[PS]Evaluating a 2-D Structural Restoration: Validating Section Balance*

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Abstract

Dahlstrom (1969) introduced the power of 2D balanced section construction for making more accurate predictions of subsurface trap geometry in the Foothills of the Canadian Rocky Mountains. Early efforts relied on hand-drafted bed-length conservation between the folded and faulted sedimentary layers of a cross-section interpretation (deformed state) and the flat-lying layer-cake geometry of its restoration (restored state). Today, computer-assisted section construction and restoration software allow the assessment of more complicated structural interpretations by applying a number of methods for forward and inverse strain transformation. While software greatly increases the speed and precision with which the unfolding of folds and the juxtapositioning of fault cut-offs can be made, the validity of material balance requires quantitative analysis beyond a visual inspection between deformed and restored state. In this work, we review the common methods of inverse strain transformations (i.e., restoration) and common pitfalls found in some published restorations:

1. Depending upon the geological setting being analyzed, some transformation methods are more appropriate than others;
2. For some settings, the extant software-based transformations (mostly simple-shear methods) may be poor approximations for the observed deformation;
3. Restorations showing restored arrays of multiple fault blocks are rarely seamless, as fault trace mismatches (gaps and overlaps) between hanging-wall (HW) and footwall (FW) are present in nearly every restoration of a structural profile derived from real data.

Most authors of restorations "cosmetically" remove the small gaps and overlaps between juxtaposed fault blocks. We emphasize that tables listing the line-lengths of key horizons and the areas of key units should be shown in order to describe the quality of balance. Three published restorations (contractional, extensional, salt diapir) are analyzed to illustrate the utility of quantitative validation.

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Evaluating 2D Structural Restoration: Validating Section Balance

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1. Introduction

In 1969, Dahlstrom argued for making balanced cross-sections as a useful constraint on subsurface interpretation. Material balance amounted to a conservation of bed line-lengths for all (pre-kinematic) sedimentary layers above a decollement in a 2D cross-section oriented parallel to the transport direction of the thrust faults. Maintaining areal 2D section balance is appropriate in any geological setting where the deformation vectors lie in the vertical plane of section and the pre-/post-deformation rock density remains constant. In current practice, a balanced section is demonstrated with a side-by-side comparision of a deformed (or final) state profile with a restored (or initial) state profile. We believe that the quality of a restoration is best judged with a tabulation or graphical display of linear and areal inverse stretch values in order to validate the precision of balance. Deviations from strict or exact balance may suggest changes to an existing interpretation. For example, consider the simple line-length balanced flat-ramp-flat fold model of Dahlstrom (1970):

In the diagram and tables at right:

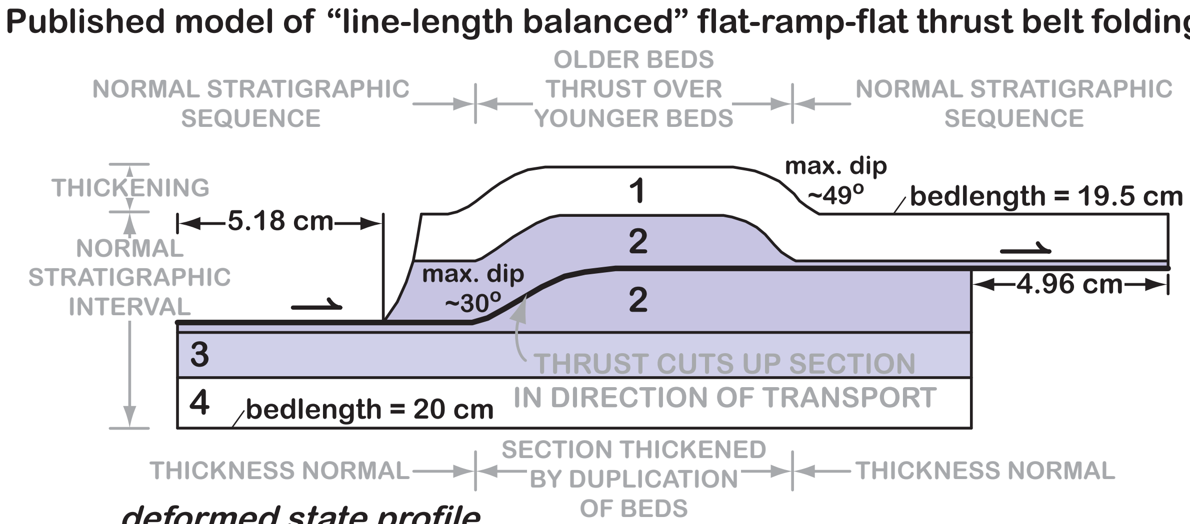
- lengths in cm; areas in cm^2
- S_{bl} is the inverse stretch
  (restored state bed-length/deformed state bed-length)
- 1+Δ is the inverse area stretch
  (Δ = dilation = change in area/bed-area)

For a condition of "perfect" balance, the stretch values should be 1.000

How are the line-lengths and areas measured?

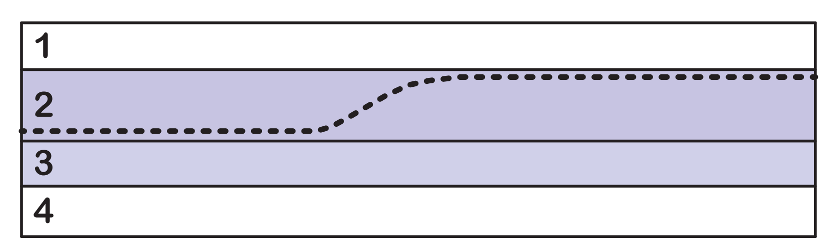
- by hand with string or ruler, line-length is plus or minus a few mm
- area is difficult to measure by hand
- computer software facilitates measurements of line-length and area
  (specialized structural analysis media: LithoTect, MOVE, Geosec or commercial drafting media: Illustrator, CorelDraw, Canvas)
  For careful drafting, this increases the precision to ± 0.1 mm. This yields three-significant figure accuracy.
- Dahlstrom's line-lengths balance at ± 2%, and the areas balance at ± 1%

Published model of "line-length balanced" flat-ramp-flat thrust belt folding: Dahlstrom (1970)



deformed state profile

unit	bed-length	LE bed-thickness	bed-area
1	19.50	1.18	23.84
2	19.71	1.80	35.59
3	20.00	1.14	22.78
4	20.00	1.28	25.48



nominal restored state profile

unit	bed-length	S_{bl}	bed-area	1+Δ
1	20.0	1.026	23.63	0.991
2	20.0	1.015	36.06	1.013
3	20.0	1.000	22.78	1.000
4	20.0	1.000	25.48	1.000

For naturally deformed profiles where an area balance is the arbiter: error <2% = excellent; 2%< error <5% = good; 5%< error <10% = poor; error >10% = unacceptable. Line-length balance may be an acceptable substitute in flexural-slip folding with concentric fold profiles as is a reasonable presumption for external foreland fold and thrust belts. In deformation settings where layer-parallel shortening or stretching processes occur, 2D area balance should be used. In deformation settings where 3D strain has occurred, 2D section restoration and 2D strain anlysis is inappropriate.

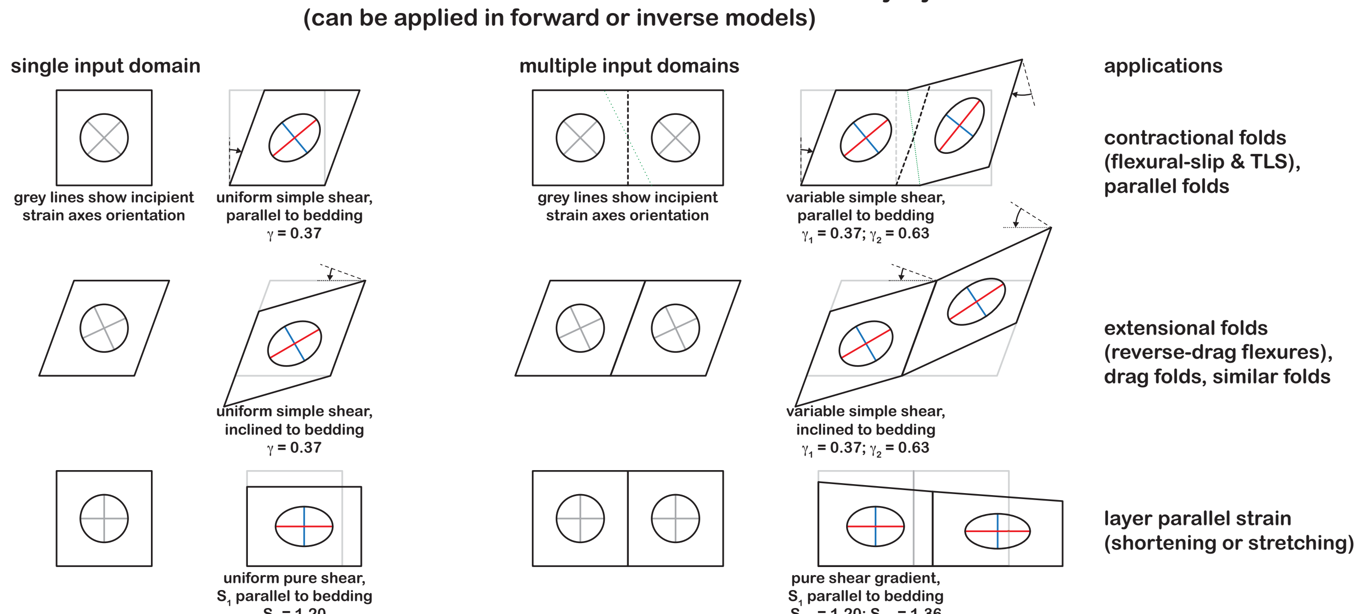
2. Methods of Transformation

In order to restore deformed sedimentary profiles, distorted layers (folds) need to be transformed back to an originally flat (typically horizontal) orientation. There are three principal means for doing this:

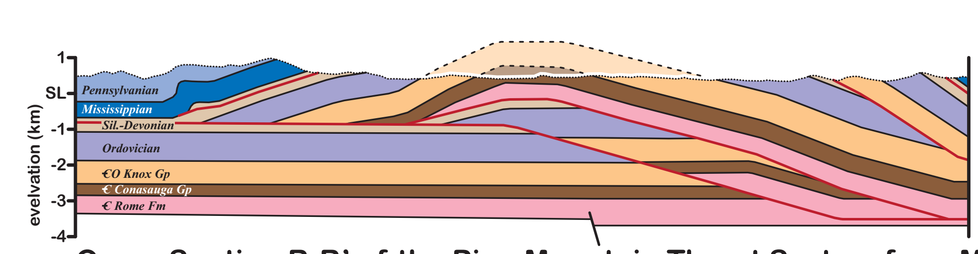
1) simple-shear with the shear direction parallel to a key horizon in the layering (flexural-slip folding deformation)
2) simple-shear with a shear direction inclined at a specified angle to horizontal (inclined-shear folding deformation)
3) pure-shear shortening or stretching (layer parallel shortening deformation)

Examples: 1) contractional folds like fault-bend folds (Suppe, 1983), 2) extensional folds like reverse-drag (Cloos, 1968; McClay, 1990), 3) layer parallel shortening prior to folding (Ramberg, 1971)

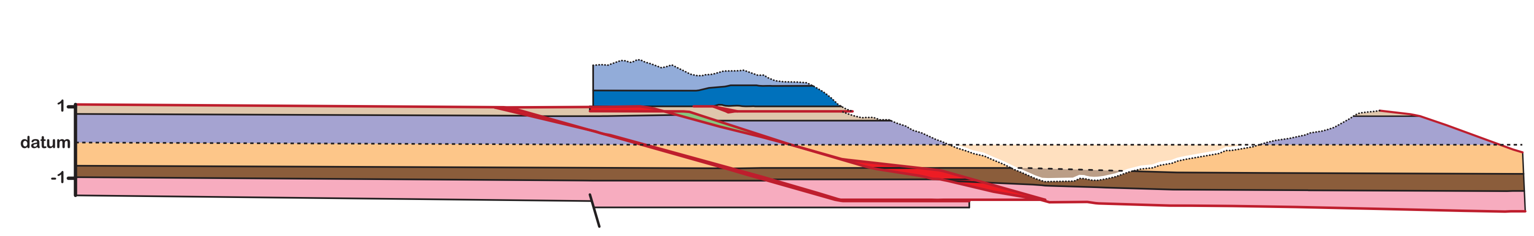
Three modes of distortional strain transformation for sedimentary layers
(can be applied in forward or inverse models)



One Step Transformation: for many deformed profiles (some external foldbelts, simple passive margin growth faults, some extensional fault blocks), a single transformation process may be applied to the deformed/-faulted units as a single step and aligned along a reference datum (key horizon). Note the example below:



Cross Section B-B' of the Pine Mountain Thrust System from Mitra (1988)



Single-step flexural-slip unfolding of Bales horse block and Pine Mountain thrust sheet: top of Knox Gp used as key horizon with vertical pin-line placed at flat-lying anticlinal crest
- red and green areas highlight slight misfit of overlaps and gaps, respectively.

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In order to show a method of validating 2D section balance, three published 2D balanced cross-sections are examined: a contractional balanced profile (Douglas, 1952; Boyer and Elliott, 1982), an extensional balanced profile (Bohanon et al., 1993), and a backstripping profile where sediment decompaction steps complicate the assessment of section balance (Bose and Mitra, 2014). In all cases an alternative restored state is shown that maintains strict area balance. Tables or graphs of inverse stretch values are used to quantify the degree of balance maintained through the restoration process. For line-length or area balance to be true, the stretch values should be close to 1.000. Red comments indicate balance problems; green comments indicate good balance.

3. Unfolding Transformations

A parallel fold geometry is a typical presumption for fold layer style in contractionally deformed sedimentary basins. If appropriate, bed-lengths and orthogonal layer thicknesses are preserved in profile. In many stratigraphic successions; however, the lithology of some rocks will be stronger (stiff units: cemented sandstones or carbonates) and others will be less strong (soft units: shales or evaporates) which can affect the geometry of folds (Ramsay and Huber, 1987; Hudelston and Treagus, 2010).

For these models with mechanical stratigraphy, line-length balance (i.e. $W_i \approx W_a$) is suitable for all scenarios with the exception of high strain Model D. In particular, the stiff units also maintain original layer thickness (Ramsay Class 1B parallel fold), again with the exception of high strain Model D. A flexural-slip inversion should accurately recover the original unfolded geometry of the layers. Flexural-slip inversion could be effective in Model D with a correction step for the hinge-thickening effect.

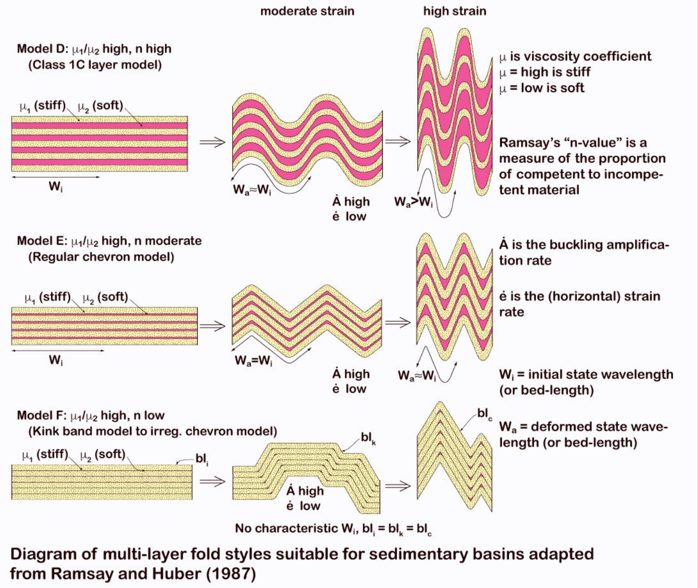
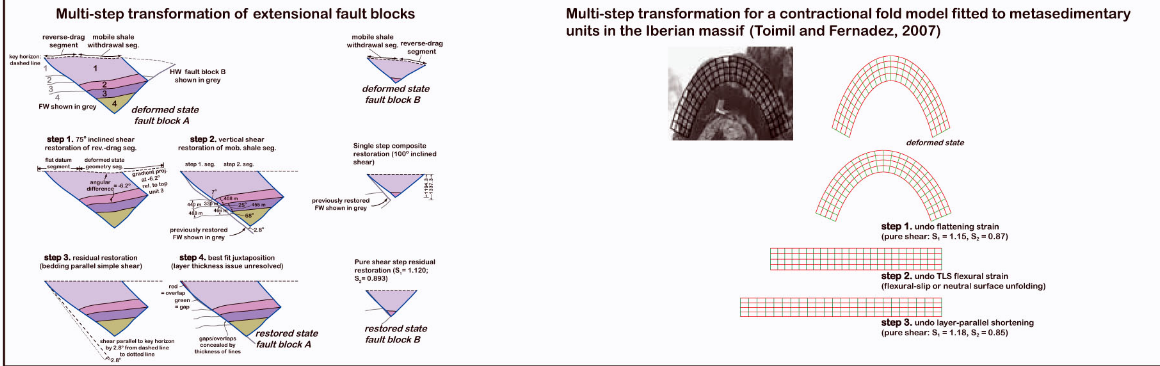


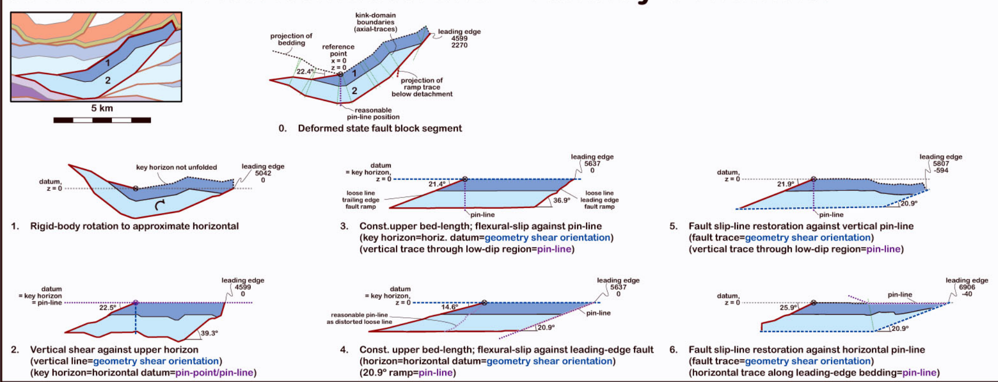
Diagram of multi-layer fold styles suitable for sedimentary basins adapted from Ramsay and Huber (1987)

4. Composite Transformations

Composite transformations can be inferred in certain situations. For example, successive inclined-shear of different polarity or a pure shear component before or after flexural-slip transformation.



5. Mode of Transformation and Boundary Conditions



line-length/area measurements and inverse stretch values

unit	bed-length def. state (m)	bed-length rest. state (m)	inverse stretch (S_{bl})	area def. state (x 10^6 m^2)	area rest. state (x 10^6 m^2)	inv. area stretch (1+Δ)
1-1	5638	5638	1.000	3.627	3.627	1.000
1-2	6393	6393	1.000	6.050	6.050	1.000
2-1	5638	4599	0.816	3.627	3.625	1.000
2-2	6393	5909	0.928	6.050	6.050	1.000
3-1	5638	5637	1.000	3.627	3.609	0.995
3-2	6393	6367	0.996	6.050	6.044	0.999
4-1	5638	5637	1.000	3.627	3.606	0.994
4-2	6393	6380	1.002	6.050	6.049	1.000
5-1	5638	6126	1.087	3.627	3.622	0.999
5-2	6393	6772	1.063	6.050	6.048	1.000
6-1	5638	6906	1.225	3.627	3.626	1.000
6-2	6393	7617	1.196	6.050	6.049	1.000

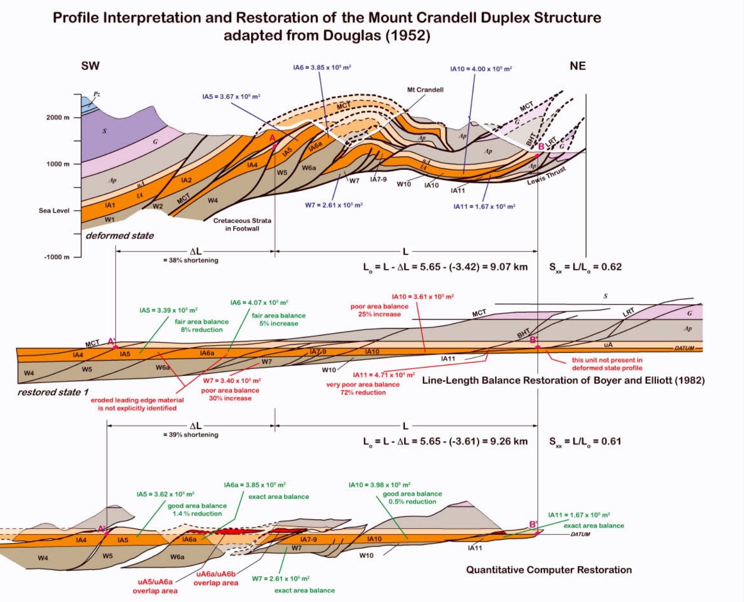
6. Restoration Analysis of an Contractional Profile

Waterton and lower Altyn bed-length measurements and stretch values

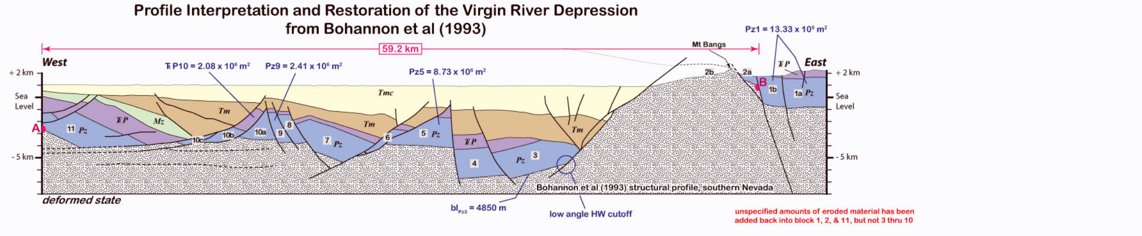
geol. unit	Douglas def. state (m)	B & E res. state (m)	B & E (S_{bl})	LT rest. state (m)	LT (S_{bl})
W1	1777	n/a	n/a	1774	1.002
IA1	2277	n/a	n/a	2277	1.000
W2	1954	n/a	n/a	1955	0.999
IA2	1785	n/a	n/a	1785	1.000
W4	2321	1456	1.594	2301	1.009
IA4	702	643	1.091	702	1.000
W5	1342	1299	1.033	1331	1.009
IA5	1649	1581	1.043	1650	1.000
W6a	1764	1969	0.896	1774	0.994
IA6a	1782	1768	1.008	1796	0.992
W7	1196	965	1.239	1195	1.000
IA7-9	1355	1170	1.159	1378	0.984
W10	2034	2123	0.958	2040	0.997
IA10	2603	2763	0.942	2603	1.000
IA11	1049	1089	0.963	1049	1.000

Waterton and lower Altyn unit area measurements and area stretch values

geol. unit	Douglas def. state (x 10^5 m^2)	B & E res. state (x 10^5 m^2)	B & E (1+Δ)	LT rest. state (x 10^5 m^2)	LT (1+Δ)
W1	2.72	n/a	n/a	2.72	1.000
IA1	6.37	n/a	n/a	6.37	1.000
W2	4.15	n/a	n/a	4.15	0.999
IA2	6.46	n/a	n/a	6.45	1.001
W4	8.23	3.81	2.163	8.23	1.000
IA4	3.91	3.51	1.113	3.91	1.000
W5	4.82	5.68	0.849	4.82	1.000
IA5	3.67	3.39	1.083	3.64	1.010
W6a	7.05	7.77	0.908	7.05	1.000
IA6a	3.85	4.07	0.946	3.84	1.003
W7	2.61	3.40	0.769	2.61	1.000
IA7-9	3.24	2.47	1.310	3.22	1.006
W10	1.46	1.94	0.752	1.44	1.015
IA10	4.02	3.61	1.115	4.01	1.001
IA11	1.67	0.47	3.544	1.67	1.000

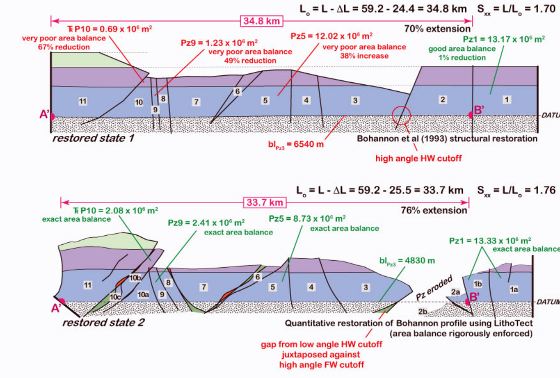


7. Restoration Analysis of an Extensional Profile



base Pz bed-length measurements and stretch values

Pz flt blk	Bohannon def. state (m)	Bohannon rest. state (m)	Boh. (S_{bl})	LT rest. state (m)	LT (S_{bl})
1	5290	5380	0.983	5270	1.004
2	6380	5920	1.078	5960	1.070
3	4850	6540	0.742	4830	1.004
4	3970	2590	1.533	3960	1.003
5	5670	6050	0.937	5670	1.000
6	290	190	1.526	290	1.000
7	2600	3720	0.699	2590	1.004
8	1050	890	1.180	1040	1.010
9	1250	510	2.451	1260	0.992
10	4100	4440	0.923	4000	1.025
11	3560	3260	1.092	3970	0.897
total bed-length	39010	39490	0.988	38840	1.004

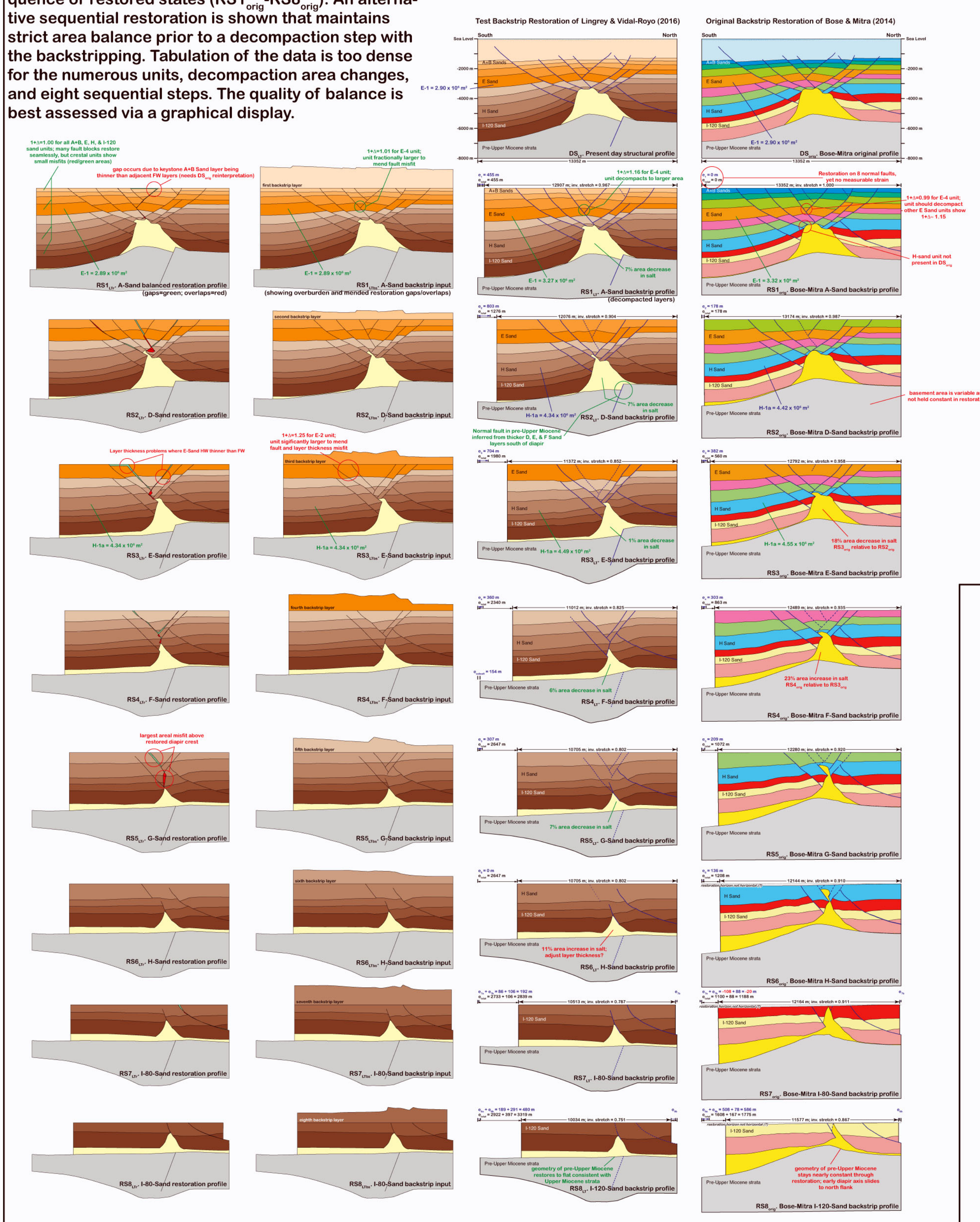


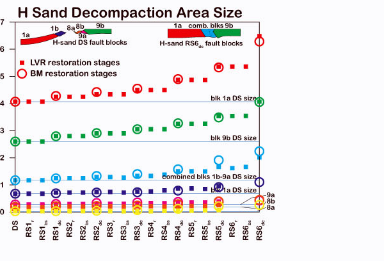
Pz unit area measurements and area stretch values

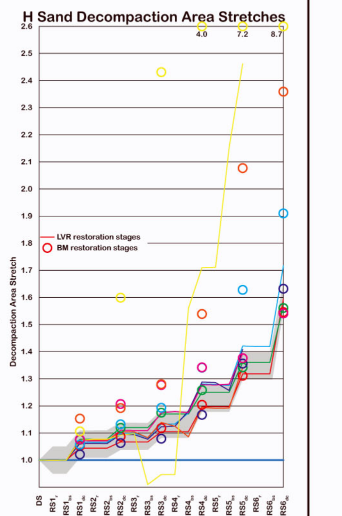
Pz flt blk	Bohannon def. state (x 10^6 m^2)	Bohannon rest. state (x 10^6 m^2)	Boh. ($1+\Delta_{Pz}$)	LT rest. state (x 10^6 m^2)	LT ($1+\Delta_{Pz}$)
1	13.33	13.17	1.012	13.33	1.000
2	0.79	n/a	n/a	0.79	1.000
3	14.12	16.60	0.851	14.12	1.000
4	8.08	6.00	1.347	8.08	1.000
5	8.73	12.02	0.726	8.73	1.000
6	1.78	1.44	1.236	1.77	1.006
7	12.02	11.76	1.022	12.00	1.002
8	2.66	2.26	1.177	2.66	1.000
9	2.41	1.23	1.959	2.41	1.000
10	7.02	6.89	1.019	7.02	1.000
11	12.93	14.33	0.902	12.93	1.000
total Pz area	83.87	85.70	0.979	83.84	1.000

8. Restoration Analysis of a Backstripping Profile

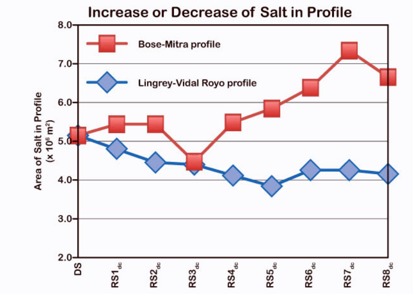
Bose and Mitra (2014) deformed state (DS_{orig}) and sequence of restored states ($RS1_{orig}$-$RS8_{orig}$). An alternative sequential restoration is shown that maintains strict area balance prior to a decompaction step with the backstripping. Tabulation of the data is too dense for the numerous units, decompaction area changes, and eight sequential steps. The quality of balance is best assessed via a graphical display.







Verifying area balance in a sequential backstripping scenario is more difficult. Stepwise decompaction of the sedimentary layers causes the area of section units to increase. There are three steps for each backstrip layer: 1) an area balanced restoration showing gaps and overlaps, 2) a backstrip input profile with the gaps and overlaps removed, 3) the decompacted profile (which becomes an deformed state input to the next backstripping). The chart above shows the changes in area for H Sand fault block elements. For balance, three succesive points should be horizontal; then a decompaction size increases and two more horizontal points. The chart at right shows these changes as area stretch values. The grey area tracks ± 5% change. For curves and points within the grey, the condition of area balance is maintained. For the Bose-Mitra restoration, the position of H Sand blocks within or without the grey band identifies those elements that show or lack good area balance.



As the salt diapir grows, does its size (area) increase or decrease? The above graph charts the areal changes through the eight backstripping steps for the two restorations. In a visual inspection it is hard to discern area changes in an irregular shape that are less than 20%. The salt flowage is doubtless in 3D, so the area is unlikely to be constant. Since the profile is centrally located across the salt diapir column, we suspect that the area would increase forward in time and that relationship is shown in the graph (blue curve; 24% area increase from RS8 to DS). The Bose-Mitra profile shows both increases and decreases, yet overall there is a decrease in salt area (red curve; 23% area decrease from RS8 to DS).

9. Conclusions

Restoration profiles constrained by material balance can show how faults and fold geometry projects into the subsurface. In 2D, the kinematics of deformation should conform to a plane strain. The mode of strain needs to be defined and should be appropriate to the tectonic setting. In presenting the restoration of folded and faulted units, explicitly showing the mismatches between adjacent unfaulted fault blocks, allows a fair assessment of the restoration balance quality. **Cosmetic removal of gaps and overlaps will make the restoration look better, but it will overstate the material balance and hide regions where re-interpretation could be changed to improve the quality of balance.** Demonstration of the veracity of material balance requires tables or graphs of linear and areal stretch values.

10. Acknowledgements and References

ExxonMobil Upstream Research Company (1981-2014) provided many of the opportunities to test the feasibility of using section balancing to judge interpretation ideas. Interactions with the developers of Geosec™, Move™, and LithoTect™ commercial restoration analysis software contributed much to the discovery of fruitful pathways of successful restoration. In particular, we appreciate numerous discussions about quantitative section construction and balancing over the past 30 years with James Geiser, Peter Geiser, Roy Kligfield, and Bob Ratliff. Halliburton is thanked for providing an academic license of LithoTect to the University of Arizona; this made a majority of the restoration, transforms in this poster possible.

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