Best practices in 2D sequential restoration – Part 2

This month's feature is the second of a two-part series outlining best practices in 2D sequential restoration. The first part (found here), outlined best practices for the preparation of cross-sections for restoration. This month's feature will discuss the tools available in Move™ to carry out 2D sequential restorations, their functionality, and some best-practice guidelines to follow. Every restoration is unique and will have its own set of steps to follow. The geological context of a model should always be considered in deciding what tools and algorithms to use. There may be geological information available to place useful constraints on the restoration (e.g. palaeo-environmental fossil markers for bathymetry), and the use of kinematic algorithms should be consistent with the nature of the rock mass and the tectonic setting. While this article will briefly discuss some of the 2D Kinematic algorithms and their applicability, a full overview of the algorithms is available in the Resources section of the Midland Valley website, under Move Documentation/Algorithm Advice.

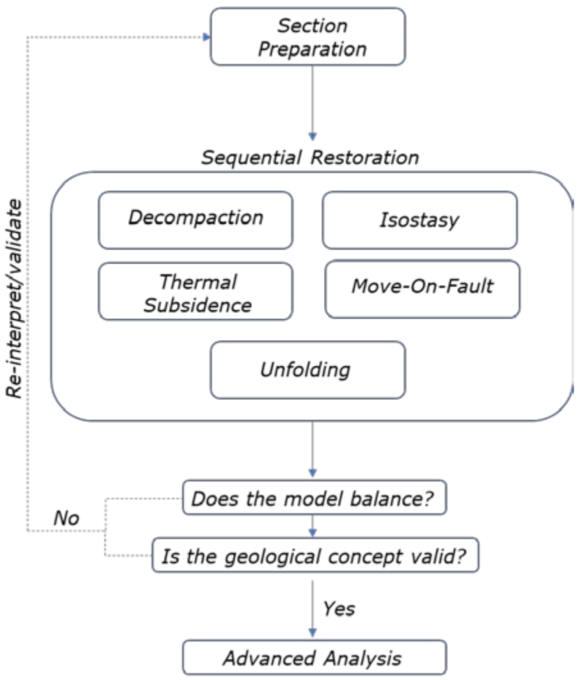

Figure 1. Sequential restoration kinematic tools as part of a broader structural analysis workflow.

The workflow and methods to be used in a restoration will largely be decided by its objective. For example, in a restoration being carried out to decipher the timing of development of an individual structure, it may not be necessary to restore the cross-section to a defined palaeo-elevation. In such cases, an arbitrary unfolding datum can be used, saving time and effort. With this in mind, it is extremely important to consider the aims of a restoration prior to determining the workflow and to select a workflow appropriate to answer the questions being asked. Figure 1 displays a general workflow diagram, which identifies the components of a sequential restoration within a higher-level, structural analysis, looped decision tree. Sequential restoration may provide the answers to the questions being asked, or it may be part of a model validation workflow carried out prior to additional analysis such as a fault seal or fracture prediction study.

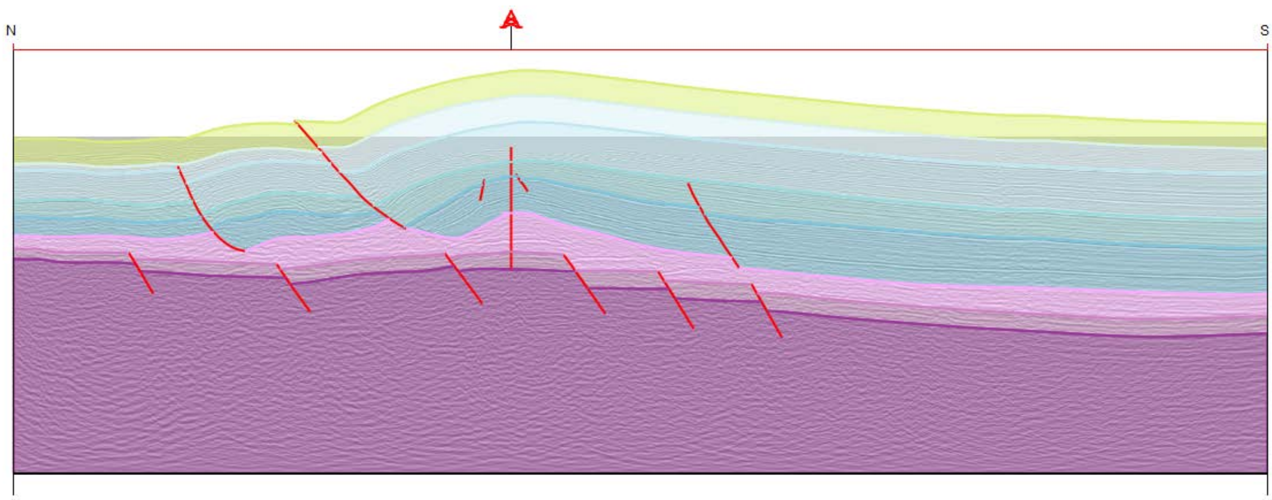

*Figure 2. Cross-section from the Wymouth anticline in the Wessex Basin, southern England. Some of the eroded section has been rebuilt using the **Horizons from Template** tool in Move.*

For the purposes of this feature, a cross-section from the Weymouth anticline in the Wessex basin of southern England will be restored (Figure 2) to determine the timing of fold and trap development relative to salt movement. Sequential restorations should be carried out backwards in time, starting by removing effects of the most recent tectonic and sedimentary events. In this example, and in many contractional settings, this is erosion and requires reconstruction of eroded stratigraphy. As part of the cross-section preparation, the eroded parts of upper strata have been reconstructed using the **Horizons from Template** tool (Figure 2). Alternatively, in an extensional setting, the most recent events will often be thickness changes due to sediment deposition, associated with porosity loss and compaction. This can be restored using the 2D Decompaction tool in Move.

1. Salt

The example used in this article is complicated by deformation, syn- and post-sedimentation, due to movement of salt. Salt or other mobile units such as shale can produce complex structures and lateral variations in sediment thickness (see Rowan & Ratliff, 2012). Salt does not compact with increased load and often will respond by moving in the subsurface, deforming overlying sediments and creating local depocentres. It can also generate a change in load on sub-salt sediments that requires a correction to load estimates solely based on the thickness of the deposited sediments (Macaulay, 2017). Deformation (e.g. faulting, folding) in the sub-salt and supra-salt units may be decoupled. If this is the case, it is advisable to restore the supra- and sub-salt sediments (Figure 3) separately.

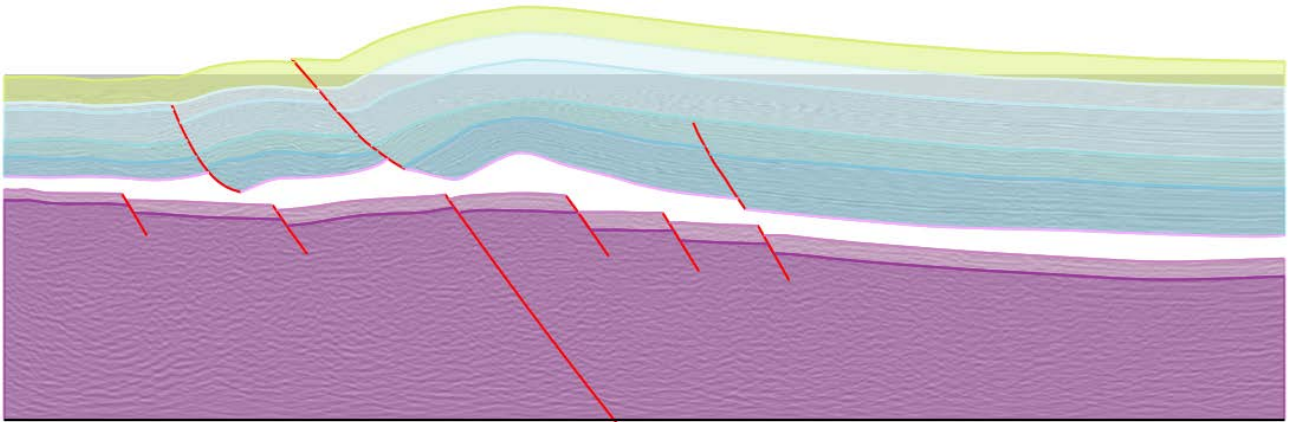

Figure 3. The polygon and seismic image representing the salt has been deleted so as the supra- and sub-salt parts of the cross-section can be restored independently.

Salt is also likely to have moved in and out of the plane of section or undergone dissolution, increasing or decreasing the area of salt in a cross-section. This undermines assumptions of plane strain and area balance, thus increasing uncertainty. Sediments should be treated as a recorder of salt movement. The polygon representing a salt unit in Move can be deleted. By restoring the surrounding sediments, the remaining space can be filled with salt at each restored time-step to produce an estimate of changing salt area and distribution.

2. Move-on-Fault

NEW TO MOVE: The Elliptical Fault Flow algorithm can be used to restore isolated faults with displacements that diminish up and down dip.

There are seven 2D algorithms in Move for restoring and forward modelling fault-related deformation: Simple Shear, Fault Parallel Flow, Fault Bend Fold, Fault Propagation Fold, Trishear, Detachment Fold, and Elliptical Fault Flow (new for Move 2017.2). These can be selected from the drop-down list at the top of the 2D Move-on-Fault toolbox. Some algorithms, such as Fault Propagation Fold, are more suited to forward modelling than restoration. The Algorithm Advice document linked in the introduction to this article outlines the most appropriate use of each algorithm and the tectonic setting they are most applicable to.

In the Weymouth anticline cross-section, some minor faulted offset has been interpreted in the supra-salt succession. Due to the fact that these are competent, lithified horizons, this deformation should be restored using the Fault Parallel Flow algorithm. The Fault Parallel Flow algorithm divides the fault into discrete dip domains and flow lines, along which, hanging wall material moves, maintaining line-length and area. It is an algorithm suited to modelling hanging wall movement on faults in fold and thrust belt settings. The **Join Beds** functionality in the Movement sheet of the tool allows the hanging wall and footwall lines representing the uppermost offset horizon to be collected and joined accurately with the Move-on-Fault operation (Figure 4).

3. Unfolding

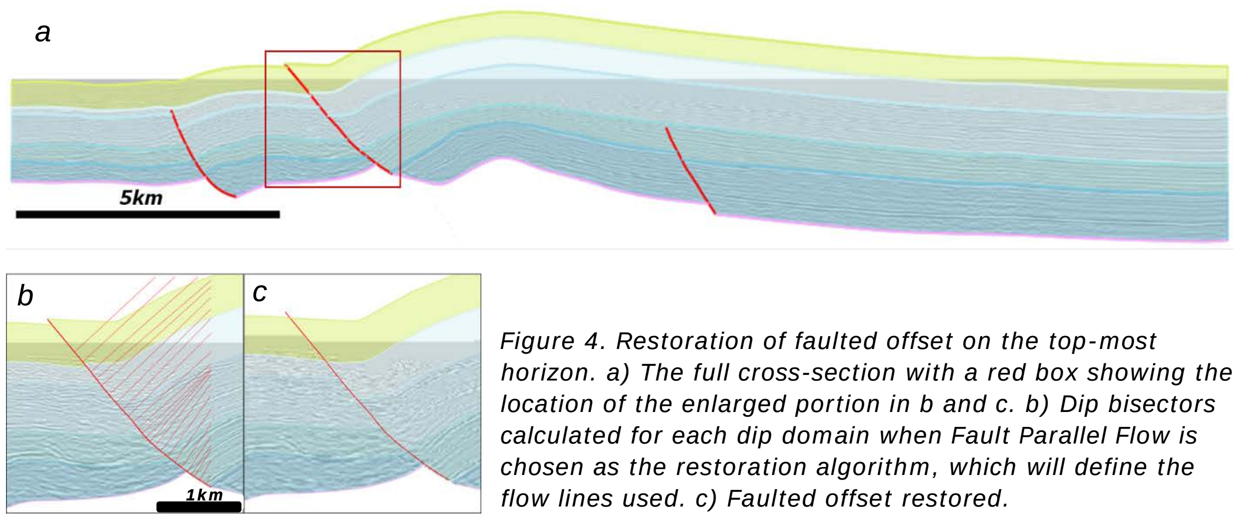

Figure 4. Restoration of faulted offset on the top-most horizon. a) The full cross-section with a red box showing the location of the enlarged portion in b and c. b) Dip bisectors calculated for each dip domain when Fault Parallel Flow is chosen as the restoration algorithm, which will define the flow lines used. c) Faulted offset restored.

There are three unfolding methods in Move: Line Length, Simple Shear and Flexural Slip. Line Length simply rotates line objects such that line length is maintained but only transforms from a deformed to a straight line. A pin is used, and lines can be unfolded to be horizontal or perpendicular to the pin but not to a defined template. A percentage unfolding can be set.

TIP: The Preview button allows the result of a Move-on-Fault or Unfolding operation to be viewed before clicking apply, without restoring any images (e.g. seismic data). Parameters can be changed and the results will instantly update in the Section View.

Simple Shear moves every point forming a line along vertical or inclined shear vectors to a horizontal datum or selected template line (Figure 5a). Area, but not line-length, is maintained using Simple Shear and thus for steeply dipping beds, this method should be used with care. Simple Shear is suited for geological settings where lithologies are semi-consolidated or behave in a ductile fashion at the time of deformation, for example clastic sediments deposited during growth faulting or salt deposits.

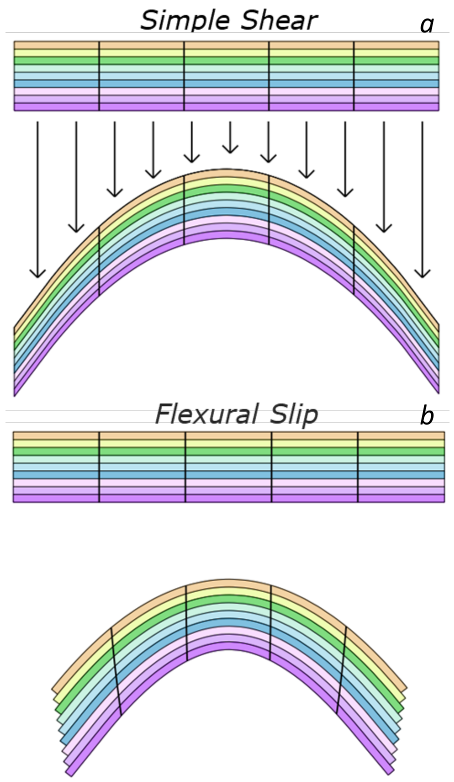

Figure 5. a) An illustration of a vertical Simple Shear Unfolding operation. b) An illustration of a Flexural Slip Unfolding operation.

Flexural Slip calculates particle paths to simulate layer-parallel slip when unfolding objects, for example the limbs of a fold, to a datum or template line. Flexural Slip Unfolding maintains line-length and area and is often compared to flexing a deck of cards. Objects are unfolded about a line where minimum curvature change is assumed to have occurred, called a pin. Points along the pin are not translated (Figure 5b). Choice of pin location can be quite important in ensuring a valid shape for the unfolded beds. For fault-related folds, the fault can be used, whereas in areas where no fault is apparent, e.g. salt-related deformation, the pin should be placed where no bed-parallel slip is thought to have occurred, such as a fold axial trace. Flexural Slip is best suited for structural settings where sediments are fully lithified at the time of deformation, such as in fold-thrust belts or extensional systems with limestones.

HINT: When the Flexural Slip method is chosen an interactive pin appears that can be translated or rotated by clicking and dragging from its centre or its top respectively.

In the Weymouth anticline cross-section, Flexural Slip Unfolding is carried out, following the restoration of the faulted displacement at the surface. The main fold deformation is in the hanging wall side of the main fault, which means that for unfolding this portion, a pin should be located in the un-deformed part of the footwall, because there has been no folding here (Figure 6). The seismic image can be carried with the restoration enabling the examination of seismic stratigraphic relationships at each restored time-step.

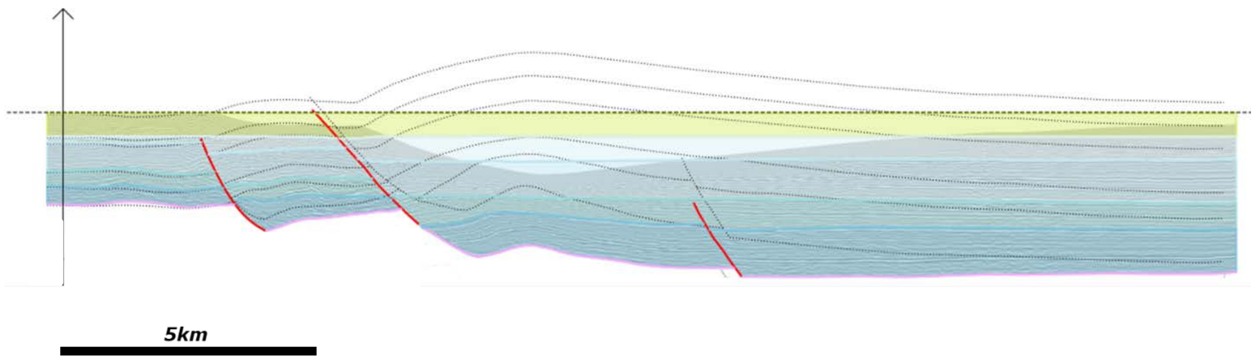

Figure 6. Unfolding carried out on the Weymouth anticline supra-salt sequence using Flexural Slip Unfolding. Original bed positions shown with black dashed lines. The pin can be seen to the far left of the cross-section.

4. Decompaction, isostasy and thermal subsidence

Each sedimentary package represents accumulated deposition, which will have compacted underlying sediments. Deformation due to physical compaction, which results from progressive porosity loss in loaded sediments, can be restored in Move. The accumulated sediment will also have depressed the lithosphere which can be modelled and restored using isostasy. In rifted basins, cooling of new lithospheric mantle following rifting generates subsidence, which provides additional accumulation space for sediment and causes long-wavelength folding. This should be restored with the 2D Thermal Subsidence tool, used concurrently with the 2D Decompaction tool to restore the effects of isostasy and physical compaction.

The 2D Decompaction tool in Move includes three, industry standard, default compaction curves, which define different relationships between porosity and depth. Sclater-Christie is a negative exponential curve with greatest porosity loss occurring at shallow depths, based on a defined depositional porosity and depth coefficient. It is most appropriate for sandstones and mixed sedimentary sequences (Sclater and Christie 1980). Baldwin-Butler and Dickson decompaction curves define power-law relationships between burial depth and porosity for shales and under-compacted/overpressured shales respectively (Baldwin & Butler, 1985). Move also allows the importing or digitization of user-defined porosity-depth data and definition of unique compaction curves. More information on these can be found in the March 2017 Monthly Feature.

Isostasy changes are restored using the 2D Decompaction tool and can be compensated for using the Airy or Flexural (Vening Meinesz) methods. Airy isostasy is most applicable to loads that are much shorter than the flexural wavelength and can be treated as rigid blocks. A bulk vertical shift using the Basic Transform tool can simulate adjustment using Airy isostasy. This can be applied to supra-salt sections to compensate for salt movement. The adjustment should be calculated on a series of vertical profiles away from the areas of salt mobility and the average value used to bulk shift the section. Flexural isostasy models the response of the lithosphere where it is less rigid, and the load has caused changes that are laterally variable. The flexural response of the crust is not generally seen on length scales less than 10 km, so this method should only be used for restoration on sections >10 km in

HINT: Use Ctrl+A to select everything in a section before opening the 2D Decompaction or Move-on-Fault tools and Move will automatically collect items into the appropriate boxes.

length. Isostasy in Move is covered in more detail in the May 2016 Move monthly feature.

Thermal subsidence due to rifting is calculated in Move according to McKenzie (1978). It is designed to account for elevation changes and deformation caused by increasing density of newly formed lithospheric mantle as it cools. During and following rifting, a basin will continue to subside on 10-100 My timescales. In Move, the Thermal Subsidence tool and the 2D Decompaction tool should be open and used together. More information and tips on the Thermal Subsidence tool can be found in the Thermal Subsidence Monthly Feature.

Here, the next step of the restoration is to remove the uppermost sedimentary unit, correct for the effects of physical compaction in the supra-salt succession and vertically shift this part of the section to simulate an isostatic adjustment for salt movement during the time-step (Figure 7). The top salt should be used as the section base and the sub-salt can be decompacted using the methodology of Macaulay (2017). It is clear from Figure 5 that an early phase of salt movement was associated with development of a growth anticline in the lowest part of the succession, but that most fold development and salt movement post-dated sediment deposition.

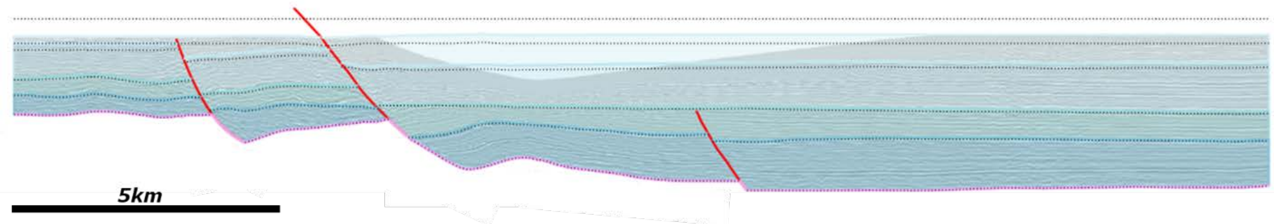

Figure 7. Decompaction carried out and isostatic adjustment made on the supra-salt sequence. Original bed positions shown with black dashed lines. Notice the expansion of each of the sedimentary packages relative to their original geometries.

5. Continuing the restoration

After each restoration step the model should be examined and the subsequent most recent event identified for restoration in the next step. It is best-practice to keep a record by duplicating a cross-section after each operation. This allows return to an interim step if required, and the restoration to be iterated with a different approach from that step. Animations can be created from cross-sections saved at each step and exported as images or 3D PDF animations, allowing the structural evolution of a model to be disseminated to a wider audience.

References

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Acknowledgement: We would like to thank the UK Onshore Geophysical Library for permission to use this data in our training and education resources.

If you require any more information about Sequential Restoration or other workflows in Move, then please contact us by email: enquiries@mve.com or call: +44 (0)141 332 2681.