) and the internal stratification of the lithofacies that make up this outcrop (Sp—sandstone, planar cross-stratification, Gm—massive gravel-cobble conglomerate lens, Spg—planar cross-stratified sandstone with gravel lags, Sl—low-angle cross-stratified sandstone, Sl-Sh—low-angle to horizontal stratified sandstone), with facies codes after Miall (1996); (C) abstraction/simplification of the outcrop example in a vertical section with grain size increasing to the right from fine sand (fs), to medium sand (ms), to coarse sand (cs), to gravel-cobble (g-c). Outcrop is located at N36.481068 W114.515145 in Valley of Fire State Park, Nevada, USA.

other constraints. However, these generalized steps likely apply to the majority of sedimentary geology workflows.

## Data Types and Specific Sedimentary Features

The fields of sedimentology and stratigraphy are broad in scope and application, such that what is considered "pertinent" data to be collected depends greatly on the purpose and central question of individual studies. General categories of field sedimentary data are described below along with what specific attributes must be preserved and incorporated into any database.

### *Observations: Attributes and Relationships*

Fundamental to any field sedimentology or stratigraphy investigation is any individual observation or the collection of multiple observations that are broadly categorized as attributes or relationships. Attributes include lithology (classification, texture, composition), sedimentary structures (stratification, bedding plane structures, bioturbation/trace fossils), diagenetic characteristics, and fossils. How these attributes are distributed throughout the outcrop then defines the relationships present in the sedimentary succession. These relationships include features like bed or package geometries, lower and upper contacts between intervals, and the vertical and lateral distribution of beds or packages throughout the outcrop.

### *Sketches and Images*

Field sketches, ranging from hand sample- to landscape-scale, have been the mainstay of field data collection in sedimentary geology since the eighteenth century (Genge, 2020). Sketches track the spatial and stratigraphic relationships between data points, record observations of multiple features and areas, and serve to focus geologic observations. Sketches themselves then become data that are useful in field sedimentology and stratigraphy. Photographs are the next level of documentation and have the added benefit of greater fidelity in documenting the feature under study. As technology has evolved, digital cameras of high quality are widely available for use in field sciences. Digital photographs are valuable but typically require annotation and/ or explanation to be useful. Consequently, the combination of sketches and images is invaluable for recording observations and documenting relationships.

### *Samples and Measurements*

Although field descriptions of sedimentary rocks are sufficient for *qualitative* understanding of sedimentary successions, hand samples, thin sections, or core plugs are required for *quantitative* characterization of grain size, composition, or diagenetic attributes. Documentation of geographic coordinates is required to provide the overall spatial context for any level of study. Additionally, for investigating stratigraphic patterns or changes, the vertical stratigraphic position and vertical/lateral relationships must also be documented. In addition to physical samples, quantitative field measurements such as those of paleocurrent orientations, clast or fossil sizes, or bed thicknesses are most beneficial when accompanied by specific stratigraphic context and surrounding lithologic information. Describing and measuring stratigraphic sections is one such method for capturing this critical context.

### *Measured Sections*

Measured stratigraphic sections are typically presented through graphic logs that allow documentation of attributes and relationships within the framework of a stratigraphic succession. Logs are accompanied by descriptive field notes or observations. Basic building blocks of the section are stratigraphic intervals composed of beds or bedsets, which have a defined stratigraphic thickness and surfaces at the top and bottom that define the individual beds or bedsets. It is often necessary to document observations at a specific stratigraphic position or interval (e.g., the occurrence of a fossil, sedimentary structure, or mineral). The use of symbols in the graphic log visually communicates observations of specific points as well as general attributes of intervals. The representation of three-dimensional bodies that contain related lithologic or genetic attributes (i.e., geobodies) is facilitated by two-dimensional sketches or images of geometries linked to the measured section.

Graphical sections are, in essence, an abstract one-dimensional stratigraphic thickness and attribute map. Expansion to the second- and third-dimensions requires correlation between at least two stratigraphic sections or between multiple sections to create a fence diagram, respectively (e.g., Ichaso et al., 2016). Geologists have numerous choices for representing the stratigraphic column. Choices may be based on the overall purpose of the study, the hypothesis in question, or simply stylistic preference. Typically, graphic sections use grain size as the horizontal axis, but using simplified rock type or weathering resistance is also common.

## ◾ SEDIMENTARY WORKFLOWS AND STRABOSPOT

Geologists have the option to incorporate StraboSpot either as the primary data collection tool while in the field or to collect data through traditional methods (i.e., field notebooks) and then use StraboSpot as a data archiving tool when back from the field. Regardless of how StraboSpot is used, the specific sedimentary vocabulary, workflow attributes, and how they relate to the fundamental functionality of the program must be considered for effective integration of workflows with digital data collection/archiving.

## Sedimentary Vocabulary Considerations

We developed the sedimentary vocabulary through a series of workshops and field trips beginning in 2017 (Chan et al., 2017; Duncan et al., 2018; Chan et al., 2020). The vocabulary is based on terms commonly used by the sedimentary community and is largely consistent with workflows and vocabulary outlined in sedimentology textbooks (e.g., Nichols, 2009; Boggs, 2012), field manuals (e.g., Tucker, 2011; Stow, 2011), and the published literature. However, in some specific cases, decisions were based solely on the literature. The basic outline of the sedimentary vocabulary and how it is organized in StraboSpot is presented in Tables 2A and 2B. For clastic sedimentary rocks, textural attributes follow the standard Wentworth grain size. Users have the option to classify the rock in the Dott (1964) or the Folk/McBride classification (Garzanti, 2019). For other noncarbonate rock types (e.g., evaporites or volcaniclastics), we followed common textbook examples or drew on the experience of expert contributors. For attributes that require descriptions that are not covered in our basic vocabulary, the user can add these in notes or as user-defined tags.

There are multiple carbonate rock classification schemes; these include, most notably, those of Folk (1962), Dunham (1962), and expansions/modifications of Dunham by Embry and Klovan (1971). A survey of classification schemes currently used by carbonate petrologists, which was carried out by Lokier and Al Junaibi (2016), revealed that out of the 241 volunteers surveyed, 89% use the modified Dunham classification. Additionally, vocabulary workshop feedback indicated a desire to only use the modified Dunham scheme. Therefore, only the modified Dunham classification is in the StraboSpot formal vocabulary, but users still have the option to use the Folk classification through other notes or as user-defined tags.

The vocabulary and user interface incorporate if/then- or if/else-style skip logic to streamline the menu options based on user inputs. For example, carbonate lithology options would not be presented if the user specified a siliciclastic lithology. This hierarchical and context-sensitive organization is an important feature of StraboSpot that streamlines the user experience and helps focus data collection workflows.

## Sedimentary Data and the Spot Concept

Data are organized in StraboSpot through a principal concept, the spot, which is defined as an area of significance over which a set of observations applies (Table 1; see Walker et al., 2019a, for a full discussion of the general nature and use of spots). StraboSpot uses point, line, and polygon spots to organize data and record geometric attributes. The scale of a spot is user-defined and can span a single measurement within a thin-section (e.g., microfossil) to an aggregate of measurements within an area (e.g., paleocurrent measurements within a channel form). The area of significance of a spot relates to its radius (point spo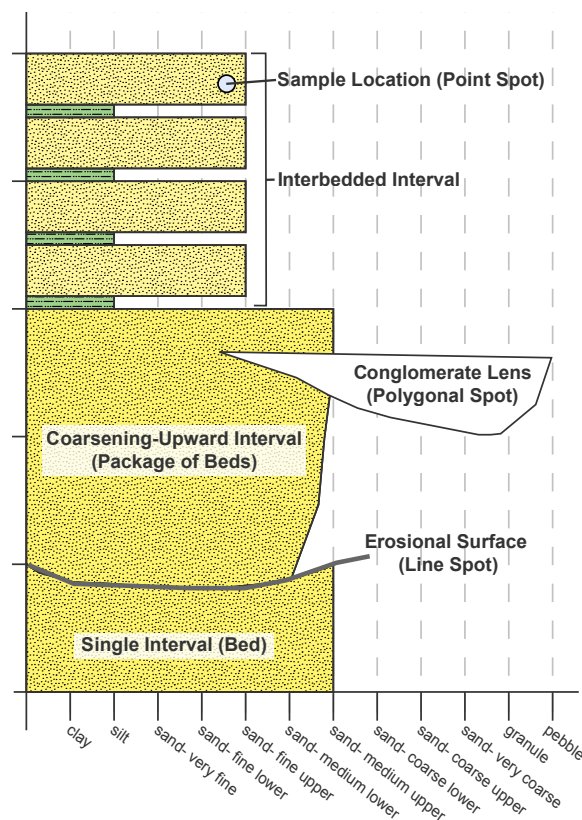t), buffer region (line spot), and enclosed area (polygon spot) (Walker et al., 2019a). This organization makes it possible to track and record spatial relationships of various data types across all spatial scales.

Sedimentary data are largely consistent with the definition and use of spots. General descriptions of a feature or lithology at a location can be facilitated by using a point spot, which allows for the recording of observations and designation over what scale those observations apply. For example, in a reconnaissance-level description of an outcrop (e.g., Fig. 2A), attributes can be associated with a point spot (e.g., trough to planar/low-angle, cross-stratified sandstone with conglomerate lenses). The radius of significance for the point spot would indicate to what extent those attributes are valid and would relate to the scale of heterogeneity of the depositional environment (e.g., greater lateral continuity in tabular shoreface deposits than in localized fluvial channels). Line spots and polygon spots work particularly well with sedimentary field data. Surfaces, contacts, bed boundaries, and other planar features are already linear features in map views or in photo panels. Laterally discontinuous beds or packages within an outcrop (e.g., lenticular beds/bedsets) are polygonal features in map view or in a vertical outcrop face. This close linkage in attributes between the lines and polygonal attributes from sedimentary outcrops simplifies the link to the StraboSpot database because the program was already designed to handle spots of point, line, and polygon geometry types.

The point, line, and polygon spots track spatial attributes, extent, and relationships within a geographic frame of reference. For tracking information within a stratigraphic frame of reference, it is necessary to record spot characteristics through a spot that represents the interval (Table 1) rather than through regular points, lines, or polygons. The extent of an interval is defined by stratigraphic position and its thickness (Fig. 3) and is similar to the extent to which observations apply to a spot as outlined above. The spots are arranged in stratigraphic order to preserve stratigraphic relationships. The idea of a spot as an interval with a defined stratigraphic thickness but variable lateral extent is the basis for Strat Mode. Just like any other spot, a stratigraphic interval can be assigned a host of attributes via the new sedimentological vocabulary. Once an interval is established, additional point, line, or polygon spots can be added to the column to preserve the stratigraphic position of those spots.

Mixed lithologies and interbedded units present a particular challenge for data recording because the attributes of each lithology must be accurately recorded in addition to the relationships between those lithologies. In StraboSpot, this is handled by the designation of "Spot Sed Characteristics," which allows the user to designate spot attributes for mixed lithologies, interbedding characteristics, or packaging attributes of beds (Fig. 3). Therefore, the observer must record information related to trends within an interval or measure those characteristics bed-by-bed if the exact stratigraphic arrangement is important. This parameter is handled by a designation for the "Type of Interval" as a bed, interbedded, or package of beds. This approach is the same as is used in the modes of data collection discussed in Walker et al. (2019a): multiscale mode (emphasizes location and distinction) applies to measuring at the interval level and multi-measurement mode (several measurements lumped together into a single spot) corresponds exactly to an interbedded interval.

**Figure 3. In an example of data organization within StraboSed, strat columns are built up by the step-wise addition of intervals that are defined by some sed attribute (bed, package of beds, or interbedded). Intervals may be edited to show top and bottom surface attributes and grain size changes. Point, line, and polygon spots may be added to the column to capture additional data. Column was created in StraboSpot and is an edited version of current export options.**

### Notes and Tags

Throughout the development of the sedimentary options for StraboSpot, it was clear that no single program could completely meet all of the expectations, needs, and preferences of such a diverse field. Because it is nearly impossible to be all-encompassing, our goal was to reach an approximate "80% applicability" threshold as a general guideline. Based on survey responses from the most recent workshop, we determined that the Sed vocabulary options now reach or exceed the 80% level for most subfields of sedimentary geology, and we anticipate that

further refinements through time can increase that percentage. Additionally, StraboSpot maintains the flexibility to record any remaining vocabulary words, or any new vocabulary developed as the field evolves, via notes and tags. Every tab has a "Notes" field where a user can capture any personalized data even if the vocabulary omits that particular desired input. The notes are stored within the database along with the rest of the data in their own unique field. Tags provide a way to conceptually group spots together (Table 1; Walker et al., 2019a) and allow the user to define tags applicable to their study. In the sedimentary context, this might be a user-defined facies, the occurrence of a unique rock type or fossil, or a particular architectural element. Tags provide a high degree of flexibility and a powerful way to organize and interact with the data.
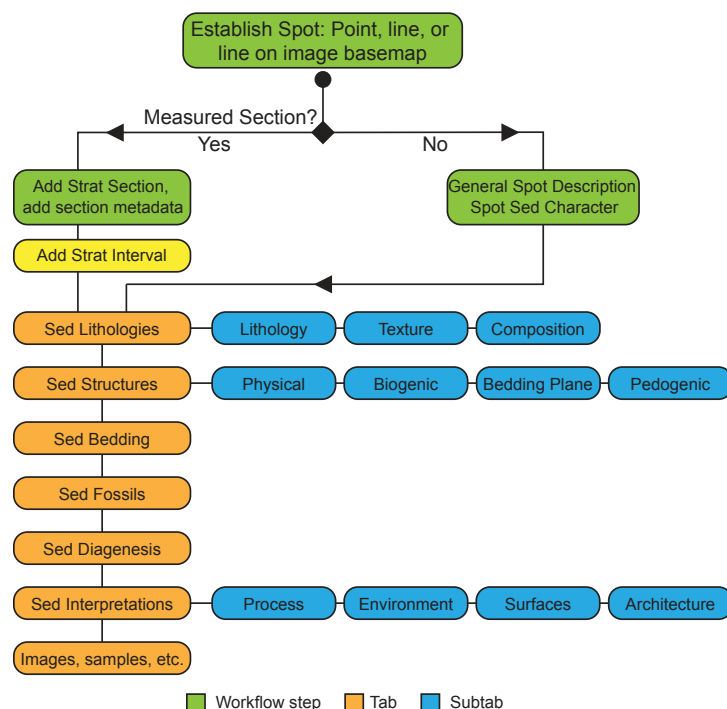
### ■ STRAT MODE

Strat Mode is a new mapping mode developed in StraboSpot to track and document stratigraphic position and relationships of sedimentary geology field observations (Fig. 4). This new mode was developed to match the workflow practitioners use in the field for measuring stratigraphic sections and logging sedimentary data. Strat Mode is a version of a basemap with its own internal coordinate system, but it is tied to a point, line, or polygon spot with real-world coordinates. The Strat Mode coordinate system replicates how sedimentary geologists record field data in a graphic log format in their field notebooks. On the x-axis of Strat Mode, an attribute of a bed or interval is plotted (typically a clastic grain size or carbonate lithology, but it could be a categorical lithology or outcrop resistance to weathering). The y-axis records stratigraphic height in metric (centimeter or meter) or imperial (inches or feet) units as designated by the user. The x-axis of each interval is dependent on the user-defined attributes, and the y-axis plotting is dependent on the order in which intervals are added or inserted and their corresponding stratigraphic thicknesses. Early feedback expressed a need for the ability to copy descriptive information from one spot to another if repeated lithologies/facies occur in the section. This functionality is essential and commonly used by stratigraphers when measuring sections and significantly increases workflow efficiency.

StraboSpot facilitates collection of critical metadata associated with measured stratigraphic sections such as study purpose, scale of interest, formation age, and the pathway taken to describe the section. New stratigraphic sections can be added to any spot and referenced to either the main map view or within image basemaps (Fig. 5). The type of spot used (point, line, or polygon) and the basemap used relate to the orientation of the strata, amount/magnitude of lateral offsets, and the lateral heterogeneity of the strata. Vertical sections through horizontal to shallowly dipping strata are best represented by point spots referenced to the main or geographic map (Fig. 5A, red spot with dashed radius of significance), because the pathway would not move much laterally in geographic space.

Stratigraphic sections described through dipping strata or where topography is sloped through horizontal strata (either case requires the stratigrapher to move laterally in geographic space) are best represented by line spots on

**Figure 4. Workflow flowchart illustrates the use of StraboSpot to describe sedimentary data. StraboSpot can be used in Strat Mode to measure and describe a stratigraphic section or to describe general sedimentary characteristics of outcrops (general spots).**

basemaps or image basemaps. The spot then records the path taken through the exposure and accurately reports lateral shifts taken through the depositional system (Fig. 5A, black line). Stratigraphic sections can also be added to point, line, or polygon spots on an image basemap (Fig. 5B; e.g., outcrop image, drone image). This option allows for clear and accurate tracking of measured section pathways at a variety of scales, particularly vertical sections and those logged at small scales below the spatial resolution obtainable with mobile device (iPad, iPhone) built-in GPS or handheld GPS units.
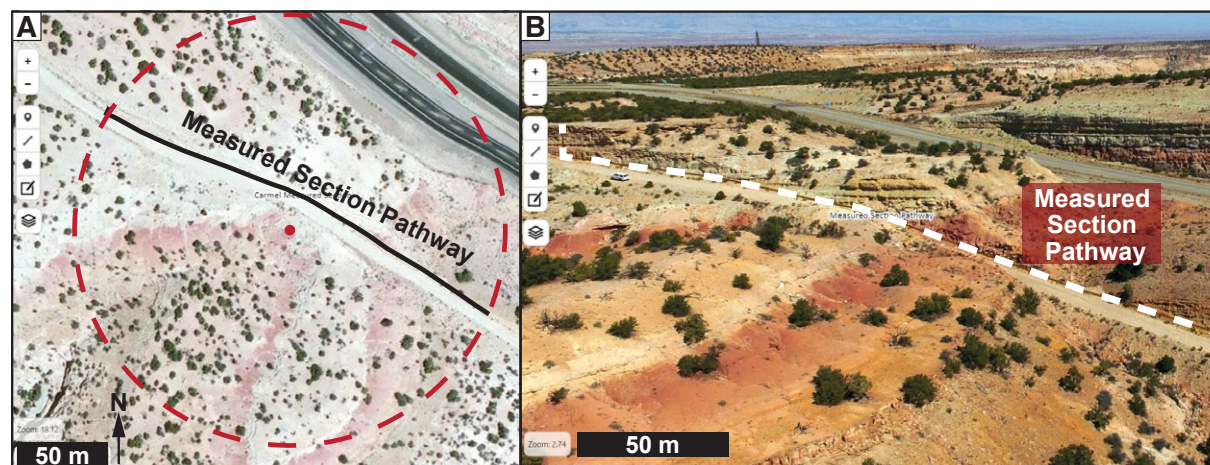
A user enters Strat Mode by first adding a stratigraphic section to a spot (Fig. 4). This action is done in the "Strat Section" tab, which also prompts the user to define necessary metadata and contextual information, set various plotting options (graphics, *x*-axis definition), and manage any image overlays/ underlays. Selecting "View Stratigraphic Section" opens Strat Mode, which allows the user to view spots as a stratigraphic column rather than in a traditional map. At this stage, the user is presented with a columnar/graphical representation of the spots corresponding to the Strat Section.

The user constructs the stratigraphic section by adding spots via the "Add Interval Dialogue." Each spot records its stratigraphic position, but the option exists for the user to record the interval's real-world geographic position using the mobile device GPS or through manual input of latitude and longitude. Since each interval is an independent spot, users have full capability to add images, sketches, samples, or any other attribute available in StraboSpot. Intervals can be added and displayed in a list view for workflows in which stratigraphic sections are measured and logged without graphics (e.g., when measuring and describing the core). Point, line, and polygon spots can also be added to the stratigraphic column (Fig. 3) to record stratigraphic position for associated features (e.g., concretion, surface, or sediment body, respectively). These are independent spots referenced to stratigraphic position in the measured section.

Strat Mode requires a few specific inputs to build the stratigraphic column: interval thickness, interval type, lithology, and grain size or Dunham classification composition (Fig. 6). StraboSpot then plots the intervals as spots with a defined stratigraphic thickness (*y*-axis). The user's choice of lithology displays on the *x*-axis as: (1) clastic lithology (i.e., grain size), (2) carbonate lithology, (3) a combination of both ("mixed" lithologies), (4) basic lithology (categorical lithology such as "sandstone," "limestone," etc.), or (5) resistance to weathering. Colors defined in CMYK values are automatically applied to each interval based on the input lithology, grain size, or composition. The present scheme is consistent with commonly used lithology coloring in sedimentary geology (e.g., yellow = sandstone, orange = conglomerates, blues = limestone, blue-greens = dolostones). The display of simple lithologic patterns can be turned on/off in the Strat Section tab. These patterns were derived from the templates provided by the U.S. Geological Survey (Federal Geographic Data Committee, 2006).

Strat Mode gives the user column display editing capabilities. Editing thicknesses within the graphic column, as well as inserting or deleting intervals anywhere, is possible without painstakingly redrawing the column. The intervals are editable to graphically show changes in grain size/composition through the section or to represent the geometry of bottom or top contacts. Any column edits only apply to the column graphical representation and do not propagate to change attributes in the data system (i.e., grain size or interval thickness remain as initially entered). Future changes to the program, which are in development, will allow for dynamic linkage between graphic modification and data attribute values.

The column is exportable in scalable vector graphic (svg) format, which preserves colors, patterns, and the horizontal-axis profile (e.g., siliciclastic) selected by the user. Since the focus of StraboSpot is on data collection, storage, and sharing, the export column presentation is basic and not intended to replace carefully drafted sections done in another software package (such as Adobe Illustrator or R and Matlab codes for rendering graphical logs). However, the export can be easily modified with any vector graphic editing package to be made suitable for submission as a figure for publication to assist in what is typically a lengthy and tedious drafting process.

Figure 5. Different ways to georeference measured sections within StraboSpot are shown using an example from the Jurassic Carmel Formation at Justensen's Flats, San Rafael Swell, Utah, USA. (A) Screenshot of the main map in StraboSpot. Georeferencing was provided by adding the stratigraphic section to a point spot of designated radius/extent, which is represented by the red spot and dashed line (more appropriate for vertical sections in horizontal/shallowly dipping strata), or by adding to a line spot with a defined buffer radius, which is represented by the black line (appropriate for dipping strata or compound measured sections). (B) Screenshot of image basemap in StraboSpot shows the line spot measured section trace. This preserves geographic data from the spot that houses the base image while also showing the pathway in relation to the outcrop described. Outcrop is located at N38.848653 W110.904381.

## Data Sharing and Export Options

Every project in StraboSpot is contributed and controlled by the data owner, and all data sets maintain a reference to that owner. The owner can choose to turn on or off public sharing of their data sets. When public, the data are visible to anyone visiting StraboSpot. Other users can download and explore data from publicly shared data sets via the StraboSpot search page. Data can be downloaded in a number of formats, including pdf Fieldbook (a sequential log of spots as part of the original StraboSpot structure workflow), kmz, xls, and/or svg file formats. StraboSpot data input/export options are still under development. Through continued sedimentary geology community discussions, we aim to create data export options that maximize compatibility with other databases and data-analysis and graphics programs.

## ■ DISCUSSION

The integration of digital technologies into field sedimentology and stratigraphy workflows is bound to be a complicated and possibly daunting process if one chooses to shift from traditional pencil and notebook. Through the development of the sedimentology and stratigraphy options for StraboSpot,

several key considerations have become apparent that must be addressed as the science moves forward with the incorporation of digital field notebooks into data collection and data storage in structured databases for the purposes of archiving and broader sharing.

## A Database for Sedimentary Geology

Sedimentary vocabulary, relationships, and interpretations are complex, which makes it challenging to integrate them into a database and app-based workflow. When compared with workflows developed for other geology sub-disciplines (Walker et al., 2019b, 2020), the StraboSpot workflow for sedimentary geology has a more extensive vocabulary in contrast to the emphasis on orientation measurements typical for structural geology or the common use of tags in igneous and metamorphic petrology. Another difference is that sedimentology and stratigraphy depend on the tracking and documentation of information relative to a stratigraphic framework. Strat Mode meets this requirement with its ability to record observations and co-register multiple data types within geographic and stratigraphic contexts.

StraboSpot for sedimentary geology is both open source and free. Other free apps are also available for the creation of stratigraphic sections, and
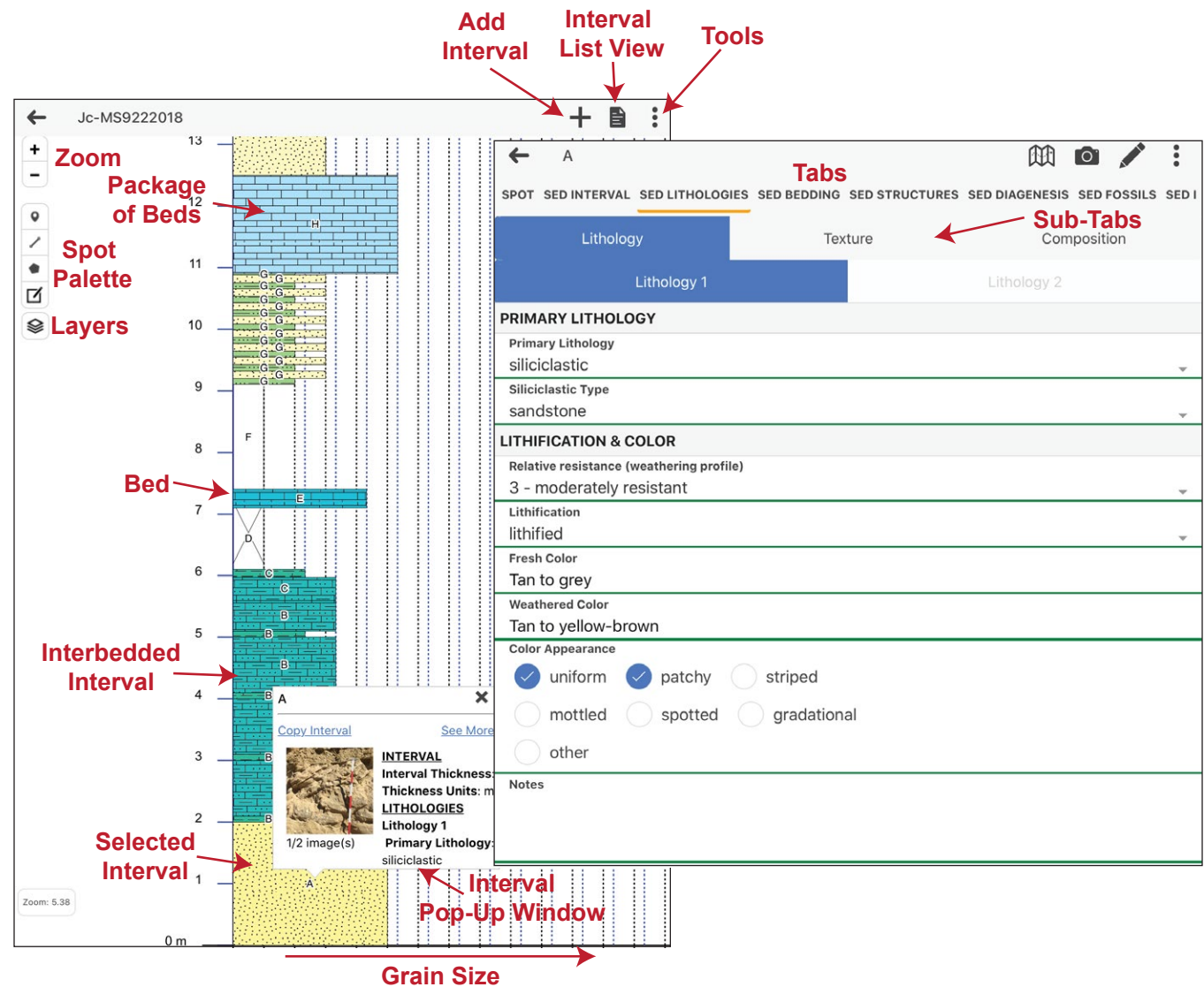
**Figure 6. Example of a measured stratigraphic section in StraboSpot at the locality of Figure 5 is shown (to access the column, go to: https://strabospot.org/d/25m7f). The window at left is the main Strat Section view, which depicts the intervals that make up the measured section and pop-up windows to give a quick summary of interval information. The window at right is of the attributes of Interval A and shows the flexibility of the program to build stratigraphic sections and then add detailed data for each interval.**

some organize data into structured arrays (e.g., Richard Allmendinger's Strat Mobile; Stratigraphic Data Analysis in R (SDAR) analytical package by Ortiz and Jaramillo, 2019). Although they are good at presenting data, they are not connected to a community-standardized backend database. In addition, there are powerful graphics programs designed to produce publication-ready measured sections (e.g., WellCAD), but these programs are commonly expensive, particularly for students, and again lack the ties to an open database.

The structured vocabulary and the requirement to tie to the database creates the ability for the system to handle and store data in a standard and uniform format. This uniformity applies to the output file types and the logical arrangement of and progression through data inputs. If a user intends to use StraboSpot in the field, conforming to program conventions is straightforward. However, if users prefer not to use the structured vocabulary, they still have the option to use notes and tags as in a regular field notebook. There are some vocabulary restrictions in Strat Mode, but flexibility is maintained with notes and tags. Additionally, users can input as little or as much data as they wish.

The future direction of StraboSpot sedimentary capabilities can be dictated by the sedimentary geology community. If changes are necessary due to advances in the field, the database can be updated accordingly. Although we are at the beginning of digital data system development, the sedimentary geology community can control the vocabulary and standards implicit in the StraboSpot data system to ensure that it remains a community-driven effort.

## Balancing Plotting with Data Collection—Lessons Learned

We faced a major challenge in deciding on methods for graphical representation of interbedded intervals on the measured stratigraphic section, because in designating interbedding the user is packing a lot of information into a single spot. The present plotting options use the relative proportion between the primary lithology (designated lithology 1) and the interbed lithology (designated lithology 2) and the thickness of the interbeds to draw the interval schematically. A geologist may draw these attributes by hand in a more detailed and customized way on a stratigraphic column in a notebook but unless they painstakingly measure and plot each interbed, the representation is still schematic and the drawing of the interbedding is almost never exact. StraboSpot's purpose is to facilitate field data collection and sharing rather than to serve as a graphics program. Thus, its graphical representation of the measured section is designed to fit the stratigrapher's workflow as closely as possible, convey the basic information to identify trends or patterns, and interpret the sedimentary succession.

StraboSpot is open source with an Application Programming Interface (API) that allows users to interact directly with the database (documented at https://www.strabospot.org/api). As a result, anyone can write code to access data directly and create custom graphical representations in another program. Such flexibility and openness could lead to wide-ranging ways to represent

the data in any desired format or to the refinement of graphical outputs of stratigraphic sections by the sedimentary geology community.

## Interaction with Other Field Geology Data Types

There is an underappreciated, major advantage of StraboSpot with respect to field geology: it is inclusive of sedimentary geology, structural geology, igneous petrology, and metamorphic petrology data. As a result, practitioners can easily explore data from other disciplines within a single data system in their field area. The single interface also has advantages for student teaching and training; only one data system is required for multiple geological classes, and the interface of StraboSpot is significantly more intuitive than that of other GIS-based digital programs. In our experience, undergraduate students are comfortable using StraboSpot within a few hours. The inclusive approach could foster more interdisciplinary collaboration and leverage preexisting work from other subdisciplines.

## Future of Digital Sed Field Data Collection and Sharing

StraboSpot is designed with data sharing as the primary goal. As stated above, anyone can access public data through the StraboSpot API or the code at GitHub (https://github.com/StraboSpot). The database contents are controlled by the user who uploads/owns the data to limit access until the user is ready to share the data. Once made public, the data can be entirely open, discoverable, and useable. Data access is a basic requirement for all data collection projects using federal funds. New opportunities will arise for the development of tools to leverage open digital sedimentary geology data sets. Tools for igneous and metamorphic petrology interface with StraboSpot (Glazner and Walker, 2020) as well as the stereonet plotting and analysis app Stereonet Mobile (Allmendinger et al., 2017). These examples serve as models for opportunities to expand the capability of the sedimentary geology options and Strat Mode of StraboSpot. New community-developed tools to leverage the database and technology could include ways to probe the database, linkages between StraboSpot and other programs (e.g., LAS export for use in Petrel), and other novel data collection methods (e.g., automated color description of sandstone beds). These are all possible now using the API and GitHub repository. The powerful approach to tool development could revolutionize field-based data collection as it has for other communities (e.g., geophysics).

Digital field data repositories will drive our science forward with the capability to integrate big data and machine learning approaches. As the database is populated with sufficient content distributed spatially and temporally through many different basins, the opportunities will increase to mine that data to test hypotheses that are simply unknown or undiscovered at the moment. Likewise, large and robust data sets will be useful for training machine learning algorithms to look for patterns/trends and to better explore the underlying

mechanisms. Digital and standardized data sets, such as those made possible by StraboSpot, will likely facilitate such exciting developments in the future.

## ■ CONCLUSIONS

Based on input from the sedimentary geology community, we created vocabulary and data collection protocols that are now built into the StraboSpot data system. This effort was a multi-year and multi-investigator endeavor that required engagement of the broader Earth science community. The implementation of the vocabulary and structure conforms with typical field sedimentology workflows. The addition of a new mode, Strat Mode, can be used to construct measured sections in StraboSpot and to track stratigraphic position and relationships between data types. Strat mode uses common vocabulary to facilitate data collection that can be as simple or complex as needed; images and lithologic descriptions can be linked, and interpretations can be applied. Data are stored in the database and can be recovered in many formats or accessed using the StraboSpot API. This facilitates open sharing of sedimentary field data, which will lead to greater community engagement and data analytics opportunities.

With the COVID-19 pandemic and the likely future of more online teaching, digital applications such as StraboSpot will be essential for helping to teach workflow and data management principles when geologists are unable to go to the field in person. StraboSpot is distinguished from other applications because it accomplishes the full collection and integration of data management with open data sharing.

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