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Automation of cross section construction and forward modelling of fault-bend folds from integrated map data

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Abstract: We present a series of software tools for the automation of cross section construction from digital geological map data and corresponding digital elevation models. Our approach integrates surface data into a 3D environment and involves three fundamental toolboxes: 1) a near-surface cross-section projection and preparation toolbox, 2) a kink-method constructor, 3) a forward modeling toolbox for fault-related folding. The programs are written using Matlab© (MathWorks Inc), and can be fully automated or operated in an interactive mode.

Keywords: fault-bend fold, cross section construction, forward modeling, Sequatchie Anticline, kink-method.

We have developed and combined three (initially separately written libraries) into a useful package for constructing balanced cross sections. While each toolbox can be implemented individually we present here the workflow for combining them together to constrain subsurface geometries. An example of the utility of these toolboxes is presented by modelling the northern terminus of the Sequatchie Anticline in eastern Tennessee illustrated in figure 1, a well established fault-bend fold with excellent surface map data (Rodgers, 1950; Milici, 1963; Mitra, 2005).

Methods

The first toolbox includes code that assists in the digitization of map data and provides data structures for storing map contacts and attitudes. The first component to the process integrates digitized contacts from geological maps, digitized attitude measurements which can be extracted from the maps by clicking their orientations and digital elevation data to generate one or multiple near-surface cross sections across a structure in an orientation interactively or automatically specified by the user. A series of subroutines allows us to readily project large dataset map data into cross sectional view, eliminating this labor-intensive process. The projection process extracts a topographic profile from an input elevation dataset, and each stratigraphic contact is posted dipping in the direction inherited from nearby computed apparent dips.

While the process objectively and accurately projects map data, missing data and local complexities that misrepresent the trend of the overall structure can limit the usefulness of completely objective projection. The Sequatchie Valley study area included 2142 digitized attitude measurements obtained both from map data and direct field measurements. The default swath selected for this study area's 20 km long cross sections is 1 km. This large volume of measurements inevitably includes measurements of localized structures that misrepresent the geologists' intuition or knowledge of the overall trend of the structure, or project poorly along strike. The toolbox provides an editing component that allows the user to interactively clean the dataset of anisotropic attitude measurements. With a dual view of the map data and the projection into the cross section, the user manually deletes a measurement as a strike and dip symbol in the map view or as its corresponding projected tadpole in cross sectional view (Figs. 2 and 3). The uneven distribution of attitude measurements yields

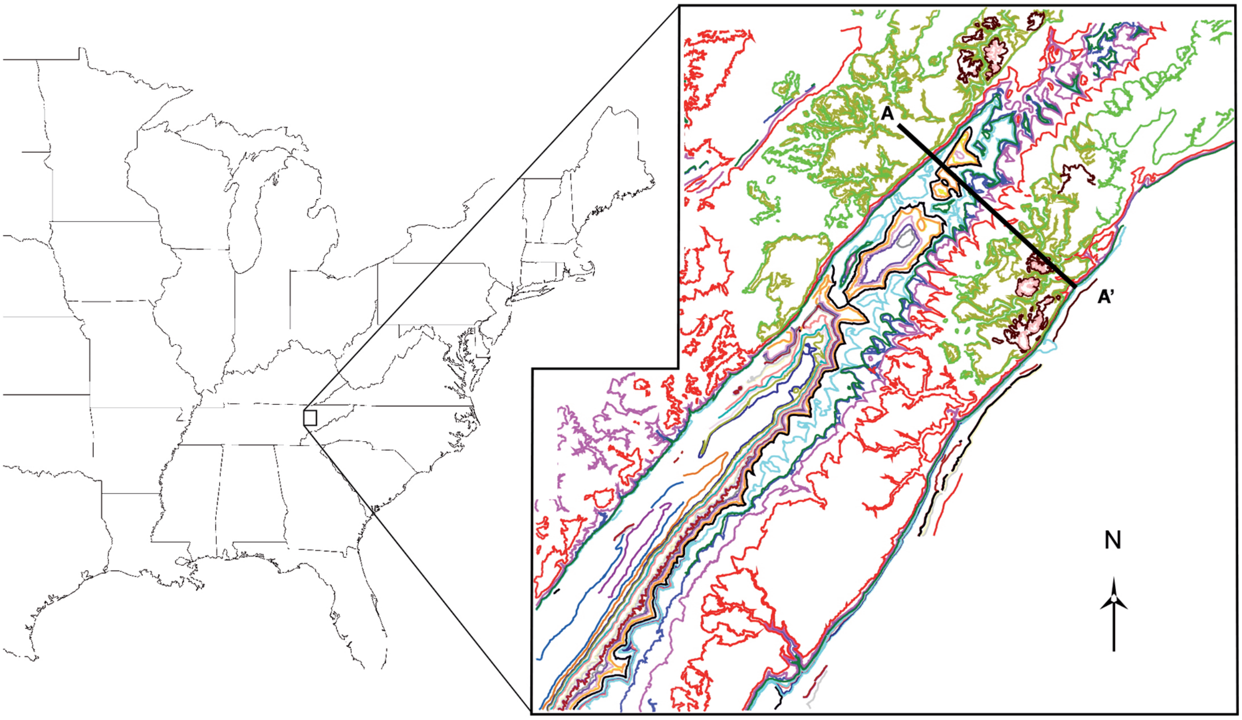


Figure 1. The study area used to test the three toolboxes covers the fault-related fold known as the Sequatchie Anticline in eastern Tennessee. This image is an example of a portion of the digitized contacts in map view, and the user selected section A-A' is the location of the cross sections extended to depth in figures 2 and 3.

many areas of sparse data, and the inherited average dips of the contacts in these areas are more susceptible to inaccuracy if suspect attitudes are not removed.

The kink-method toolbox allows us to obtain the geometric solution that conserves layer thickness and line length of a given stratigraphy interactively by clicking and editing the fold shape of any layer (see figure 4). The development of interactive editing within this program provides mechanisms for perfecting the orientation and location of dip domains within the structure that best honor the observed projected cross-sectional data. The kink method toolbox allows the user to evaluate the cross section to depth with a purely geometric approach based only on the current bedding orientations along the topographic profile, ideally obtained through the implementation of the first toolbox. The interactive ease with which a good fit kink method solution is extended to depth is illustrated in figures 4a, 4b and 4c.

The forward modeling toolbox for fault-bend folding (Connors *et al.*, 2007) incorporates a velocity description to obtain balanced sections of the structure of interest. This can be based on the previously generated cross section using the kink-method toolbox or by directly modelling the projected cross-sectional data. The toolbox quantifies the fold shape at each time step by calculations of the fault-bend fold equations of Suppe (1983). The user inputs a known stratigraphy, including detachment levels, and initial fault, and then makes subtle changes by manually adjusting the combination of amount of slip, stratigraphy, and fault geometries to converge on the closest fit of the folded stratigraphy in the model to the observed contact locations and dips (see figure 5).

Results

Our modelling of the northern terminus of the Sequatchie Anticline in eastern Tennessee using this approach shows that the underlying fault geometry is very curved, and slip required to generate the structure is on the order of 1200-1500 m, consistent with previous work (Milici 1965; Mitra 2005).

Discussion and conclusions

Accuracy and trustworthy data points are achieved through the combination of objective automation of shallow subsurface cross section and removal of suspect attitude measurements. The accuracy of the initial toolbox ensures the ability to test kink method toolbox and fault-bend-fold toolbox on the dataset. Future work

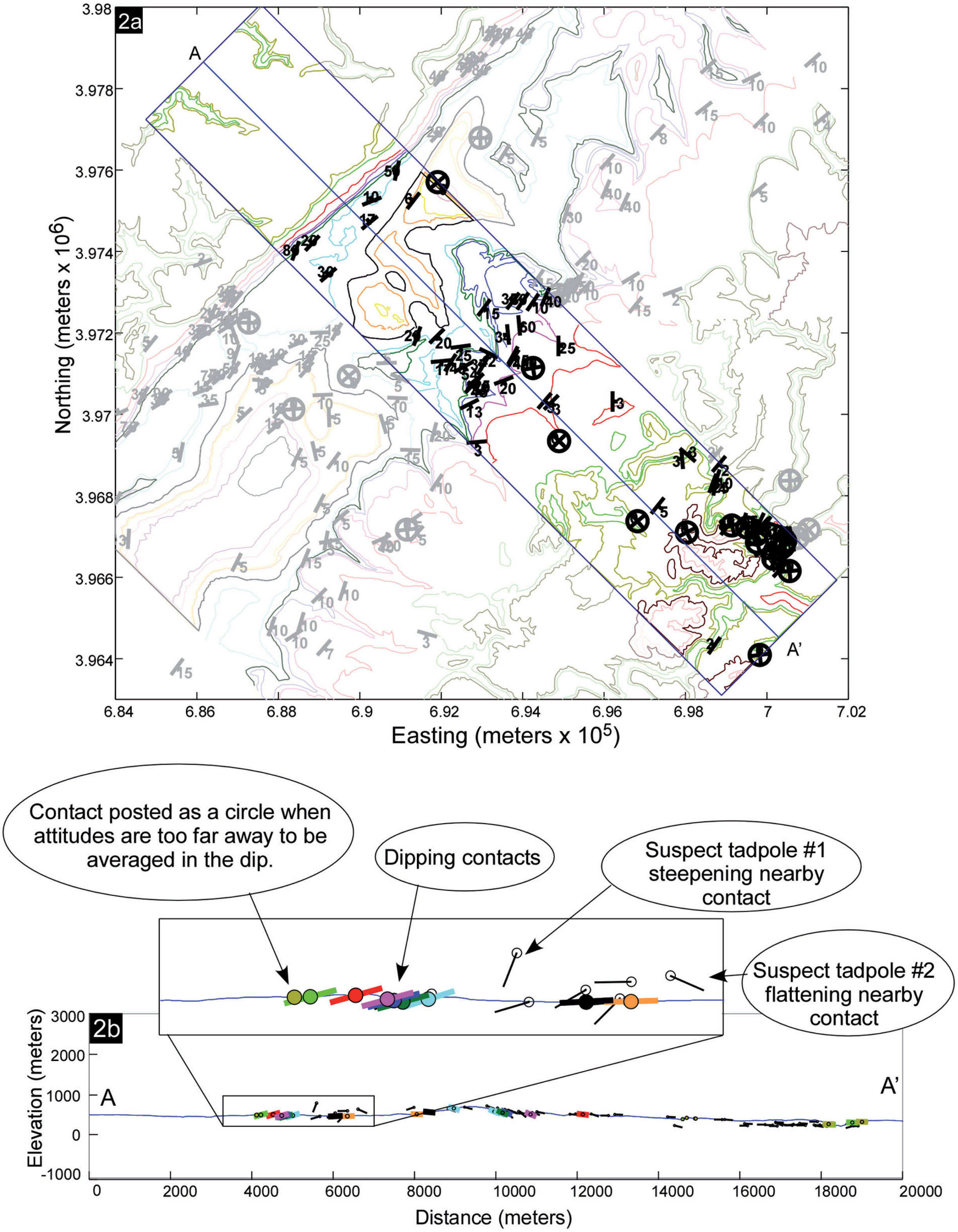
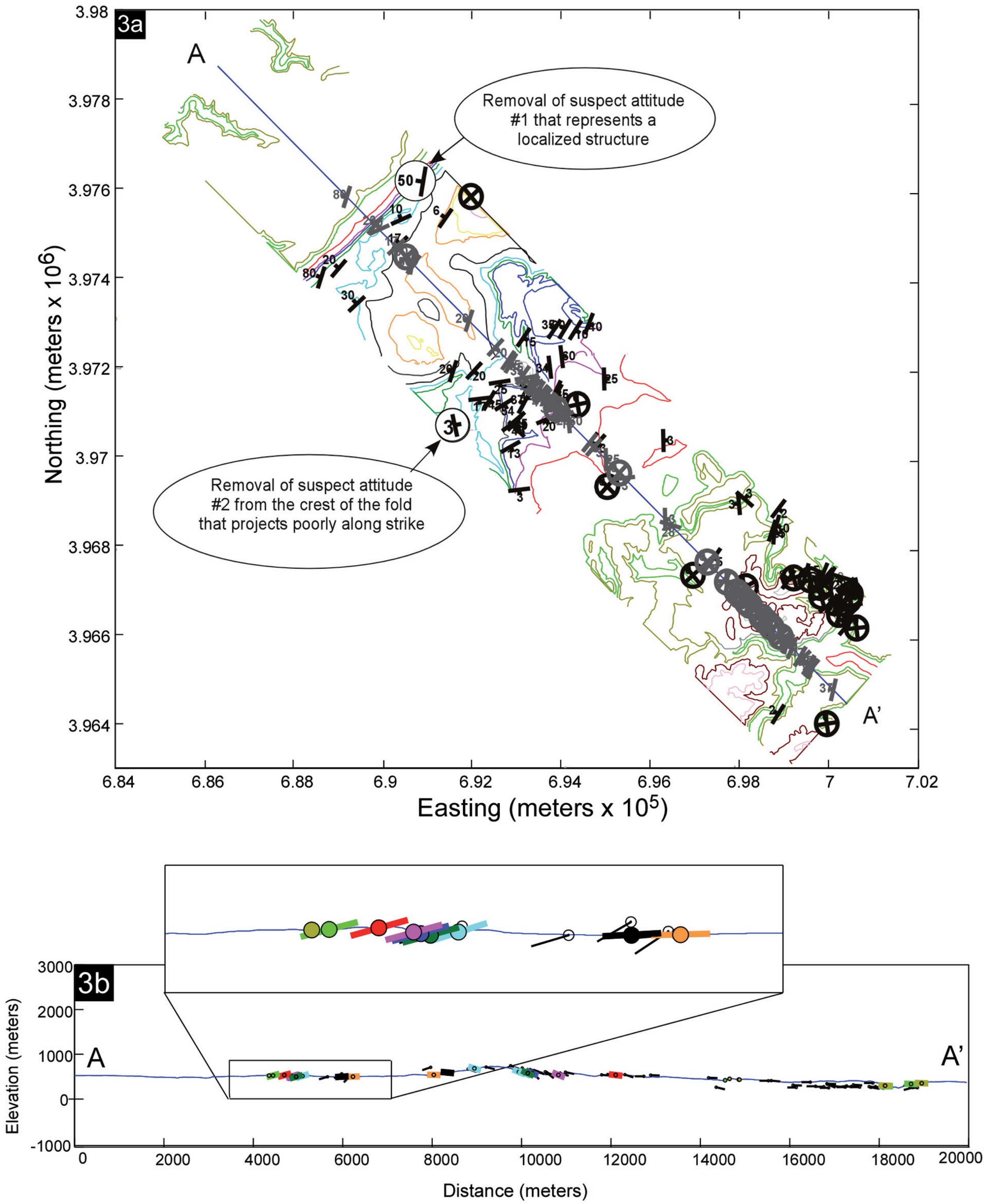


Figure 2. Attitudes within a user defined swath are selected for projection along strike onto the section line (in black), while attitudes outside the swath are removed from the dataset (gray, figure 2b). For each contact intersection extracted along the section line's topographic profile, a dip magnitude is obtained by averaging nearby projected apparent dip values. If there are no attitude measurements within a user defined (nearby) radius around the contact location, then a circle is posted in cross sectional view with no dip.


Removal of suspect attitude #1 that represents a localized structure

Removal of suspect attitude #2 from the crest of the fold that projects poorly along strike

Figure 3. The toolbox has the utility of the simultaneous map view/cross sectional view capability of interactively deleting attitude measurements. The outcome of deleting the measurements is illustrated in the smoother contact dips in figure 3b.

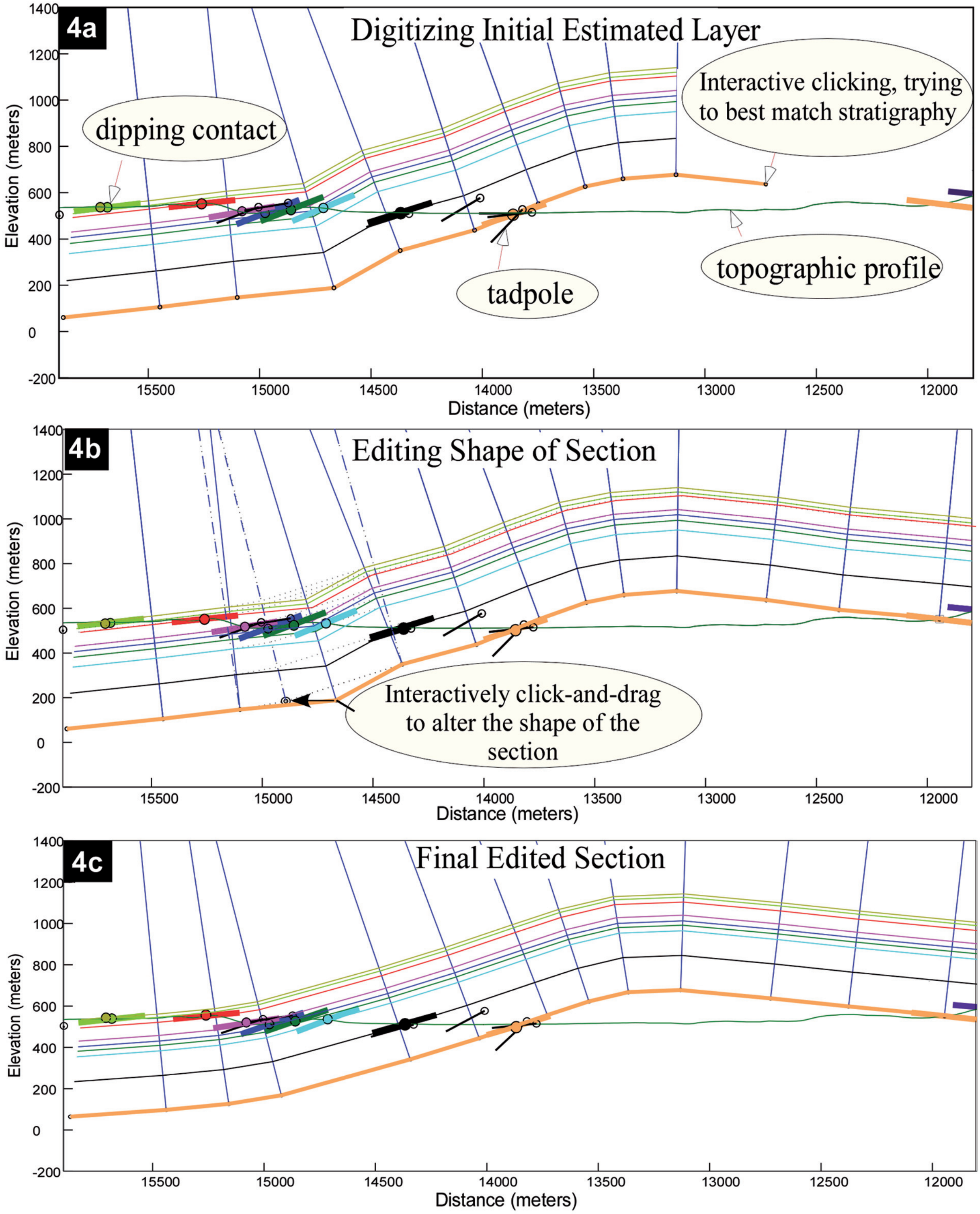


Figure 4. (a) A visual representation of the interactive kink method cross section construction. The toolbox allows the user to digitize with a series of clicks an estimate of the shape of an arbitrary layer. From the calculated axial surfaces, the other layers are calculated above (or below) the clicked layer. The cross section forms instantaneously with each click. To refine the section to match the contact tadpole locations and dips, the user manually adjusts the points along the digitized layer to improve the geometry of the section, as illustrated in figures 4b and 4c is the edited kink method solution that best fits the data obtained from the first toolbox.

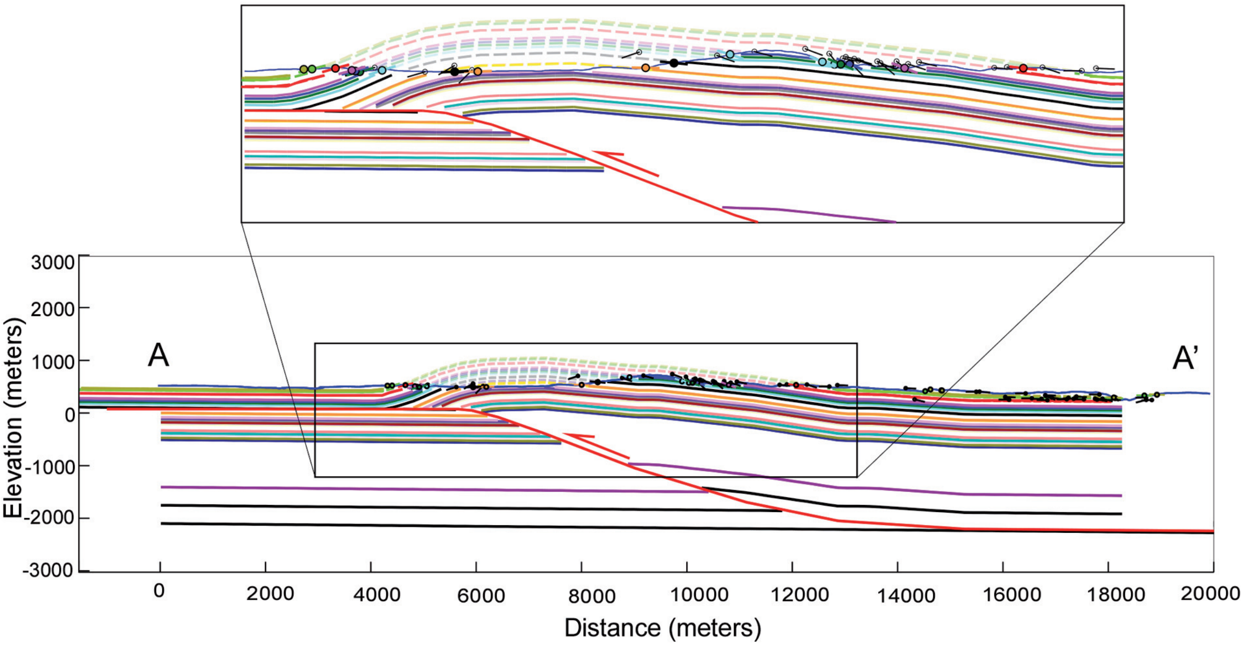


Figure 5. The last time step of the best fit fault-bend-fold solution (3rd toolbox) of the topographic profile and surface data from the same cross section in figures 1, 2 and 3.

includes stitching together multiple along-strike, forward-modeled solutions to model fault-bend folds in three dimensions, and to constrain changes in slip and fault geometry of structures along strike. In addition, we intend to invert for the best fit fault-bend fold solution to the observed projected cross-section data by using an additional toolbox of inverse modeling code developed by Connors *et al.* (2007).

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