# Episodic Deformation Rates Recovered from Growth Strata, Pyrenees*

**David Anastasio[1], Kenneth Kodama[1], and Josep Parés[2]**

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## Abstract

Growth strata are used to recover high-resolution incremental deformation rates in syntectonic strata. The synsedimentary strata preserve the interaction between uplift and sedimentation and require deconvolution of deformational and depositional processes. We used magnetostratigraphy and biostratigraphy to determine absolute time and to calibrate rock magnetic-based cyclostratigraphy for three regional Paleogene structures near the South Pyrenean mountain front. Incremental folding or fault slip rates were determined for each structure.

At Sant Llorenç de Morunys, a fault-propagation fold records uncoupled deformation and depositional rates and folding rates of 0 to 100 degrees/myr, which resulted from thrusting rates of 115-255 m/myr over 3 myr. At Pico del Aguila, the décollement anticline developed for 5.23 myr and records variations in folding rate of 0 to 95 degrees/myr as a result of episodic thrusting in the fold's core. Near Sos del Rey Católico, the Peña duplex records the growth of a thrust-related anticline that delineates the southwestern mountain front. Shallowing of the growth strata up-section was related to slip on a mountain front backthrust where deformation and deposition were coupled. Folding rates calculated from the growth strata at the resolution of the polarity chrons (0.42-2.5 myr), varies from 4 to 13 degrees/myr over 10 myr. At each location, our metronome was cyclostratigraphy related to magnetic-mineral concentration variations in the growth strata that were modulated by astronomically forced climate changes. Each fault related-fold recorded episodic deformation at 104 years time scales accompanying depositional rate variations. The marine and continental growth deposits had order of magnitude difference in accumulation rate variability depending on facies and accommodation space development.

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# EPISODIC DEFORMATION RATES RECOVERED FROM GROWTH STRATA, PYRENEES


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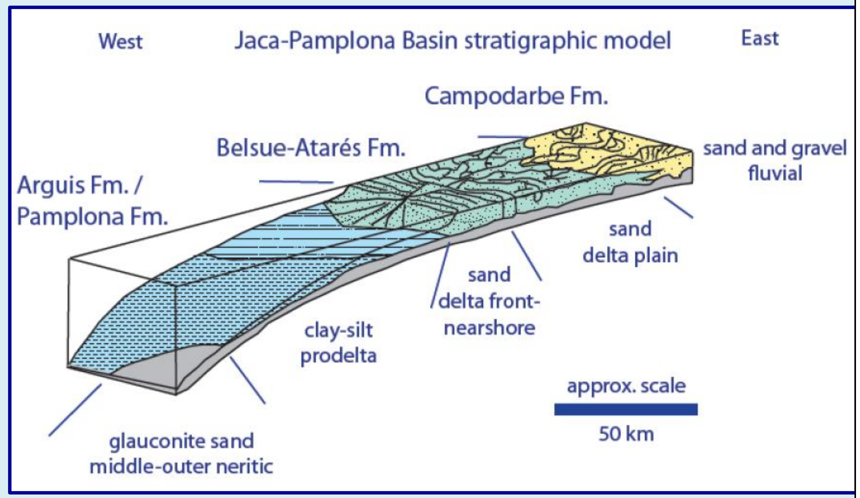
Presenter's Notes: Thanks for staying until the end of the session. Today I will focus on the intermediate scales of deformation-$10^{4-5}$ years, 10 thousand to 100 thousand year timespans; longer than geodesy but shorter than traditional numerical ages from many radioisotope-based systems. My group has determined these from the magnetostraphic dating and rock magnetic based cyclostratigraphy we have recovered from terrestrial and marine growth strata.

As we work to sort out what intrinsic and extrinsic processes modulates deformation, it is important we understand the characteristic patterns –fast or slow, and time scales behavior – steady or unsteady, of deformation.

Today a insights from my and my students work in the Pyrenees.

# Pico del Aguila anticline




*Anastasio et al., 2015*

- Deformation begins, accelerates to a maximum rate, then decelerated to the end of deformation
- Deformation is unsteady at $10^4$ and $10^5$ time scales
- Deformation of the regional scale structure took ~5myrs
- Deformation includes periods of tectonic quiescence

Presenter's Notes: The first example comes from the central thrust front of the Spanish Pyrenees. Pico del Aguila anticline is a transverse décollment fold that developed atop the frontal thrust sheet of the southern Pyrenees during basin and strike parallel delta progradation in the Paleogene wedge-top basin. A reconstruction of the delta is shown on the right, the fold is pictured on the left. The horizontal dimension of the image is ~6km. *(Presenter's notes continued on next slide.)*

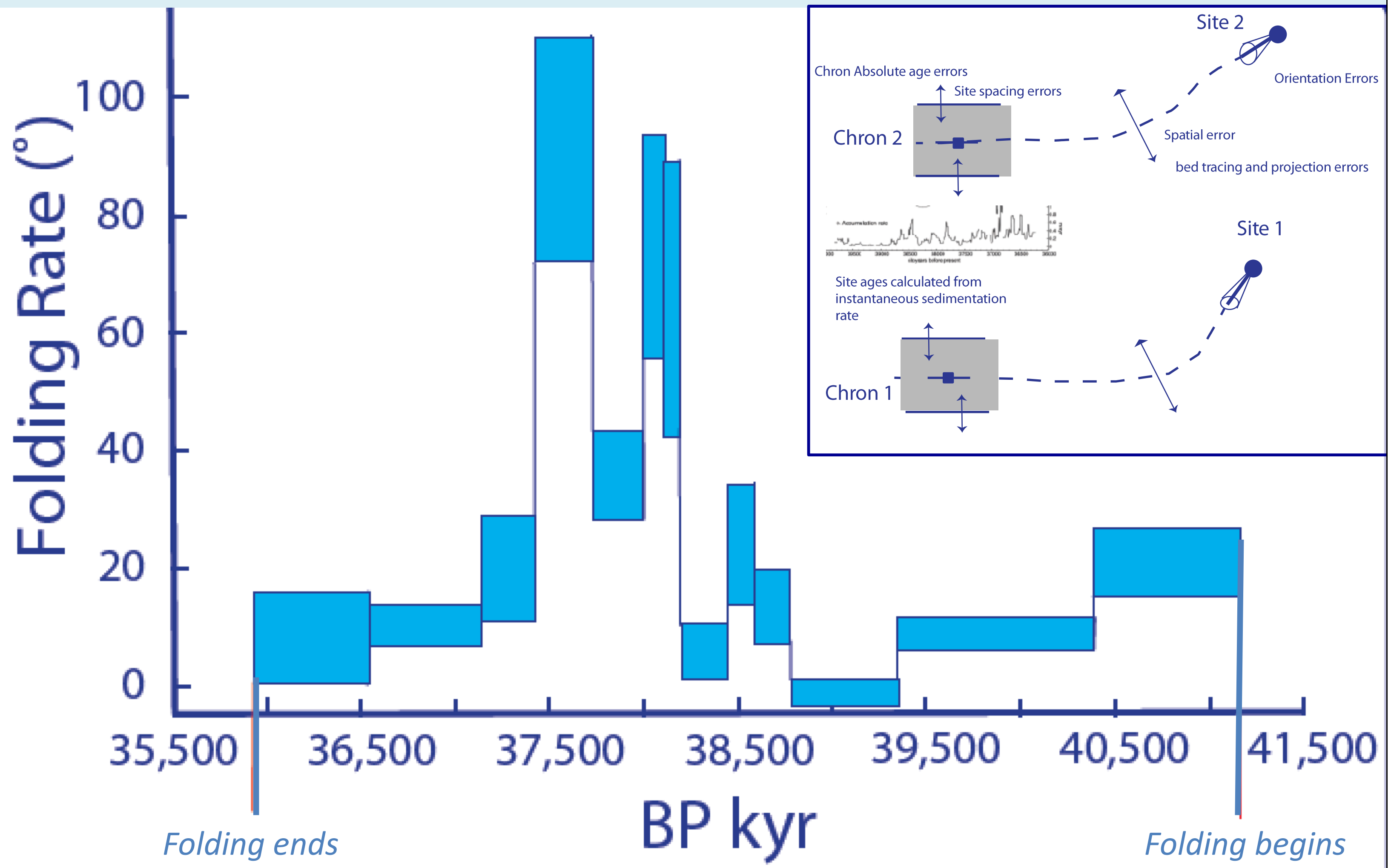
*(Presenter's notes continued from previous slide.)*

The main conclusions are as follows

- Deformation begins, accelerates to a maximum rate,
  then decelerated to the end of deformation
- Deformation is unsteady at $10^4$ and $10^5$ time scales
- Deformation of the regional scale structures took ~5myrs
- Deformation includes periods of tectonic quiescence-I'm not sure some of you would have guessed that

Notice that eventually the fold went from displaying positive topography-growth strata onlaps on to the structure to the fold being buried-growth strata overtops the anticline.  The sedimentation rate ultimately exceeded the uplift rate as deformation progressed and deposition rate increased while folding was slowing down.

# Pico del Aguila Anticline




*Anastasio et al., in prep.*

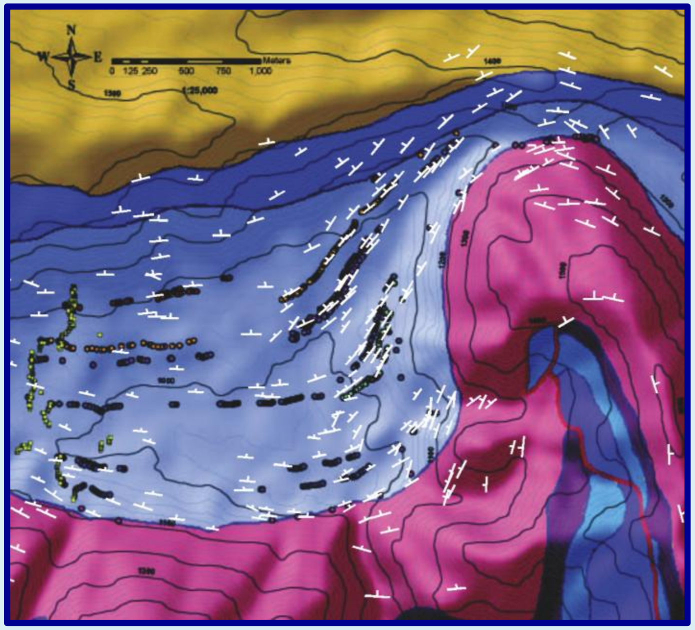
Presenter’s Notes: At intermediate timescales deformation was episodic or unsteady through time. This conclusion is robust with a careful consideration of uncertainties. *(Presenter’s notes continued on next slide.)*

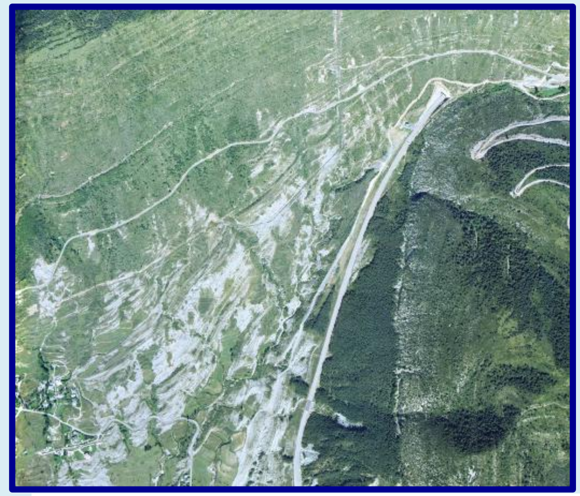
*(Presenter's notes continued from previous slide.)*

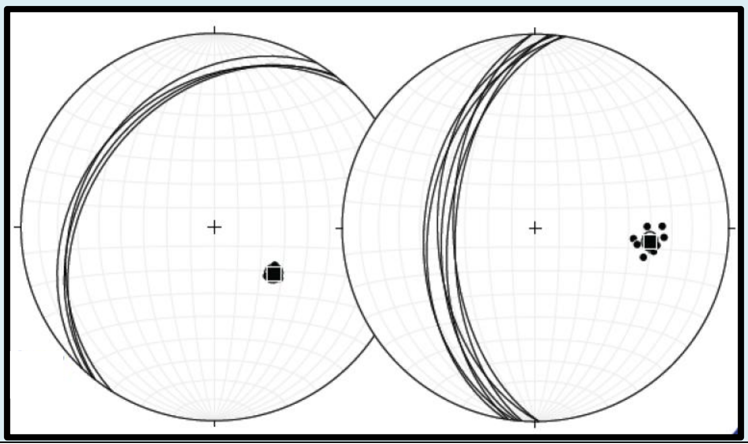
The uncertainty analysis was determined by Monte Carlo simulation which propagated uncertainties in bedding orientation, which are expected to be ±1° by down plunge assessment or ± 3° (2σ) by direct measurement with a geologic compass; stratigraphic position error ± 10 - 50 m depending on where we were in the growth section; chron age errors as published; and paleomagnetic site spacing that was 3m and the uncertainty in sites could vary over the full extent of the sample spacing-box car distribution whereas other errors are treated as Gaussian. Within the sample spacing, depositional age was determined by a look up function for depositional rates determined by cyclostratigraphy. Site spatial errors and correlation of the proxy ARM record to seasonal variations in insulation are correlated and therefore not propagated. Small and correlated errors due to sample sizes and orbital motions are also not propagated  The beginning and end of folding was determined by magneto- and biostratigraphy when going from pre-growth to growth overlying bed geometries.

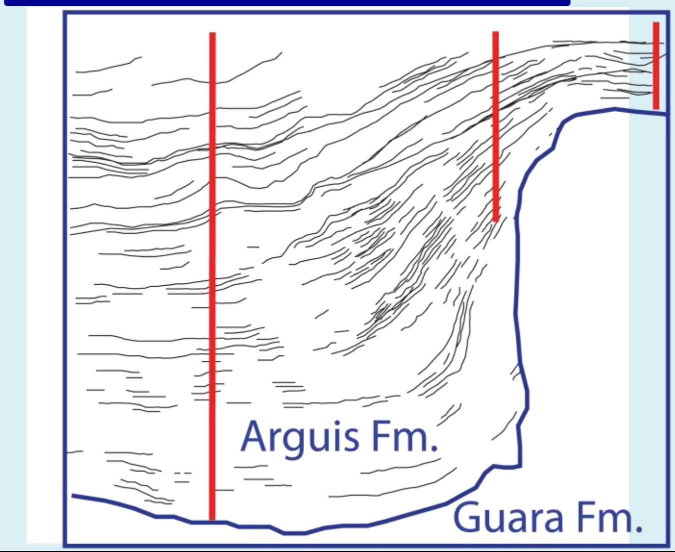
Bed inclination uncertainty was the largest source of uncertainty in folding rate.

# Fold Geometry



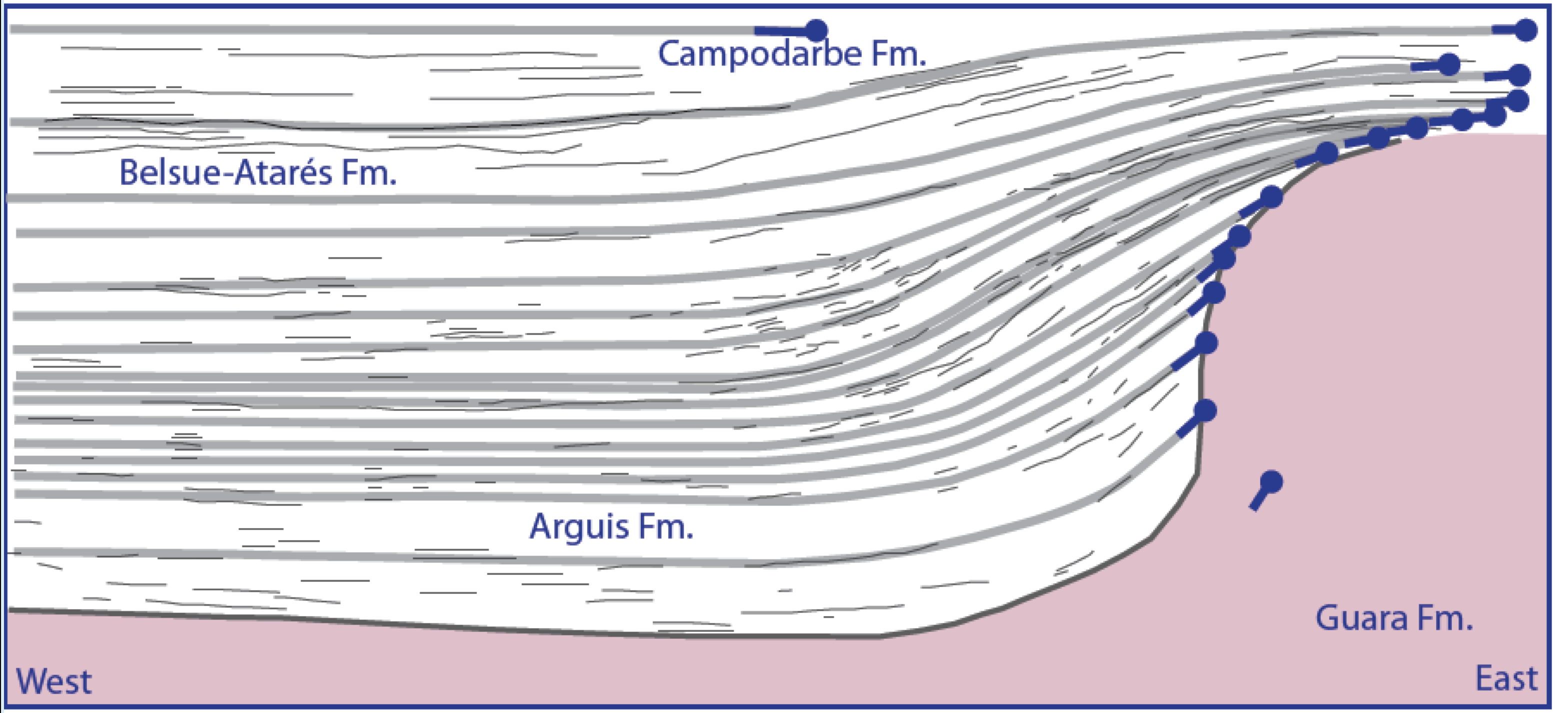





Presenter's Notes: Geometry
Spatial position was determined during field mapping when the bedding orientation data was collected, including at times with precision GPS with a local base station -cm scale accuracy, bed mapping with precession GPS m scale accuracy, or with a handheld GPS, barometric altimetry for elevation, we also interpreted growth strata on registered 1:5000 orthophotographs, and 1:5000 DEMS, and measured sections at positions shown by vertical lines, this study and Castelltort, 2003 ±2σ,conservatively estimated at 10m. Bedding orientation by repeat measurements with bedding measured many times, typical α95 on vector mean of bedding is ±3°. This is a large source of the spatial uncertainty. This is due to the nature of bedding, not operator error with a compass.

# Growth Geometry

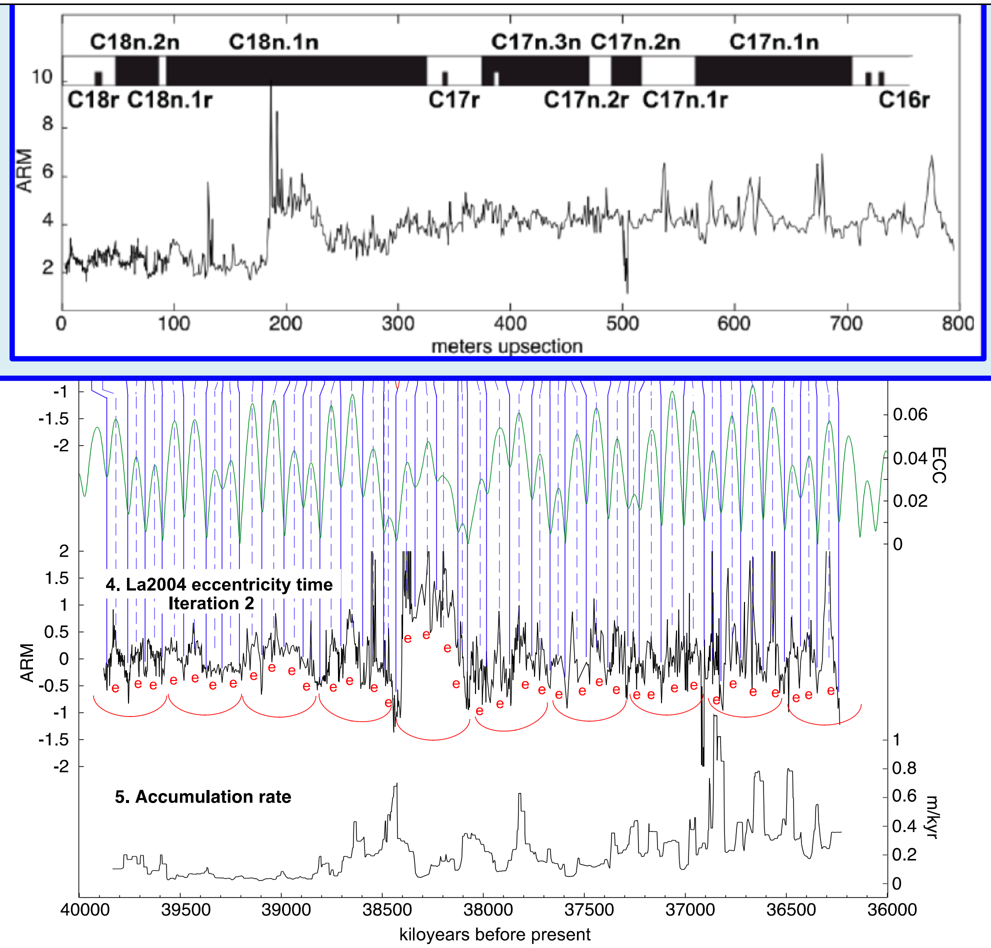
## Down-Plunge Projection of Pico del Aguila Anticline




*Anastasio, et al., in prep.*

Presenter's Notes: Geometry
Down-plunge projection of Pico del Aguila anticline with the various data sets in the background, bedding attitude determinations, growth strata, anprecision GPS bed mapping

We put time in the expanded section in the Arguis syncline and recorded the folding on the flanks of Pico de Aguila in the growth strata
Incremental folding rate was determined for the dip changes indicated.




Tune to Full Theoretical Eccentricity

Kodama et al., 2010. G[3]

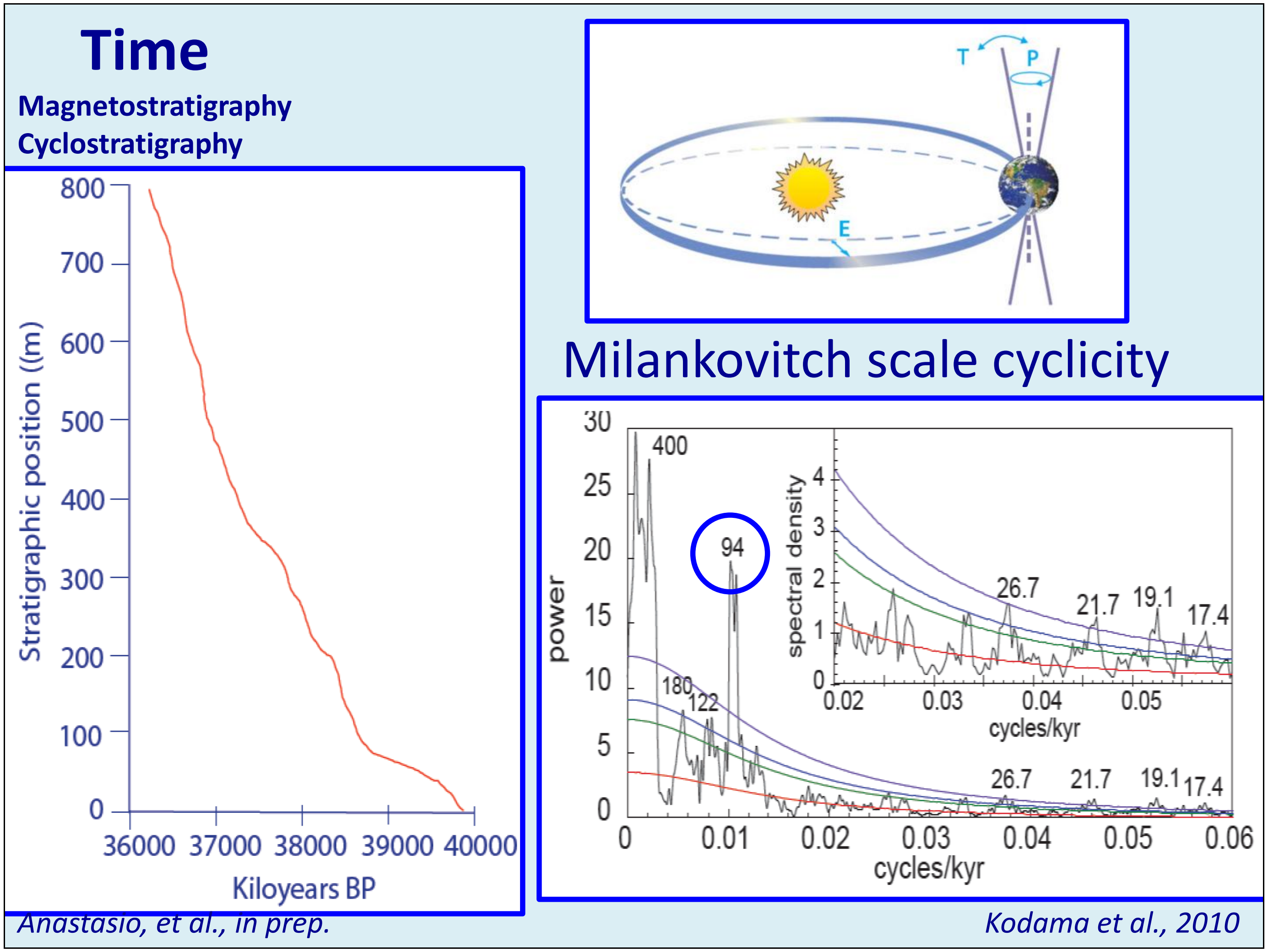
Presenter's Notes: Timing

Magnetostratigraphy and rock magnetic based cyclostratigraphy was used to go from the depth domain to the time domain. Paleomagnetic results correlated to GPTS using biostratigraphy assuming reversals were at the midpoint of the polarity chron.

Reversals, were used to calibrate the ARM data series. There were nearly 1400 samples measured in the ARM data series, 0.25-1m sample spacing depending on the paleomag. determined accumulation rate.

Band passed data was slightly tuned to the Earth's theoretical orbital eccentricity.

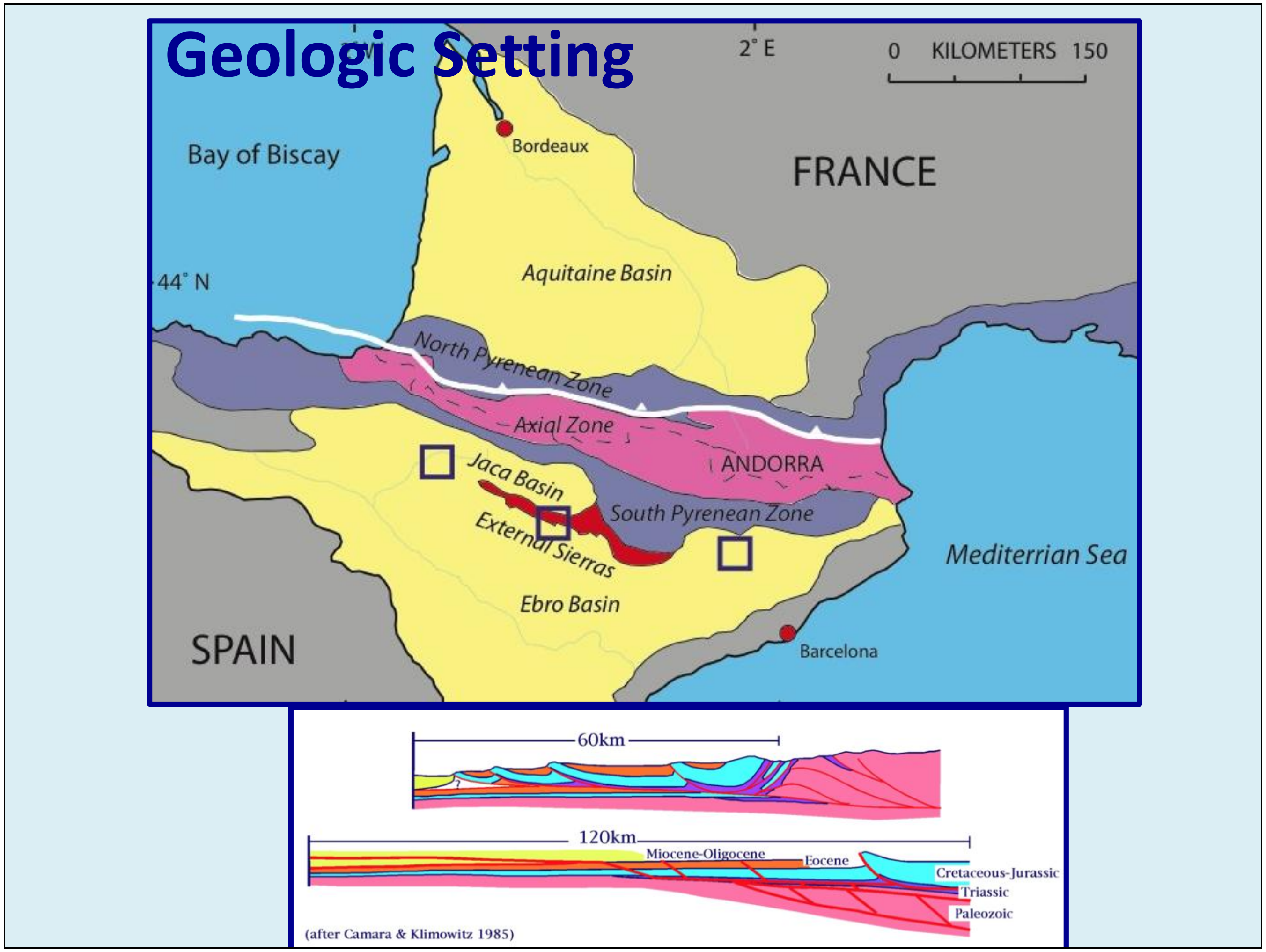
Note the lines correlating the 400 and 100 year orbital cycles are nearly parallel between the expected and recovered data
And the gradual increase in sediment accumulation rate associated with delta front progradation while still recording fluctuation at time scales associated with orbital mechanics.




Presenter's Notes: Analyzing the timing data:
ARM is a laboratory induced magnetization involving AF demagnetization done in the presence of a biasing DC field set for particular minerals and grain sizes. In this case, the AF demag had a 100mTelsa maximum AC field and a 0.97 □□□□̃Telesa constant DC field to activate <5 micron size ferromagnetic particles of magnetite and its authogenic product pyrrhotite-iron sulfide from the original iron oxide.

La2004 eccentricity-tuned MTM spectrum. Red curve is robust red noise, confidence is at 90% green, 95% blue,99% purple.

Cyclostratigraphic age model based on the eccentricity tune, note the very significant short eccentricity peak we used as the metronome in the section.

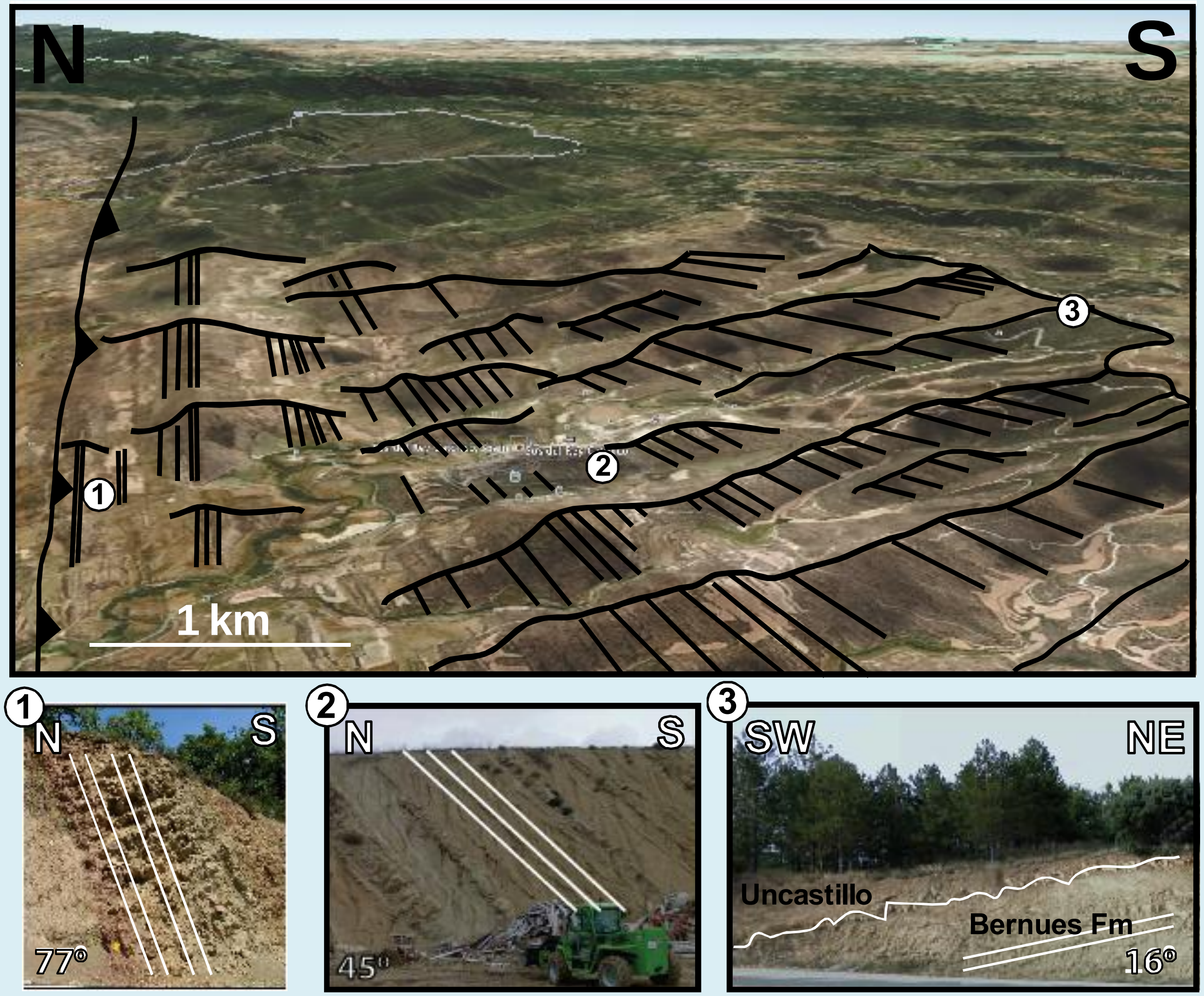



Presenter's Notes: Pico del Aguila is located along the central thrust front in the External Sierra. The next structure we are going to look at is located to the west along the thrust front. Here, the duplex structure known as the Peña flexure marks the topographic division between the Jaca-Pamplona wedge-top basin and the Ebro foreland basin.

The Pyrenees are a typical dual vergent, 2 tiered Alpine mountain belt with the majority of the shortening directed southward. It consists of a central Axial zone-a crystalline duplex surrounding cover thrust sheets directed outward.

The Southern Pyrenees are shown on the accompanying cross section showing the wedge-top and foreland basin, cover and crystalline thrust sheets which were transported to the south from Cretaceous to Miocene.

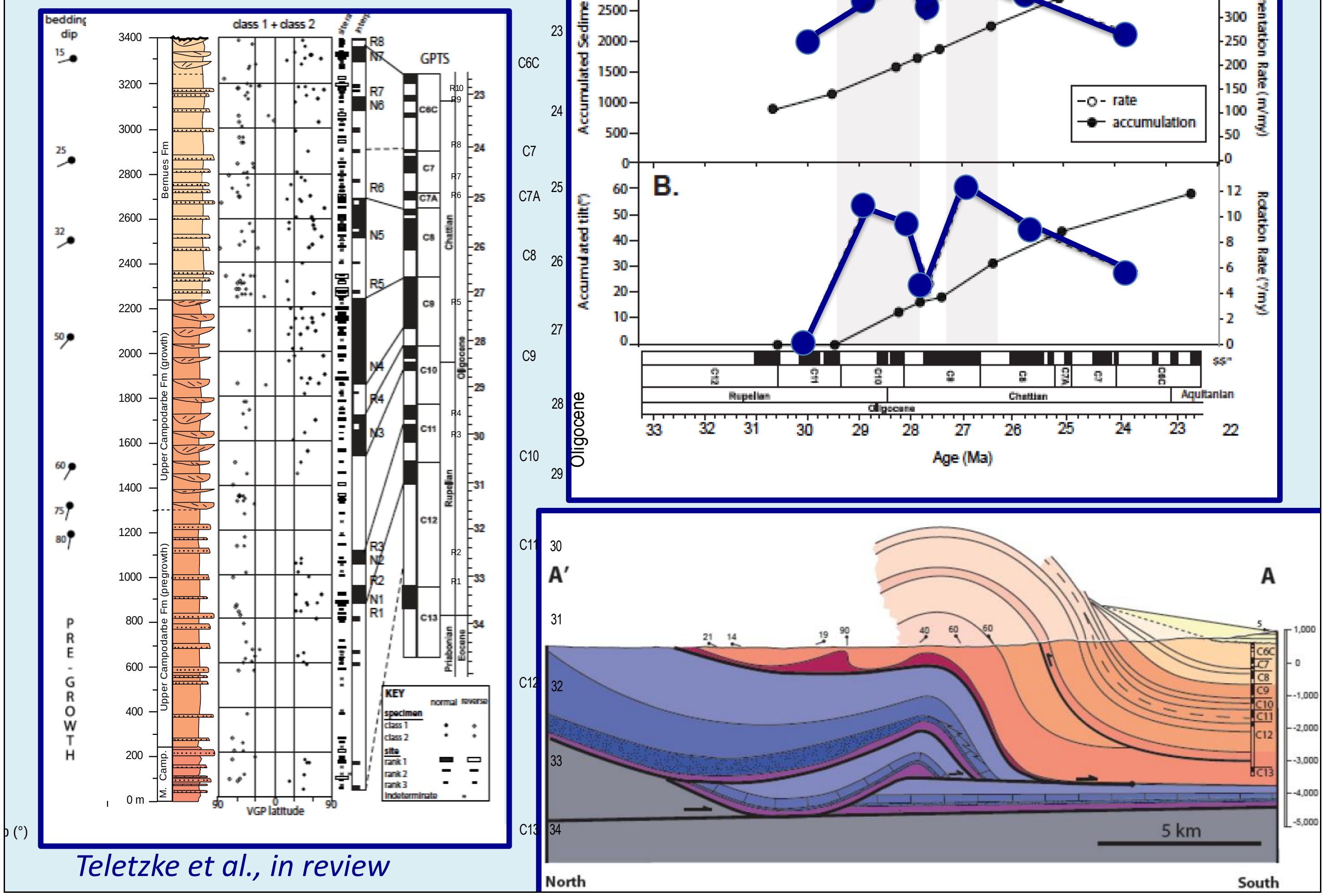
# Geometry: Sos del Rey Católico




Presenter's Notes: Oblique Google Earth view of the area just north of Sos del Rey Catolico, view looking east. The locations name--Sos the Catholic king, where Ferdinand of Ferdinand, Isabella, and Christopher Columbus fame, was born while the royal family was there during peace negotiations between the kingdoms of Aragon-Catalonia and Navarra in the 15th century.

Growth geometries are shown on the insets, shallowing from left image to the right. Deformation rates were determined for bedding dips of ~80˚ S to 16˚S at the polarity chron or $10^{5\text{-}6}$ scale .

# Coupled Deposition and Deformation

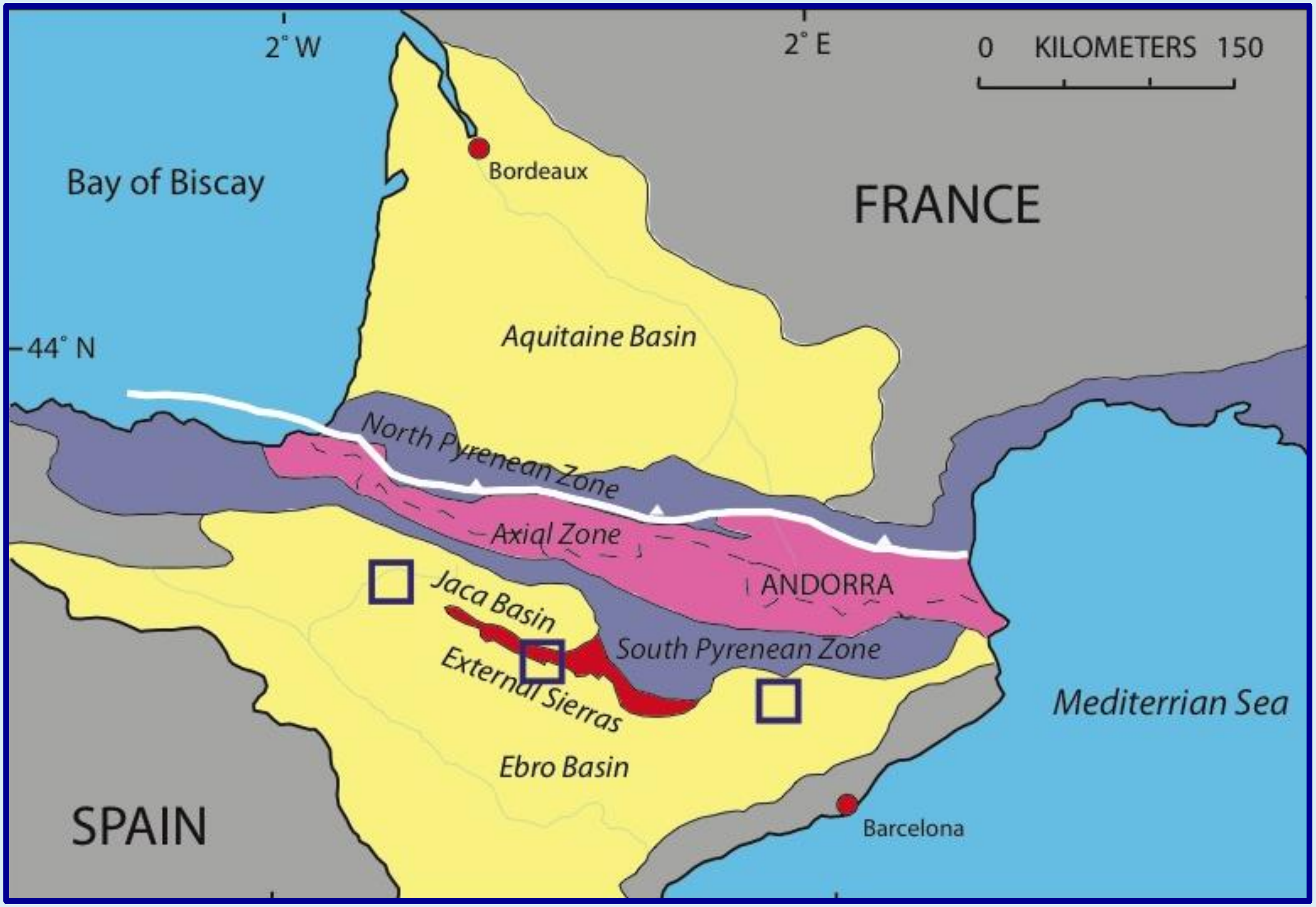



*Teletzke et al., in review*

Presenter’s Notes: Time and Geometry for Peña structure:
Principal data sets, mapping from which the cross section was interpreted and 3.2km long measured section with dip amounts used to reconstruct deformation rates. Forward model experiments with MOVE2D constrains the growth strata to be related to slip on the mountain front back thrust, here rather than the hinterward dipping passive roof duplex.

At this location the accommodation space was built by the developing mountain front structure and the sediment, which is fluvial and largely sandstone was locally derived and deposited. Notice that deformation rates shown by the bold line line in B correlates to the depositional rates shown by the bold blue line in A. Synorogenic deposition and deformation were coupled at the paleomagnetic time scale.

# Geologic Setting

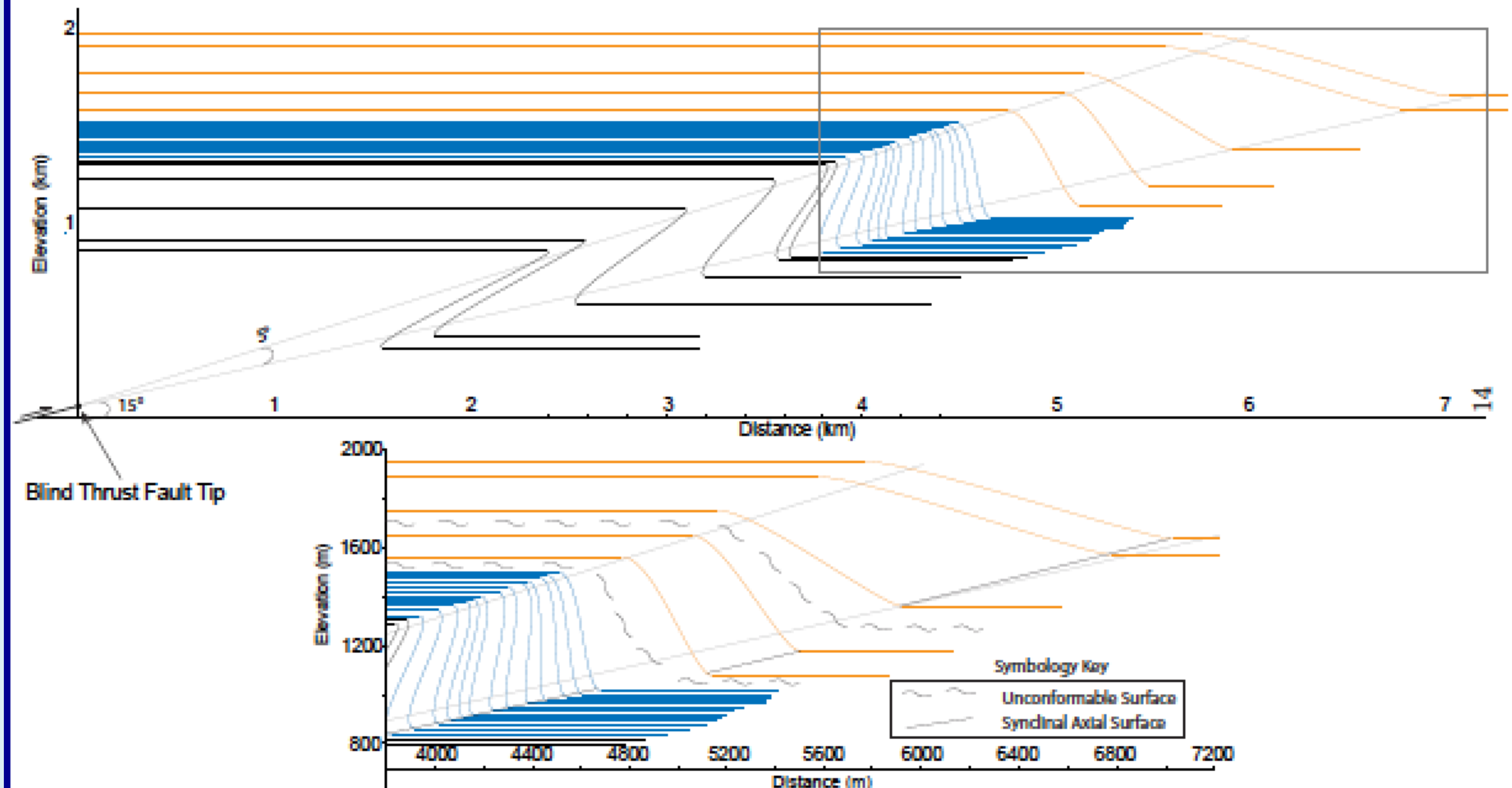



Presenter's Notes: Back to the location map to locate the third structure, in the eastern Pyrenees, again along the thrust front, here in Catalonia at Sant Llorenç de Morunys. Site of one of the original progressive unconformities described in the literature, reported by Oriel Riba in the 1970s, studied more fully by Ford and others and Suppe and others in the 1990s, and Alonzo and others within the last decade. In this instance, sediment in the foreland basin was derived from a large antecedent watershed without accommodation space limitations.

# Sant Llorenç De Morunys

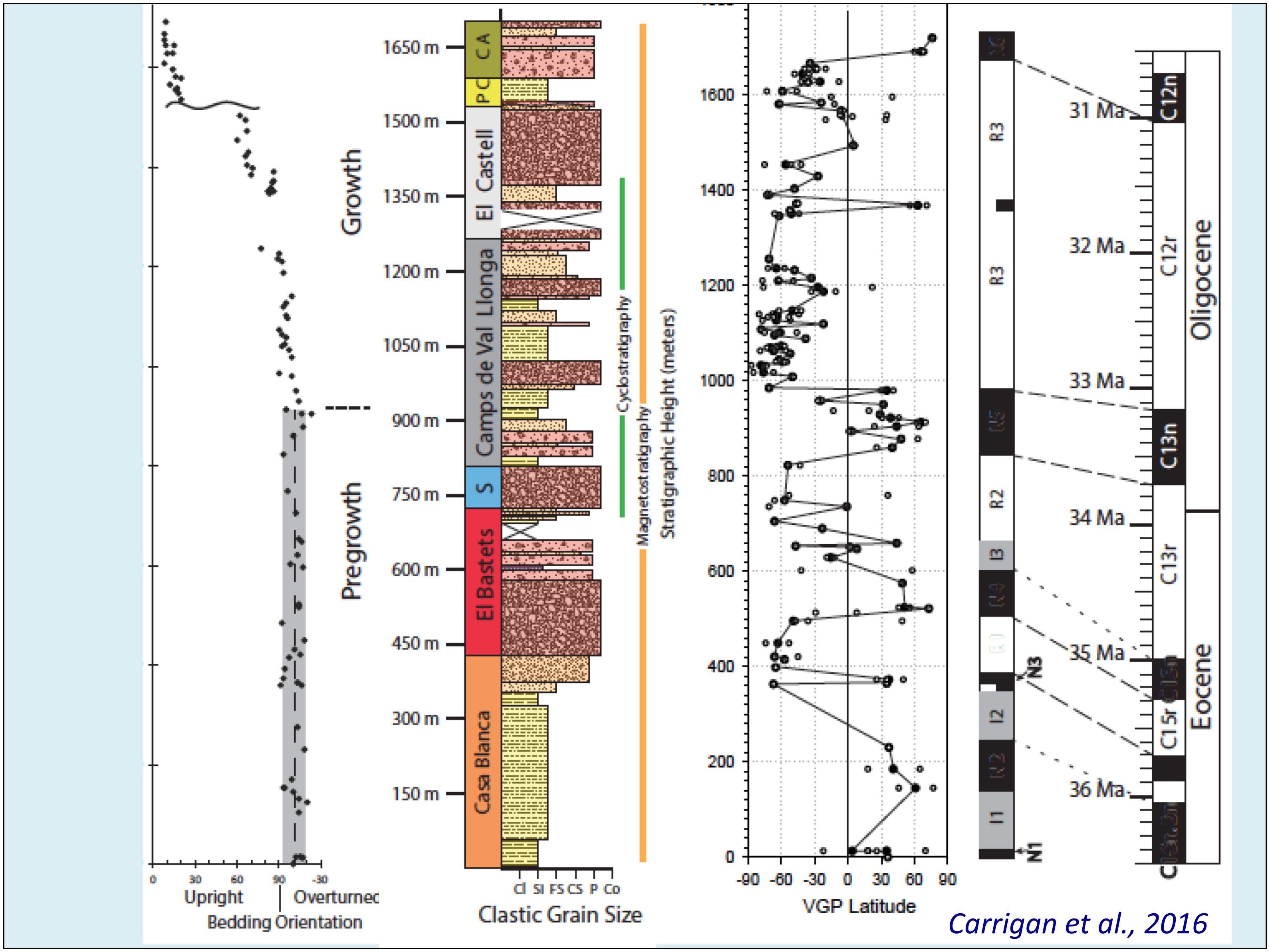

Presenter's Notes: Field view of the forelimb of the fault-propagation fold we studied which has dips varying from 70˚ north and overturned to 4˚ south atop Sierra de Busa; so 110˚ of synsedementary folding.  The Vallfogona thrust sheet is visible in the distance, the fault-related fold is developed above a blind thrust in the footwall.

# Model of Fault-Propagation Fold

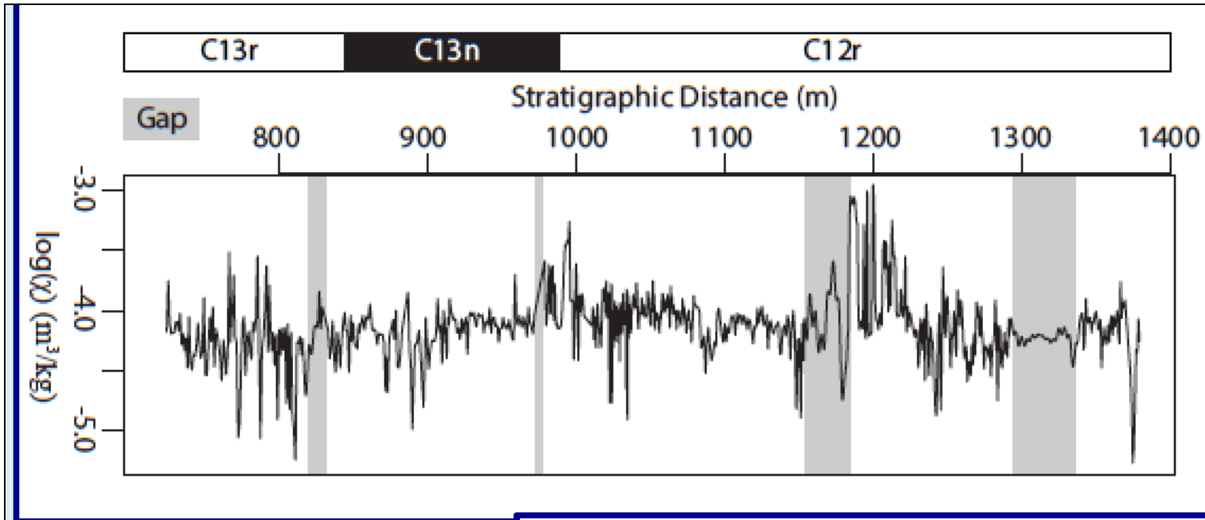



*Carrigan et al., 2016*

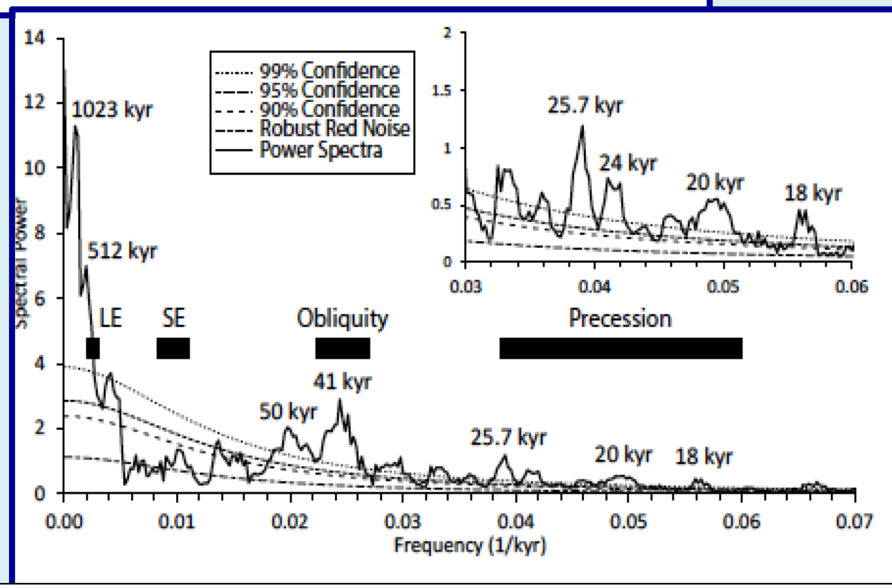
Presenter's Notes: Model of the fold-fault structure using Allmindinger's Fold-Fault software with trishear kinematics. We have used these models to gain confidence in our estimation of missing time at the unconformaties and to transform our assessments of limb tilt on the fold forelimb into fault slip rates on the associated blind thrust. The cross section reproduces the geometry well. For example, the synformal axial surface moves higher on the forelimb across the unconformity, as in the natural example.




Presenter's Notes: Measured section, inclination data showing growth and pre-growth strata, VGP latitudes from the paleomagnetic analysis of oriented samples, the local magnetostratigraphy, and the correlation to GPTS which provides absolute ages to calibrate the cyclostratigraphy. Sediment wise this is the coarsest section we have studied but there was plenty of accommodation space in the Ebro foreland basin. The magnetostratigraphy is for the full 1.7km long section, the next figure will present a cyclostratigraphic analysis of the growth section, which was 800m long.

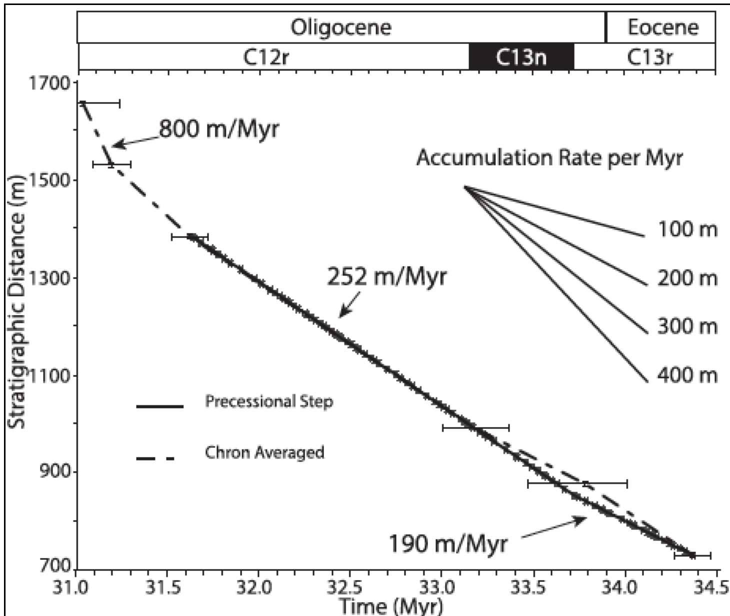



# Cyclostratigraphy




*Carrigan et al., 2016*

Presenter's Notes: The top figure is a bulk magnetic susceptibility data series using an applied field strength near the strength of the Earth's field. The signal is largely controlled by paramagnetic phyllosilicate mineral grains as determined by low temperature experiments on growth section samples. The data curve showing multi-hierarchical cyclicity was collected every 0.5-1m depending on the accumulation rate, the gray areas were not sampled, outcrop is shotcreted in tunnels. For this portion of the data, ~10% was filled in using a SSA filling using the surrounding frequencies to fill in covered intervals. The power spectrum of the data is shown below with a robust red noise model showing significant peaks at expected Milankovitch frequencies as marked with the black bars. We next use this cyclostratigraphy to constrain depositional and deformation rates. Again see very significant power at Milankovitch time scales.

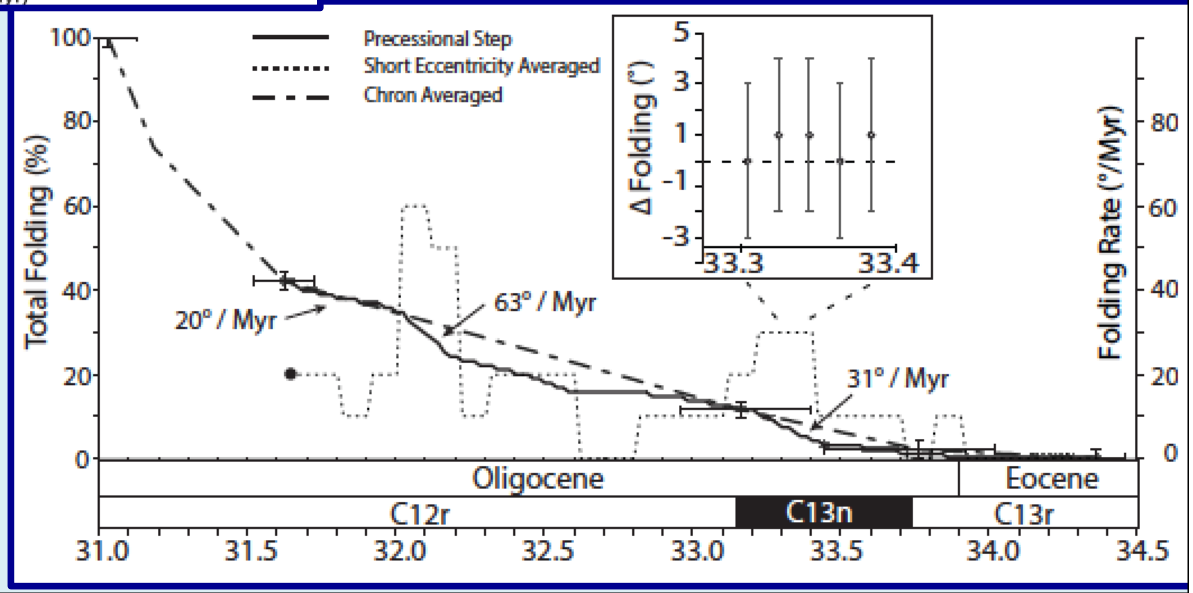



## Accumulation Rate

**Accumulation is STEADY at $10^{4-6}$ time scales**

## Deformation Rate

**Deformation was UNSTEADY at 100kyr time scales**
**Need cyclostratigraphy to see the episodic behavior of deformation**



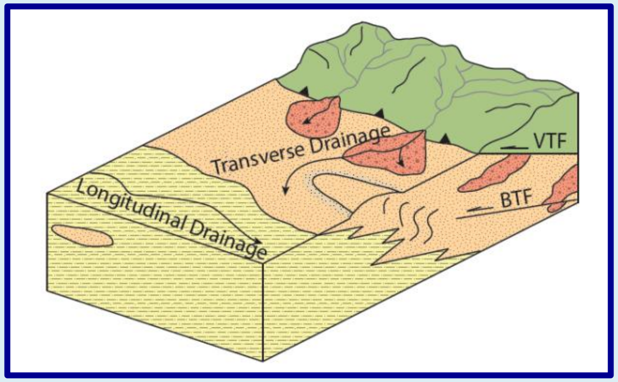

*Carrigan et al., 2016*

Presenter's Notes: Growth sediment accumulation rates at polarity chron and precessional time scales with uncertainties. For the most part there is no difference in the curves as the depositional rate was mainly constant, the growth sediment was not sourced locally. The accumulation rate was not coupled to deformation, the antecedent watershed was big relative to the structure and the depositional basin was under-filled, accommodation space was not an issue. *(Presenter's notes continued on next slide.)*

*(Presenter's notes continued from previous slide.)*

The lower figure displays incremental folding amount at chron and precessional scales-the slope is the rate.  Deformation rates were unsteady at 100kyr time scales as shown by the dotted line. One needs to know the cyclostratigraphic time scale to see the episodic folding behavior well.

While we have confidence we can distinguish the chronology of beds at the 20,000 time scale, we can not distinguish deformation with as fine of resolution.  Inclination uncertainty is the biggest source for deformation rate uncertainty.  When taking inclination uncertainty into account, we are left with confident rate determinations at 100kyr increments but not at 20kyr time scales as illustrated by the inset.  Deformation rate is constant at the polarity chron time scale, variable at the 100kyr time scale, but the uncertainties overlap if we try to get higher temporal resolution so it is important to understand the chronology of the recording stratigraphy.




# Conclusions

Sedimentary rocks often record Milankovitch-scale cyclicity, which can be revealed by rock-magnetic methods.

Growth Strata can be use to constrain temporal history of deformation as well as kinematics.

Foreland basins provide ideal examples of synsedimentary structures in terrestrial rocks because accommodation space is generally plentiful, so high frequency cyclicity is preserved.

The source and sink locations of growth deposits matters with respect to the coupling of depositional and deformational rates.

Deformation is episodic at all time scales and includes periods of unrecorded activity. This impacts how we think about what intrinsic and extrinsic processes modulate deformation.

Presenter's Notes: Conclusions:
Sedimentary rocks often record Milankovitch-scale cyclicity, which can be revealed by rock-magnetic methods.
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Foreland basins provide ideal examples of synsedimentary structures in terrestrial rocks because accommodation space is generally plentiful, so high frequency cyclicity is preserved.
The source and sink locations of growth deposits matters with respect to the coupling of depositional and deformational rates.
Deformation is episodic at all time scales and includes periods of unrecorded activity. This impacts how we think about what intrinsic and extrinsic processes modulate deformation.

# Thank You

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WHERE DISCOVERIES BEGIN


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