Siliciclastic Sequence Stratigraphy: Application to Exploration and Production

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Or...

Wheeler’s Confusion and the Seismic Revolution: How Geophysics Saved Stratigraphy
Outline

• A Brief History of Sequence Stratigraphy
• Lithostratigraphy in the 20th Century
  – Failure
• The Seismic Revolution
• Applications using well logs and outcrops
• Conclusion
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Amadeus W. Grabau (1906)

- Showed onlap, offlap relationships in Paleozoic strata of North America.
- Illustrated time associated with a given unconformity.
Offlap, facies versus time lines

- Grabau also showed diachronous relationships between facies and time in offlapping, regressive strata.

Shazam Lines show diachroneity between facies

- Grabau (1906)

Sandstone  Shale  Limestone
Diachronous facies boundaries cut across time lines.

Grabau - 1906

Beds follow time lines.

Van Wagoner et al., 1990  94 years later

PROGRADATION OF PARASEQUENCE (A) DURING A TIME WHEN THE RATE OF DEPOSITION EXCEEDS THE RATE OF WATER-DEPTH INCREASE. BEDSETS COMPOSE THE PARASEQUENCE. THE YOUNGEST BEDSET SURFACE IS NONDEPOSITIONAL.
Eliott Blackwelder (1909)

- Recognized importance of unconformity-bounded strata across North American continent.

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Rocks

Hiatus
Larry Sloss (1963): Father of American Stratigraphy

- Named six major sequences in North American Stratigraphy, representing major tectono-eustatic events.
  - Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni, Tejas.
- Defined continent-wide unconformity-bounded units, which he termed sequences.
- Co-supervised graduate student Peter Vail at Northwestern University.
Larry Sloss (1963): Father of American Stratigraphy

- Sloss was heavily influenced by Harry Wheeler (Washington University) who coined the term Sequence to describe an unconformity bounded unit.
Harry Wheeler (1958)
Inventor of Sequence Stratigraphy

- Wheeler depicted unconformity-bounded Sequences defined by arbitrary vertical cutoffs.

Time-Stratigraphy - Wheeler, 1958
Wheeler Diagrams (1958)

- Exploded cross sections in Time.
- Wheeler insisted on arbitrary vertical cutoffs to define different sequences.
- No correlative conformities.
- Unwieldy scheme resulted in a proliferation of sequence names!
- Why did Wheeler adopt such a confusing approach?
Concept of lithofacies represented a bulk, average property of several formations over a significant area, versus the environmental lithofacies concepts developed in the 60’s and 70’s. Lithofacies boundaries were vertical.
- Formations were defined by arbitrary vertical and horizontal boundaries.
- Nomenclature problems were acute where there was interfingering of lithofacies.
Use of Arbitrary Cutoffs in Lithostratigraphy in Clastic Wedges

- Tongues (i.e. members) can be assigned either to Formation A or Formation B.
- Wheeler and Mallory were concerned that using the same name for each finger on a map would be misinterpreted as structural repetition.
  - Concepts were not developed with subsurface applications in mind.
  - Pre-environmental lithofacies

Modified after Wheeler and Mallory, 1953
Example of complex lithostratigraphic nomenclature using arbitrary vertical and horizontal cutoffs in the Book Cliffs.

- Interfingering units in the Book Cliffs, Utah.
- Note Buck Tongue shale is considered a member of the Price River Fm., *not* the Mancos Shale.

Wheeler and Mallory, 1953
State-of-the-art Stratigraphy in 1953

• Who would place orange boxes in different Formations?
• Which of these boundaries would produce a seismic reflection?

Flags or Reality?

Wheeler and Mallory, 1953
Harry Wheeler

• Good:
  – Wheeler (1958) formalized concept of time-stratigraphy
  – Wheeler recognized that hiatuses are as important as the rocks.
  – Wheeler depicted “exploded” stratigraphic cross sections with time on the vertical axis.
  – Wheeler defined sequences as unconformity bounded units.

• Confusing:
  – Wheeler’s sequences were defined by arbitrary vertical cutoffs.
  – No correlative conformity.
  – Vertical cutoffs also were key in defining lithostratigraphic units.
    • This may not be widely appreciated!

Special Note: Wheeler did not accept plate tectonics and was likely derided by fellow academicians.
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Failure of Stratigraphy in 1960

- “Stratigraphy is the complete triumph of terminology over facts and common sense.”
- Paul D. Krynine, circa 1960

Slide courtesy of A. Embry
Failure of Stratigraphy in 1960
Stratigraphy in mid-70’s

- Stratigraphy was considered a largely dead field caricatured by endless debates about what to name units.
- Same lithologies with same-age fossils were placed in different Formations because of arbitrary vertical cutoffs.
- Sedimentologists became more focused on tectono-petrographic studies or on environmental facies analysis.
- Facies models replaced stratigraphy in the classroom.
  - Wheeler’s science was ignored because he did not accept plate tectonic theory!
  - There were many “enlightened” but more applied “oily” stratigraphers (Rich, 1951; Asquith, 1970, 1974; Busch, 1972; Forgoston, 1957; Frazier, 1974), but they seemed to have been rather ignored by the greater academic community as reflected in the textbooks of the time.
State-of-the-art Stratigraphy in 1971 Using Environmental Lithofacies Concepts

Which of these arbitrary lithostratigraphic units will produce a coherent reflection?

Facies correlation

Fig. 4.—Schematic cross section of Medina Formation along Niagara escarpment, showing sequence of environments of deposition.

Flags or Reality?

Martini, 1971
State-of-the-art Stratigraphy in 1981 Using Environmental Lithofacies Concepts

- Which of these arbitrary lithostratigraphic units will produce a coherent reflection?
- Clearly facies analysis isn’t getting us where we need to go!

Facies correlation  
Hobday et al., 1981

Flags or Reality?
Stratigraphy or Flags in 2001?

- Representations of lateral transitions.
- No outcrop or seismic line even vaguely resembles these geometries!
- This is what the latest textbooks teach to undergraduates.

Boggs, 2001
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Seismic Stratigraphy

- Seismic reflections assumed to image bedding surfaces.
- Stratal discontinuities identified by reflection terminations (lapout).
- “Depositional Sequences” bounded by unconformities and their correlative conformities.
  - Typical resolution of about 10-100m.
Chronostratigraphic Significance of Seismic Reflections

- Why would anyone assume or assert that seismic reflections are effectively “time lines”?
  - “Primary seismic reflections are generated by stratal surfaces which are chronostratigraphic rather than by boundaries of arbitrarily defined lithostratigraphic units” - Vail et al., 1977

- What does this mean?
- The conclusion, that seismic reflectors are chronostratigraphic horizons “is clearly untenable in a literal sense…”
These Stratigraphic Depictions Don’t Look Like Seismic Lines!

What does the seismic image show that the geological cross sections fail to convey?

Muntingh and Brown, 1993
Stacking Fundamentally Enhances the Signal to Noise Ratio and Allows Imaging of Bedding Contacts, Even Where the Changes in Acoustic Properties Are Minimal.

All of these data = 1 trace (X) on a seismic line

- Coherent reflections (off bedding surfaces) constructively interfere.
- Incoherent reflections (lithofacies shazams) destructively interfere.

*The conclusion, that seismic reflectors are chronostratigraphic horizons “is clearly untenable in a literal sense.”*

Seismic vs. Well Logs

Vail, 1987
• Lithostratigraphic facies boundaries are gradational and form “Shazam”-type, interfingering boundaries.
• Seismic reflections are interpreted to mark bed, bedset or parasequence boundaries.
• Bed, bedset or parasequence boundaries are typically sharply defined surfaces across which there is a marked lithological change.

Vail, 1987
Lapout

- Termination of reflections termed lapout.
- Used to separate apparently conformable sedimentary units.

Vail, 1987
Incised Valleys

- Truncation of strata at valley floor and margins.
- Onlap and downlap of strata within valley.
Ferron Valleys - Outcrop Example

- Truncation of strata at valley floor and margins.
- Onlap and downlap of strata within valley.

Barton et al., 2004
Accommodation Successions: Brazil

PASS—PA sequence set; RSS—R sequence set; APSS—APD sequence set
Stratal stacking patterns associated with changing rates of coastal accommodation creation ($\delta A$) and sediment fill ($\delta S$): accommodation succession or clinoform trajectory

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Accommodation Successions and Clinoform Trajectory

A. Accommodation succession sets
- APD (aggradation-progradation-degradation)
- R (retrogradation)
- PA (progradation-aggradation)

B. Idealized facies distribution
- Nonmarine
- Coastal marine
- Shelfal marine/hemipelagic
- Incised valley fill
- Deep marine fan
- Mass transport complex
- Coal
- Stratal surfaces

Retrogradation (backstepping) $\delta A/\delta S > 1$
Aggradation to progradation (degradation possible) $\delta A/\delta S < 1$, decreasing
Bypass (?) then progradation to aggradation $\delta A/\delta S < 1$, increasing

Downward (basinward) shift in coastal onlap (and facies)
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Well Log Example: Dunvegan Formation, Alberta, Canada

Seismic stratigraphic concepts led to a re-evaluation of well-log stratigraphic approaches

A.G. Plint, 2000
Pseudoseismic Display: Using Well Logs

From J. Hammett, 2009, MS UH
Outcrop Correlation Panel

Bentonites = Datum

Cretaceous Ferron Notom Delta, Utah
43 Parasequences, 18 Parasequence Sets, 6 Sequences
Well-developed parasequence stacking patterns define systems tracts.
• Evidence for 60 m drops of relative sea-level, assuming horizontal datum
• High frequency sequences, could be eustatic?
• Stacking Patterns
  A - Aggradational, P - Progradational, D- Degradational, R - retrogradational
Wheeler Diagram  
Relative Sea Level 

Yijie Zhu, 2010
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Conclusion: What Are Sequences Made Of?

The seismic approach led to a more detailed application of Sloss and Wheeler’s ideas to the stratigraphic record.

Van Wagoner et al., 1990
Conclusion:

- If an outcrop or well log cross section looks like a seismic line, it’s probably right!

Outcrop Lithostratigraphy

Seismic Stratigraphy, Modern Rhone shelf

Wheeler and Mallory, 1953

Well Log Sequence Stratigraphy

Plint, 2000

Tesson et al., 1993
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