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A high-precision Jacob's staff with improved spatial accuracy and laser sighting capability

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Abstract

A new Jacob's staff design incorporating a 3D positioning stage and a laser sighting stage is described. The first combines a compass and a circular spirit level on a movable bracket and the second introduces a laser able to slide vertically and rotate on a plane parallel to bedding. The new design allows greater precision in stratigraphic thickness measurement while restricting the cost and maintaining speed of measurement to levels similar to those of a traditional Jacob's staff. Greater precision is achieved as a result of: a) improved 3D positioning of the rod through the use of the integrated compass and spirit level holder; b) more accurate sighting of geological surfaces by tracing with height adjustable rotatable laser; c) reduced error when shifting the trace of the log laterally (i.e. away from the dip direction) within the trace of the laser plane, and d) improved measurement of bedding dip and direction necessary to orientate the Jacob's staff, using the rotatable laser. The new laser holder design can also be used to verify parallelism of a geological surface with structural dip by creating a visual planar datum in the field and thus allowing determination of surfaces which cut the bedding at an angle (e.g., clinoforms, levees, erosion surfaces, amalgamation surfaces, etc.). Stratigraphic thickness measurements and estimates of measurement uncertainty are valuable to many applications of sedimentology and stratigraphy at different scales (e.g., bed statistics, reconstruction of palaeotopographies, depositional processes at bed scale, architectural element analysis), especially when a quantitative approach is applied to the

analysis of the data; the ability to collect larger data sets with improved precision will increase the quality of such studies.

Keywords: Jacob's staff; Stratigraphic thickness; Sedimentary logging; Outcrop; Measuring errors.

1. Introduction

Measuring stratigraphic thicknesses in an accurate manner is one of the key data acquisition workflows for sedimentologists and stratigraphers. Some examples of the type of research that benefits from high precision stratigraphic thicknesses measurements include: characterisation of depositional processes at bed scale (e.g., Eggenhuisen et al. 2011; Sumner et al., 2012; Fonnesu et al., 2015); reconstruction of short-time variability of creation and fill of accommodation space (e.g., Banham and Mountney, 2003); architectural analysis (e.g., palaeo-depths of channels related to measurements of channels fills and bars, Bridge and Tye 2000; deep water lobe thicknesses, Prélat and Hodgson, 2013; Marini et al. 2015); outcrop-derived angles of progradation or aggradation of parasequences (e.g., Zhu et al 2012); analysis of bed thickness statistics (e.g., Marini et al., 2016); population of numerical models using thickness data from outcrop (e.g., Amy et al., 2013).

The simplest tool used in the field to measure stratigraphic thicknesses is a tape measure, commonly the rigid folding type. This is quite effective in certain outcrop conditions, such as when measuring horizontal beds on a vertical outcrop face or dipping beds on a face parallel to their dip direction (e.g., along a road cut), because the apparent and real thicknesses of the beds in these configurations coincide. However, when the apparent and real thicknesses of beds diverge, measurement using a tape can be very difficult to carry out in a precise manner. For example, this is the case with low relief outcrops where bedding is anything but vertical, such as while logging along a ridge crest leading to a hilltop or along a wave-cut platform (Figure 1). Another situation when a tape measure is not very effective is the case of a significant interval (e.g., metres to tens of meters) without clear surfaces indicating the structural dip (e.g., a very thick unit without internal bedding or with disrupted bedding or a covered interval). In these scenarios stratigraphic thickness measurements must be carried out by sighting, for which the most effective tool is a Jacob's staff (see Merriam and Youngquist (2002) for an historical prospective and for a discussion on the origin of the name). In its simplest version a Jacob's staff for logging purpose is a vertical rod of known height with a device to help sighting mounted on its top (e.g., a sight or a flat disc). The rod is then placed orthogonal to bedding (often with the aid of a compass and a clinometer) and the sighting device is used to measure true stratigraphic thicknesses (Figure 1; see also Compton (1985), chapter 11, and references therein). In the last twenty years, improved models of Jacob's staff have been developed (e.g., Elder, 1989; Brand, 1995; Evans, 2002), aiming to increase measurement precision and ease of use, while at the same time maintaining reasonable manufacturing costs. This paper describes a new Jacob's staff, with some key improvements over the currently used models.

2. New Jacob's staff

2.1. Design

The new Jacob's staff (Figure 2A) consists of three main parts: a vertical rod measuring 210 cm, a 3D positioning stage (Figure 2B-C) and a laser sighting stage (Figure 2D). The vertical rod is composed of four pieces which can be connected and disconnected in the field for ease of carrying. Three of the pieces are 50 cm long, and the uppermost is 60 cm long (see Figure 2E for a detail of the connecting mechanism between rod pieces) combining to allow measurements up to 2 metres. The rod has a cm-scale graduation from 0 to 210 cm, with each 10s of centimetre mark highlighted to make reading vertical values easy. A first novelty of this new design is the 3D positioning stage (Fig. 2B-C). This consists of a base plate compass and a circular spirit level glued on to a plate, which is connected to an adjustable angle gauge by a 90 degree bracket. The bracket is mounted on a vertically sliding block that can be fixed in a defined position using a screw clamp. With the angle gauge set at zero, the plate on which compass and spirit level are hosted is orthogonal to the vertical rod, but can be rotated in the vertical plane using the angular scale to match the structural dip of bedding before being clamped in position. The second element of the novel Jacob's staff is a laser sighting stage (Fig. 2D), which allows a pen-shaped laser to rotate around and to move up and down along the rod. Note that the laser is only able to rotate on a plane orthogonal to the rod itself.

The materials were selected for their strength, weight, durability to wear and tear and for their lack of magnetism, to avoid the compass being affected (aluminium being chosen for most of the parts, including the rod). The rod parts and the angle gauge can be bought from most builders merchants, while the laser holder was manufactured. Regarding the compass, a relatively inexpensive base plate compass was deemed sufficient. For the laser, a very inexpensive green light 1mW laser was chosen to allow its light to be visible even in bright sun and to a reasonable distance. The maximum sighting distance is dependent on lighting conditions, and can vary from around 10-20 metres under direct sunlight on a bright sunny day to >100 metres in dark cloudy conditions. Manufacturing and assembly was carried out by Antony Windross and Stephen Burgess at the instrument workshop of the School of Earth & Environment (University of Leeds).

2.2. Suggested mode of use

Before starting logging, as with any Jacob's staff, a precise measure of the strike and dip of the bedding should be obtained. The four parts composing the rod should be assembled and the two moving pieces (3D positioning stage and laser holder) inserted and fixed to the rod. The compass dial should be set to the structural dip direction and the angle gauge should be set to the angle of dip.

To begin the measurement, the user should place the base of the rod on the initial point of measurement (e.g., the base of a bed; a trowel inserted in the soil below the bed might be used to provide a solid base in case of loose sediments). The Jacob's staff should then be aligned to be orthogonal to structural dip checking that the North needle of the compass aligns with the North on the compass dial and that the air bubble of the circular spirit level is in its central position (Figure 3). At this point the user should start moving the laser holder vertically along the rod intermittently activating the laser beam to check where the laser projects on the outcrop. Once a surface to be recorded on the log (e.g., an internal surface within a bed, a base or a top of a bed, etc.) is illuminated by the laser dot, a measure can be read off the graduated values on the rod. If in the first 2 metres there is not any significant surface, the position of the 2 m point (or another suitable value, chosen to make the measurement easier) should be used as the starting point for the next measurement. It should be noted that if the surfaces to be measured are very closely spaced (e.g., a few centimetres in true vertical distance), it might be more time efficient to only use the Jacob's staff to measure key surfaces spaced around 1-2 metres in true vertical distance and use a conventional tape measure to integrate the measure by adding the intervening surfaces. By applying this technique, the speed of measurement using the new Jacob's staff is roughly comparable to that of a conventional staff.

2.3. Main use of the rotatable laser

Ideally, it would be best for the trace of the log to follow the direction of the structural dip of the succession. However, this is not always possible and in some cases, a lateral shift is required. When possible, this should be performed by walking a known surface parallel to bedding and restarting the log in the new location. However, when this is not possible, accurate sighting may be necessary to find a new starting point. A key design feature of the described Jacob's staff improves this action by allowing the rotatable laser to describe a plane orthogonal to the Jacob's staff rod (i.e. on a bedding plane). The user is therefore able to project the laser dot on the outcrop at any angle away from the dip direction of the bedding (Figure 3). However, care must be taken as the larger the angle away from the direction of the dip the more any error in the measured value of the strike direction and dip angle used to orientate the Jacob's staff will be amplified. This effect is in addition to the error caused by the longer sighting distance associated with this action. If the outcrop is mainly oriented parallel to the bedding strike, any error on the strike value will be significantly amplified – errors on the dip angle less so – and vice versa, so that on an outcrop mainly extending along the dip direction errors in dip angle will be the most amplified. This type of error can be minimised by improving the measurement of the direction and angle of the dip by using the rotatable laser (see next paragraph).

2.4. Other uses of the rotatable laser

If the outcrop is laterally extensive, rotating the laser holder will result in the laser dot projected on the outcrop to 'follow' a surface parallel to the regional dip (e.g., the planar base of a thin sediment bed). This technique can be used to verify and refine the value of strike and dip angle of the bedding measured with a conventional compass. If it is clear from other sedimentological observations that the surface in observation should be parallel to the regional dip and the laser dot on the outcrop does not 'follow' it, it is likely that the values of dip direction and angle chosen to orientate the Jacob's staff are not correct. Conversely, if the values of dip direction and angle are known to be correct and the laser dot on the outcrop does not 'follow' a certain surface, it is possible to infer that the surface in question is not parallel to structural dip. For example, this technique could help recognise shallow clinoforms, levees, bar forms or remobilised deposits. In a sequence of amalgamated event beds, it could make possible to establish if the amalgamation surfaces are bedding-parallel or are at an angle to it, indicating incision. Similarly, in a section characterised by low angle unconformities, this approach might improve their recognition and help establish the degree of change in bedding attitude.

3. Measuring errors

Whichever technique is used, evaluating errors affecting stratigraphic measurements is difficult, mainly because of the lack of a 'true' value against which to validate the results (in a tabular succession, core from a behind outcrop drilling project could provide such 'true' value). In addition to the skill of the user, key factors defining the amount of error are the type of instrument used for logging (e.g., tape measure or different models of Jacob's staff) and the type of exposure. The latter component can be broken down into the geometrical configuration of the topography in relation to the regional structural dip (hence the required sighting distance; see Figure 1) and into the quality of exposure (e.g., presence of soil or plant cover, intensive rock weathering, etc.).

The amount of error associated with measurements of stratigraphic thicknesses can be highlighted by comparing logs of the same stratigraphic section by different authors. An example is provided by the work of Kneller and McCaffrey (1999) and Patacci et al. (2014) who logged the same section outcropping along the road D110 to the village of Braux, in the French Alps (Annot Sandstones). Comparison of the 46m thick interval between the base of beds Z and A of Patacci et al., 2014 reveals that measurements of 24 1-3 metres thick intervals (from bed base to bed base) with rare exceptions have differences of up to 10%. However, the differences tend to compensate each other and differences for stretches of several meters are between 1% and 3%; both sections have excellent outcropping conditions along the road cut and were logged with a tape measure.

The lack of a 'true' reference value when measuring stratigraphic thicknesses means it is difficult to assess the precision of the newly designed Jacob's staff. However, Marini et al., (2016) recently published the first dataset acquired with the new Jacob's staff described in this paper, a portion of which can be compared with Log VI of Southern et al. (2015), logged with a traditional Jacob's staff. Although the purpose of the work was different, both logs were measured at the same resolution down to 1 cm. The logged section includes a mix of different logging conditions along a mountain crest, with some very difficult stretches, both because of the geometrical configuration (e.g., bedding shallowly dipping into the subsurface and shallowly sloping terrain) and also because of some covered or poorly outcropping intervals, making the use of the Jacob's staff essential. Comparison of 19 selected 1-5 metres long intervals for which original measurement data were available (for a total thickness of 48 metres) indicates differences up to 20%. As in the Braux road section example, the differences tend to compensate, resulting in errors for stretches of several meters between 2% and 5%. It should be noted that the larger differences in this case are likely due to the difficult outcrop conditions and that a major benefit of the new Jacob's staff is thought to be in reducing the larger errors associated with this type of scenario therefore improving measurement repeatability.

Although the examples provided above (chosen principally on the basis of the data availability to the author) might help the interpretation of stratigraphic thickness measurements and their associated errors, a detailed comparison of different logging techniques and the resolution and repeatability of such measurements is outside the scope of this paper; it is an area of methodological research awaiting further study.

4. Conclusions

The described new Jacob's staff design includes a number of improvements which can be achieved at a reasonable cost and are aimed at increasing the precision of stratigraphic thicknesses measurement while maintaining the logging speed of a traditional Jacob's staff.

A number of factors contribute to an increase in measurement precision and repeatability compared to a traditional Jacob's staff: a) improved 3D positioning of the rod through a revised compass and spirit level holder; b) more precise sighting of measurement points due to movable laser stage; c) reduced error when shifting the trace of the log laterally (i.e., away from the dip direction) and d) improved measurement of bedding necessary to orientate the Jacob's staff. The last two factors are possible due to the ability to turn the laser and project a visual planar datum to aid in the recognition of depositional or erosional surfaces at an angle to structural dip.

Although defining the precision of the new instrument is challenging and awaits further work, a short compilation of examples shows that stratigraphic thickness measurement errors can be significant, especially when values for individual metres-long stretches are required. It is also apparent that the largest errors occur most likely when outcrop conditions are difficult, in terms of orientation of the geological structure to the land surface, or the degree of outcrop. In these scenarios the new Jacob's staff can help to improve precision and repeatability of stratigraphic thickness measurements and hence to reduce the associated uncertainty in the description and interpretation of the dataset.

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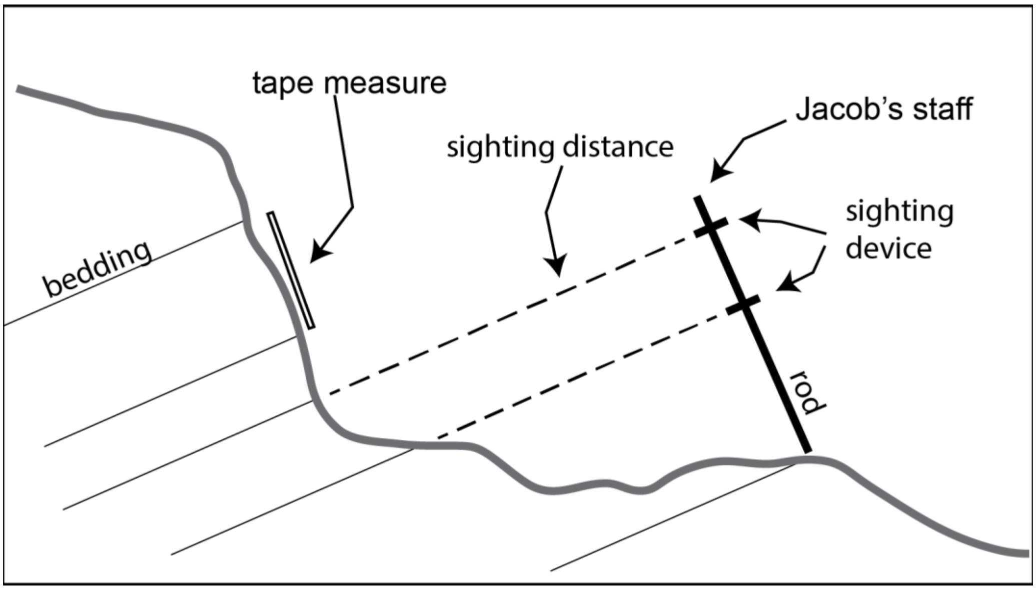

Figure 1. A tape measure is an effective tool for measuring stratigraphic thicknesses when apparent and real thicknesses tend to coincide (e.g., shallow dipping beds on a vertical cliff). When apparent and real thicknesses of beds diverge (e.g., shallow dipping beds along a crest leading to a hilltop), measurement must be carried out by sighting. In this scenario a Jacob's staff (comprising a rod and sighting device) is the most effective tool for measuring stratigraphic thicknesses. Note that the sighting device can be fixed (as in most traditional designs) or be able to move along the rod (as shown here, in the new design).

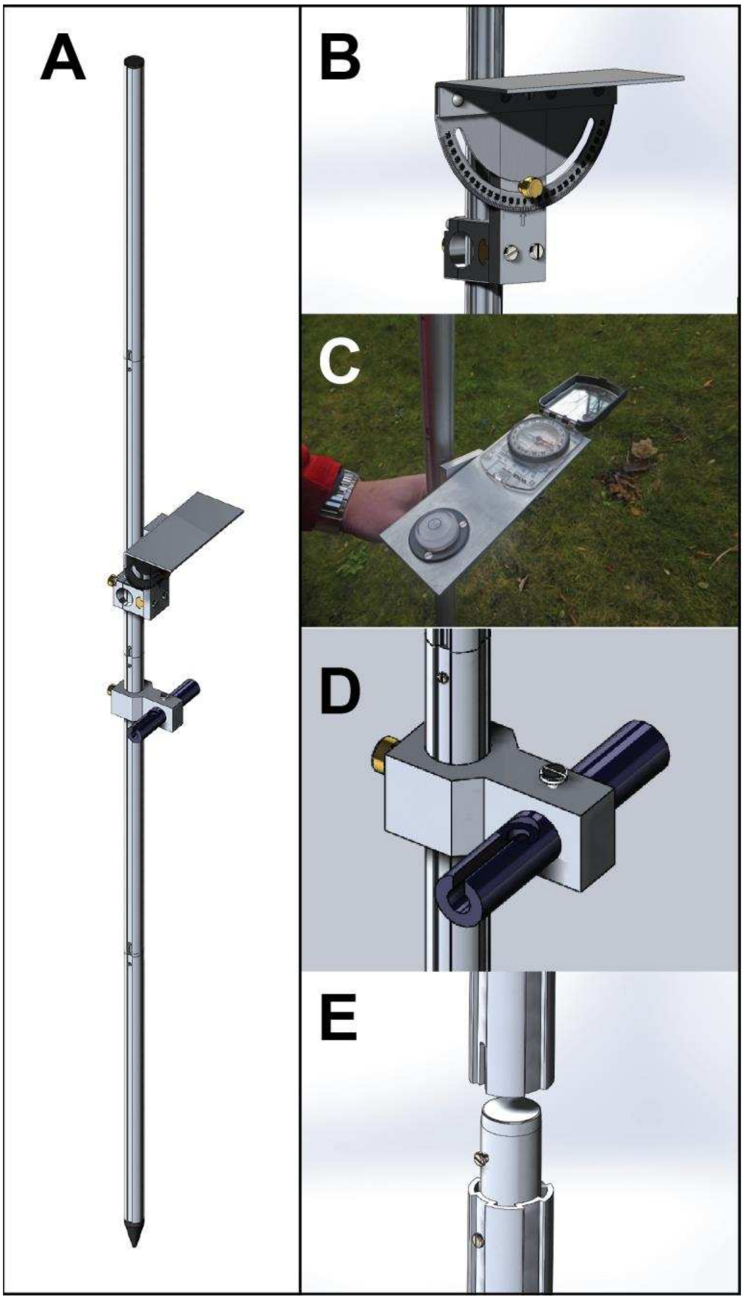

Figure 2. A) The new Jacob's staff design. B-C) 3D positioning stage, including an angle gauge with the attached bracket holding a circular spirit level and a base plate compass (note that spirit level and compass are not shown in the technical drawings). D) Laser sighting stage (laser is not shown). E) Connecting mechanism between pieces of the rod. Technical drawings courtesy of Antony Windross.

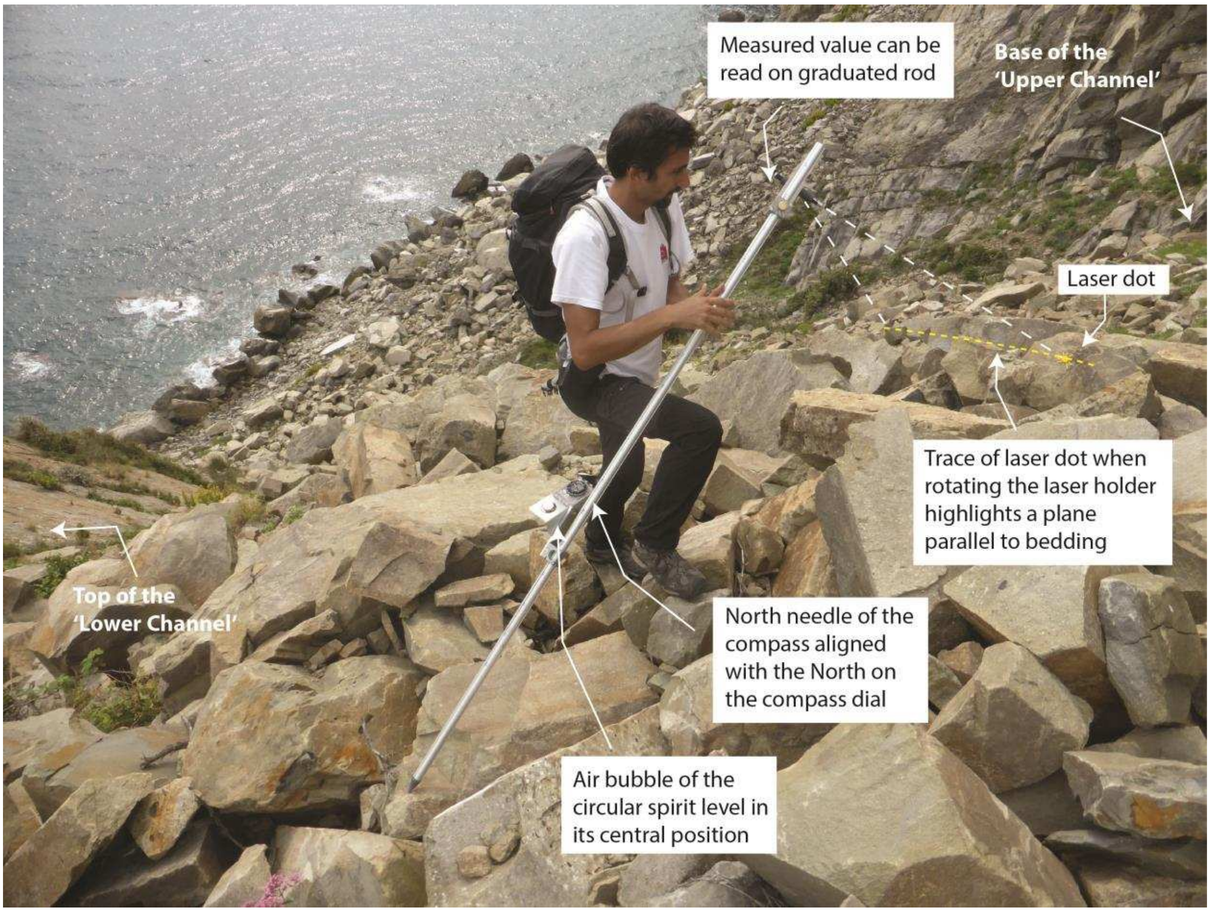

Figure 3. The new Jacob's staff in action, measuring the stratigraphic thickness of the covered interval between the top of the 'Lower Channel' and the base of the 'Upper Channel' at the Monterosso outcrop (Gottero Sandstones, NW Italy). Photo courtesy of Marco Fonnesu.