A Stand-Alone Open-Source MATLAB Program for Sequence Stratigraphic and Chronostratigraphic Analysis of Geological Data

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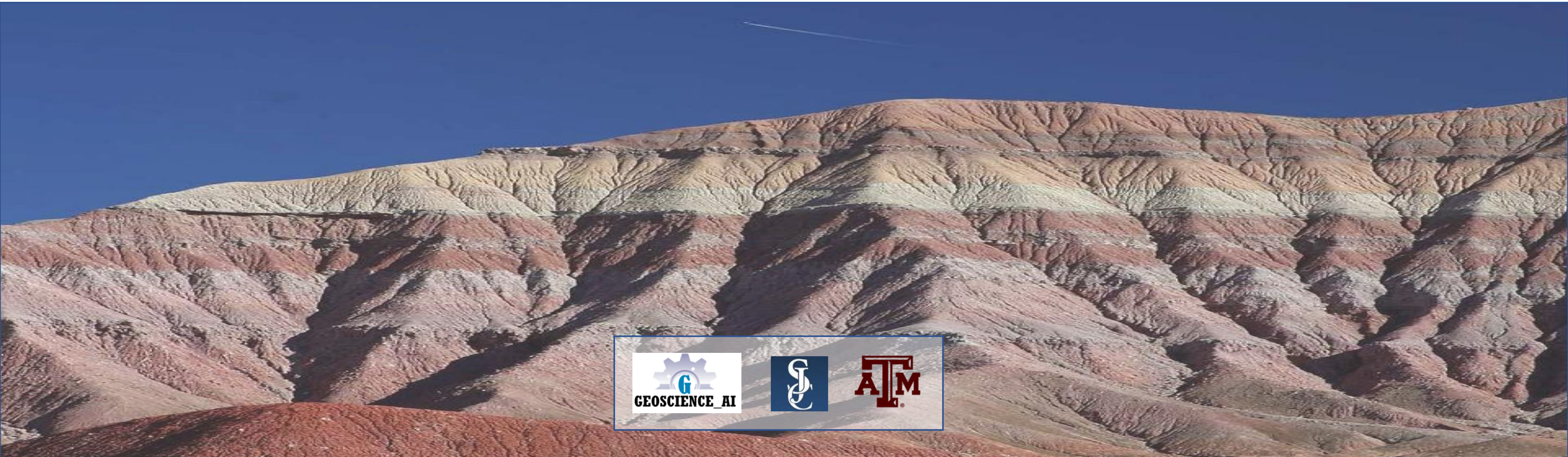


Outline

Definitions and Concepts

Introduction to Sequence Stratigraphy

Chronostratigraphy and Wheeler Diagrams

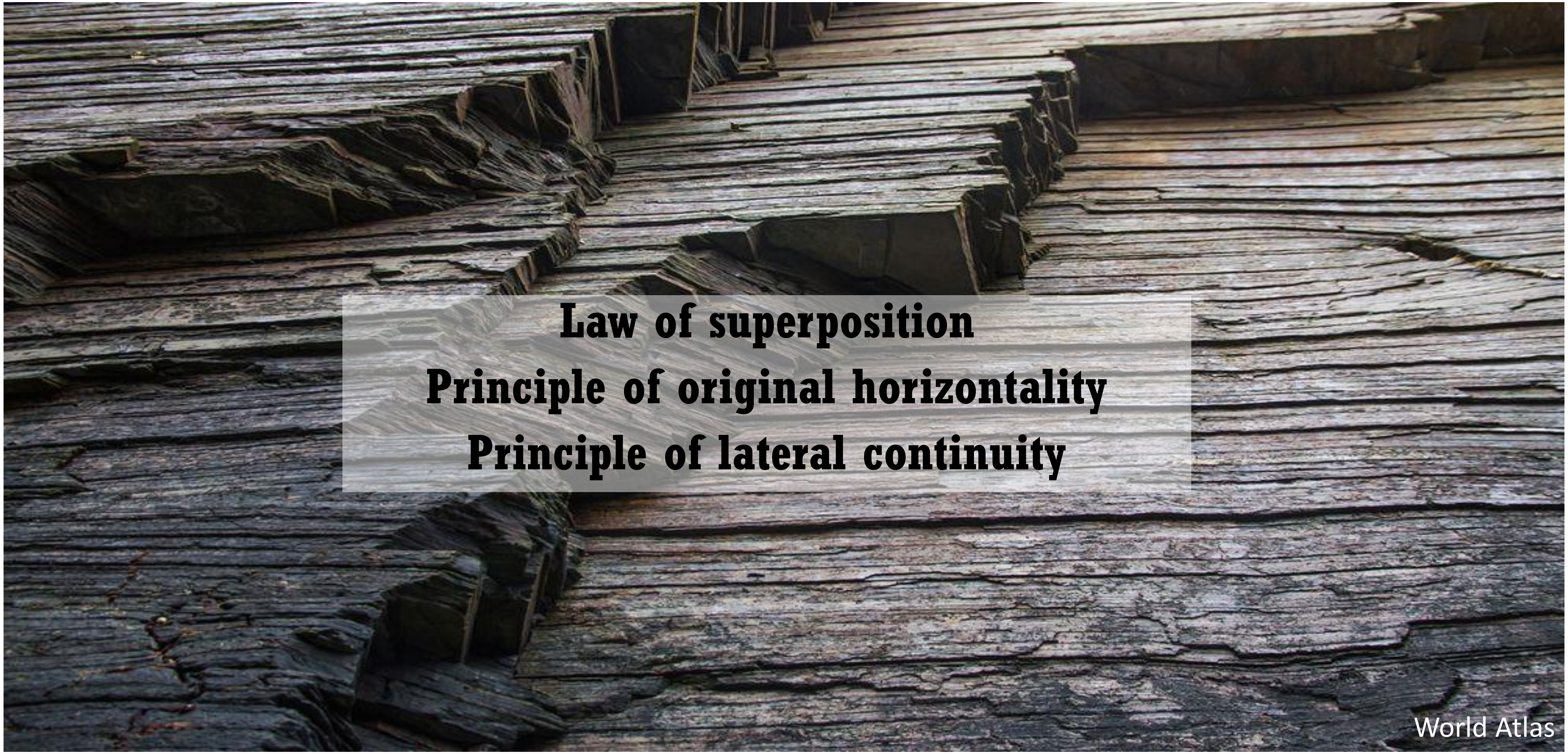
Geological Data Types

WheelerLab

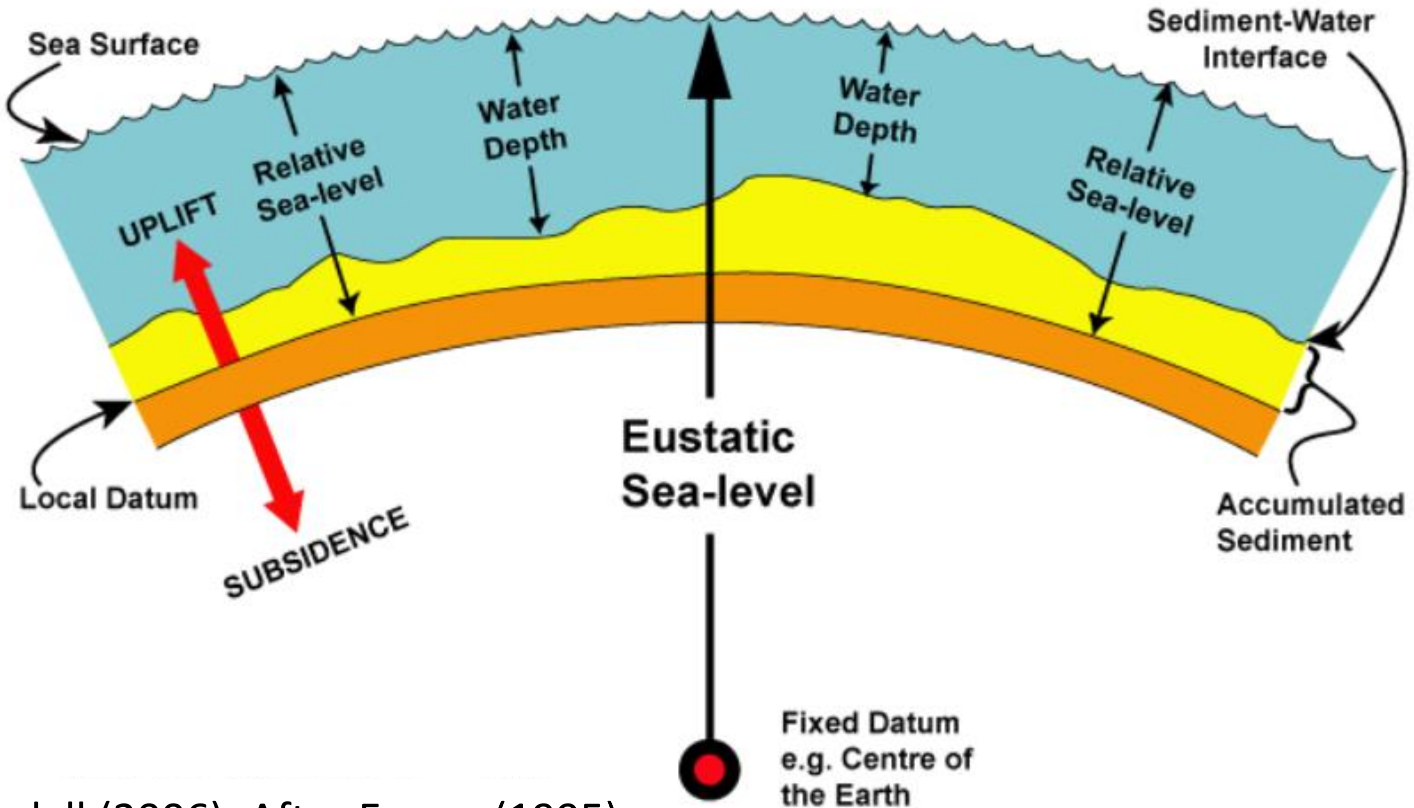
- Introduction
- I/O
- Demonstration

Conclusions

Definitions and Concepts: Stratigraphy

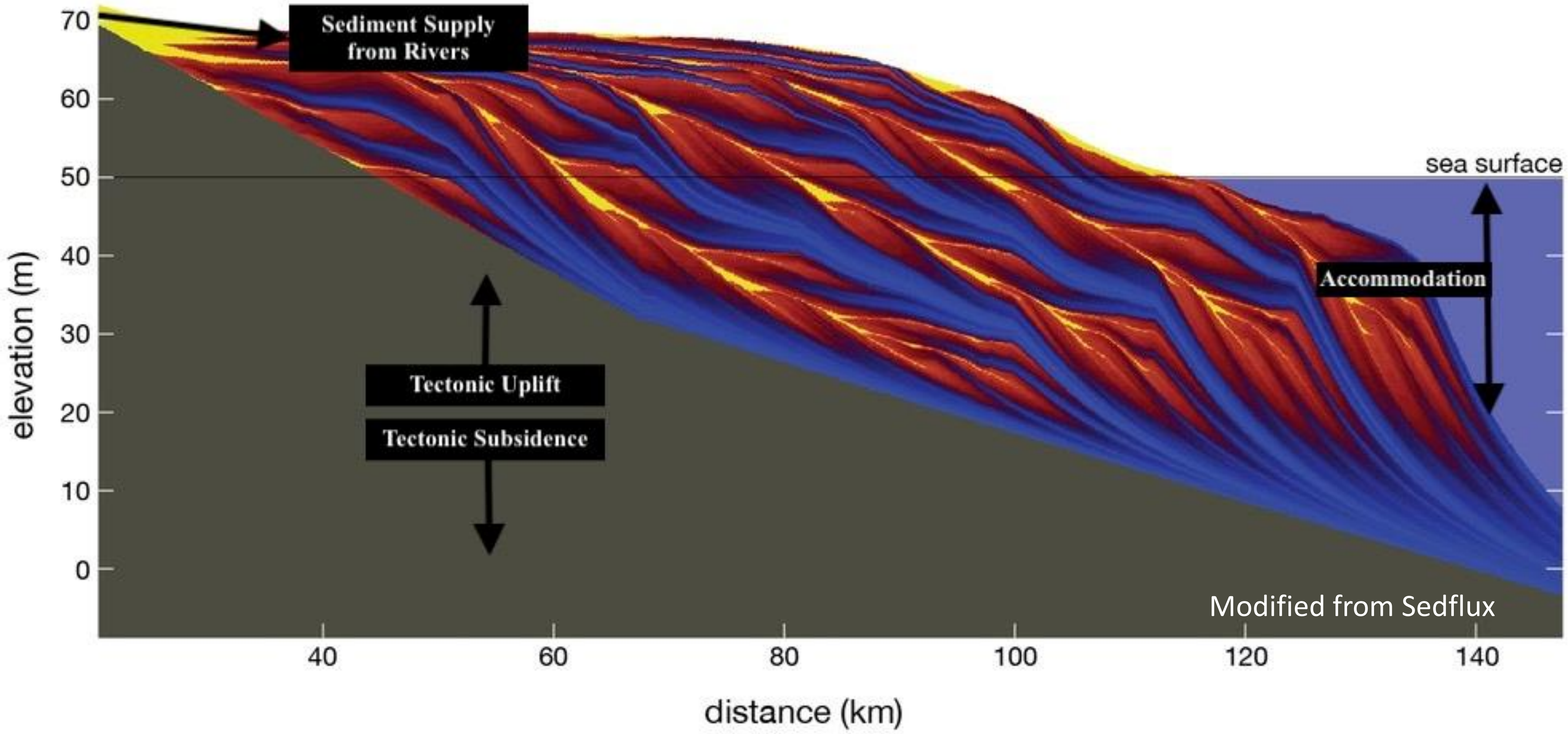


Definitions and Concepts: Relative Sea Level

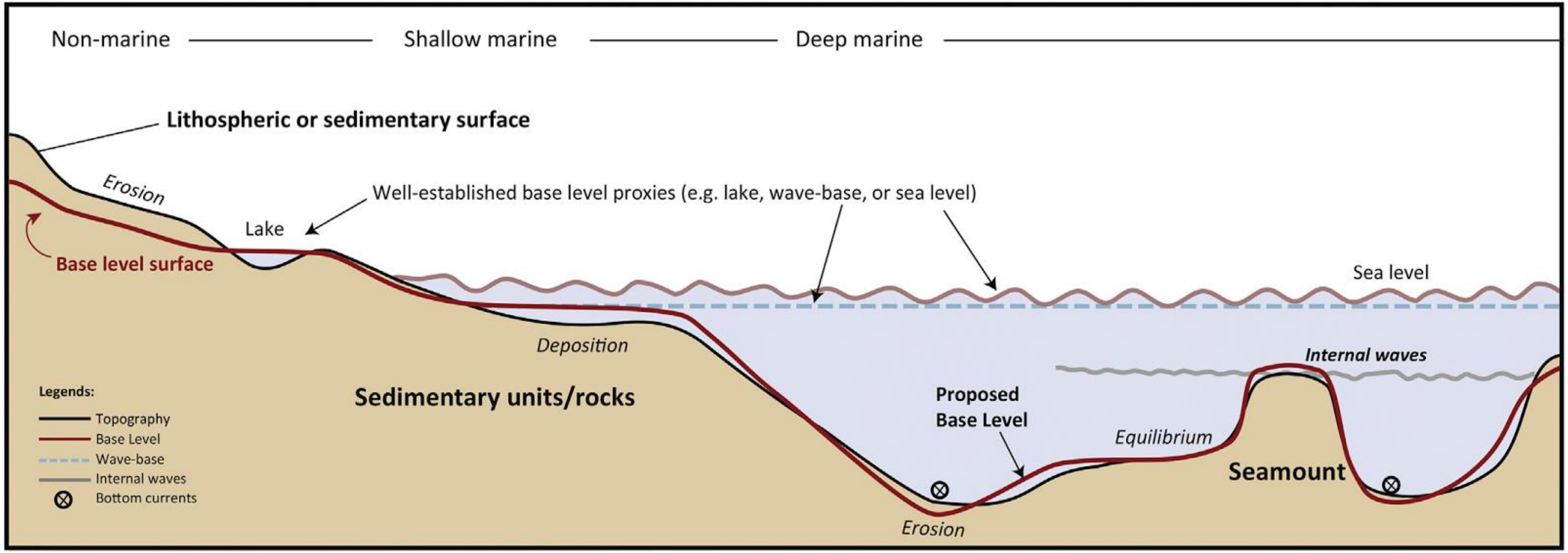


Kendall (2006); After Emery (1995)

Definitions and Concepts: Accommodation

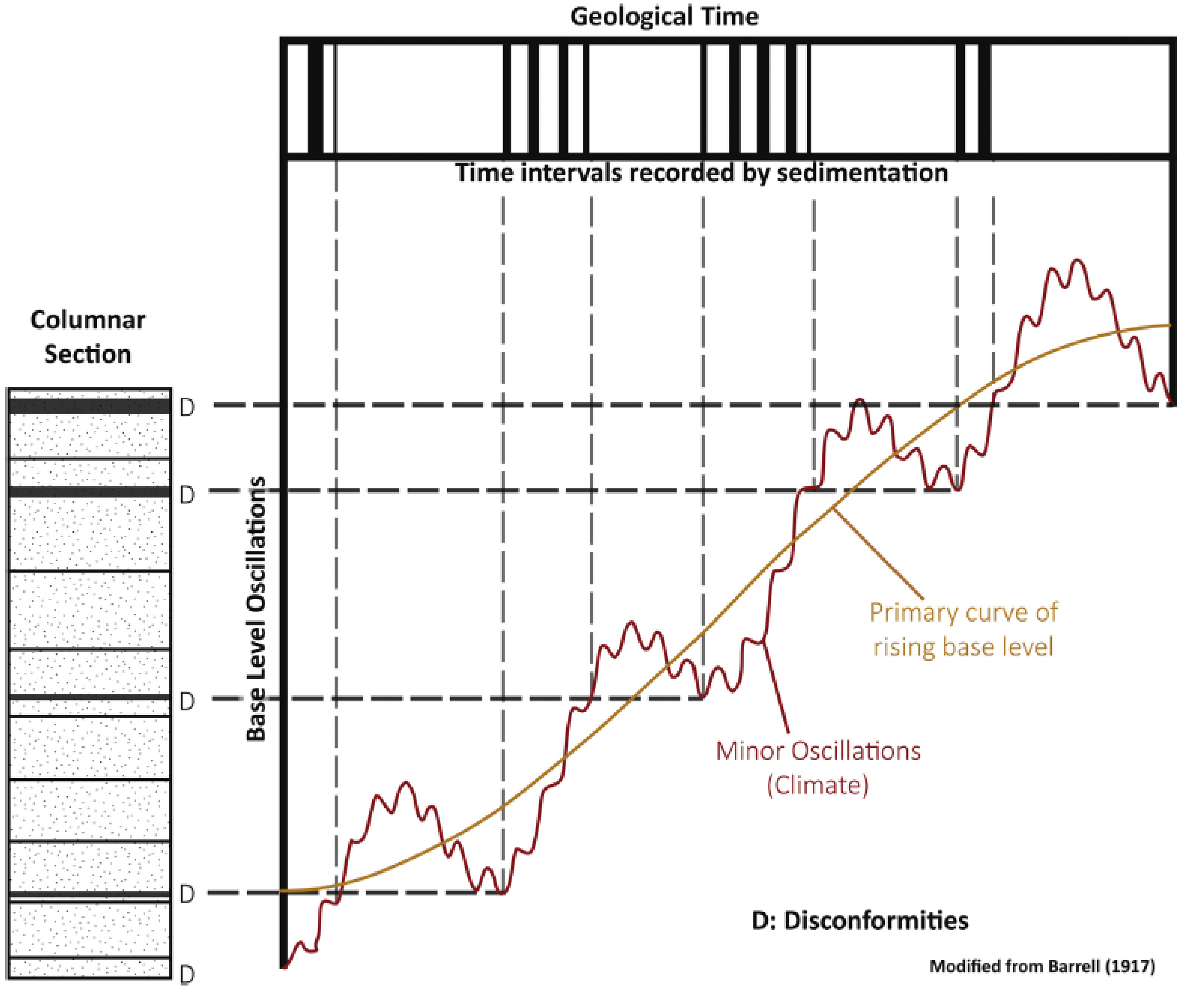


Definitions and Concepts: Base Level



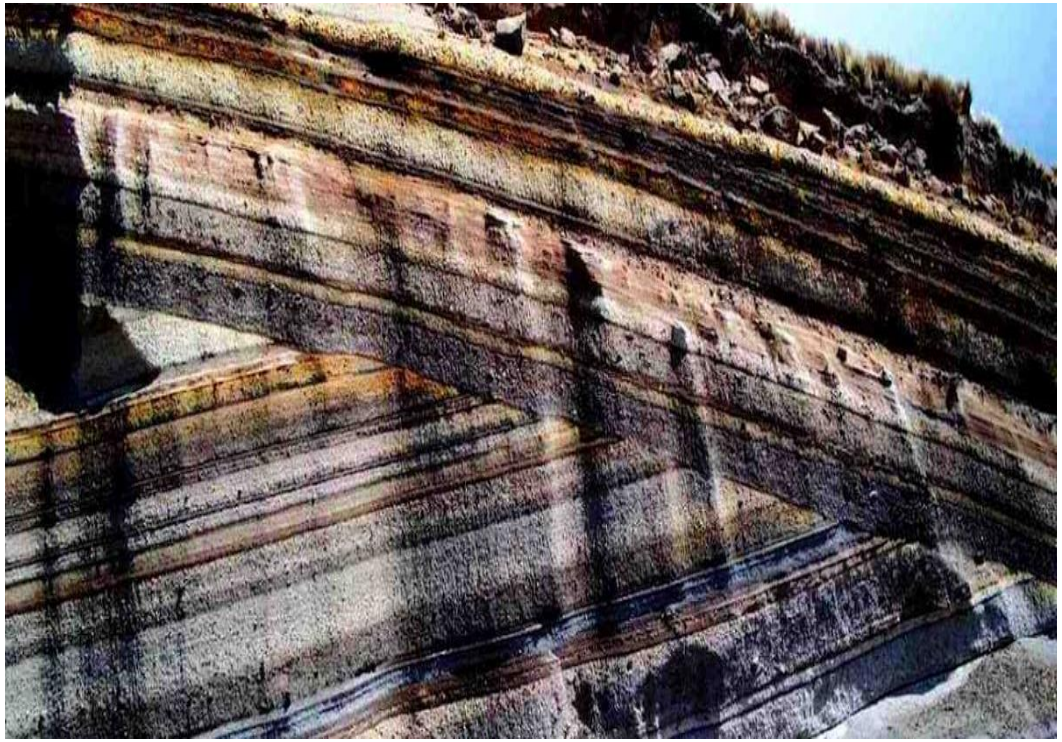
Qayyum et al., (2017)

Definitions and Concepts: Base Level



Barrell (1917); Qayyum et al., (2017)

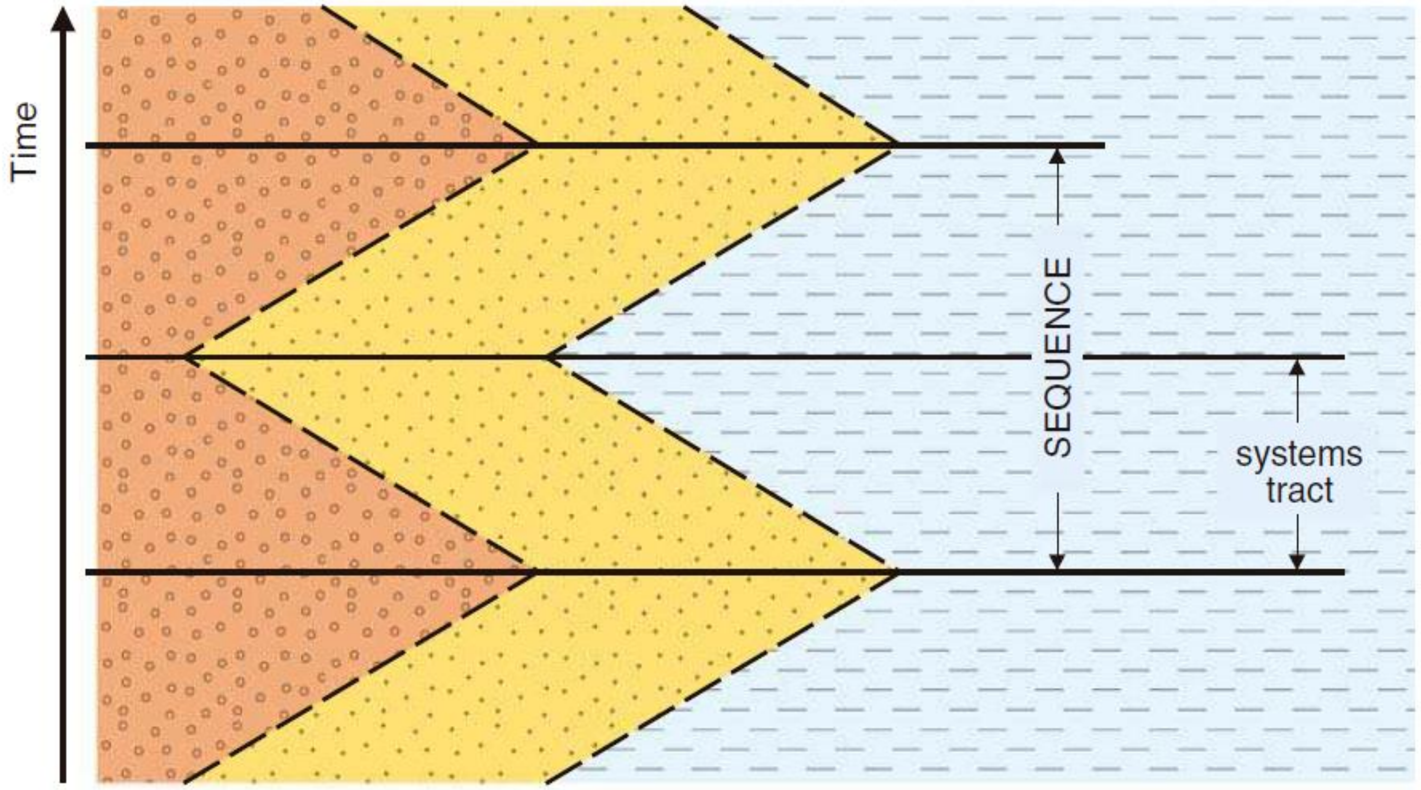
Definitions and Concepts: Unconformity



Road Cut, Ecuador

Catuneanu (2006)

Definitions and Concepts: Lithostratigraphy vs. Sequence Stratigraphy



Catuneanu (2006)

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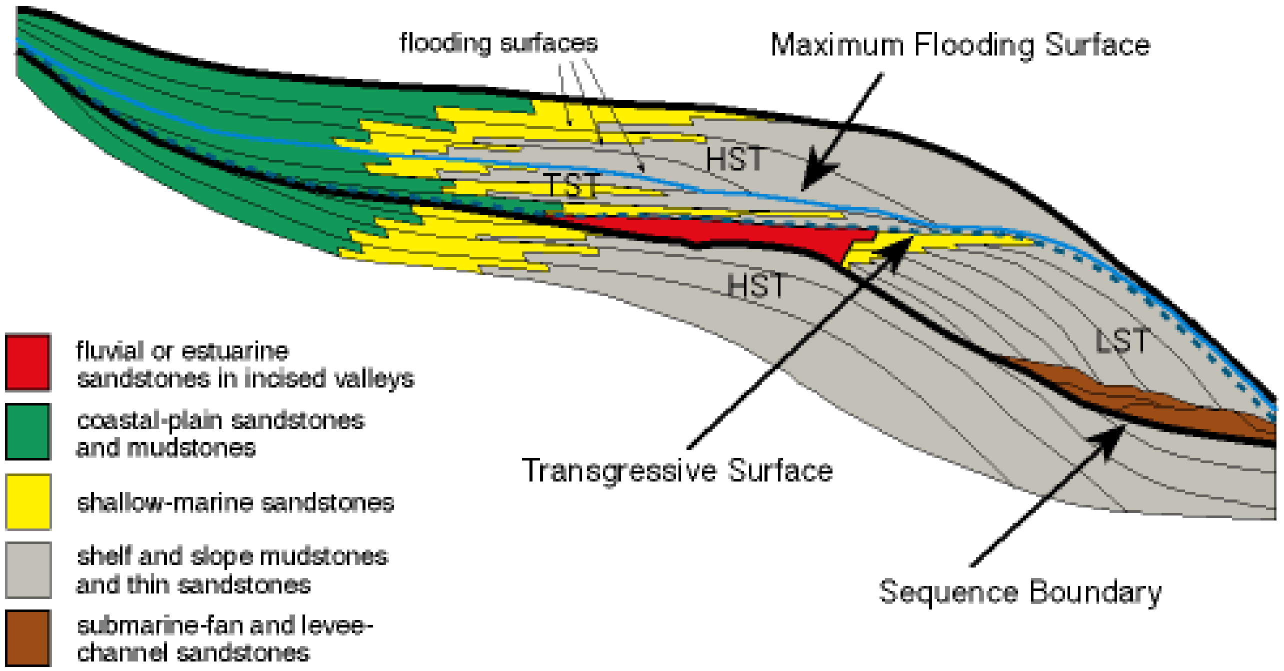
Sequence Stratigraphy

The study of the rock relationships of repetitive, genetically related strata bounded by unconformities or their correlative conformities, within a time-stratigraphic framework (Posamentier et al., 1988; Van Wagoner, 1995).



Adapted from Van Wagoner (1990). strata.uga.edu

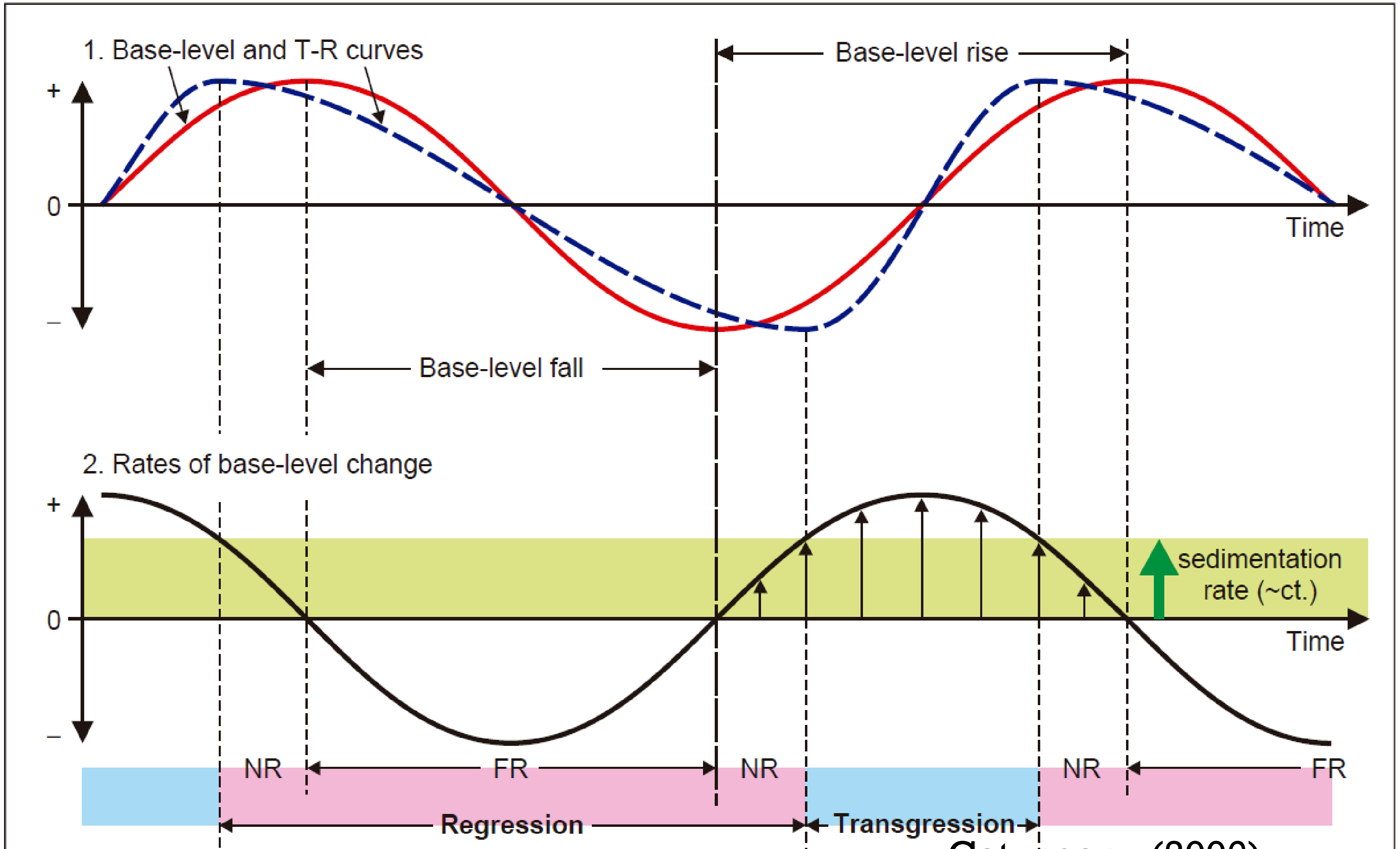
Basic Units

Sequence: the primary unit of sequence stratigraphy bound by unconformities or their correlative conformities (Sloss,1949; Mitchum et al., 1977), irrespective of temporal and spatial scales (Catuneanu, 2006)

Systems tract: a linkage of contemporaneous depositional systems, forming the subdivision of a sequence. A systems tract includes all strata accumulated across the basin during a particular stage of shoreline shifts (Brown and Fisher, 1977)

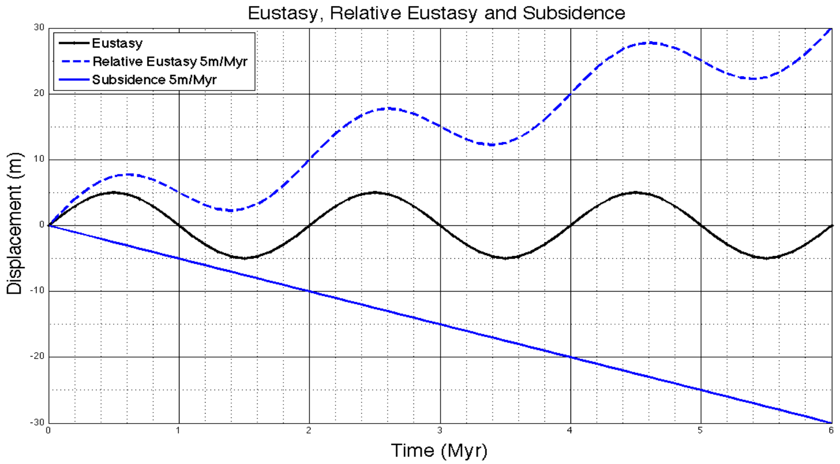
Depositional systems: three-dimensional assemblages of lithofacies, genetically linked by active (modern) processes or inferred (ancient) processes and environments (Fisher and McGowan, 1967, in Van Wagoner, 1995)

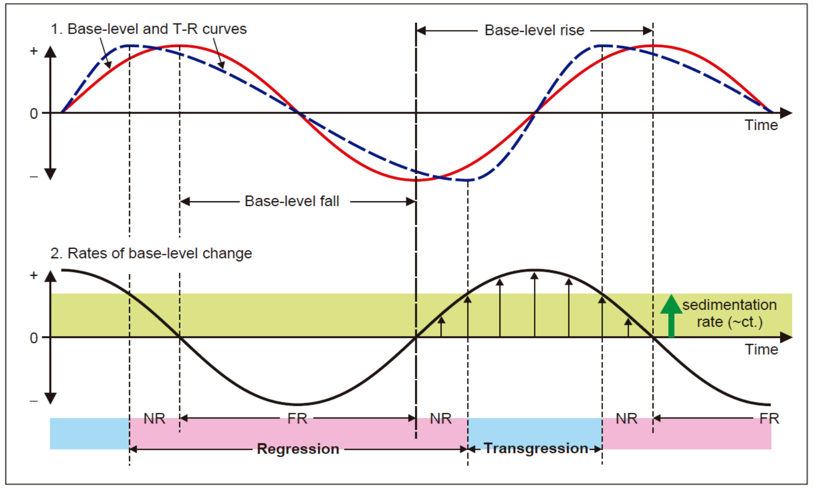
Base Level and T-R Curves



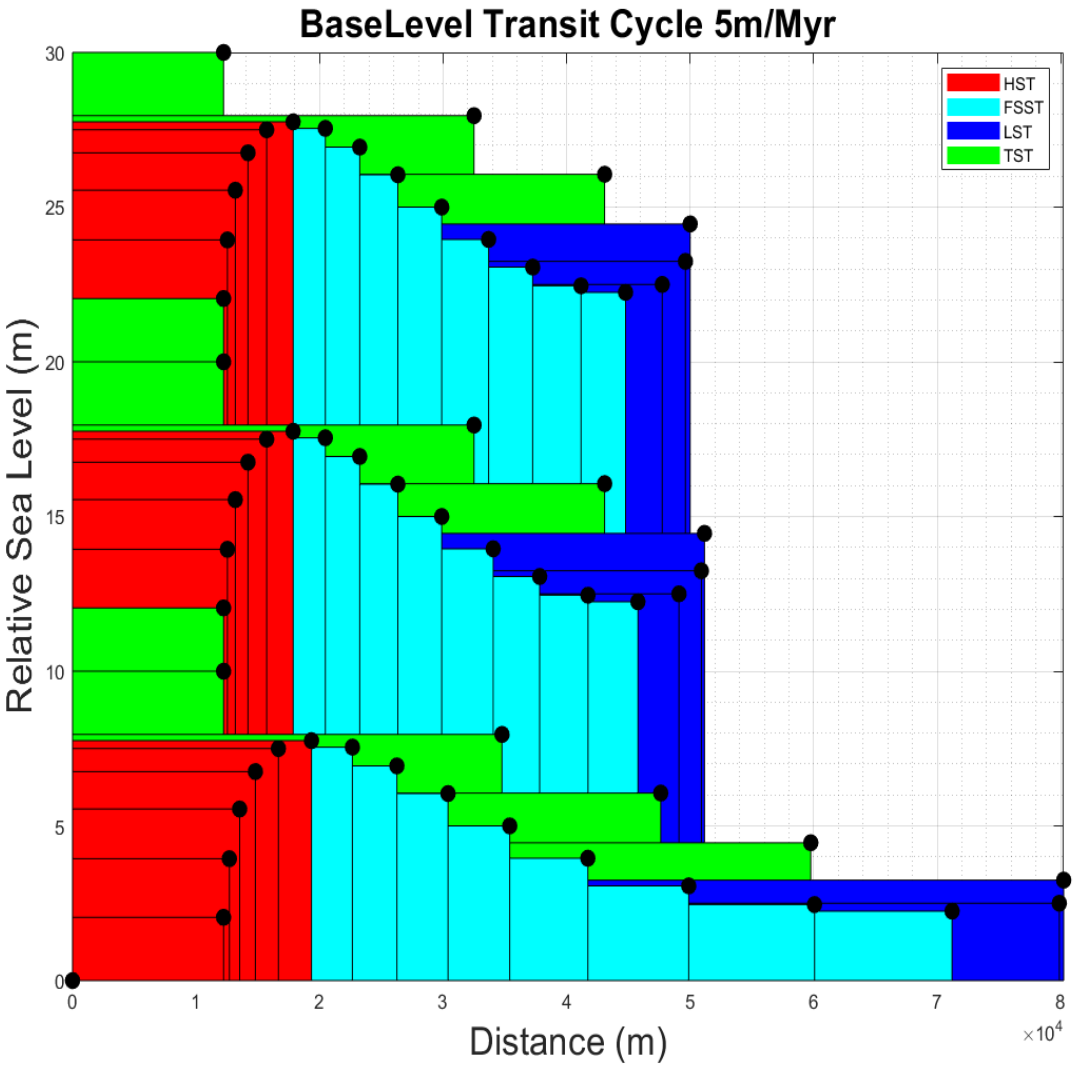
Catuneanu (2006)

Base Level Transit Cycle: Simplified Model

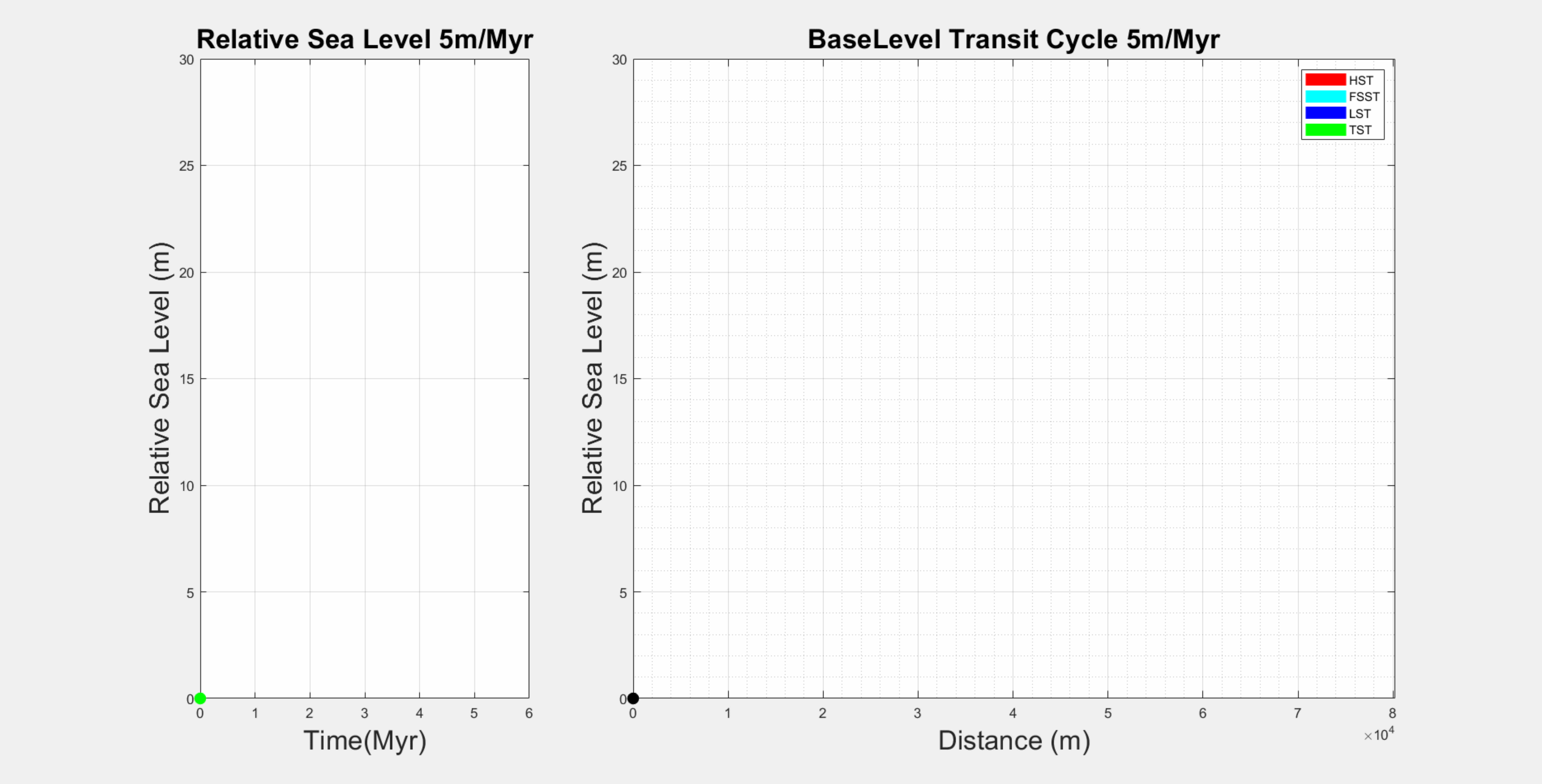




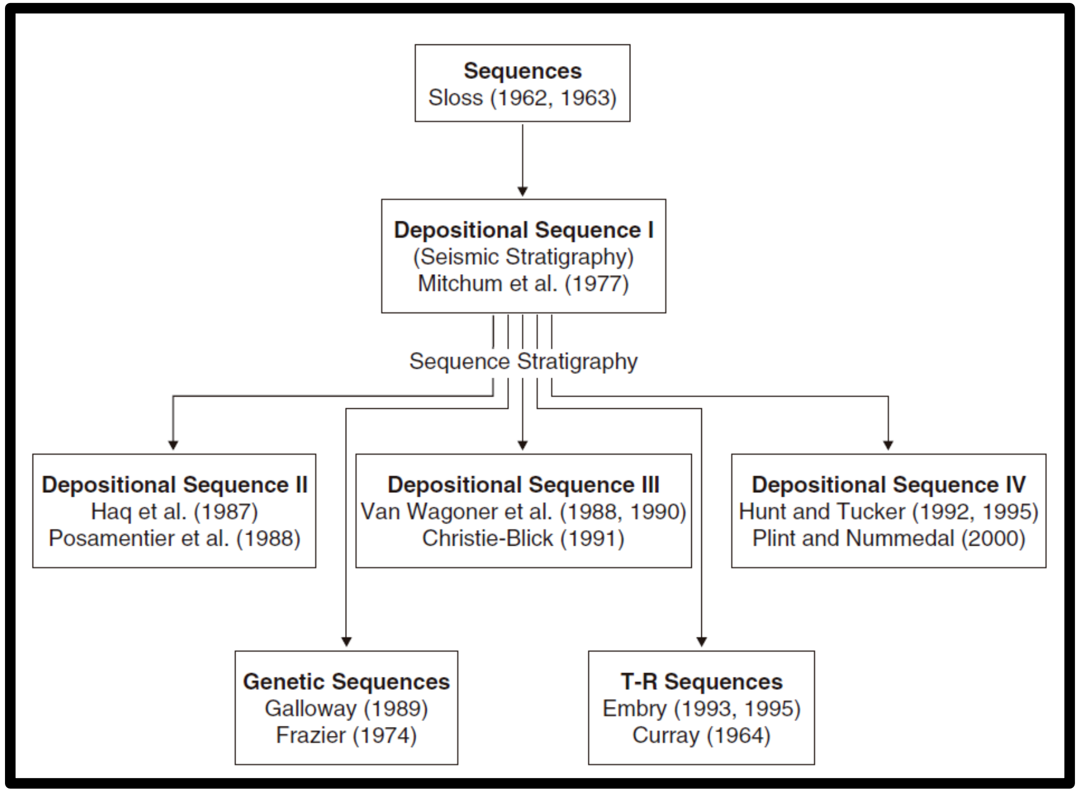
Catuneanu (2006)



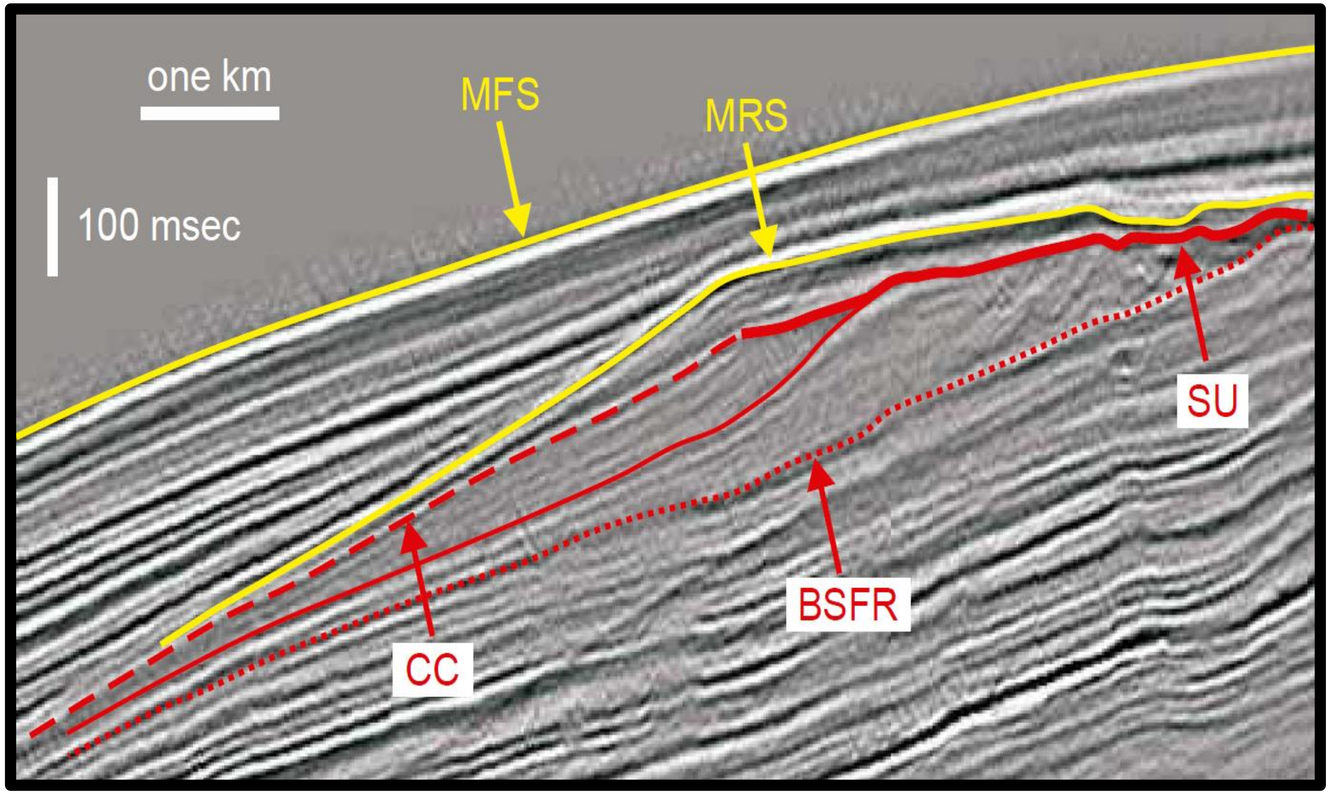
Base Level Transit Cycle: Simplified Model



History and Schools of Thought



Catuneanu (2006)



Catuneanu (2006)

Systems Tracts and Surfaces

Depositional Sequence Approach	T-R Sequence Approach
Surfaces	
Subaerial Unconformity	Subaerial Unconformity
Maximum Regressive Surface	Maximum Regressive Surface
Maximum Flooding Surface	Maximum Flooding Surface
Regressive Surface of Marine Erosion	Unconformable Shoreline Ravinement
Shoreline Ravinement	Diastemic Shoreline Ravinement
Correlative Conformity	Slope Onlap Surface
Basal Surface of Forced Regression	Regressive Surface of Marine Erosion
System Tracts	
Transgressive Systems Tract	Transgressive Systems Tracts
Falling Stage Systems Tract	Regressive Systems Tracts
Highstand Systems Tract	
Lowstand Systems Tract	

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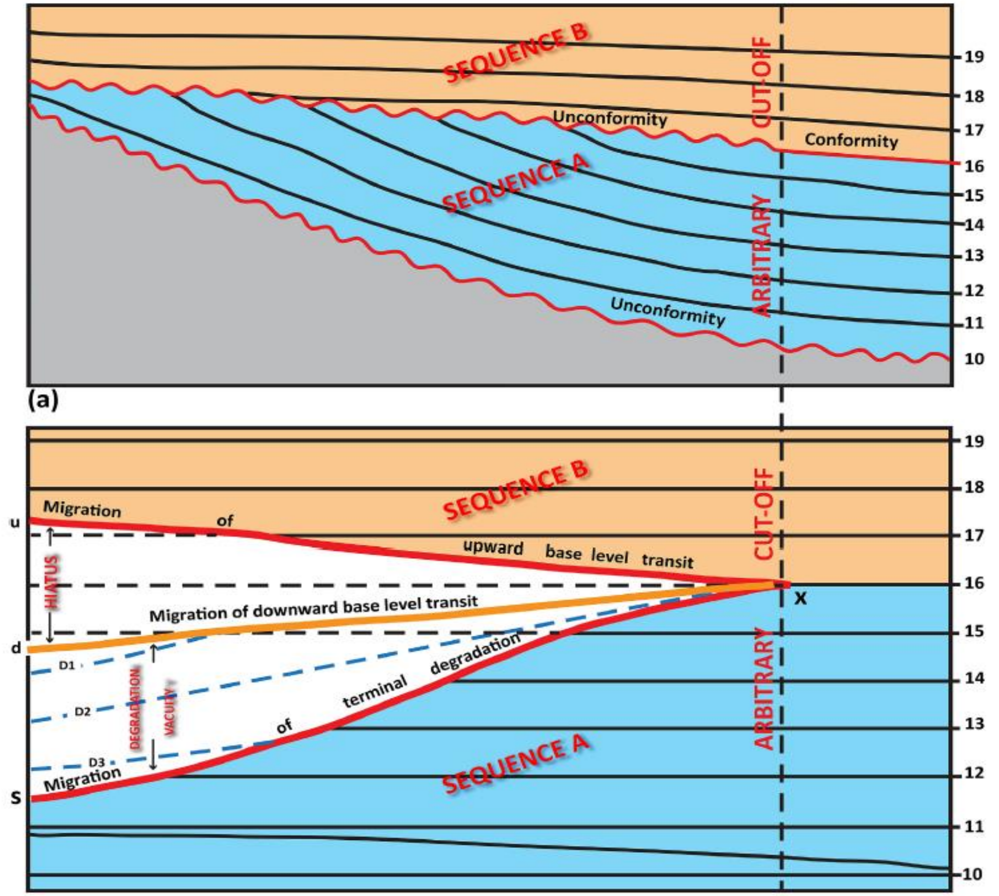
Chronostratigraphy

Harry E. Wheeler introduced the concept of time-stratigraphy in 1958, and his charts are referred to as Wheeler diagrams

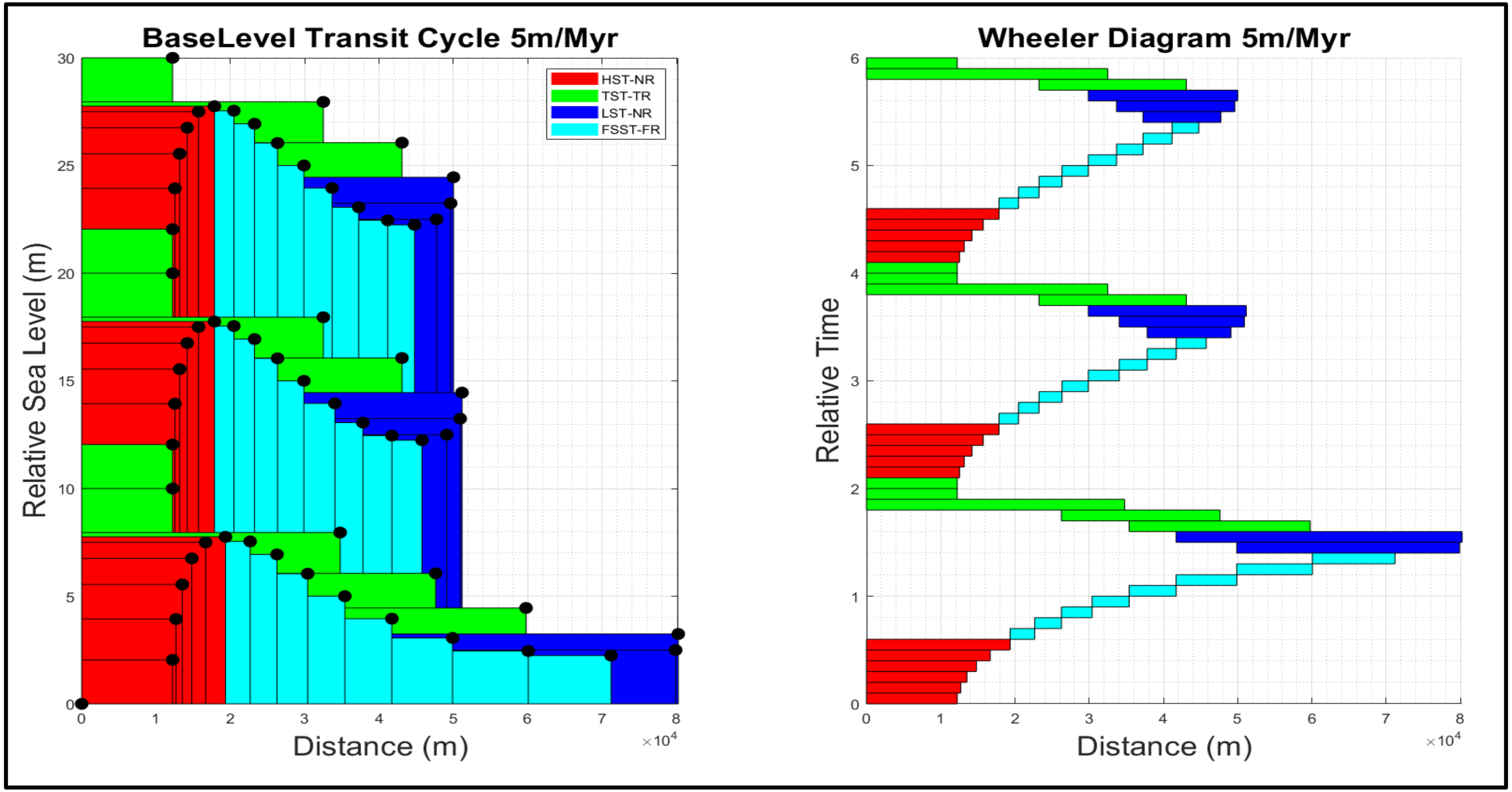
An arbitrary time is assigned to each surface following the law of superposition such that a surface is considered as a time barrier separating older strata from the younger

Strata is flattened along the time-surfaces. The y-axis is the relative geological time. The x-axis is usually distance



Wheeler (1964), Qayyum et al., (2017)

Simplified Model



Developments in Chronostratigraphy

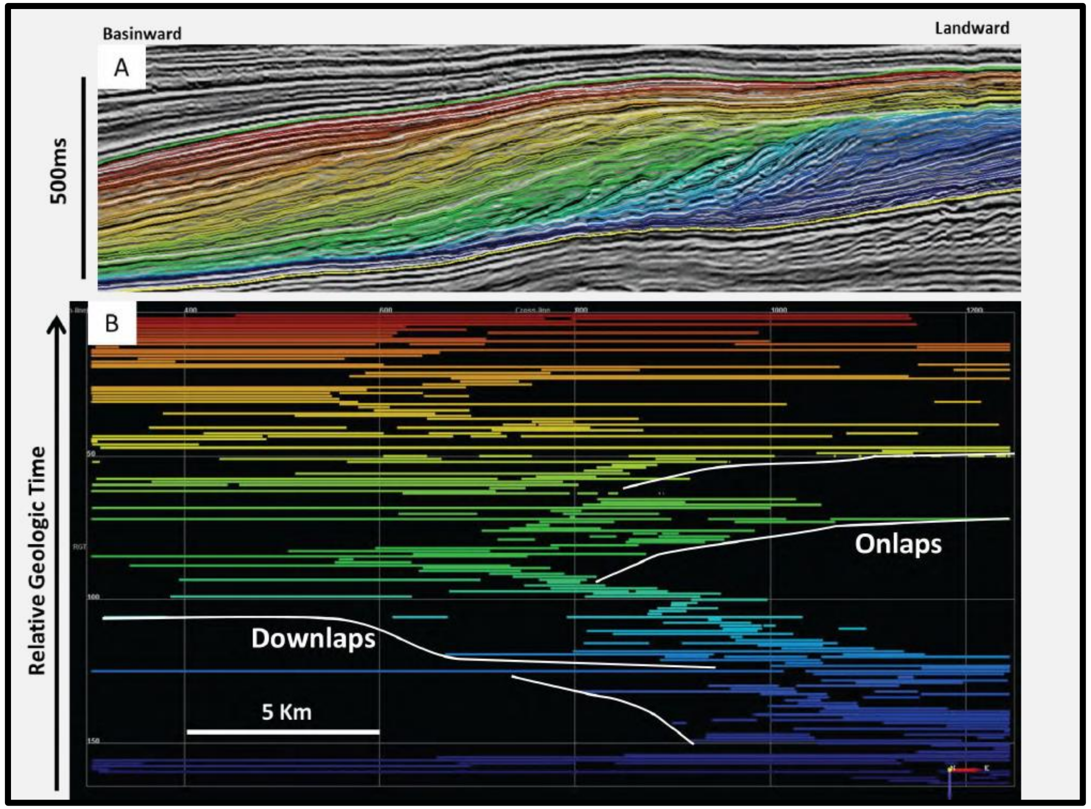
Semi-automated approaches in the construction of Wheeler diagrams from seismic data started in 1990s

Global Seismic Interpretation Techniques: Age Volume, PaleoScan, Volumetric, Flattening and HorizonCube

They differ in how correlation of timelines are established and stored

Focus on seismic data but not suitable for other geological data types

Most are not open-source



Qayyum et al., (2012)

Developments in Chronostratigraphy

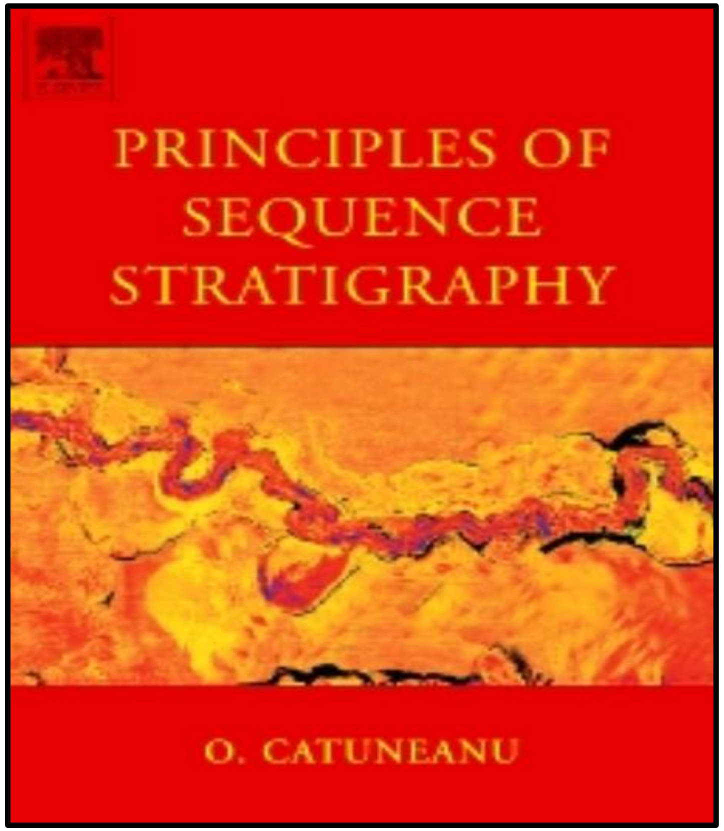
An overview of the technologies used to flatten the seismic data. Two groups of technologies are introduced: one that follows the model-driven approach, and the other that follows the data-driven approach. In a model-driven approach, only a limited set of seismic reflectors are used. In a data-driven approach, all seismic reflectors are used to flatten the seismic data.

Techniques	Summary
Chronosomes	Flattening based on correlated horizon patches on 2D seismic data (e.g. Nordlund and Griffiths, 1993a,b). It does not flatten every single seismic reflector. Flattening is partly done by interpolating between two successive horizons/chronosomes.
Stratal Slicing[a]	A model-based approach to flatten a volume based on a given set of horizons. Originally, proportional slicing was introduced by Zeng et al. (1998). Thereafter, parallel to upper/lower has also been introduced by various researchers.
GeoTime	Total/Elf introduced a method of volumetric flattening by solving numerical problems (Keskes, 2002). They presented two ways of correlating timelines: amplitude correlation and matching horizon dips with the seismic dips.
Age Volume	This solution was based on seismic phase (Stark, 2003, 2004). The data are sorted and correlated by unwrapping the phase and thereafter an RGT series is established by counting.
UVT Transform	This was perhaps the first attempt with a hope to restore 3D seismic data in case of deformation (Mallet, 2004). They named it a Geochron or G-space Model. At present, it is known as UVT Transform. This algorithm solves a series of linear equations to attempt the restoration of a structural seismic into a stratigraphic seismic. As a result, it obtains a flattened volume.
Volumetric Flattening	Another sophisticated algorithm to solve an inverse problem between seismic dips and reflector's dip to compute a solution to fully flatten a given seismic volume (Lomask, 2003; Lomask and Guitton, 2007). Later on, the algorithm has been tuned to perform flattening with given constraints (horizons and faults). Contrary to UVT Transform, this method performs flattening within a given spatial coordinates system.
HorizonCube/SSIS[b]	This method originally provides both model-/data-driven solutions based on tracking in a pre-computed dip volume from the seismic data (Ligtenberg et al., 2006). The same method has been upgraded to solve a system of linear equations based on the work of Colorado School of Mines given below.
Domain Transform	An interpretation guided model based approach to flatten seismic data. Much similar to Zeng's work of stratal slicing (Dorn et al., 2008; Dorn, 2013). However, this method incorporates faults as well.
Paleoscan	Another mathematically approach to provide data-driven results and perform flattening based on a pre-computed model (Pauget et al., 2009). Contrary to other automated approaches, this software works directly on the seismic amplitudes (Peaks/Troughs). Once the seismic

WheelerLab[a]	This is the first image-based model driven approach to prepare Wheeler diagrams. It is a 2D solution which can also be applied to prepare Wheeler diagrams of an outcrop image (Amosu and Sun, 2017).

[a] Open source codes are publicly accessible.
[b] Available for academia.

For Further Reading



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Contents lists available at ScienceDirect

Marine and Petroleum Geology

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Research paper

The Wheeler diagram, flattening theory, and time

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ABSTRACT

Wheeler diagrams are excellent tools to represent time stratigraphy. These diagrams are produced by considering interpreted surfaces as snapshots of geologic times linked with transit cycles of the base level. The base level, defined in the nineteenth century, can be regarded as an ultimate 'time' reference for stratigraphic units. The application of the base level concept to deep marine settings is a more recent development, even though the same definition applies to all depositional environments. Flat timelines are also known as flattening theories can produce similar looking diagrams and have an edge that they operate in 3D. However, flattening of a dataset can be achieved with various techniques, which are reviewed and the optimum algorithm, which has a future application for hydrocarbon and research communities, is improved to honor geological constraints such as faults and horizons. A secondary aspect of the Wheeler diagrams is the dual nature of geological timelines. The diagrams are originally plotted on a relative geological time scale and no formal technique has yet been recommended for time calibration. In this paper, a nomogram approach is proposed to calibrate the timelines. The representation of unconformities that are parallel to bedding planes is another important idea presented in this paper.

SoftwareX 6 (2017) 19–24

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journal homepage: www.elsevier.com/locate/softx

WheelerLab: An interactive program for sequence stratigraphic analysis of seismic sections, outcrops and well sections and the generation of chronostratigraphic sections and dynamic chronostratigraphic sections

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ABSTRACT

WheelerLab is an interactive program that facilitates the interpretation of stratigraphic data (seismic sections, outcrop data and well sections) within a sequence stratigraphic framework and the subsequent transformation of the data into the chronostratigraphic domain. The transformation enables the identification of significant geological features, particularly erosional and non-depositional features that are not obvious in the original seismic domain. Although there are some software products that contain interactive environments for carrying out chronostratigraphic analysis, none of them are open-source codes. In addition to being open source, WheelerLab adds two important functionalities not present in currently available software: (1) WheelerLab generates a dynamic chronostratigraphic section and (2) WheelerLab enables chronostratigraphic analysis of older seismic data sets that exist only as images and not in the standard seismic file formats; it can also be used for the chronostratigraphic analysis of outcrop images and interpreted well sections. The dynamic chronostratigraphic section sequentially depicts the evolution of the chronostratigraphic chronosomes concurrently with the evolution of identified genetic stratal packages. This facilitates a better communication of the sequence-stratigraphic process. WheelerLab is designed to give the user both interactive and interpretational control over the transformation; this is most useful when determining the correct stratigraphic order for laterally separated genetic stratal packages. The program can also be used to generate synthetic sequence stratigraphic sections for chronostratigraphic analysis.

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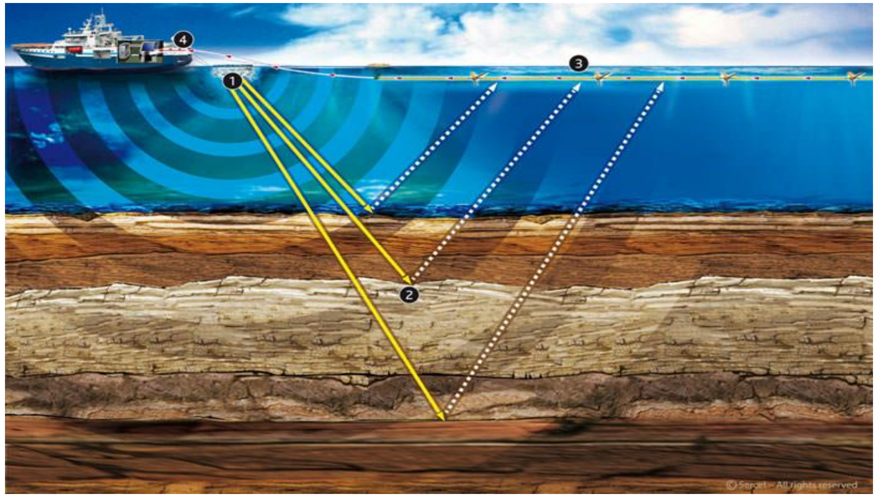
Geological Data Types: Seismic



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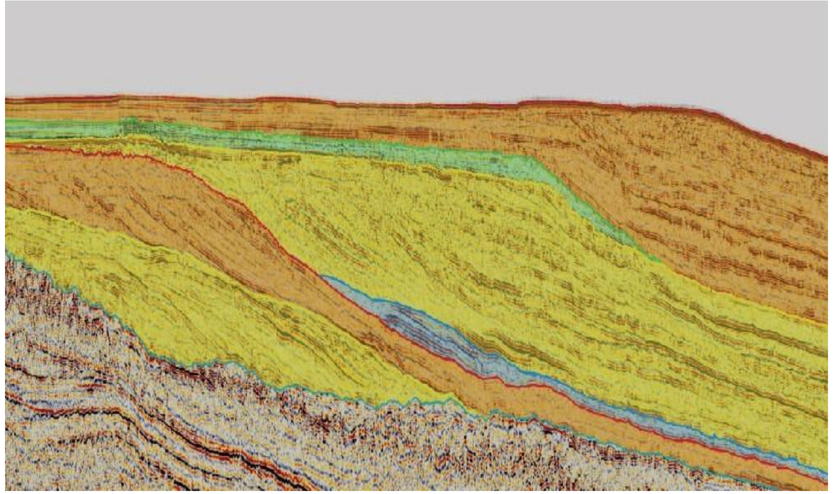
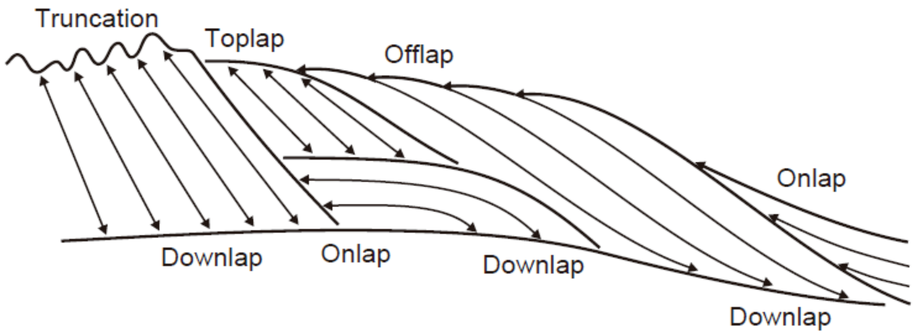
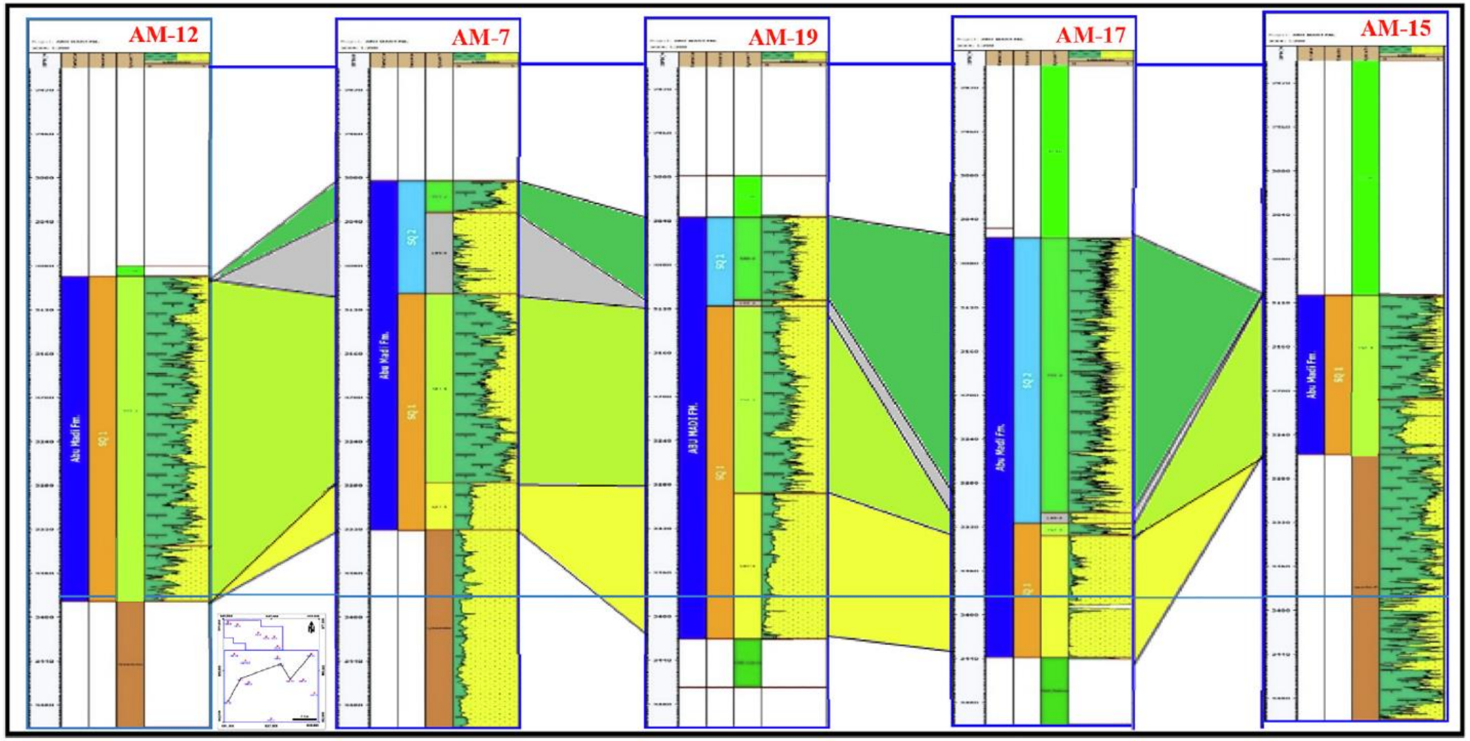


dGB Earth Science; De Bruin et al., (2007)



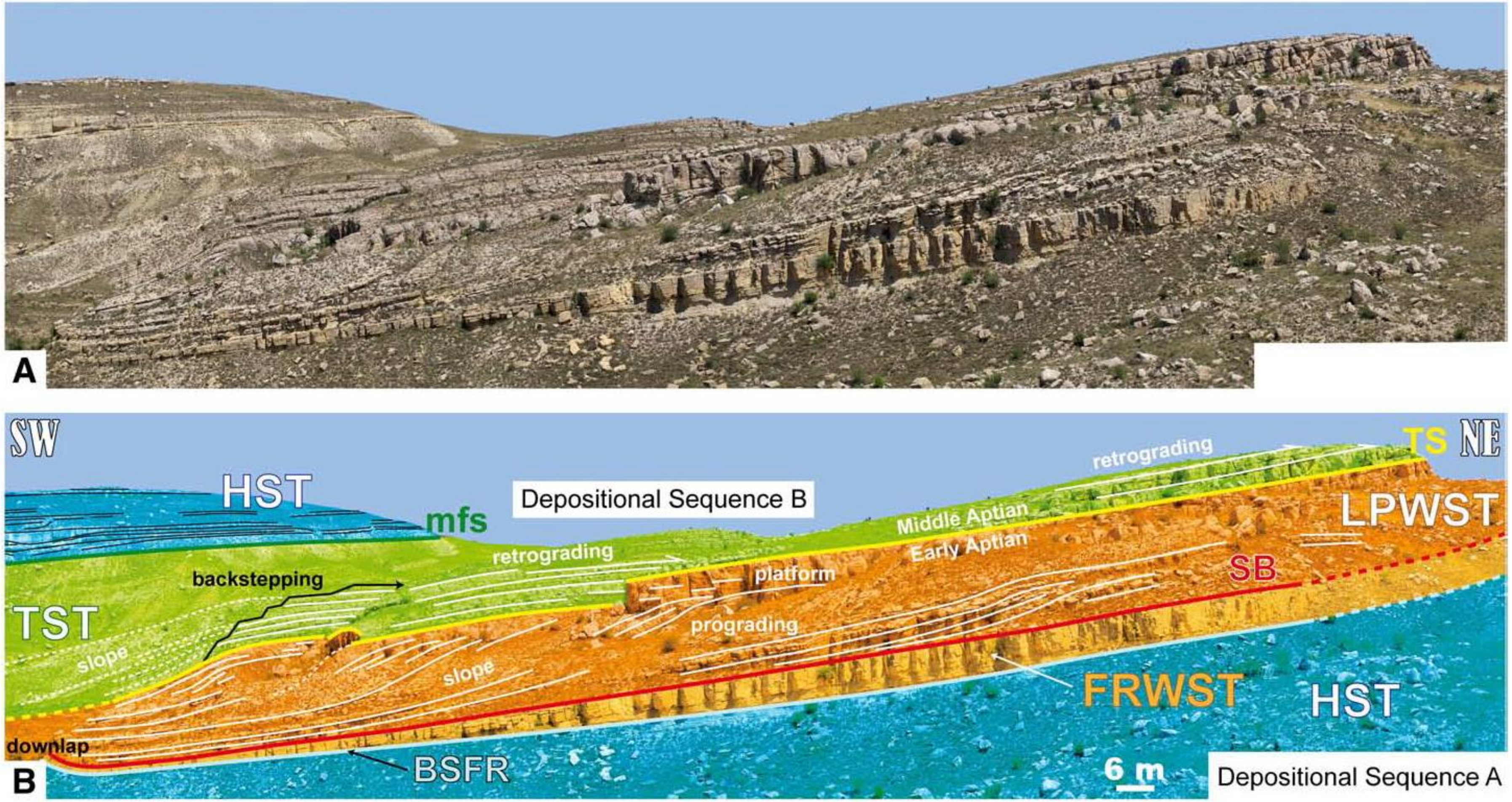
Catuneanu (2006)

Geological Data Types: Well-Sections



Shebl et al., (2019)

Geological Data Types: Outcrops



Bover-Arnal et al., (2009)

Geological Data Types

Data set	Main applications / contributions to sequence stratigraphic analysis
Seismic data	Continuous subsurface imaging; tectonic setting; structural styles; regional stratigraphic architecture; imaging of depositional elements; geomorphology
Well-log data	Vertical stacking patterns; grading trends; depositional systems; depositional elements; inferred lateral facies trends; calibration of seismic data
Core data	Lithology; textures and sedimentary structures; nature of stratigraphic contacts; physical rock properties; paleocurrents in oriented core; calibration of well-log and seismic data
Outcrop data	3D control on facies architecture; insights into process sedimentology; lithofacies; depositional elements; depositional systems; all other applications afforded by core data
Geochemical data	Depositional environment; depositional processes; diagenesis; absolute ages; paleoclimate
Paleontological data	Depositional environment; depositional processes; ecology; relative ages

Catuneanu (2006)

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WheelerLab - Introduction

WheelerLab is the first image-based model driven approach for constructing Wheeler diagrams

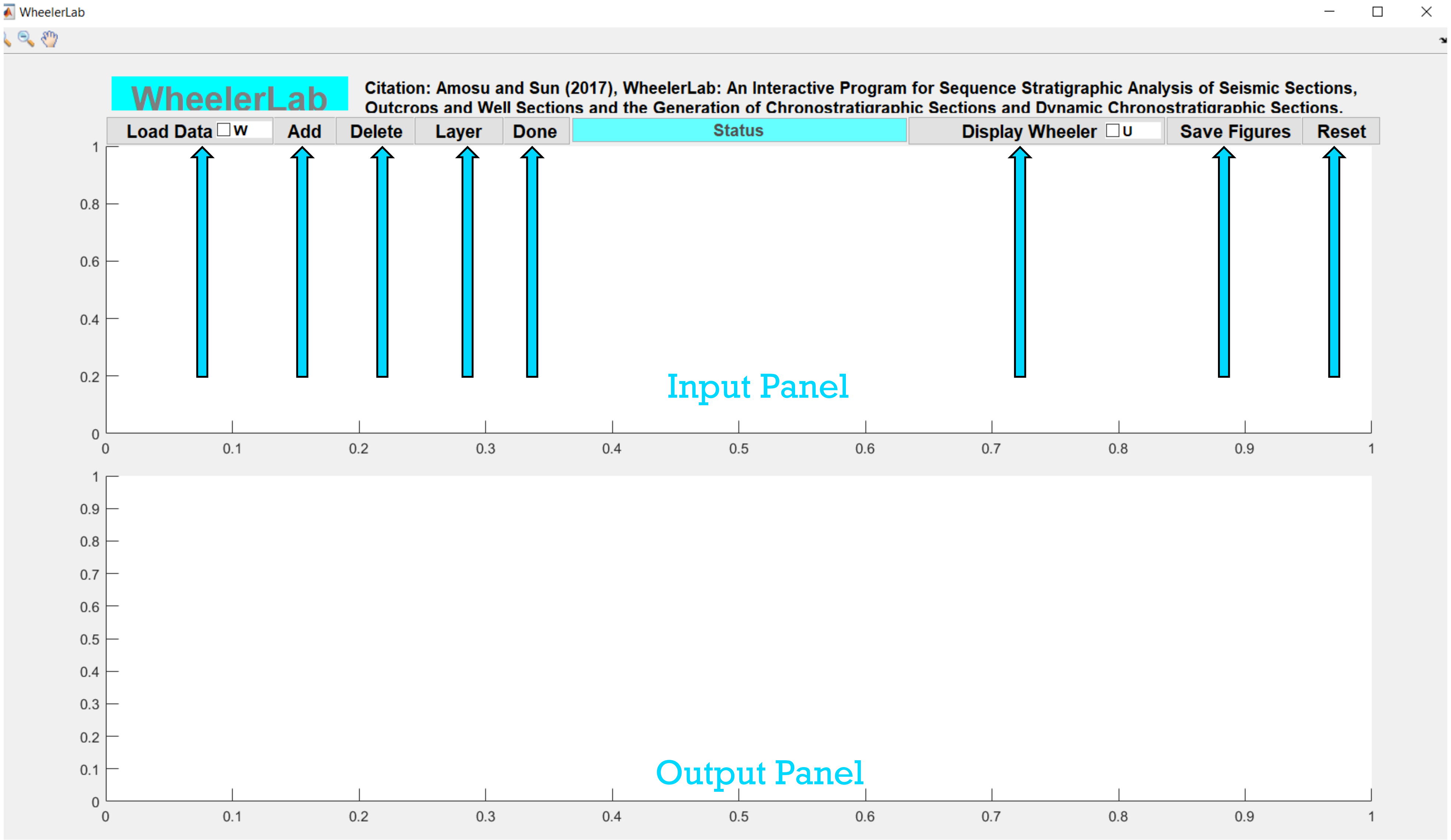
Written in MATLAB and is an interactive program with a GUI

Stand alone versions for MAC, LINUX, and Windows are available on google drive

Source Code is available on github and zenodo

Email me for links: adewale@tamu.edu

WheelerLab GUI



WheelerLab I/O

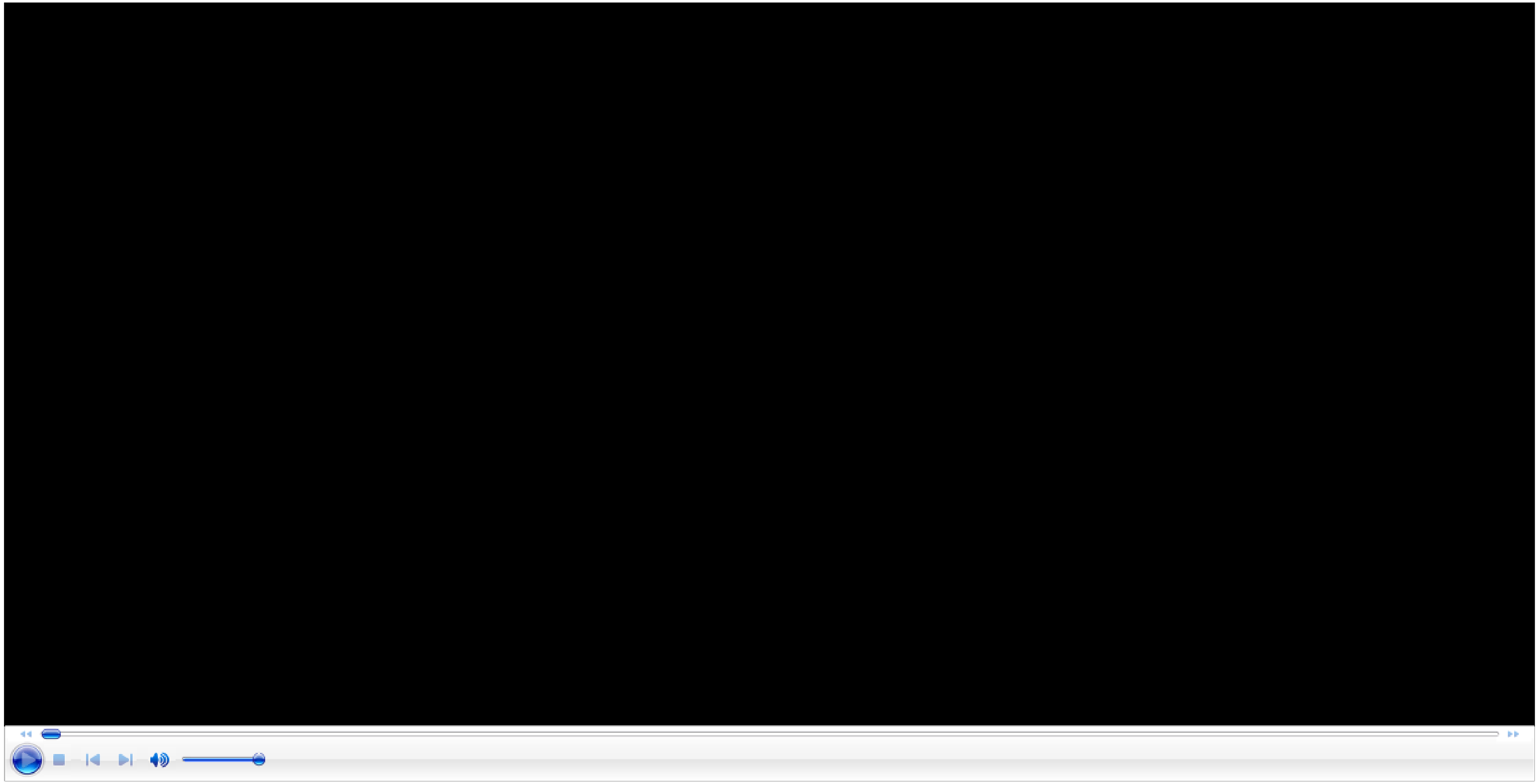
Input

- Seismic: SEGY or Image (JPG, PNG, TIFF, …)
- Outcrop: Image (JPG, PNG, TIFF, …)
- Well-Section: Image (JPG, PNG, TIFF, …) from concatenated LAS files
- Synthetic: No input required

Output

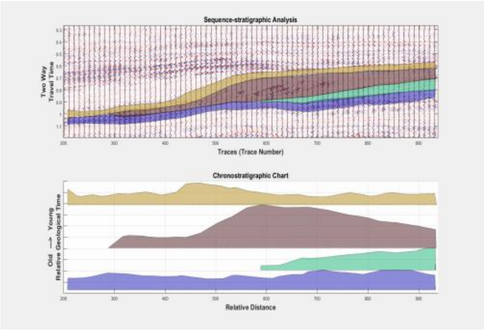
- Wheeler Diagram: MATLAB FIG, PNG,
- Dynamic Wheeler Diagram: AVI GIF
- Data: ASCII

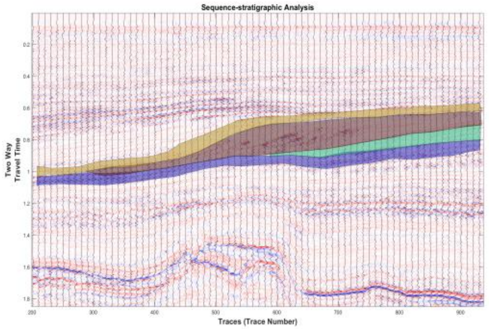
WheelerLab Demonstration

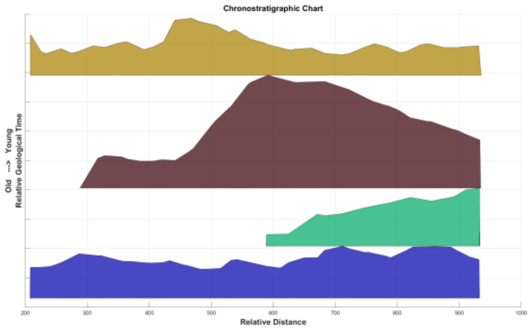


Data: F3 block, Netherlads, dGB Earth Science

WheelerLab Output

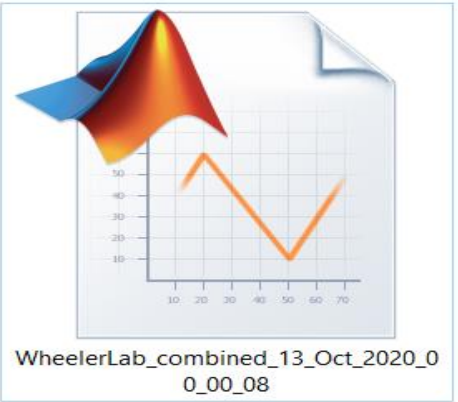


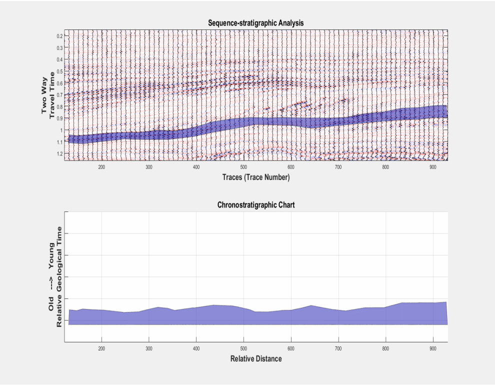


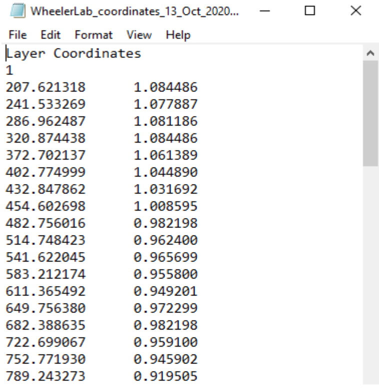


Transgressive Systems Tract

Highstand Systems Tract



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File Edit Format View Help

Layer Coordinates
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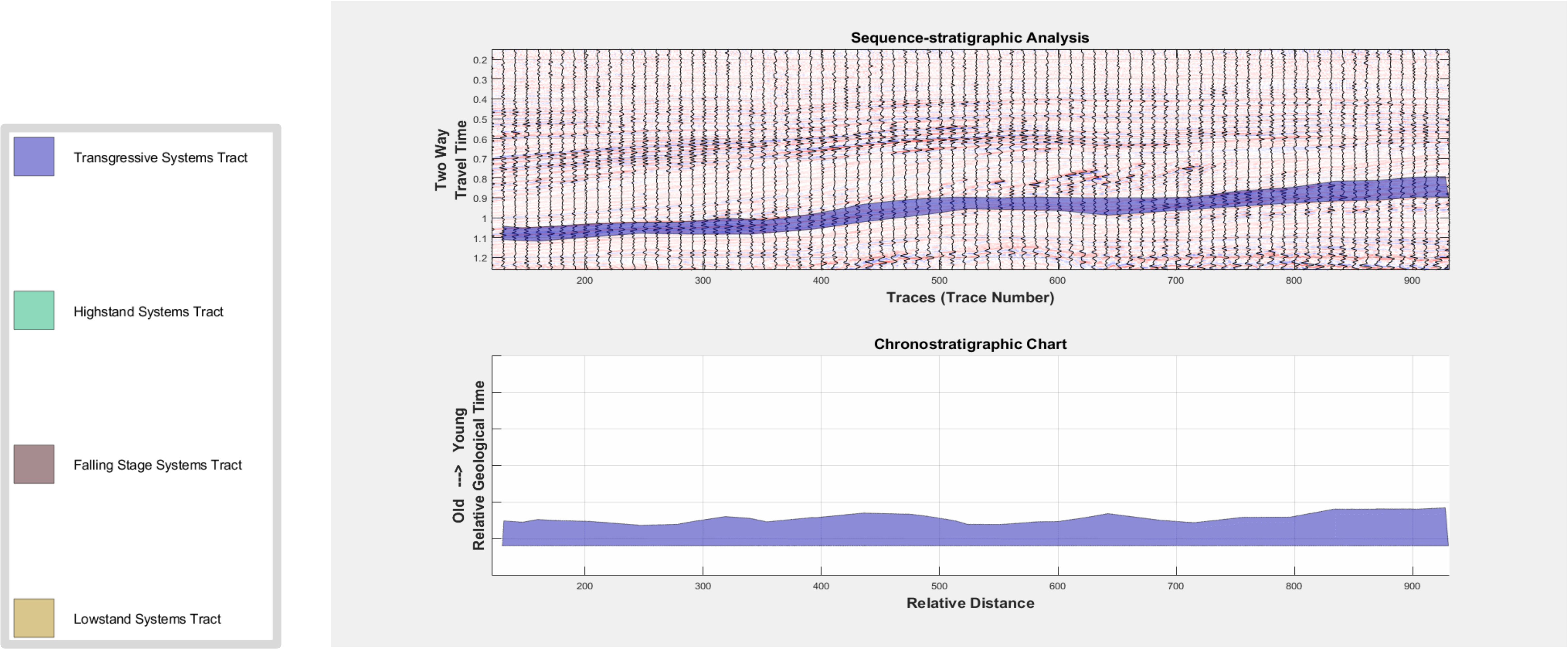
Falling Stage Systems Tract

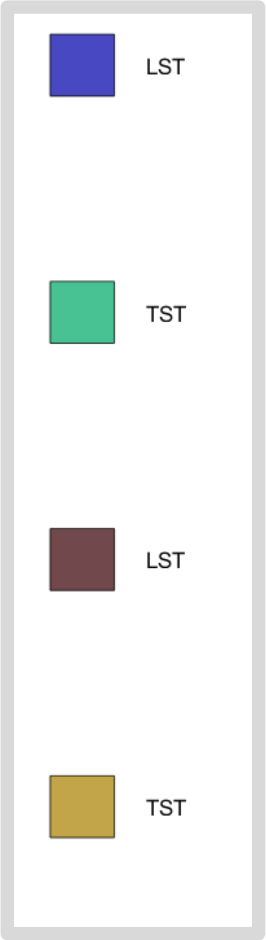
Lowstand Systems Tract

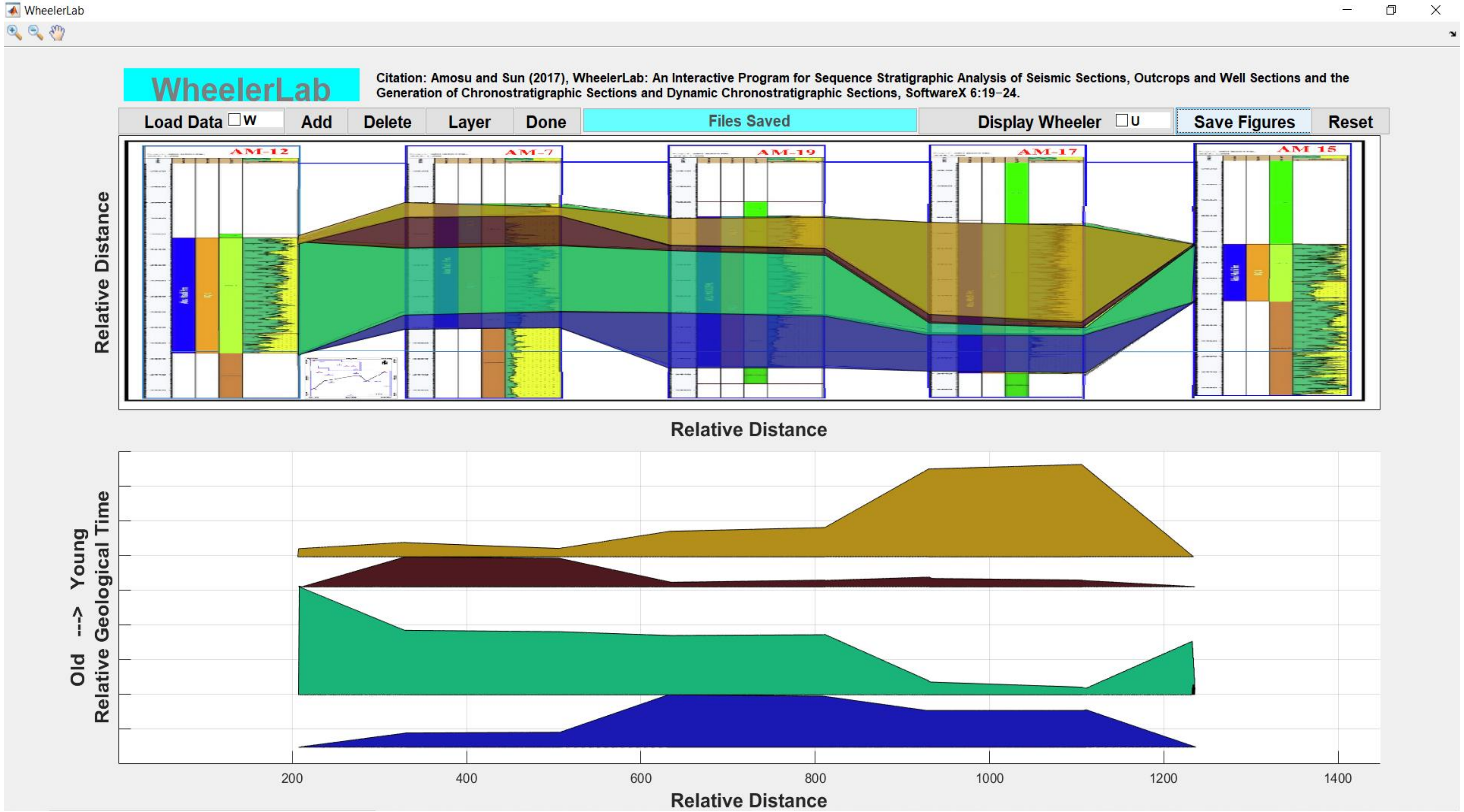
WheelerLab Demonstration: Seismic



Data: F3 block, Netherlads, dGB Earth Science; Amosu and Sun (2017)

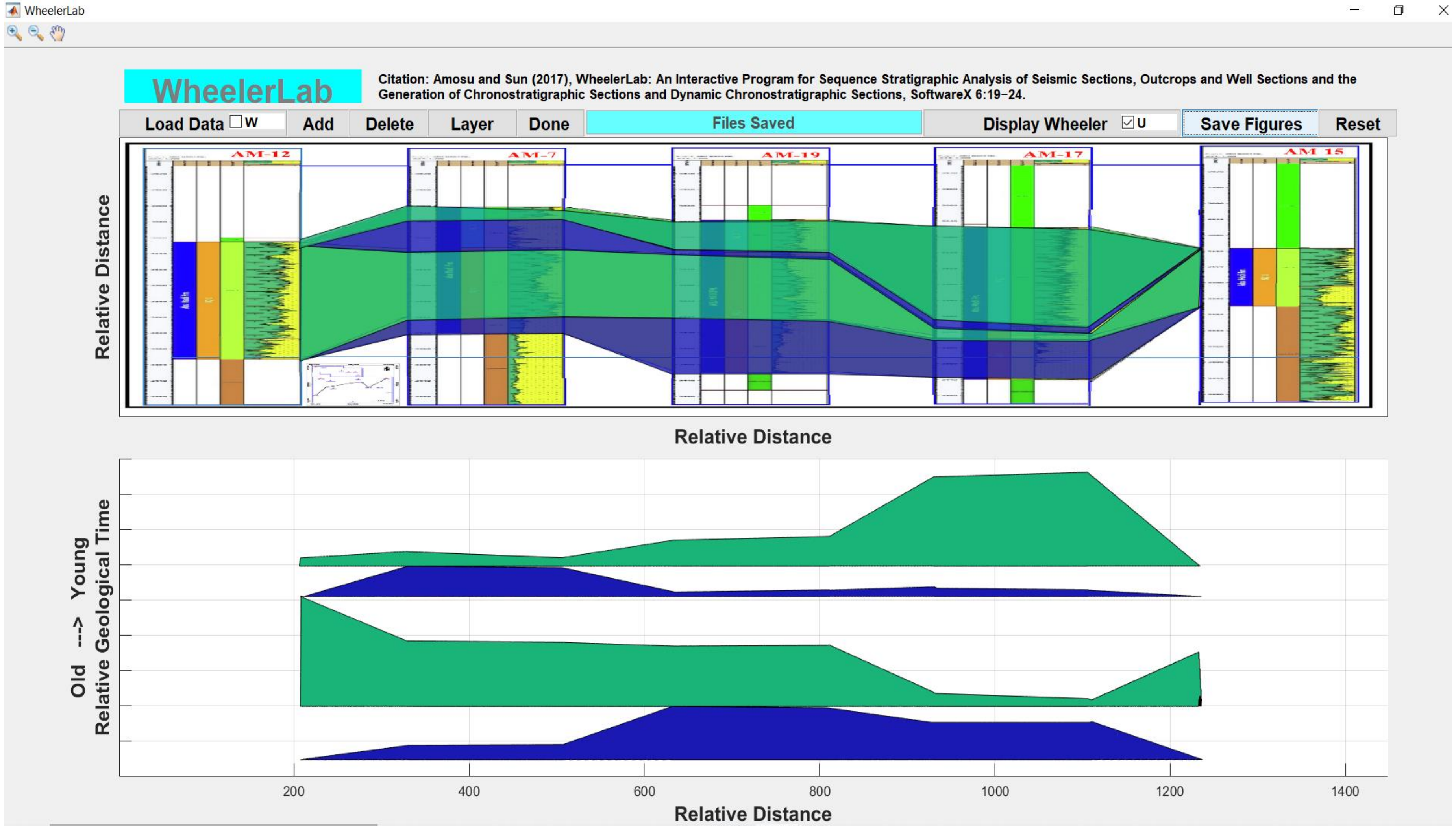
WheelerLab Demonstration: Well-Section

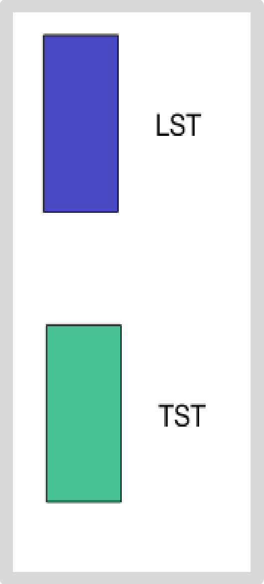




Modified from Shebl et al., (2019)

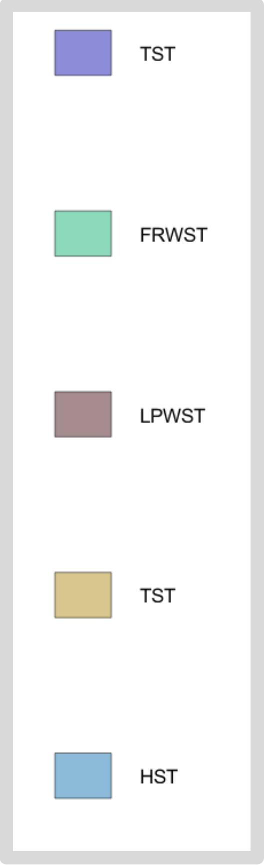
WheelerLab Demonstration: Well-Section

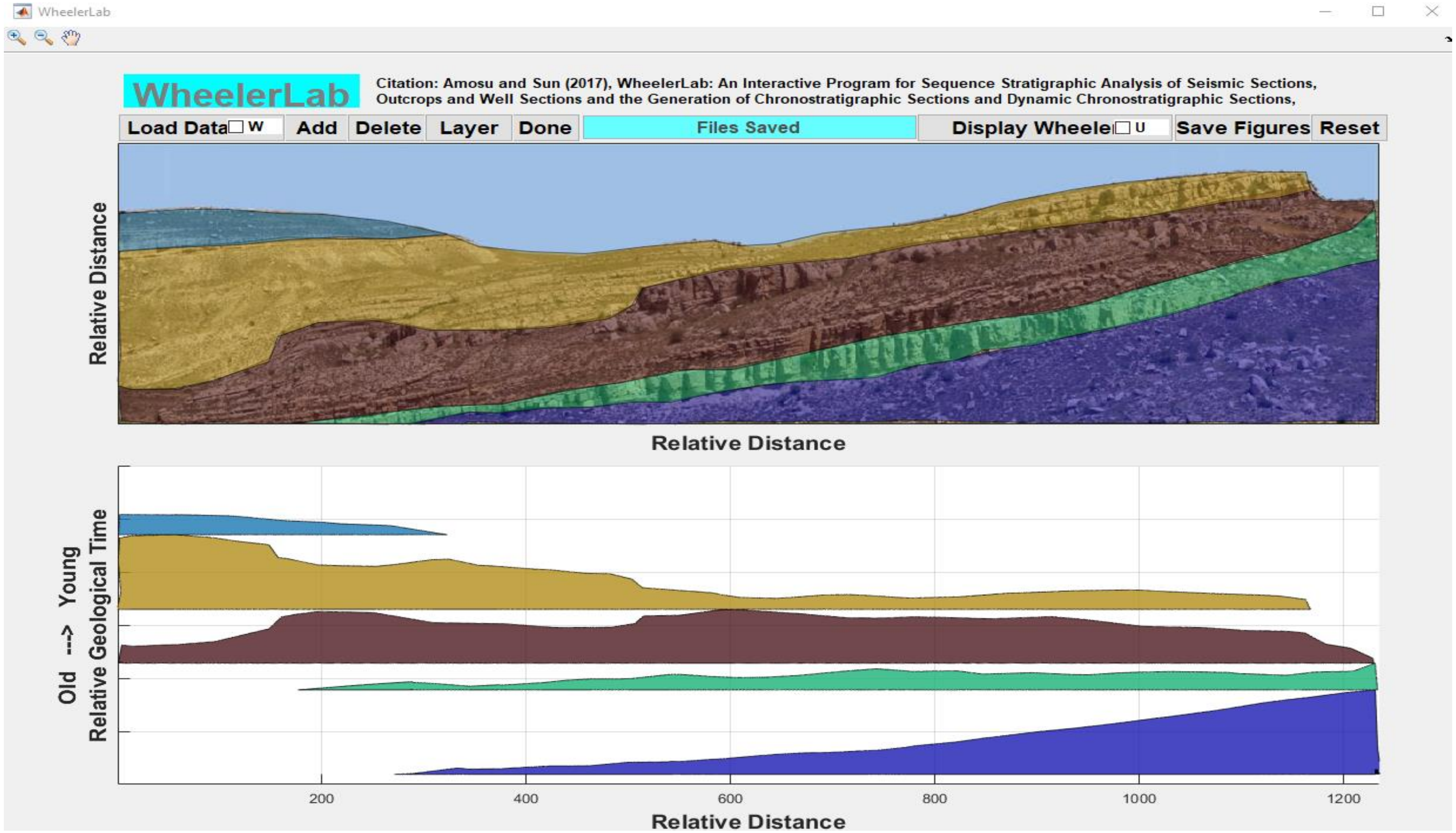




Modified from Shebl et al., (2019)

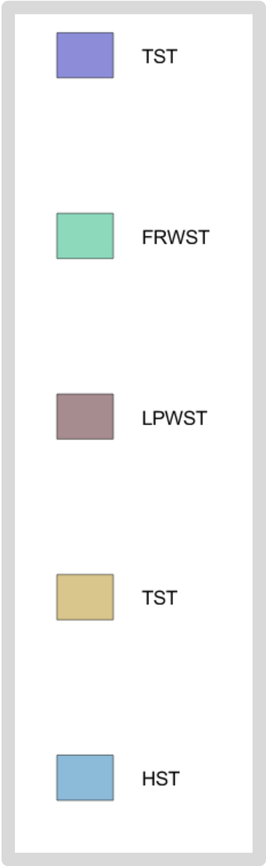
WheelerLab Demonstration: Outcrop

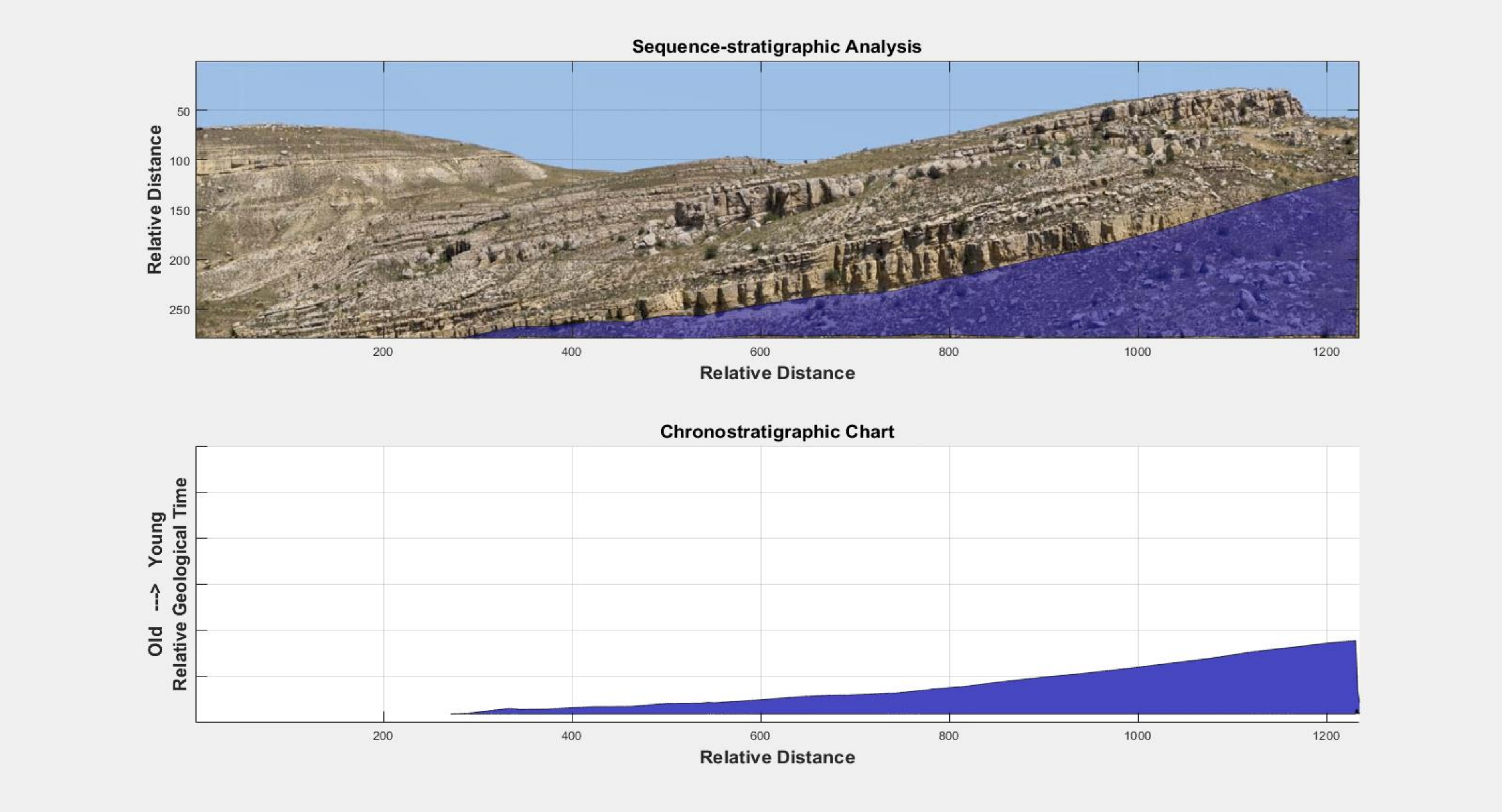




Modified Bover-Arnal et al., (2009); Amosu and Sun (2017)

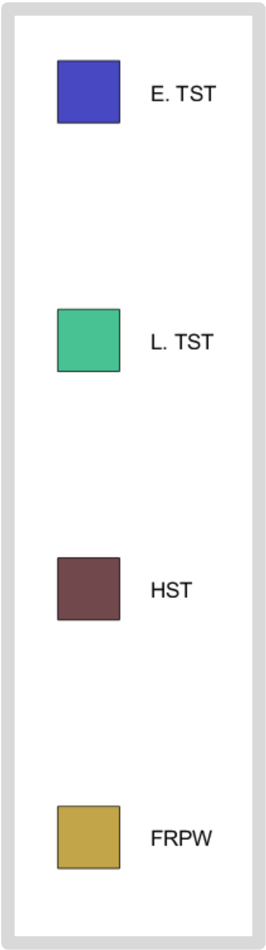
WheelerLab Demonstration: Outcrop

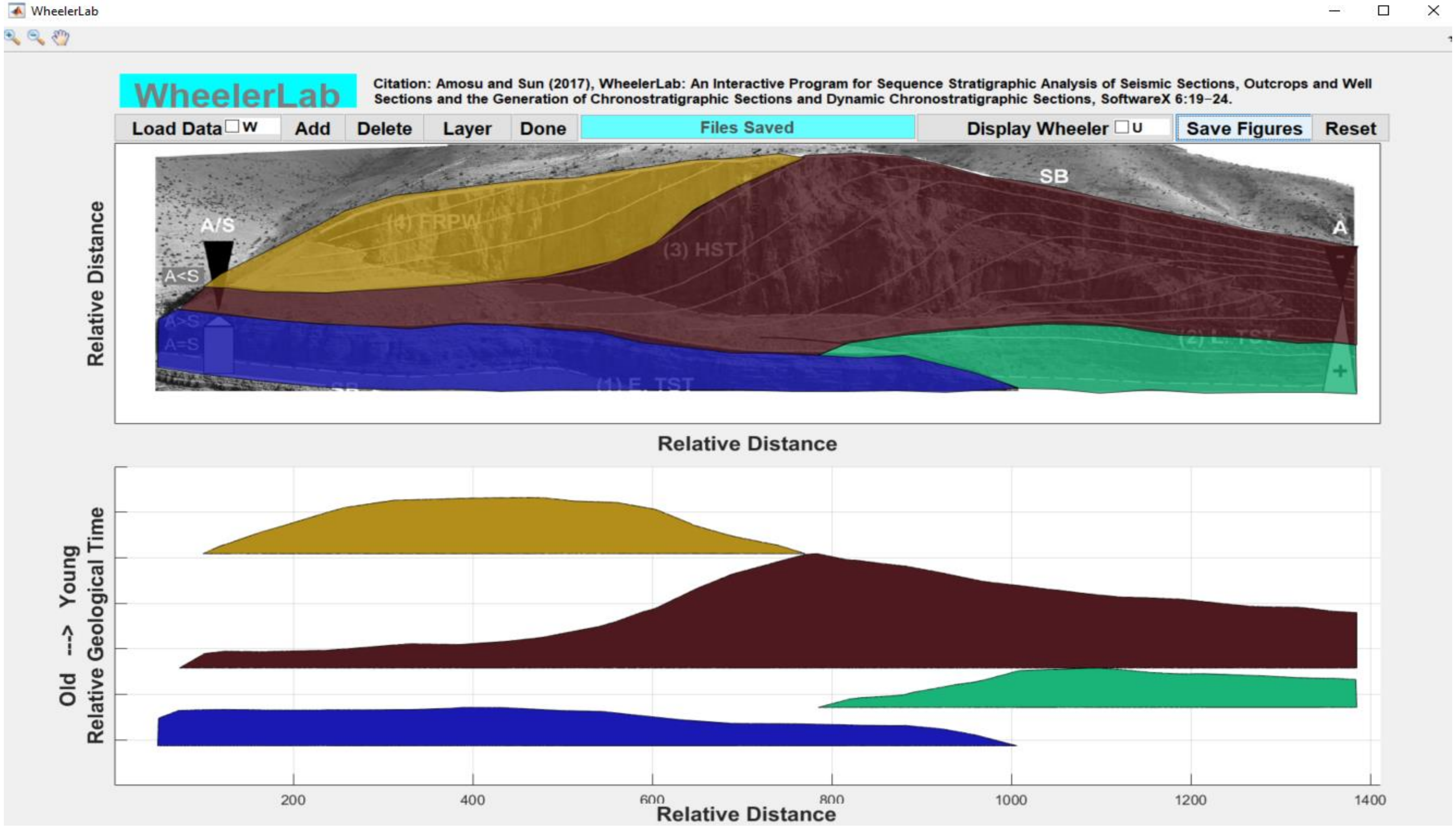




Modified Bover-Arnal et al., (2009); Amosu and Sun (2017)

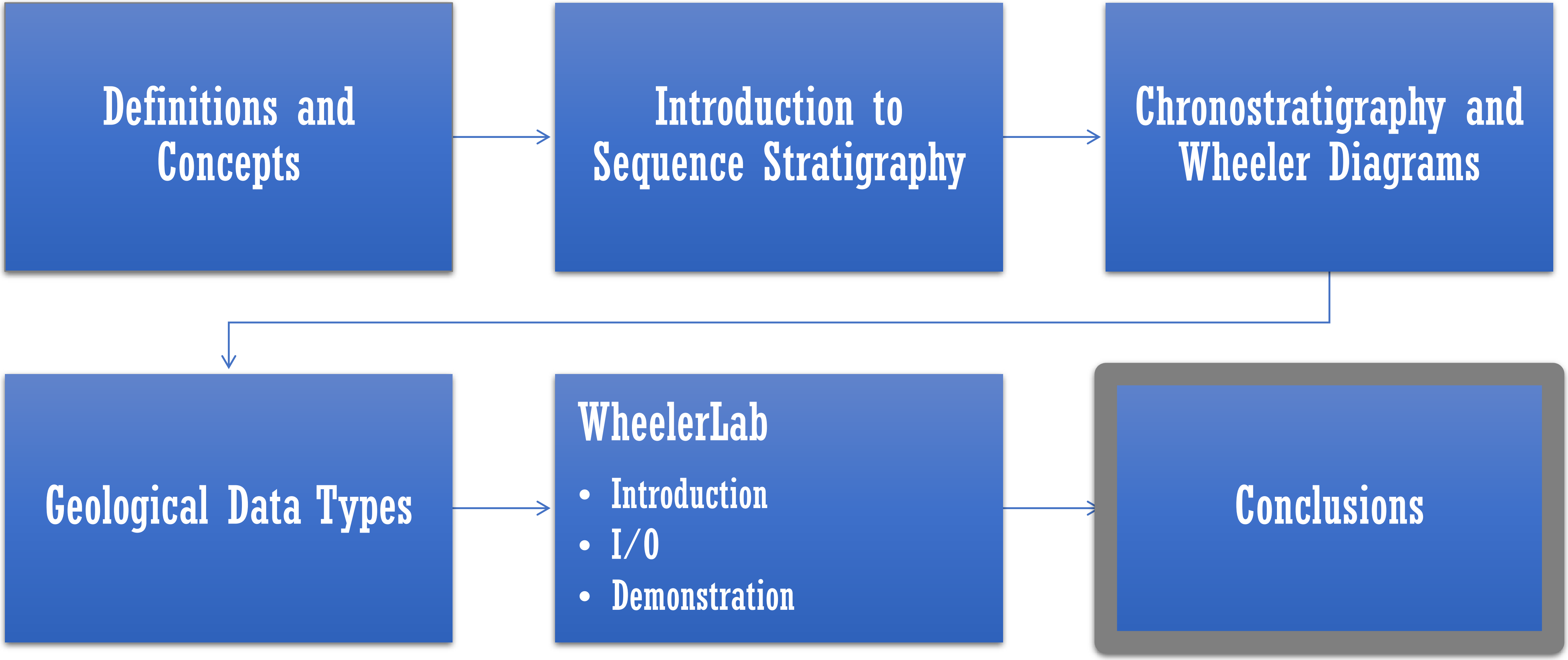
WheelerLab Demonstration: Outcrop





Modified from Razin et al., (2010)

Outline


Definitions and Concepts
Introduction to Sequence Stratigraphy
Chronostratigraphy and Wheeler Diagrams
Geological Data Types
WheelerLab
• Introduction
• I/O
• Demonstration
Conclusions

Conclusion

We have developed an open-source program for sequence stratigraphic and chronostratigraphic analysis of geological data

It is the first model-driven image-based program for sequence stratigraphic and chronostratigraphic analysis

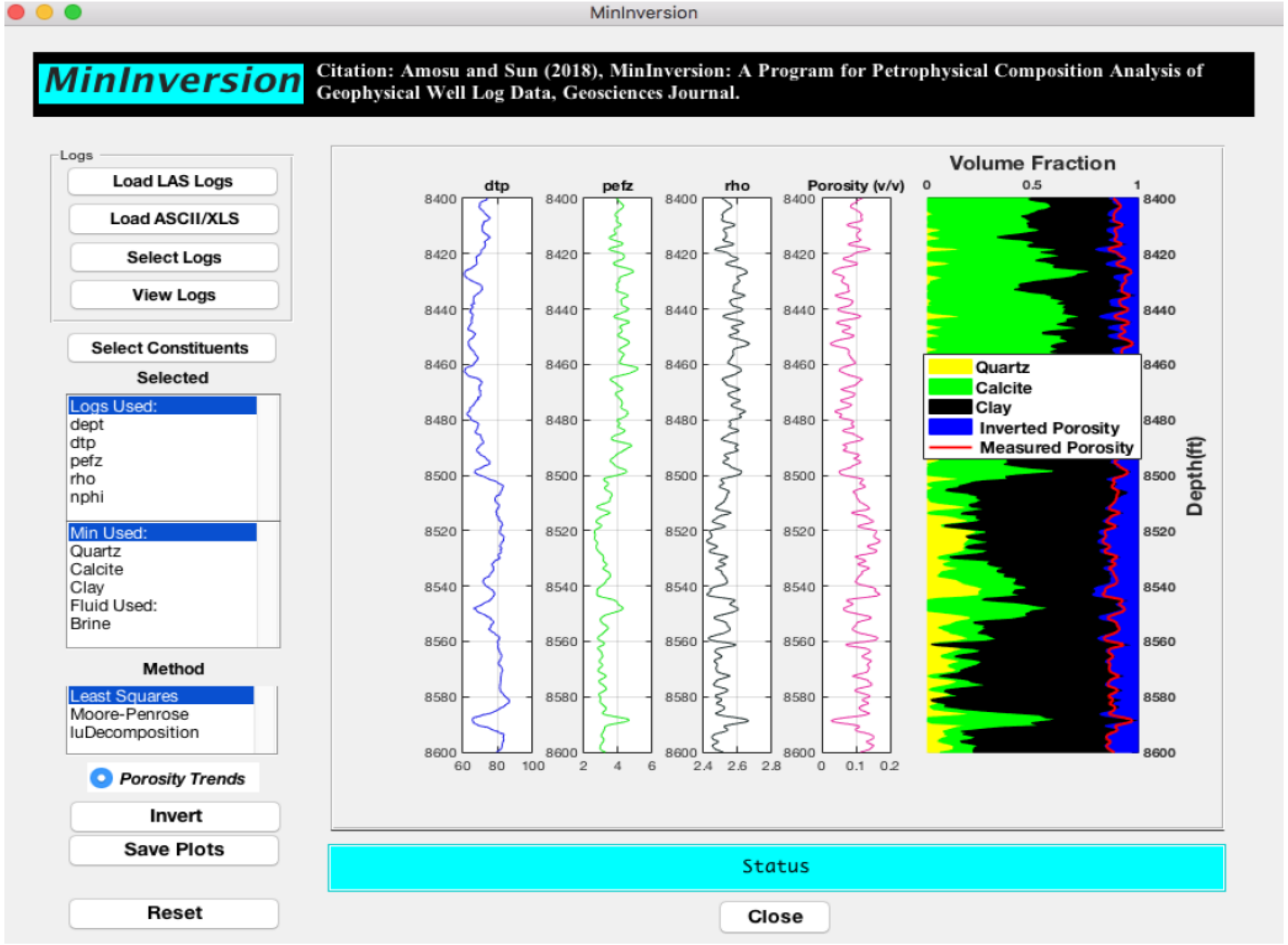
The program permits flexibility of interpretation and sequence stratigraphic model or approach

Can be applied to different geological data types including seismic data, well-sections and outcrops

Future Work

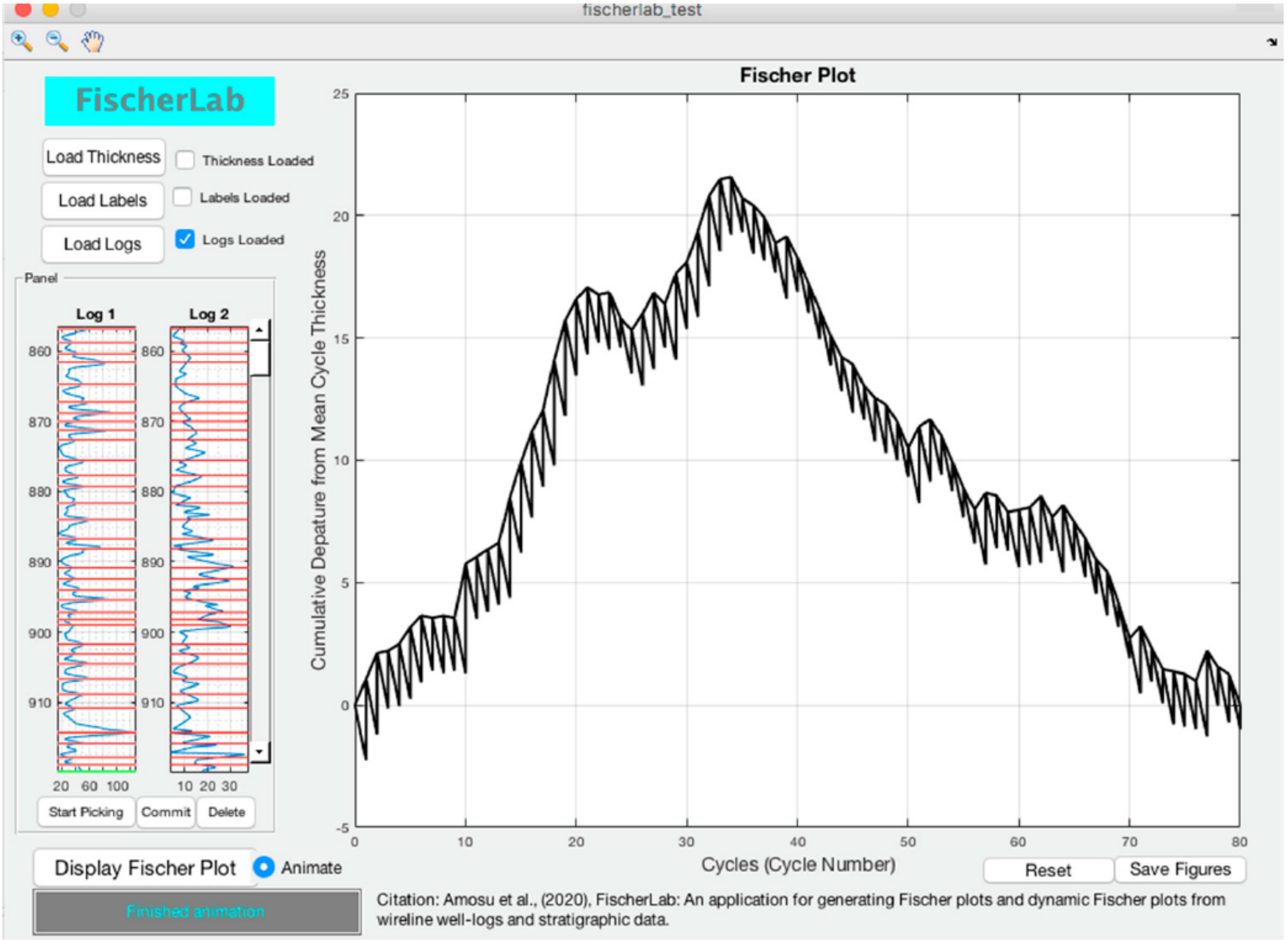
- Incorporation of top flattening of systems tracts
- AI-detection of sequence tracts in seismic data and outcrop images
- Extension to 3D seismic data
- Extension to 3D outcrop images (DOMs)
- Version 2 in MATLAB AppDesigner

Other MATLAB Projects: MinInversion



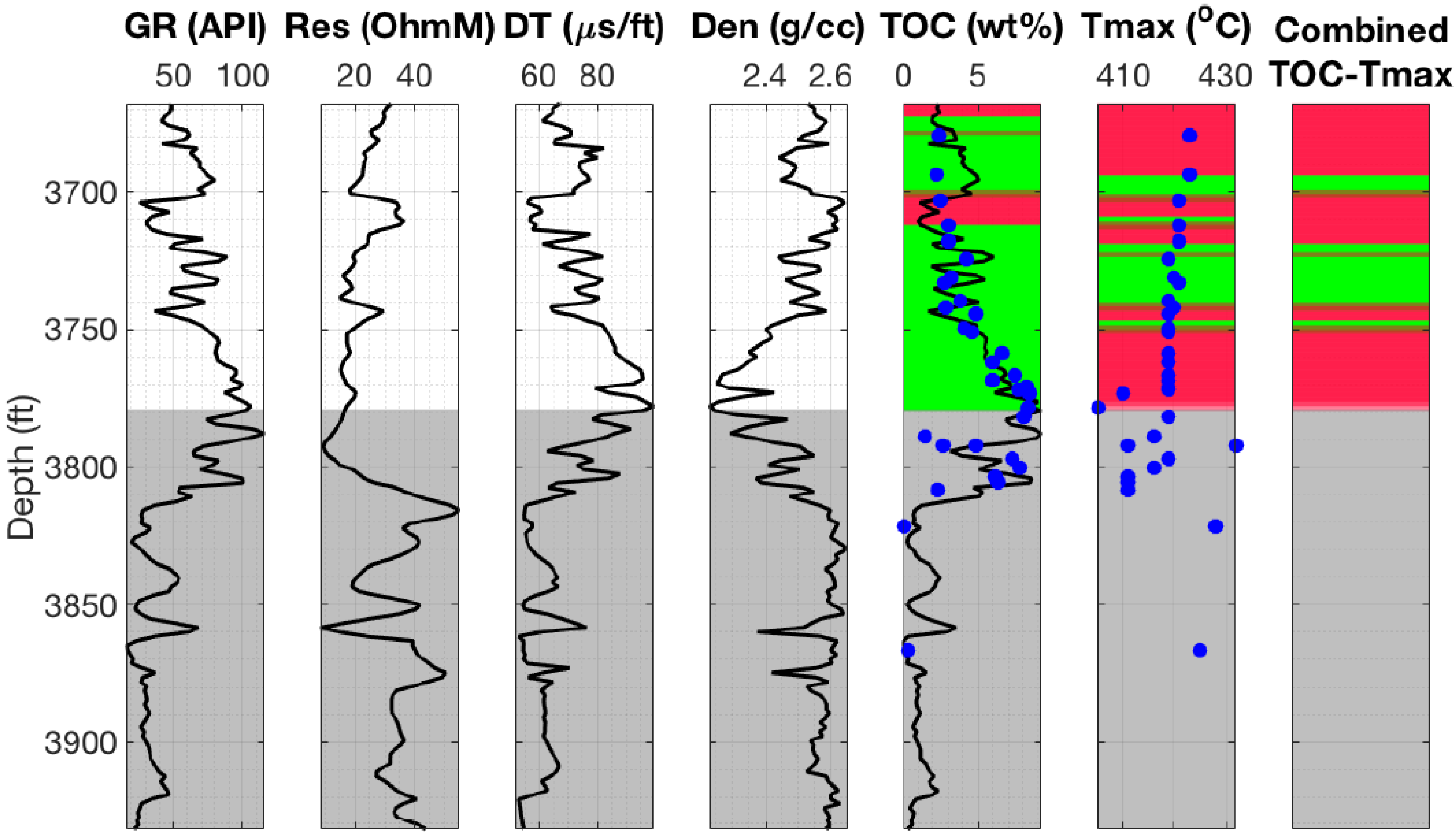
Amosu and Sun (2018)

Other MATLAB Projects: FischerLab



Amosu et al., (2020)

Other MATLAB Projects: ML Prediction in Unconventionals



Amosu and Sun (2019)

References

- Amosu, A. and Sun, Y., 2017. WheelerLab: An interactive program for sequence stratigraphic analysis of seismic sections, outcrops and well sections and the generation of chronostratigraphic sections and dynamic chronostratigraphic sections. *SoftwareX*, *6*, pp.19-24.
- Amosu, A. and Sun, Y., 2017, WheelerLab: An Interactive Program for Sequence Stratigraphic Analysis of Seismic Sections and the Generation of Dynamic Chronostratigraphic Sections, AAPG Datapages.
- Amosu, A. and Sun, Y., 2018. MinInversion: A program for petrophysical composition analysis of geophysical well log data. *Geosciences*, *8*(2), p.65.
- Amosu, A., Imsalem, M., Raymond, A. and Sun, Y., 2020. FischerLab: An Application for Generating Fischer Plots and Dynamic Fischer Plots from Wireline Well-Logs and Stratigraphic Data. *Earth*, *1*(1), pp.36-48.
- Amosu, A. and Sun, Y., 2017, FischerLab: An Interactive Program for Generating Dynamic Fischer Plots From Wireline Logs and Stratigraphic Data, AAPG Datatpages
- Amosu, A. and Sun, Y., 2019. Effective machine learning approach for identifying high total organic carbon formations. In *SEG Technical Program Expanded Abstracts 2019* (pp. 2363-2367). Society of Exploration Geophysicists.
- Bover-Arnal, T., Salas, R., Moreno-Bedmar, J.A. and Bitzer, K., 2009. Sequence stratigraphy and architecture of a late Early–Middle Aptian carbonate platform succession from the western Maestrat Basin (Iberian Chain, Spain). *Sedimentary Geology*, *219*(1-4), pp.280-301.
- Brown Jr, L.F. and Fisher, W.L., 1977. Seismic-stratigraphic interpretation of depositional systems: examples from brazilian rift and pull-apart basins: section 2. Application of seismic reflection configuration to stratigraphic interpretation.
- De Bruin, G., Hemstra, N. and Pouwel, A., 2007. Stratigraphic surfaces in the depositional and chronostratigraphic (Wheeler-transformed) domain. *The Leading Edge*, *26*(7), pp.883-886.
- Catuneanu, O., 2006. *Principles of sequence stratigraphy*. Elsevier.
- Kendall, C.G.S.C. and Lerche, I., 1988. The rise and fall of eustasy.
- Embry, A.F. and Johannessen, E.P., 2017. Two approaches to sequence stratigraphy. In *Stratigraphy & Timescales* (Vol. 2, pp. 85-118). Academic Press.

References

- Fisher, W.L. and McGowen, J.H., 1967. Depositional Systems in the Wilcox Group of Texas and Their Relationship to Occurrence of Oil and Gas (1).
- Hutton, E.W. and Syvitski, J.P., 2008. Sedflux 2.0: An advanced process-response model that generates three-dimensional stratigraphy. *Computers & Geosciences*, *34*(10), pp.1319-1337.
- Nesbit, P.R., Boulding, A.D., Hugenholtz, C.H., Durkin, P.R. and Hubbard, S.M., 2020. Visualization and Sharing of 3D Digital Outcrop Models to Promote Open Science. *GSA Today*, *30*, pp.4-10.Qayyum, F., Betzler, C. and Catuneanu, O., 2017. The wheeler diagram, flattening theory, and time. *Marine and Petroleum Geology*, *86*, pp.1417-1430.
- Qayyum, F., De Groot, P. and Hemstra, N., 2012. Using 3D Wheeler diagrams in seismic interpretation–the HorizonCube method. *first break*, *30*(3).
- Razin, P., Taati, F. and Van Buchem, F.S.P., 2010. Sequence stratigraphy of Cenomanian–Turonian carbonate platform margins (Sarvak Formation) in the High Zagros, SW Iran: an outcrop reference model for the Arabian Plate. *Geological Society, London, Special Publications*, *329*(1), pp.187-218.
- Shebl, S., Ghorab, M., Mahmoud, A., Shazly, T., Abuhagaza, A.A. and Shibl, A., 2019. Linking between sequence stratigraphy and reservoir quality of Abu Madi Formation utilizing well logging and seismic analysis at Abu Madi and El Qar'a fields, Nile Delta, Egypt. *Egyptian Journal of Petroleum*, *28*(2), pp.213-223.
- Sloss, L.L., 1949. INTEGRATED FACIES AN ALYSIS1. In *Sedimentary facies in geologic history: Conference at meeting of the Geological Society of America held in New York, New York, November 11, 1948* (Vol. 39, p. 91). Geological Society of America.
- Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. and Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies.
- Van Wagoner, J.C., 1995. Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, USA.
- Wheeler, H.E., 1964. Baselevel, lithosphere surface, and time-stratigraphy. *Geological Society of America Bulletin*, *75*(7), pp.599-610.

References

- https://www.worldatlas.com/
- http://strata.uga.edu
- http://sercel.com
- https://www.dgbes.com/

Thank You

Questions?