PS Reservoir Scale Modulation of Turbidite Architecture Related to Paleo-gradients Generated by Syn-sedimentary Structural Growth and Segmentation of an Overfilled Foreland Basin System: The Marnoso-Arenacea Formation at the Coniale Anticline, Northern Apennines, Italy*

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Abstract

The link between tectonics and sedimentation is arguably best exemplified in deep-marine foreland basin systems where structural deformation is contemporaneous with turbidite sedimentation. The distribution and modulation of sedimentary attributes defining deepwater sedimentation regions record changes in paleo-gradient framed by five orders of tectonic deformation. Second-order foreland basin systems consist of third-order wedge-top, foredeep, forebulge, and back-bulge structural domains. Fourth-order structural growth of a submarine anticline segments and transforms the third-order foredeep into the wedge-top structural domain. The Coniale Anticline manifests a fourth-order structure containing attendant fifth-order mass-transport-deposits defining four sedimentation regions represented by pre- and syn-kinematic turbidite distributions across the structure.

Tabular lobes and fine-grained carbonate drapes are the dominant sedimentary bodies in an overfilled basin, where lateral expansion of large turbidity currents scale to the basin width. Consequently, sedimentation units are equivalent to sedimentary bodies, simplifying the number of sedimentary attributes required for analysis. Wavy stratification is moderately subordinate to structureless sandstone in pre-kinematic turbidite sedimentation units which contain thinner mudstone caps, but separated by thicker calcareous mud drapes. There is more uniformity in these attributes across the structure (~5 km distance). By contrast, syn-kinematic turbidites show more variation in component facies, sedimentation unit thickness, and cyclic modulation of sedimentary bodies across the structure, including the addition of mass-transport deposits on the east flank of the structure.

Paleo-gradients of fourth- and fifth-order tectonic surfaces are determined from a partial 3D restoration of the structure and correlate structural growth to turbidite distribution and modulation. Fourth-order structural growth segments foreland domains and combined with fifth-order structure-generated surfaces explains changes in the four sedimentation regions. This suggests that lower resolution structural features can be used to assess smaller reservoir-scale architecture relevant to subsalt prediction in the Gulf of Mexico.

Reservoir Scale Modulation of Turbidite Architecture Related to Paleo-gradients Generated by Syn-sedimentary Structural Growth and Segmentation of an Overfilled Foreland Basin System: The Marnoso-arenacea Formation at the Coniale Anticline, Northern Apennines, Italy

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The link between tectonics and sedimentation is arguably best exemplified in deep-marine foreland basin systems where structural deformation is contemporaneous with turbidite sedimentation. The distribution and modulation of sedimentary attributes defining deep-water sedimentation regions record changes in paleo-gradient framed by five orders of tectonic deformation. Second-order foreland basin systems consist of third-order wedge-top, foredeep, forebulge, and back-bulge structural domains. Fourth-order structural growth of a submarine anticline segments and transforms the third-order foredeep into the wedge-top structural domain. The Coniale anticline manifests a fourth-order structure containing attendant fifth-order mass-transport-deposits defining four sedimentation regions represented by pre- and syn- kinematic turbidite distributions across the structure.

Tabular lobes and fine-grained carbonate drapes are the dominant sedimentary bodies in this overfilled basin, where lateral expansion of turbidity currents scale to the basin width. Consequently, sedimentation units are equivalent to sedimentary bodies. Wavy stratification is moderately subordinate to structureless sandstone in pre-kinematic turbidite sedimentation units which contain thinner mudstone caps, but separated by thicker calcareous mud drapes. There is more uniformity in these attributes across the structure. By contrast, syn-kinematic turbidites show more variation in component facies, sedimentation unit thickness, and modulation of sedimentary bodies across the structure.

Paleo-gradients of fourth- and fifth- order tectonic surfaces will be examined from a 3D restoration of the structure and cross-referenced with turbidite distribution and modulation. Comparing tectonic evolution to sedimentation heterogeneity will test wether lower resolution structural features can be used to assess reservoir-scale architecture relevant to subsalt prediction in the Gulf of Mexico.

Introduction:

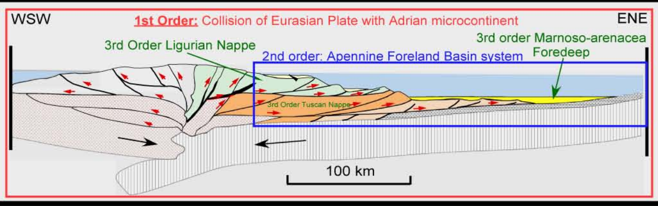
The Problem:

Can low magnitude, high frequency physical growth of a submarine fault propagation fold generate a recognizable response in turbidite architecture?

High order modulation in sedimentary attributes documented across time space domains.
Multiple possibilities on forcing functions to drive sedimentary modulation
Alpine vs. Apenine source: Event Frequency and Magnitude

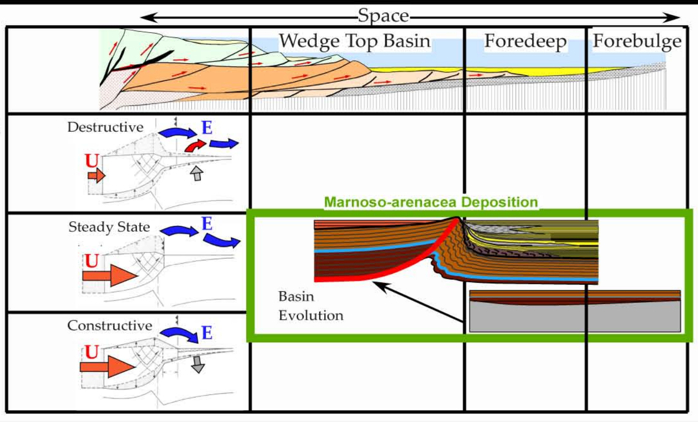
Tectonic Orders of Deformation Affecting Gradient:

- Five Orders
- Correlate to 5 gradient types (Gardner, 2011)
- Process = Cycles of structural growth and quiescence
- Response = sedimentary attributes
- Marnoso-arenacea: Outcrop laboratory

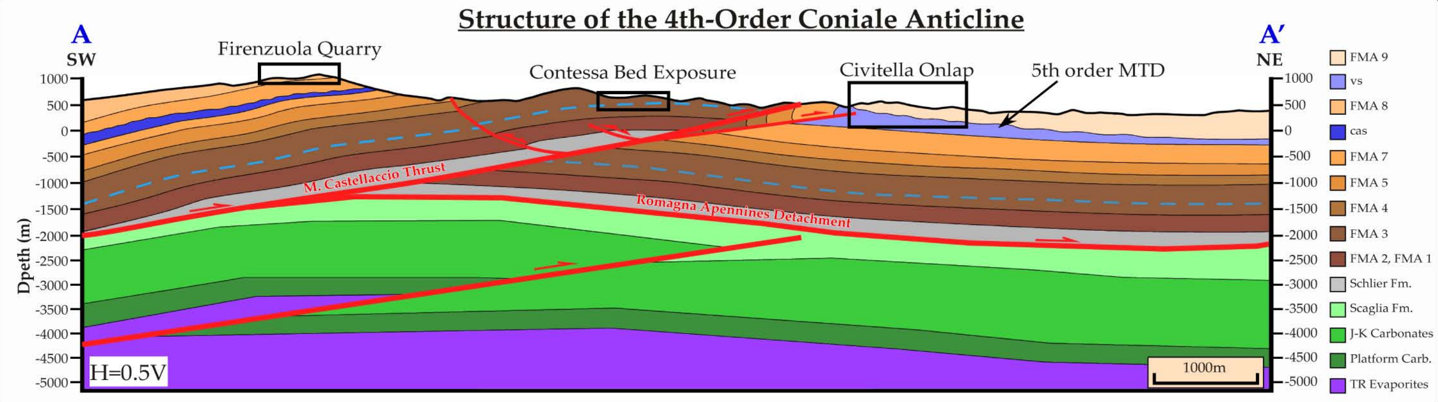


Define Sedimentary Response by Time-Space Domains

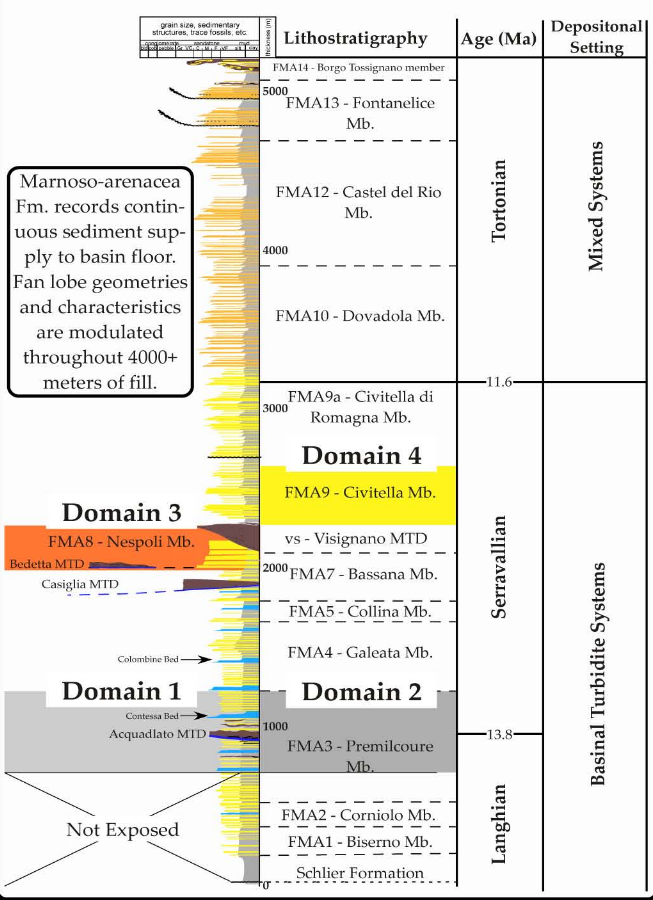
- Foreland basin system = dynamic
- Phases of orogeny correlate to sedimentary energy
- Study area examines evolution from foredeep to wedge top domain during steady state phase of Alpine orogeny (Bernet et al., 2001).

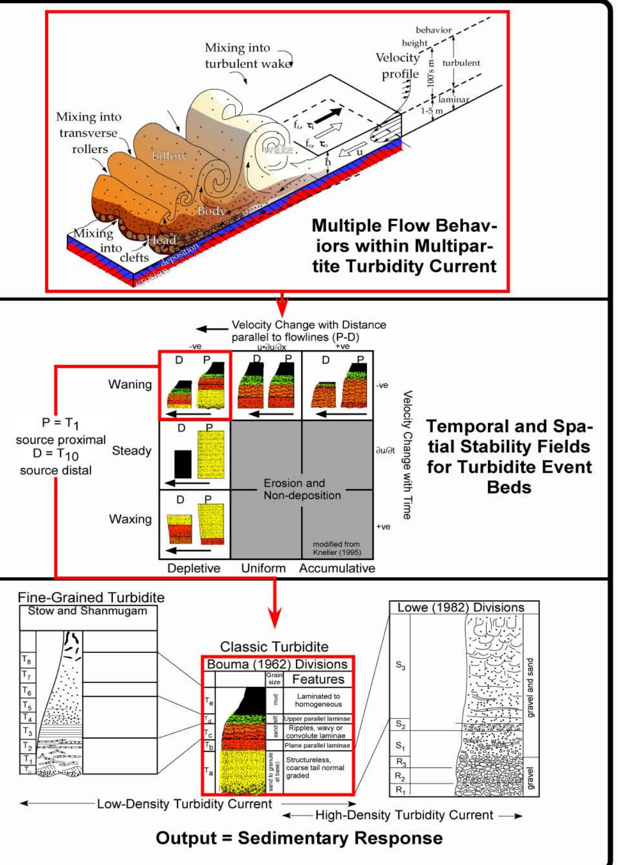


Structure of the 4th-Order Coniale Anticline

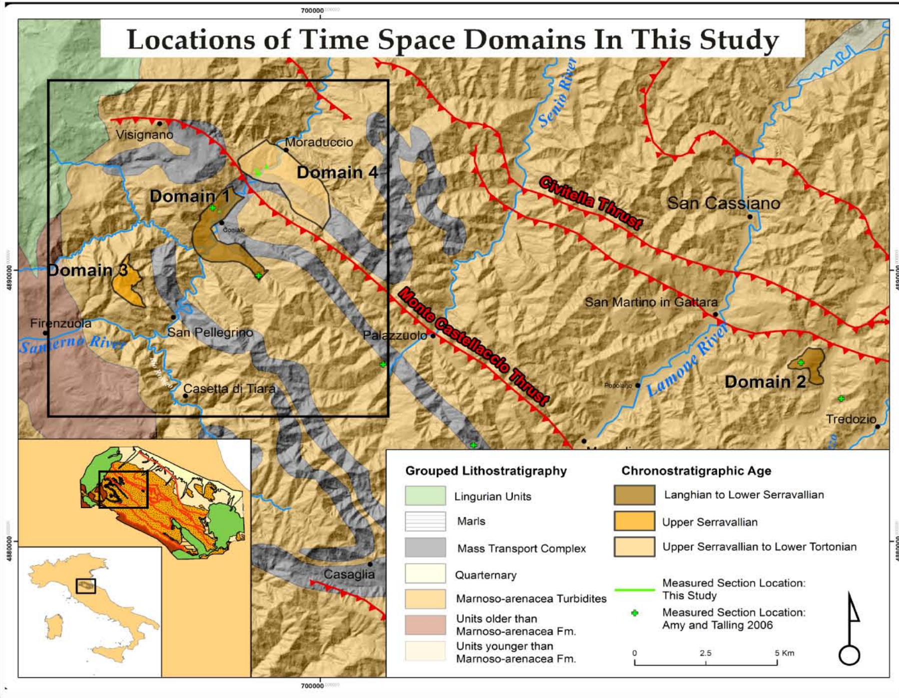


Generalized Stratigraphic Profile of the Santerno River Valley



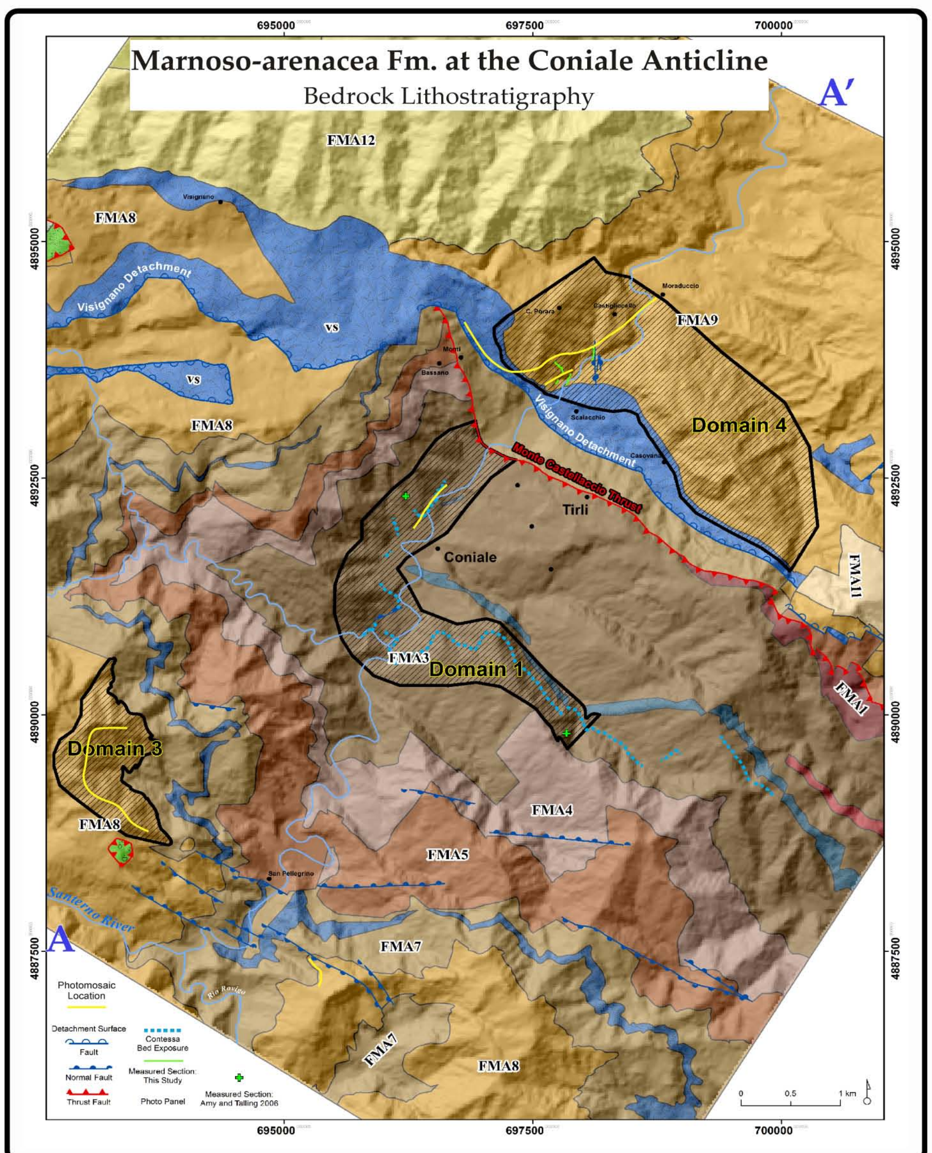


Locations of Time Space Domains In This Study



Marnoso-arenacea Fm. at the Coniale Anticline

Bedrock Lithostratigraphy



Key Concepts

- Intraclasts: Bed amalgamation vs. flow reflection
- Provenance: Two sources
- Calcareous mudrocks = pelagic deposition
- Hummocky-swaley cross stratification = shallow water, not flow reflection

Range and Importance of Hydrodynamic Facies in Basin Plain Setting

Increasing Process of Formation Energy

Sandstone		
4	Intraformational pebble to granule mudrock intraclasts (<20%) in vf - med sand	High Conc. SGF
5	Cm-spaced, low-angle to planar stratification	Low Conc. SGF / High Conc. SGF
6	Planar-tabular cross stratification	Low Conc. SGF / High Conc. SGF
7B	Mounded to wavy laminated cross-stratified sandstone	Low Conc. SGF / High Conc. SGF
8A	Structureless Sandstone (Depositional)	Low Conc. SGF / High Conc. SGF
8B	Structureless Sandstone (Post-Depositional)	High Conc. SGF
9	Plane-parallel Laminated Sandstone	Low Conc. SGF
10B	Sub-critically climbing asymmetrical cross laminated sandstone	Low Conc. SGF
10E	Super-critically climbing asymmetrical cross laminated sandstone	Low Conc. SGF
11A	Muddy sandstone with unorganized intraclast fraction	Debris Flow
11B	Muddy sandstone with organized intraclast fraction	Debris Flow
11C	Intraclast deficient muddy sandstone	Debris Flow
Mudrock		
12A	Slurry bed with silt dominated matrix and unorganized suspended intraclasts	Debris Flow
12B	Slurry bed with silt dominated matrix and organized suspended intraclasts	Debris Flow
12C	Intraclast deficient slurry bed with silt dominated matrix	Debris Flow
13B	Plane parallel laminated siltstone	Low Conc. SGF
13C	Ripple cross-laminated siltstone with organic rich drapes	Low Conc. SGF
14A	Carbonaceous Silt-dominated, clay-bearing organized mudstone	Low Conc. SGF
14Bi	Carbonaceous Clay-dominated, silt-rich organized mudstone	Low Conc. SGF
14Bii	Carbonaceous Clay-dominated, silt-bearing unorganized mudstone	Suspension Fallout
15A	Organized calcareous clay-dominated, silt-bearing mudstone	Suspension Fallout
15B	Disorganized calcareous clay-dominated, silt-bearing mudstone	Suspension Fallout
Post-Depositional		
16	Intercalated deformed sandstone and mudrock	
17A	Burrowed and bioturbated sandstone	
17B	Burrowed and bioturbated mudrock	

Genetic Implications for Hummocky Swaley Cross-Stratification

Interpretation: Turbidity current interacts with secondary bore reflection from local seabed relief

Genetic Implications for Debris Flow Depositional Mechanisms

Interpretation: Hybrid "sandwich" bed with cm to m-scale intraclasts and secondary fluidization and liquefaction structures. Rapid transition from turbulent to cohesive flow during collapse.

Interpretation: Linked debrite with cm-scale intraclasts. Rapid transition from turbulence to cohesion by matrix added from surging to collapse upper part of late stage flow.

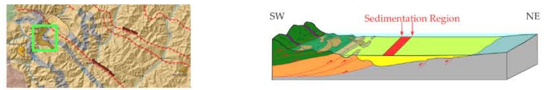
Interpretation: Silty sandstone "grunge". Turbulent suppression by cohesion from increased silt concentration by hydraulic fractionation in source-distal flow.

Genetic Implications for Calcareous Mudrock Depositional Mechanisms

Interpretation: Hemipelagic deposition from tail end of late stage low density turbidity current where suspension settling rates > shear velocity.

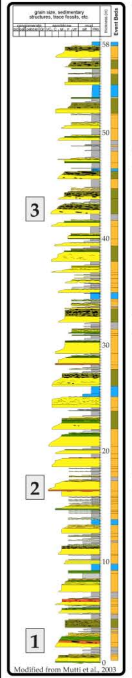
Interpretation: Pelagic deposition from paratochthonous carbonate mud sources on local intrabasinal highs.

Domain 1: Contessa Interval at Coniale

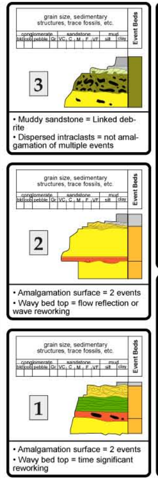


Key Concepts

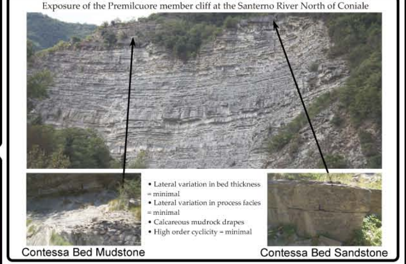
- Hanging wall of Monte Castellaccio Thrust
- Long correlation lengths of both turbidite and debrite sandstones
- Lower frequency and magnitude of sedimentation events:
  - Higher frequency of pelagic mudrocks and wavy stratification
- Low lateral facies evolution in turbidite and debrite event beds
- High frequency vertical cyclicity weakly expressed
- <u>Low spatial-temporal attribute modulation consistent with flat, low gradient basin plain interpretation</u>

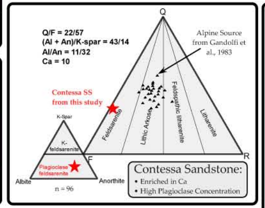


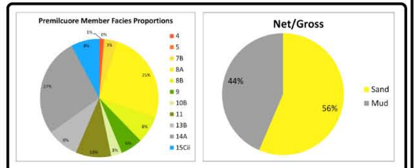
Modified from Mutti et al., 2003



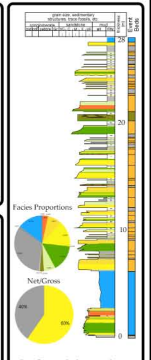
Exposure of the Premilcuore member cliff at the Santerno River North of Coniale





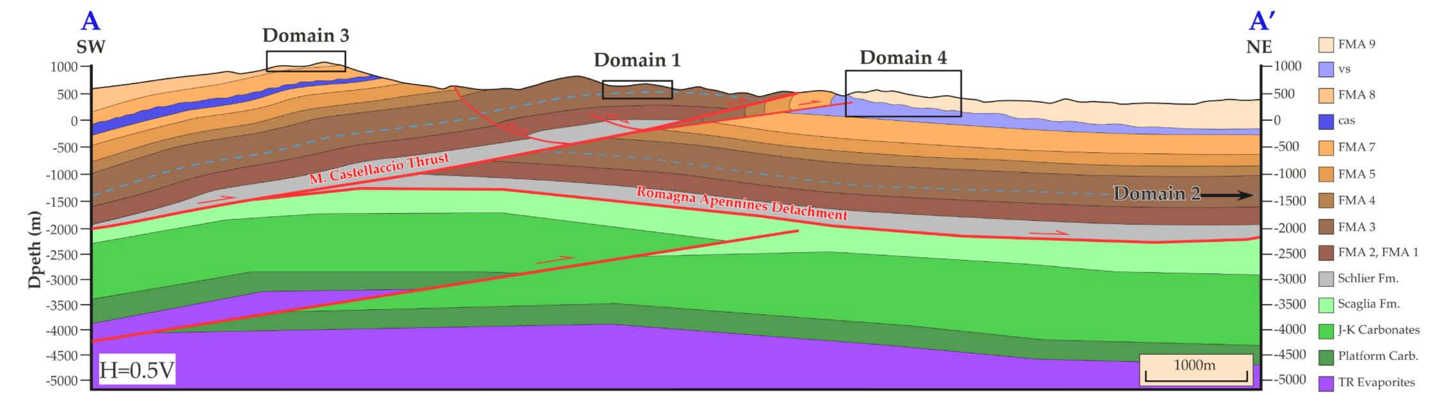


Detailed facies proportional analysis of the Premilcuore Member at Coniale

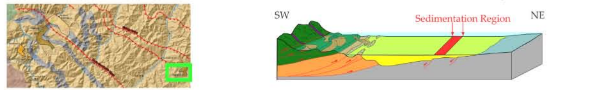


Post-Contessa bed measured section at Coniale. Modified from Amy and Talling, 2006

Attributes of Time Space Domains for this Study

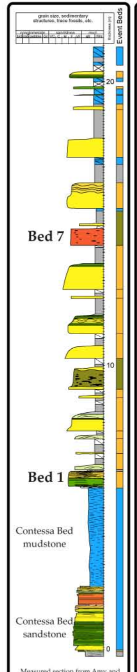


Domain 2: Contessa Interval NW of Modigliana

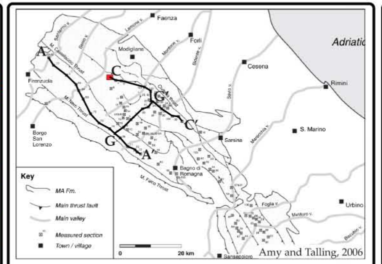


Key Concepts

- Footwall of Monte Castellaccio Thrust
- High fidelity correlation of sedimentary attributes with Domain 1
- Lower net/gross = down-flow evolution
- Higher proportion of pelagic mudrocks
- Higher frequency of wavy stratification at bed tops, often bioturbated
- <u>Low spatial-temporal attribute modulation across modern structure is consistent with flat, low gradient basin plain interpretation</u>

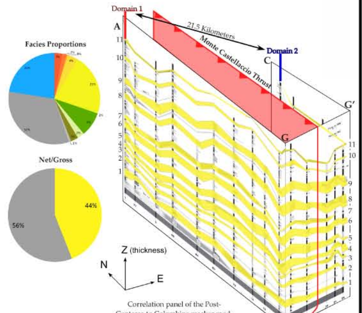


Measured section from Amy and Talling, 2006

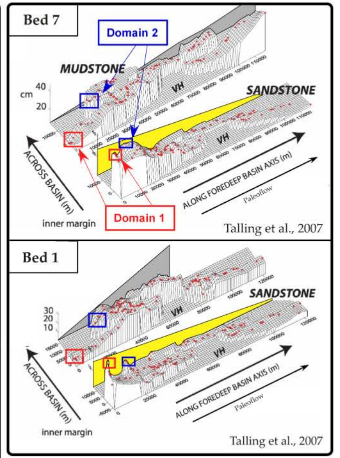


<u>Talling et al., 2007: Basin wide correlation of Contessa to 1st Colombine bed interval:</u>

- Low lateral variation across large distances
  - SS bed thickness constant
  - Few bed pinchouts
  - Sand and mud ratios reflect downcurrent hydraulic segregation
- Structural elements of present day Romagna Apennines were not present during deposition of this interval



Correlation panel of the Post-Contessa to Colombine marker modified from Amy and Talling, 2006.

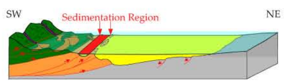


Tobler's first law of geography:

"Near things are more related than distant things"

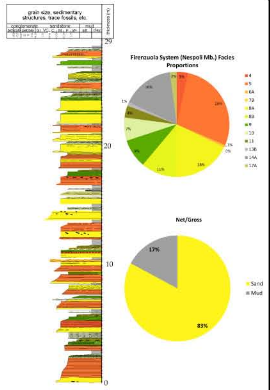
- 21 kilometer distance between domains 1 and 2
- Similarity in process facies
  - Wavy stratification
  - Structureless sandstone
  - Muddy sandstones
- Correlation of sedimentation events
  - 11 events correlated
  - Sand thins, muds thicken in down-flow direction

Domain 3: Firenzuola System at Quarry



Key Concepts

- Hanging wall of Monte Castellaccio Thrust
- Thick bedded, sandstone dominated wedge top basin
- High net/gross
- Structureless and space stratified sandstone dominant, wavy and plane-parallel sandstones subordinate
- Amalgamation surfaces frequent; intraclast horizons = amalgamations, not sandwich beds
- No calcareous mudrocks
- Energy increases, but modulation of sedimentary attributes is limited



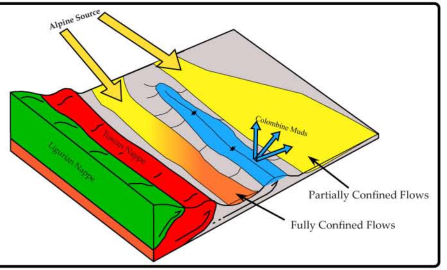
Grain size distribution for the Firenzuola system measured section modified from Mutti et al., 2003.

Quarry in the Firenzuola system. Crane for scale

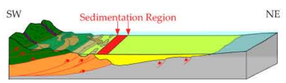
Outcrop photos of the Firenzuola system showing thick bedded, coarse nature of wedge top basin.

Wedge Top Domain:
High Energy

↑ Event Magnitude
↑ Event Frequency
↓ Calcareous Drapes
↓ Wavy stratification
↓ Sedimentological modulation

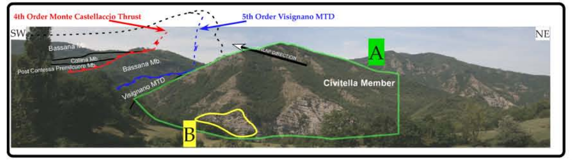


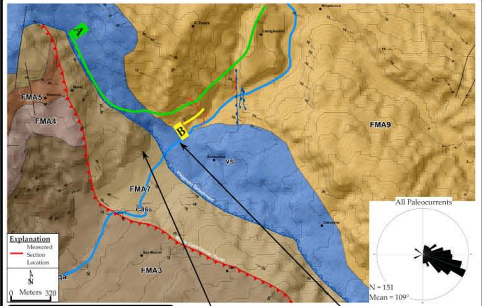
Domain 4: Civitella Onlap Growth Strata



Key Concepts

- Footwall of Monte Castellaccio Thrust
- High order stratigraphic cyclicity recorded by multiple sedimentary attributes
- Variation in component facies through time
  - Lower calcareous mudrock and wavy stratification frequency
  - Intraclast bearing sandstones: amalgamation surfaces, *not sandwich beds*
- Debrite concentration greatest during Initiation and increases towards onlap
- No calcareous mudrocks
- Some sedimentary attributes similar to Domains 1 and 2, but high order modulation suggests syn-sedimentary growth





Geologic map displaying data distribution used in this analysis. Interpreted photomosaic lines shown by color.

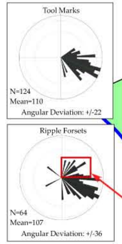
Disharmonic Tectonic Folding

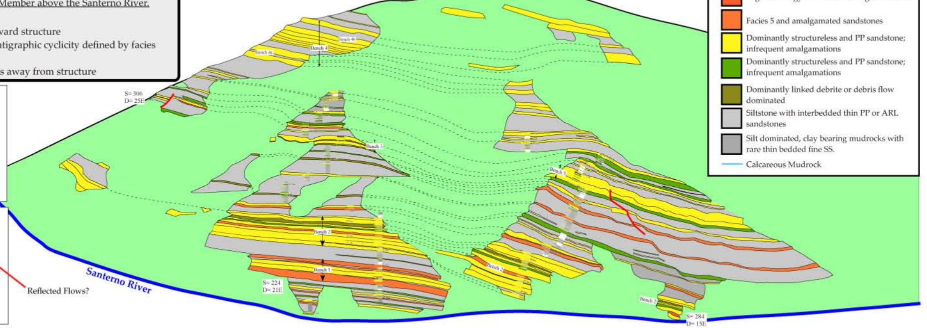
Mass Transport Folds

A Interpreted photopanel of a depositional strike view of the Civitella Member above the Santerno River.

Note:

- Dip change toward structure
- High order stratigraphic cyclicity defined by facies associations
- Amalgamations away from structure



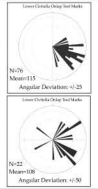


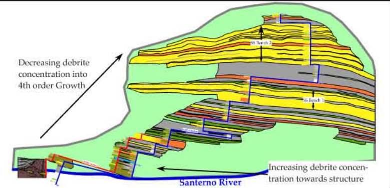
- Highest Energy: Intraclast bearing sandstones
- Facies 5 and amalgamated sandstones
- Dominantly structureless and PP sandstone; infrequent amalgamations
- Dominantly structureless and PP sandstone; infrequent amalgamations
- Dominantly linked debrite or debris flow dominated
- Siltstone with interbedded thin PP or ARL sandstones
- Silt dominated, clay bearing mudrocks with rare thin bedded fine SS.
- Calcareous Mudrock

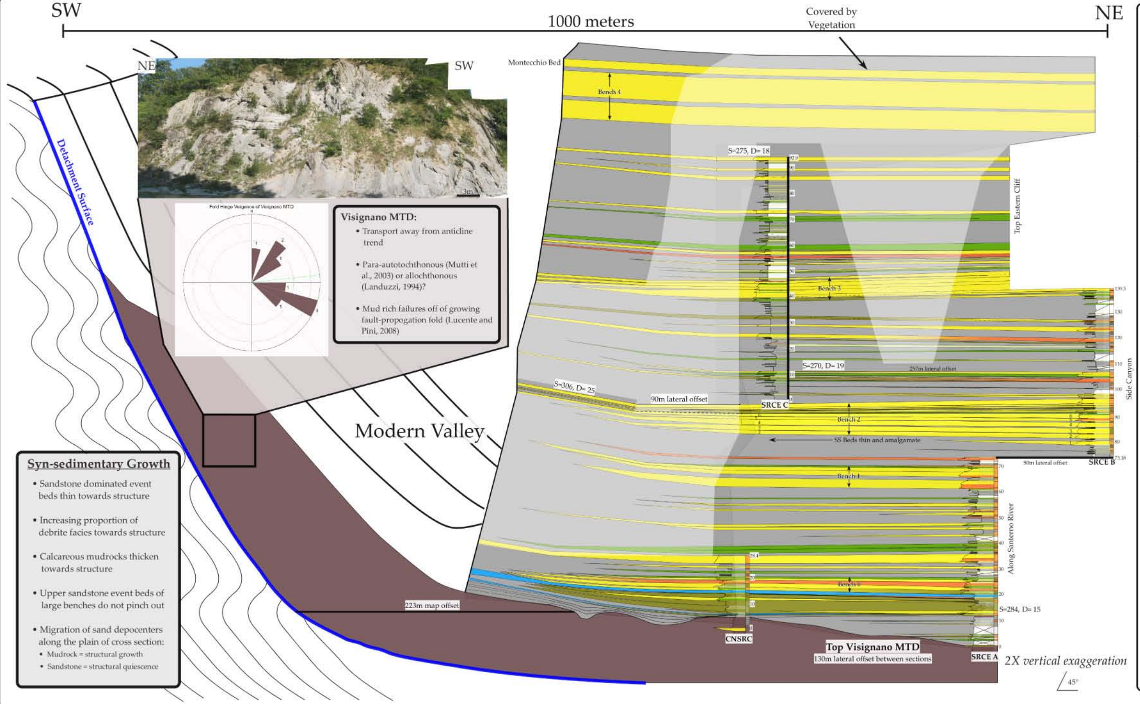
B Interpreted photomosaic of the lower onapping strata of the Civitella Mb.

Note:

- Rapid lateral facies changes
- Rapid lateral thickness variation in thin and thick beds
- Amalgamation of beds off structure
- Amalgamation of beds towards struc ture in Bench 2





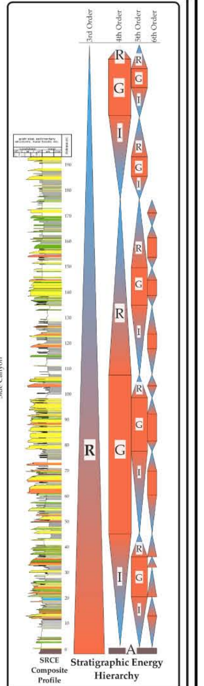


Visignano MTD:

- Transport away from anticline trend
- Para-autotochthonous (Mutti et al., 2003) or allochthonous (Landuzzi, 1994)?
- Mud rich failures off of growing fault-propogation fold (Lucente and Pini, 2008)

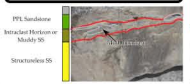
Syn-sedimentary Growth

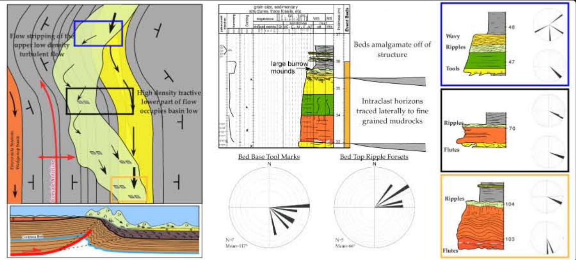
- Sandstone dominated event beds thin towards structure
- Increasing proportion of debrite facies towards structure
- Calcareous mudrocks thicken towards structure
- Upper sandstone event beds of large benches do not pinch out
- Migration of sand depocenters along the plain of cross section:
  - Mudrock = structural growth
  - Sandstone = structural quiescence



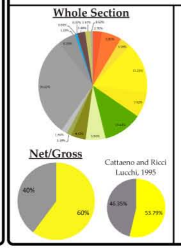
Sandwich Beds vs. Bed Amalgamation: Evidence for flow reflection

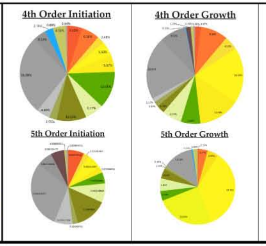
- Intraclast not requirement for flow reflection
- Paleoflows on bed tops and bottoms are not uniformly varying
- Intraclast horizons turn into mudrock layers laterally
- Consequence of amalgamating off of structure

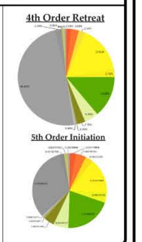




Sedimentology Attributes by Ordinal Stratigraphic Phases







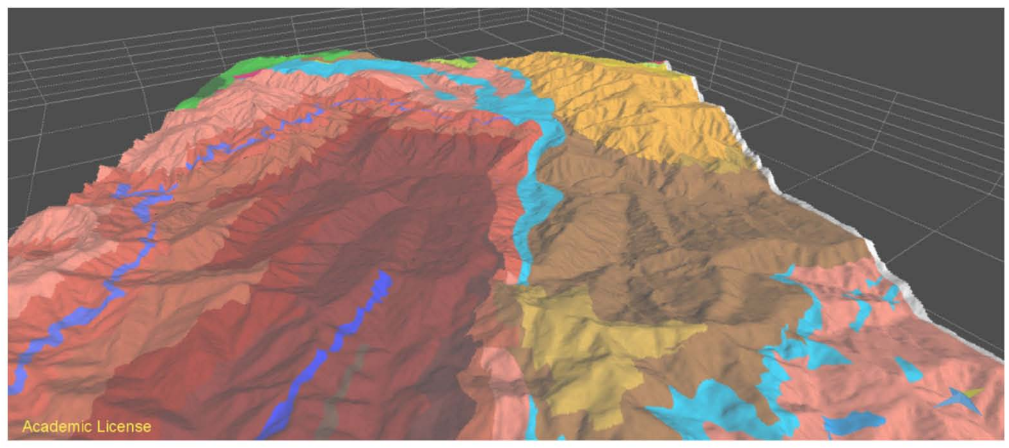
Conclusions

- Stratigraphic metrics defining each domain record multiple orders of tectonic deformation
- Domains 1 and 2 record flat basin plain modified only by 3rd order tectonic evolution:
  - Monte Castellaccio thrust not emergent
  - Remarkable continuity of process facies, sedimentation units and sedimentary bodies:
    depositional topography + climate + far-field tectonics > local tectonic gradients as forcing function
- Domains 3 and 4: Decoupled relationship of syn-kinematically developing wedge top to foredeep domains:
  - Domain 3 = high frequency and magnitude turbidite events bypassing fine grained sediment
    - Lack of high order stratigraphic modulation
  - Domain 4 = High order modulation of turbidite event frequency and magnitude combined with MTD detachments and facies diversity
    depositional topography + climate + far-field tectonics < local tectonic gradients as forcing function

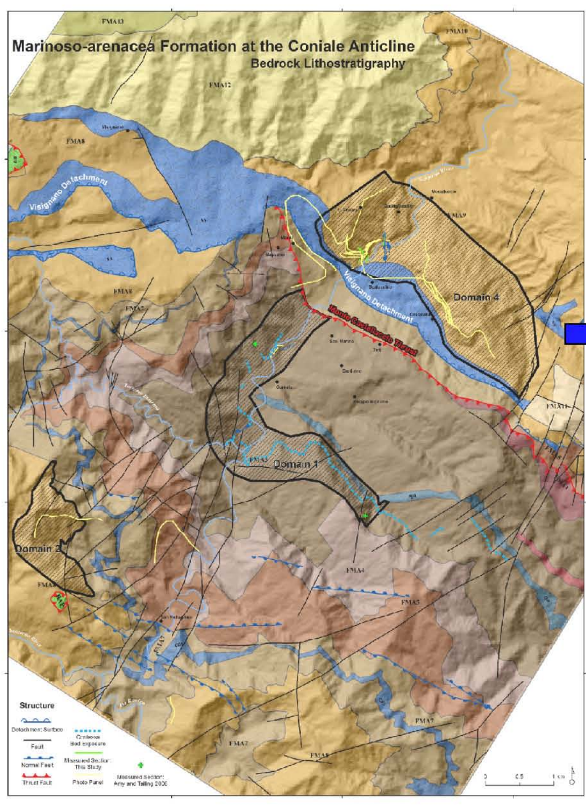
Current Work: Structural Modeling

Use 3D structural restoration of Coniale Anticline to restore to Domain 1 time of a undeformed basin plain

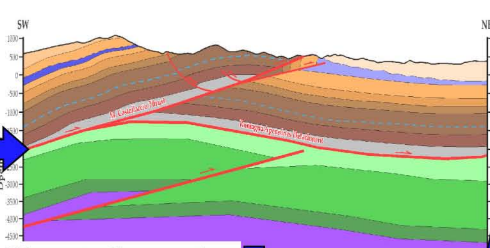
- Test validity of structural motion to accommodate gradient modifications
- Input horizons from lithostratigraphic mapped units, time constrained by biostratigraphic markers.
- Populate deformed model with measured section data and high resolution mapped horizons from photopanels projected onto DEM surface
- Project into cross section network and interpolate horizons
- Retrodeform according to time steps defined by:
  - Low order = Lithostratigraphic chronostratigraphy
  - High order = mapped energy cycles of each domain



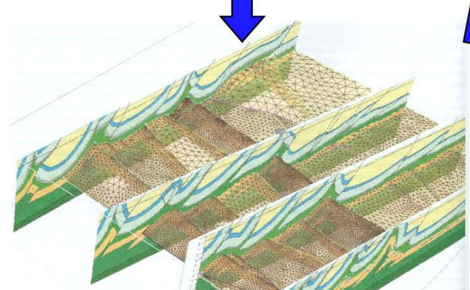
3D model of surface geology in the study area



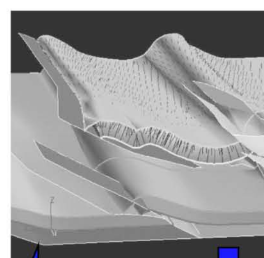
Workflow of structural restoration project



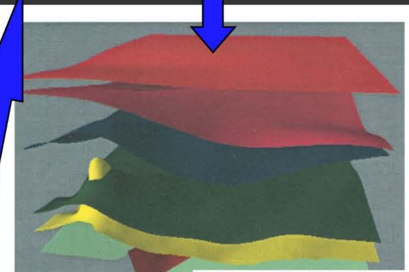
Generate Cross sections



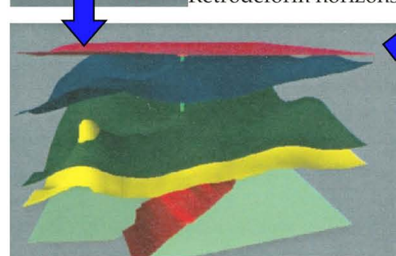
Interpolate Horizons



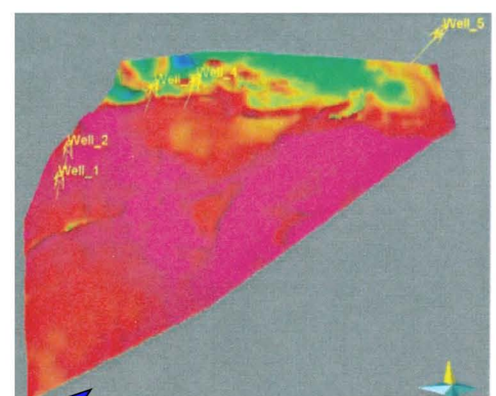
Interpolate Faults



Retrodeform horizons



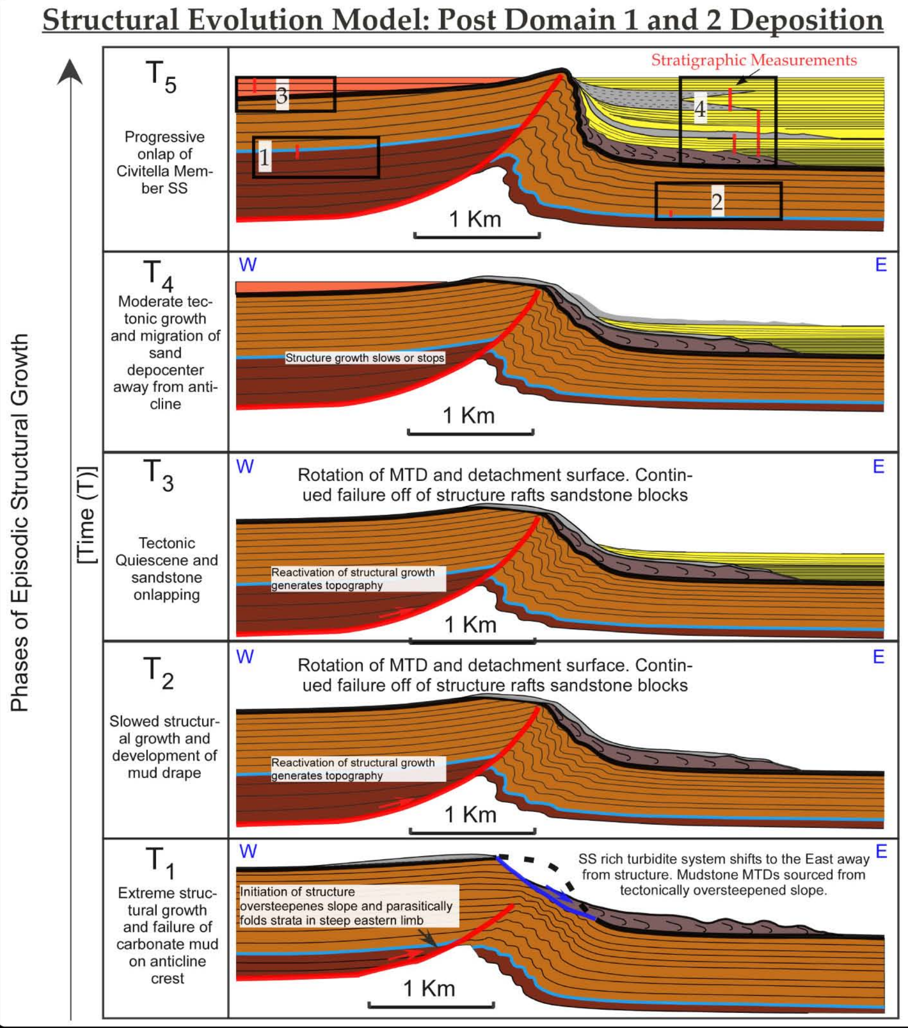
Remove horizons and decompact



Measure gradients

Does Paleo gradient evolution match stratigraphic energy evolution?

Structural Evolution Model: Post Domain 1 and 2 Deposition



GOM Application:

- Deepwater turbidite depositional systems from Paleogene to Miocene
- Allochthonous salt coverage increases uncertainty in subsalt interpretation
- Visible structures that can be mapped
- Use structural hierarchy for prediction
- Sedimentary response documented at Coniale anticline = pattern for subsalt prediction.

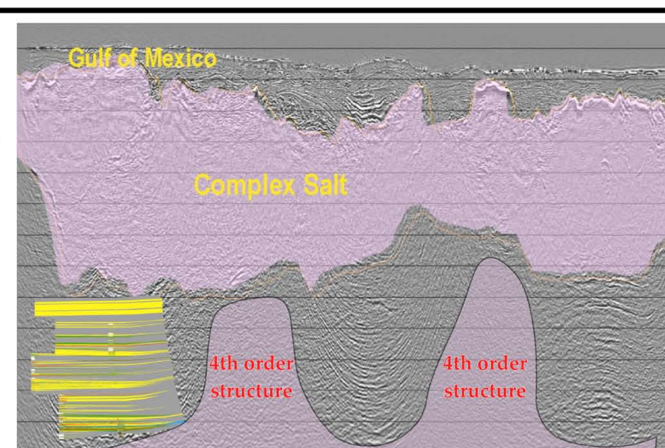


Image from Nick Moldoveanu (Courtesy Schulumberger WesternGeco)

Autotochthonous salt diapir overlain by allocthonous salt canopy from the GOM

Autotochthonous salt diapir from the North Sea

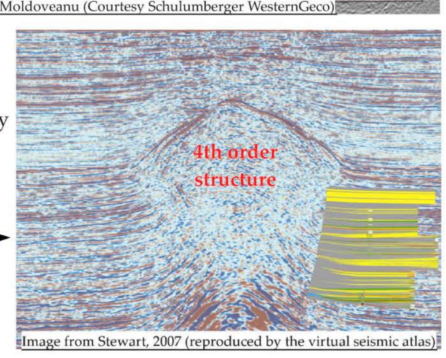


Image from Stewart, 2007 (reproduced by the virtual seismic atlas)

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References:

- Amy, L.A., and Talling, P.J., 2006, Anatomy of turbidites and linked debrites based on long distance (120X30 km) bed correlation, Marnoso-arenacea Formation, Northern Apennines, Italy: Sedimentology, v. 53, p. 161-212.
- Bernet, M., Zattin, M., Garver., J.I., Brandon, M.T., Bance, J.A., 2001, Steady-state exhumation of the European Alps: Geological Society of America, v. 29, p. 35-38.
- Gandolfi, G., Paganelli, L., 1983, Petrology and dispersal pattern in the Marnoso-Arenacea Formation (Miocene, northern Apennines): Journal of Sedimentary Petrology, v. 53, p. 493-507.
- Gardner, 2011, Deepwater reservoir presence and architecture field course: Illustrated with examples from the Permian Brushy Canyon Formation, Guadalupe and Delaware Mountains, West Texas: Unpublished Fieldtrip Guidebook.
- Landuzzi, A., with a contribution by Negri, A., 1994, Relationships between the Marnoso-Arenacea Formation of the inner Romagna units and the Ligurids (Italy): Memorie della Società Geologica Italiana, v. 48, p. 523-534.
- Lucente, C.C., and Pini, G.A., 2008, Basin-wide mass-wasting complexes as markers of the Oligo-Miocene foredeep-accretionary wedge evolution in the Northern Apennines, Italy: Basin Research, v. 20, p. 49-71.
- Mutti, E., Ricci Lucchi, F., Roveri, M., 2002, Revisiting turbidites of the Marnoso-arenacea Formation and their basin-margin equivalents: problems with classic models: in Excursion Guidebook of Turbidite Workshop organized by Dipartimento di Scienze della Terra, Universita di Parma and Eni-Agip Division of the 64th EAGE Conference and Exhibition, Florence, Italy, 27-30 May 2002. 128 p.
- Ricci Lucci, F., Valmori, E., 1980, Basin-wide turbidites in a Miocene, over-supplied deep-sea plain: a geometrical analysis: Sedimentology, v. 27, p. 241-270.
- Talling, P.J., Amy, L.A., and Wynn, R.B., 2007, New insight into the evolution of large-volume turbidity currents: comparision of turbidite shape and previous modelling results: Sedimentology, v. 54, 737-769.
- Tinterri R., Magalhaes, P.M., 2011, Synsedimentary structural control on foredeep turbidites: An example from the Miocene Marnoso-arenacea Formation, Northern Apennines, Italy: Marine and Petroleum Geology, v. 28, p. 629-657.