FOLDS AND THRUST SYSTEMS IN MASS TRANSPORT DEPOSITS

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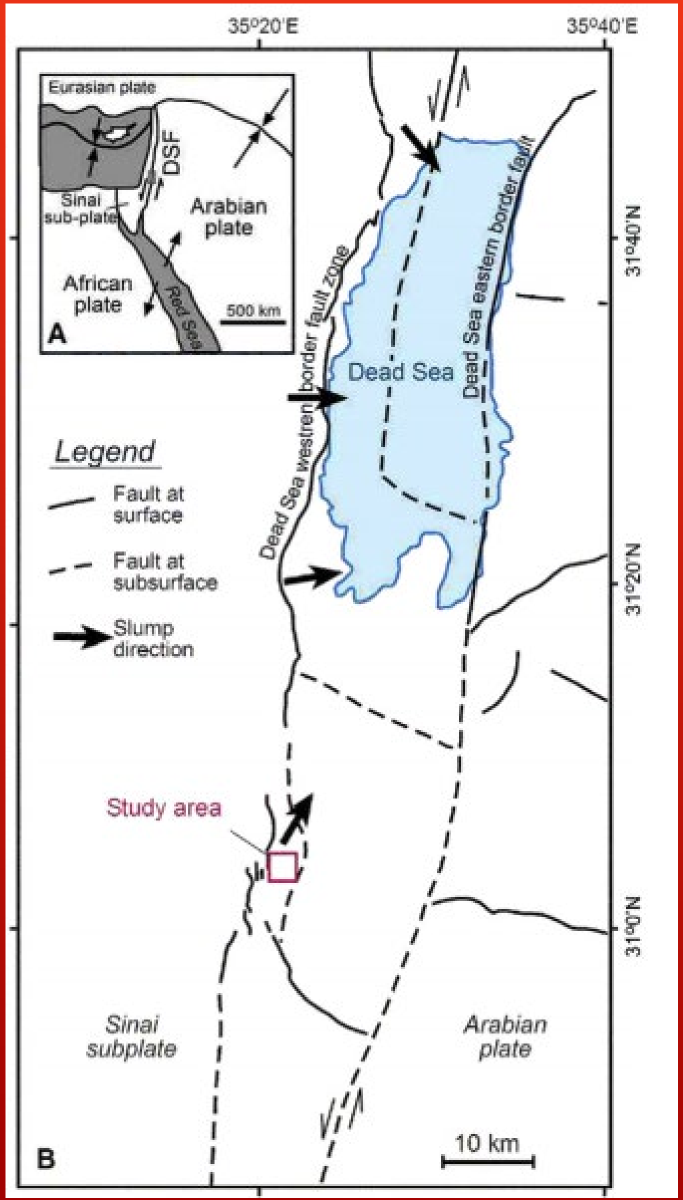
INTRODUCTION

- Examine fold and thrust geometries associated with downslope movement of unlithified sediments within mass transport systems (MTDs)
- Improvements in seismic surveys have helped better understand geometries in these systems, but seismics are still limited in ability to image complex and local detail

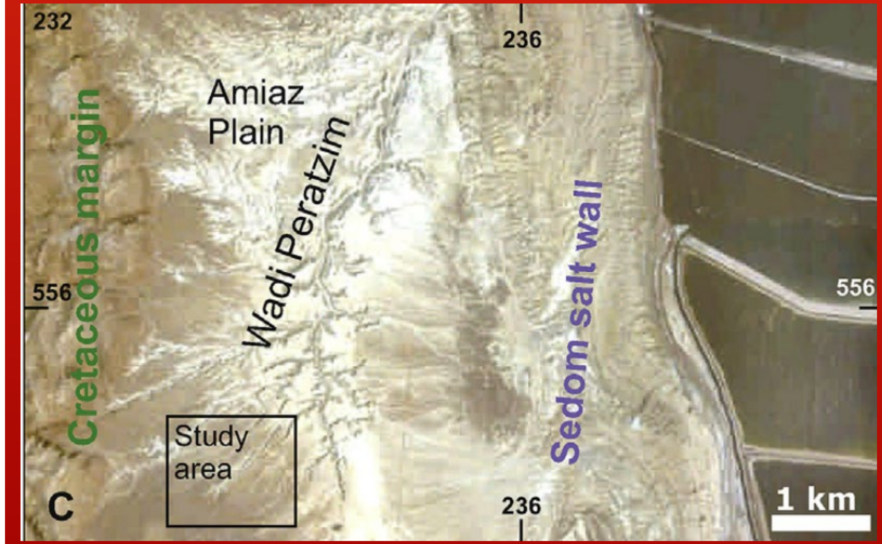
IN THIS STUDY:

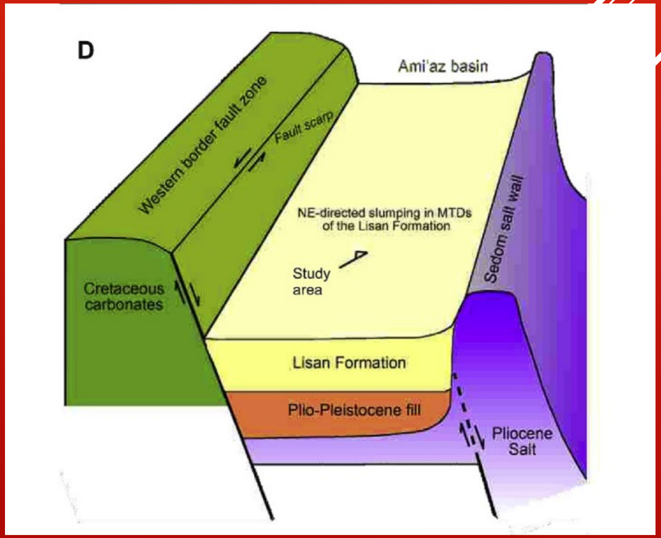
- Examine relatively recent (Late Pliestocene), large scale (dm-km) structures
- Fully exposed
- Paleo-geography still evident today
- Employ established techniques of fold & thrust systems in lithified rocks on similar systems in unlithified sequences

GEOLOGICAL SETTING: DEAD SEA BASIN



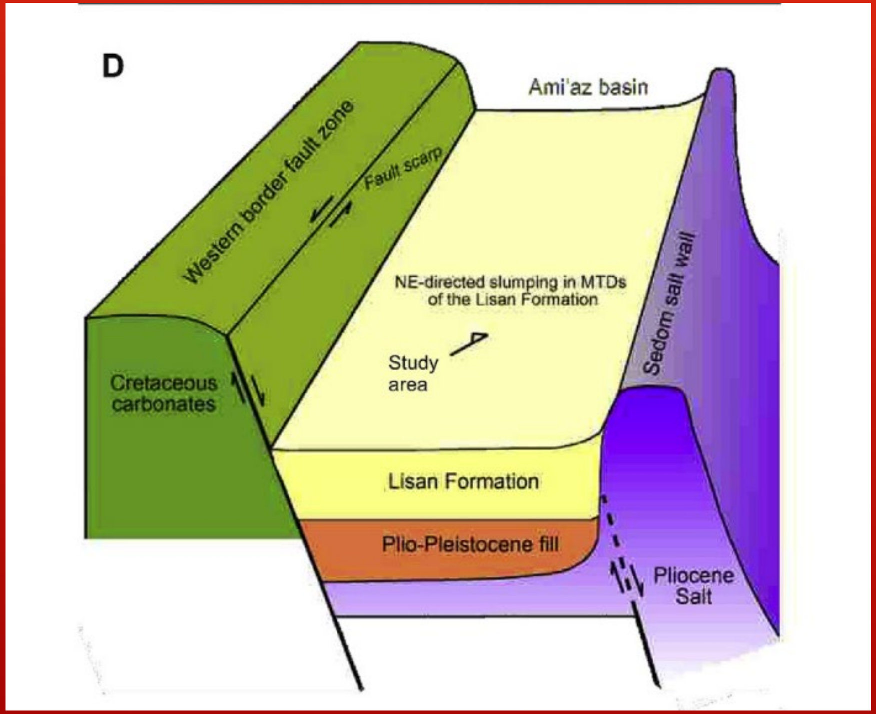
- Dead Sea Basin= pull apart basin between two fault strands that define Dead Sea Fault (a & b)
- Dead Sea Fault has been active since Early to Middle Miocene
- Lisan Formation- deposited in Late Pleistocene (d)
- Study Area: Peratzim, located on Am'iaz Plane (c)
- Seismic events trigger soft sediment deformation & slumping in Lisan Formation

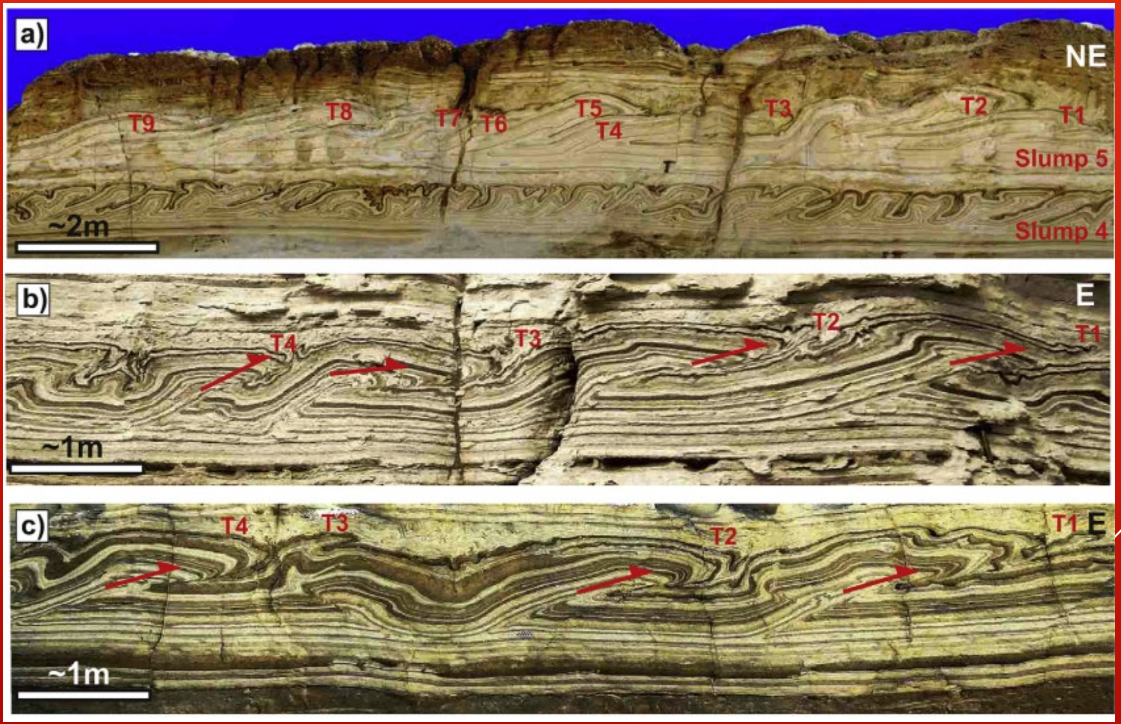




LISAN FORMATION

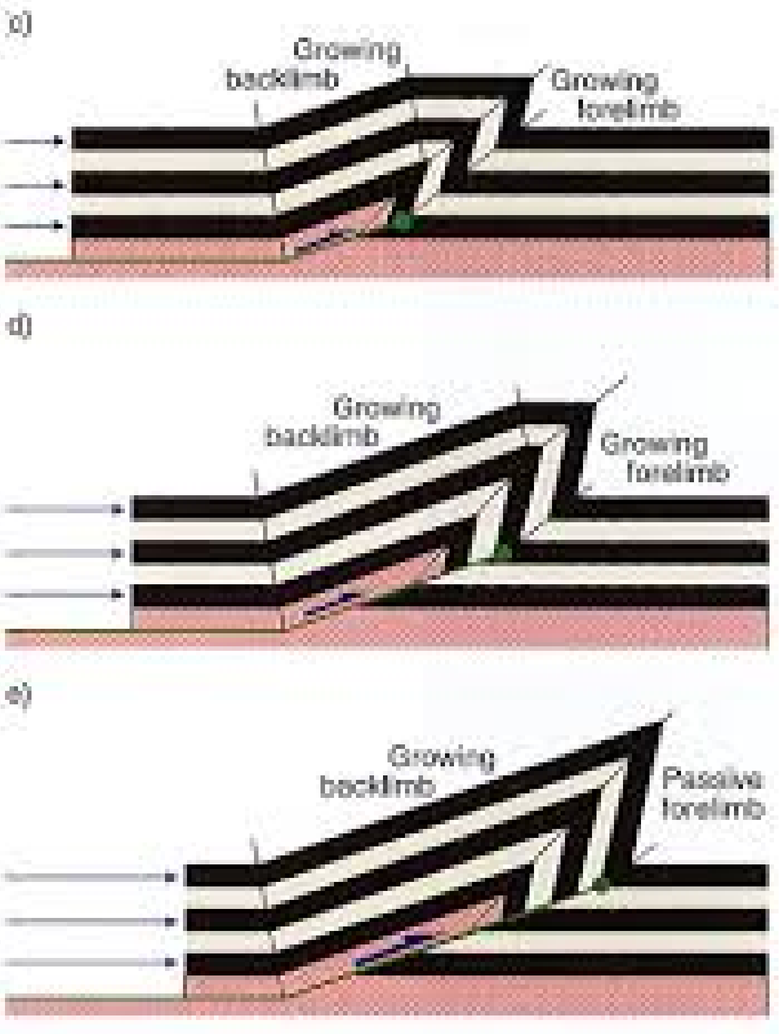
- Sequence of alternating aragonite-rich & detrital laminae (sub-mm scale)
- Represent annual varve-like cycles- aragonite-rich laminae precipitating from hypersaline waters in summer, and clastic material washed in from winter floods
- Seismic events trigger slumps and MTDs within formation, resulting in well developed soft sediment fold and thrust systems





FOLD TYPE: THRUST & FAULT PROPAGATION FOLDS

- A fault propagation fold forms above the tip line of a thrust to accommodate the deformation in the wall rock around the tip (Fossen, 2016)
- Ductile fold zone around tip

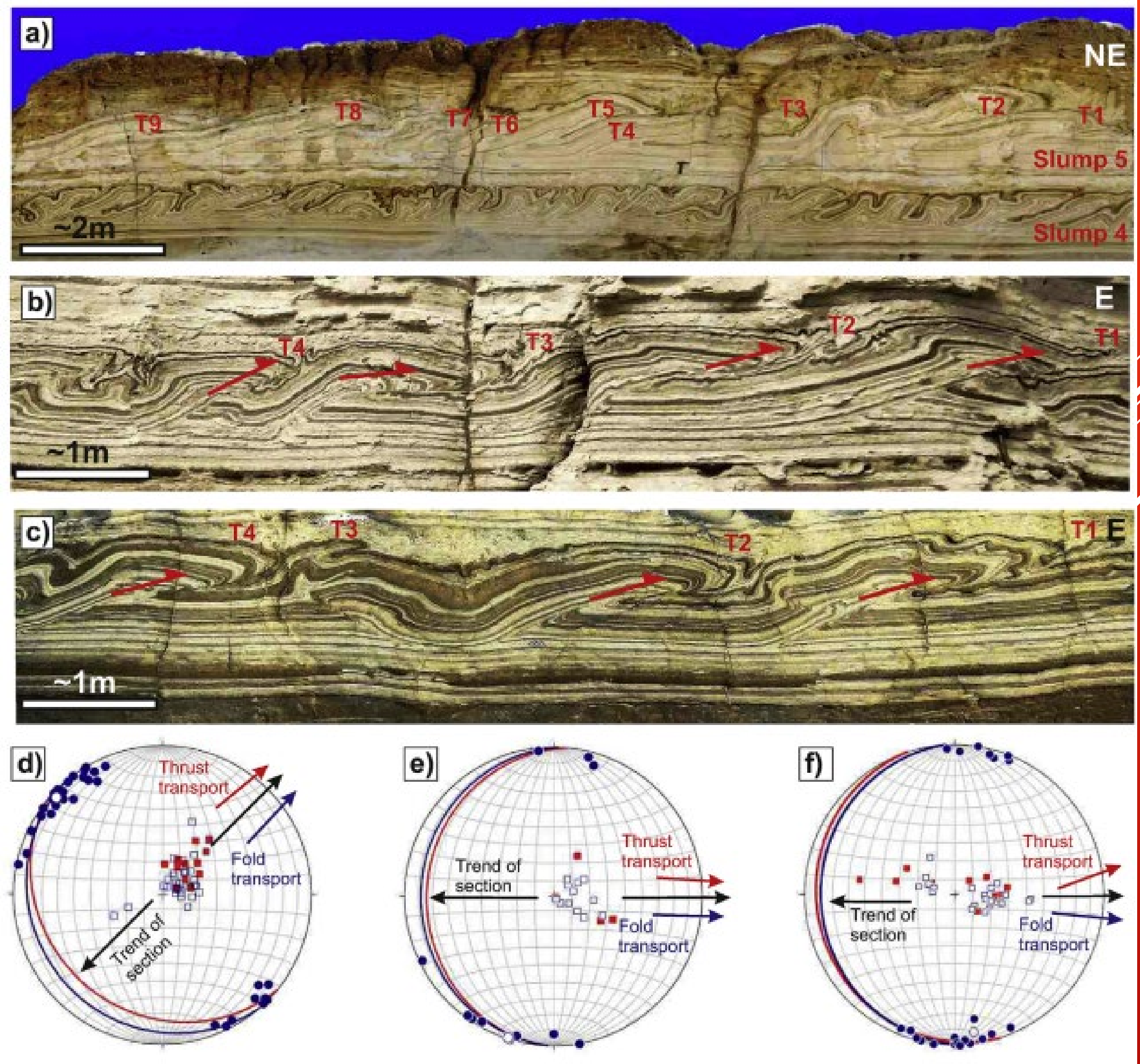


igure 16.18 Progressive development of a fault-propagation fold.

(from Fossen, 2016)

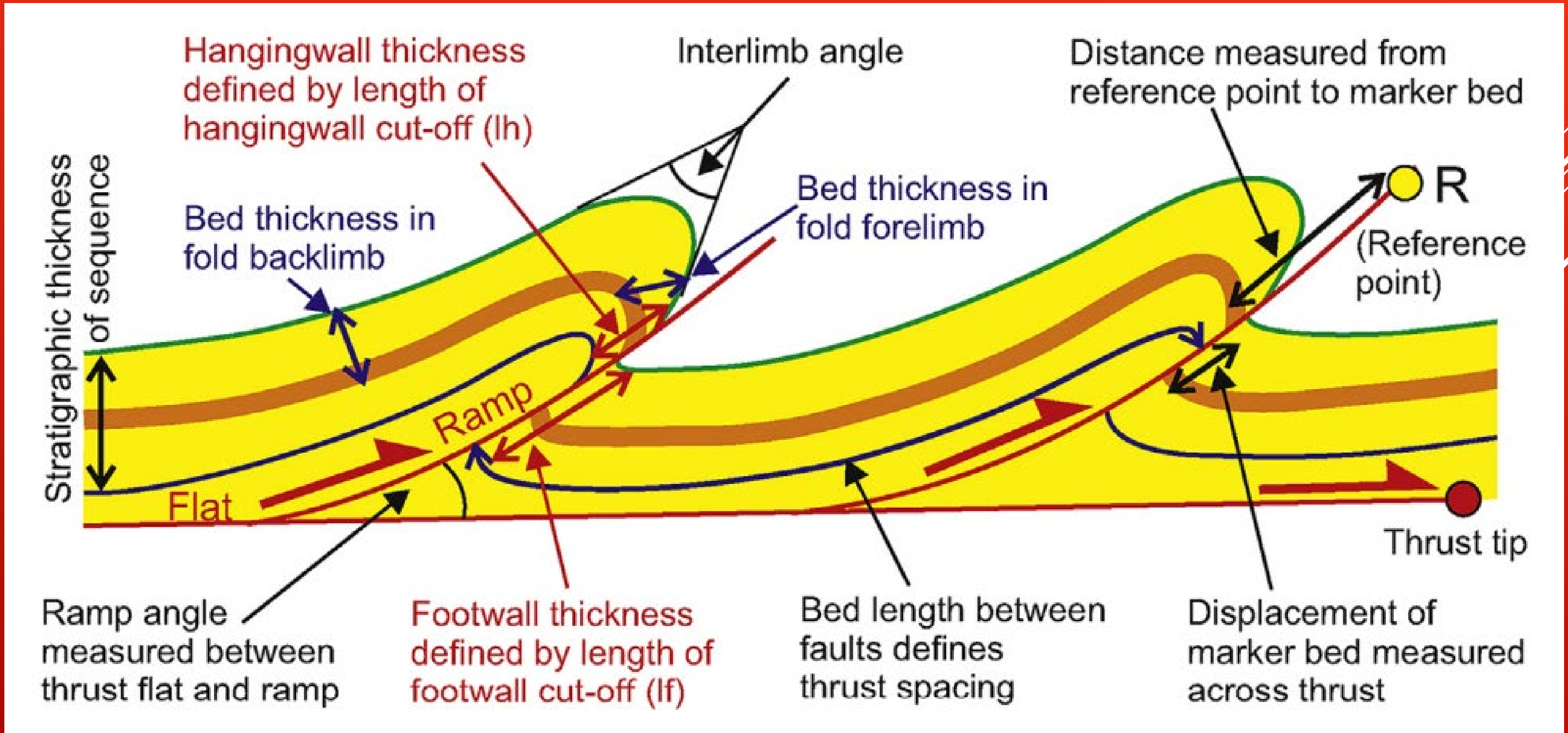
ORIENTATION & GEOMETRY

- Orientation of transport direction and associated paleo slope inferred to be 045^{O} in Peratzim area
- Trends of fold hinges and strikes of thrust planes develop normal to transport direction
- Of six exposed MTDs, three are oriented within 5^{O} of transport direction

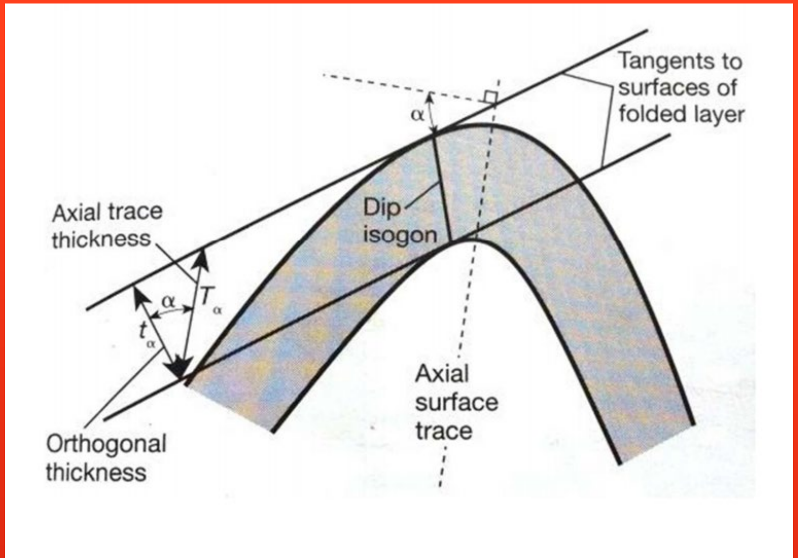


RELATIONSHIP OF STRATIGRAPHIC THICKNESS TO THRUST DISPLACEMENT AND SPACING

- Thickness of sequence measured orthogonal to bedding in non-folded area
- Hanging wall and footwall thickness measured parallel to transport along thrust ramp
- Relative stretch=lh/lf
- Spacing between thrust ramps defined as bed length between adjacent measured parallel to transport (average ratio 5:1 spacing/thickness for area)



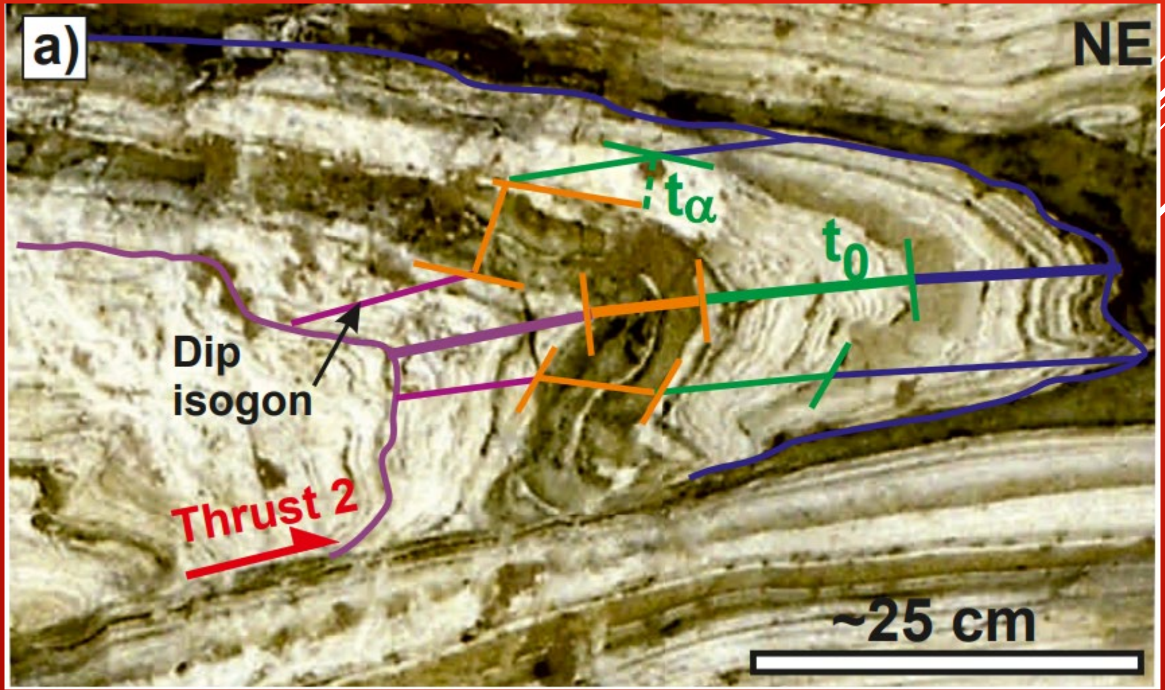
ANALYSIS: DIP ISOGON ANALYSIS



Dip isogons connect points of equal dip along outer edges of fold boundaries.

Used to compare fold geometries between aragonite-rich (green & blue) layers to detrital-rich (orange) layers

- aragonite rich layers define Class 1C (limbs thinner than hinge) to 2 (similar) Folds
- Detrital rich layers define Class 1B (parallel) folds => more competent layer

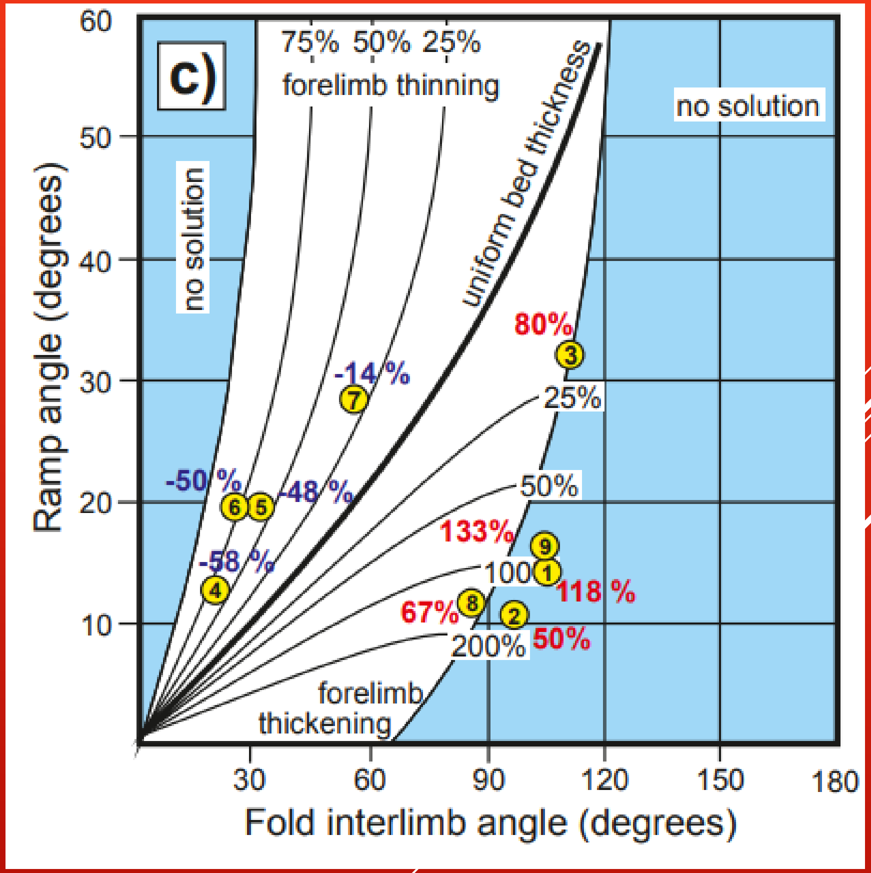


ANALYSIS: FAULT PROPAGATION FOLD CHARTS

Jamison (1987): "Interlimb angle of fault propagation folds are a function of ramp angle as measured from the flat of the thrust, and the amount of forelimb thickening or thinning"

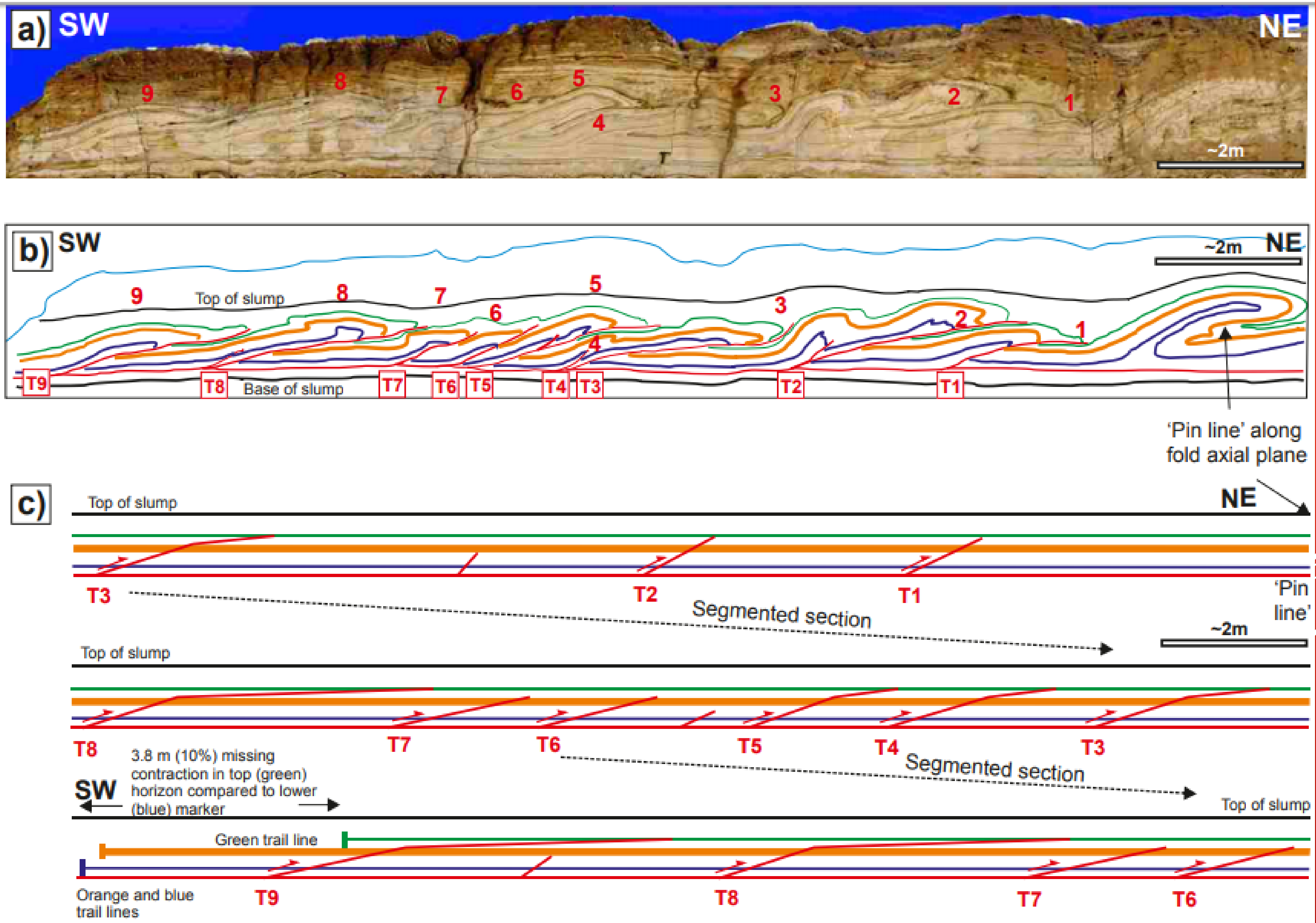
Folds at Peratzim generally follow predicted patterns, although observed forelimb thinning is less than predicted, and forelimb thickening is generally greater than predicted.

=>Suggests that compared to model, interlimb angles are too small, and/or ramp angles are too great



ANALYSIS: BALANCING OF THRUST SECTIONS AND LATERAL COMPACTION

- Line length balancing exercise across a well developed fold and thrust system
- Both fold styles displayed by aragonite & detrital rich layers generally preserve bed length, making them suitable for this method



a) SW
NE
9
8
7
6
5
4
3
2
1
~2m
b) SW
NE
~2m
9
Top of slump
8
7
6
5
3
2
1
4
T9
T8
Base of slump
T7
T6
T5
T4
T3
T2
T1
'Pin line' along fold axial plane
c)
Top of slump
NE
T3
T2
T1
'Pin line'
Segmented section
~2m
Top of slump
T8
T7
T6
T5
T4
T3
3.8 m (10%) missing contraction in top (green) horizon compared to lower (blue) marker
SW
Segmented section
Top of slump
Green trail line
Orange and blue trail lines
T9
T8
T7
T6

- % Thrust shortening increases down sequence
- % Fold shortening increases up sequence
- 3.8 m of missing shortening from lower blue layer to top green layer
    - 9.7% of blue restored length
    - 23.2% of blue shortening

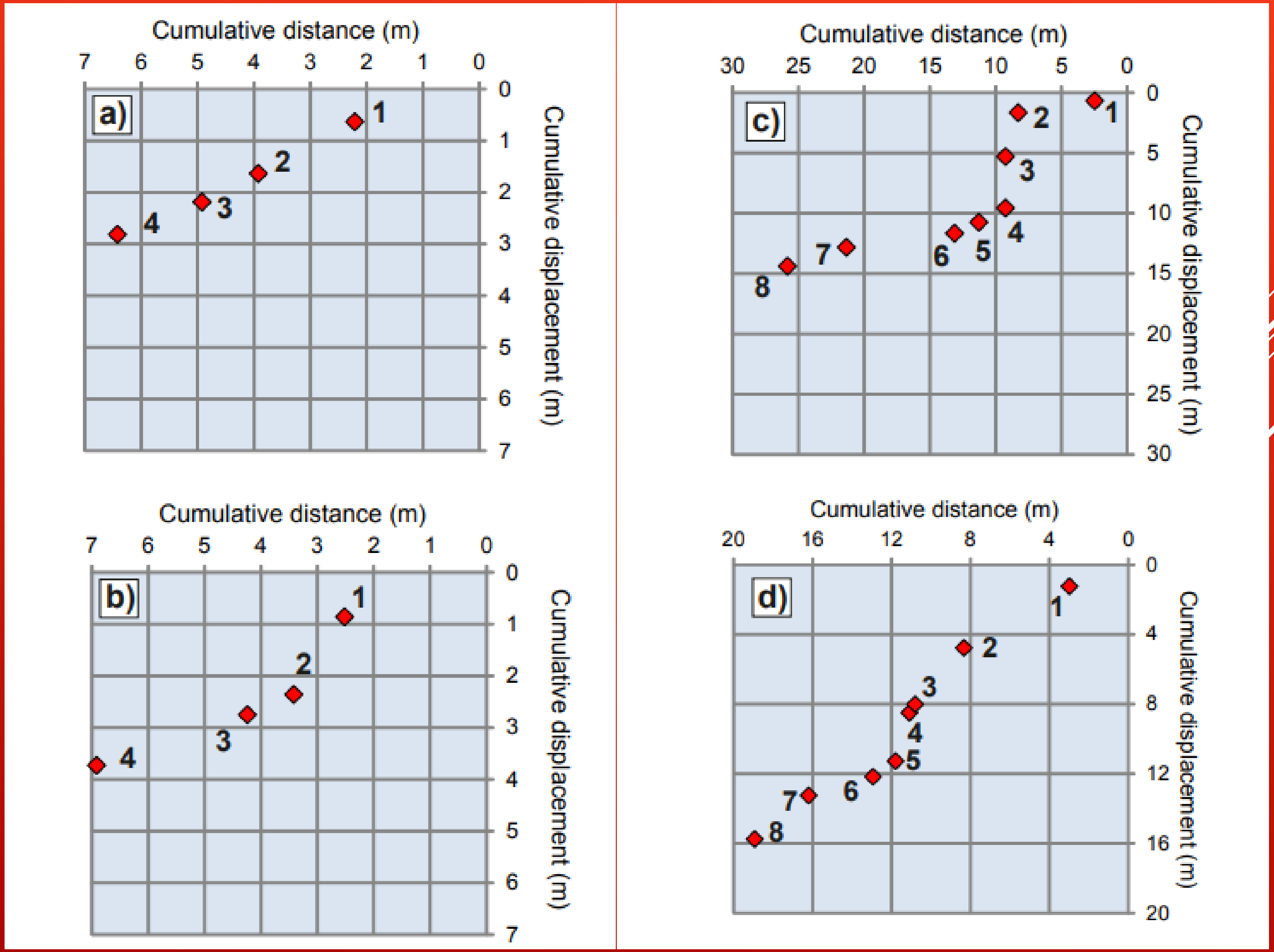
Table 1

Balanced line-length restoration values of linked fold and thrust system in Slump 5 (see Fig. 7).

Marker horizon	Present length	Restored length	Shortening (thrusts only)	Shortening (folds only)	Shortening (thrusts and folds)	Missing shortening (as a % of blue 39.2 m restored length)	Missing shortening (as a % of blue 16.4 m shortening)
Top Green	22.8 m	35.6 m	9.3 m (26.2%)	3.3 m (9.3%)	12.6 m (35.4%)	3.8 m (9.7%)	3.8 m (23.2%)
Middle Orange	22.8 m	38.8 m	13.6 m (35.1%)	2.4 m (6.2%)	16 m (41.2%)	0.4 m (1%)	0.4 m (2.4%)
Lower Blue	22.8 m	39.2 m	15.9 m (40.6%)	0.5 m (1.3%)	16.4 m (41.8%)	0 m (0%)	0 m (0%)

ANALYSIS: CUMULATIVE DISPLACEMENT-DISTANCE GRAPHS

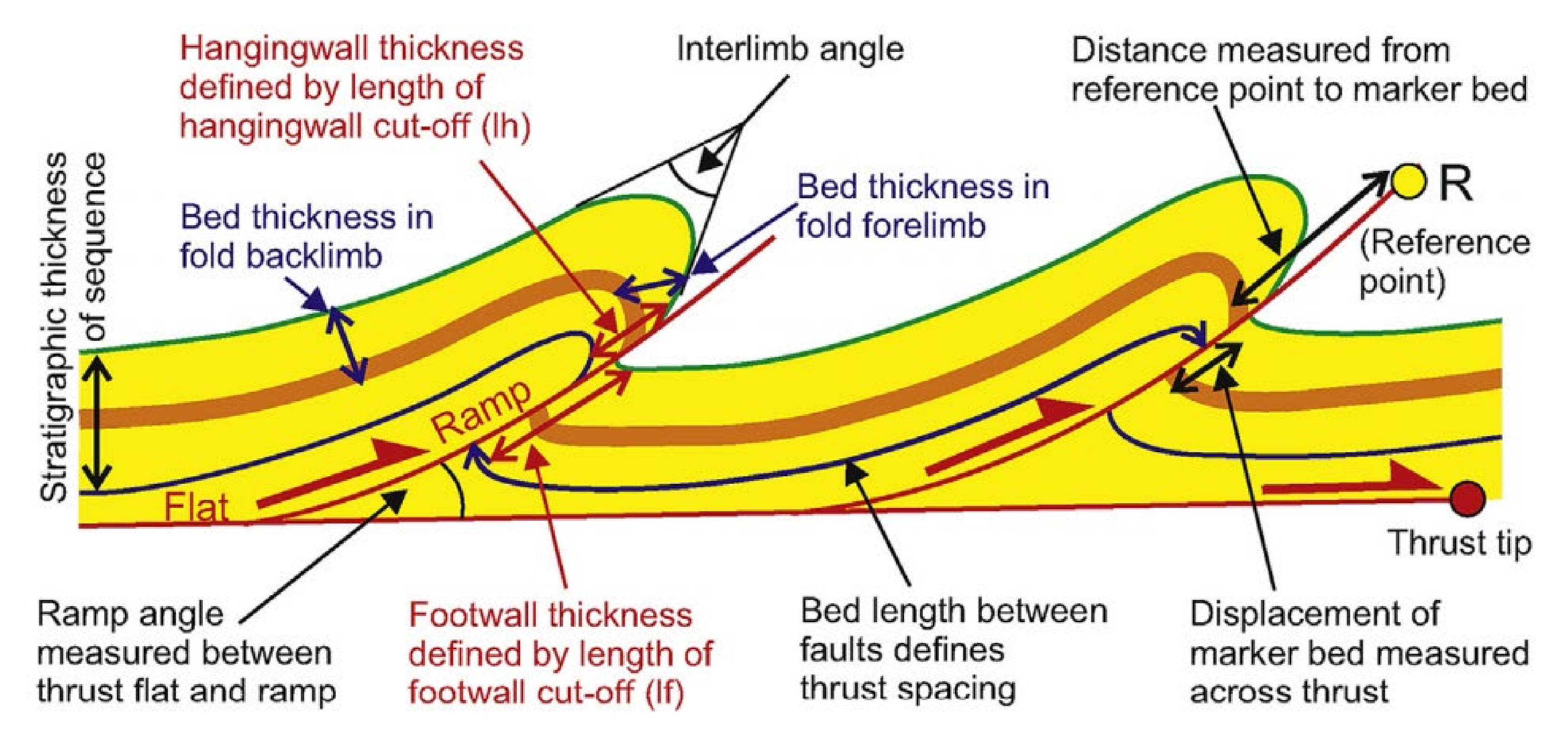
- Measure thrust displacement
- Fixed reference point where leading imbricate thrust branches from floor thrust
- Measured distance from reference point along floor thrust to where successive thrusts branch from floor thrust
- Displacement measured across each individual thrust starting with first thrust ramp and progressively combined with subsequent ramps
- Aragonite rich & detrital poor systems with relatively small displacements show more or less linear profile (a & B)
- Increases in displacement & varied stratigraphy show variable profiles with distinct “step” (c & d)



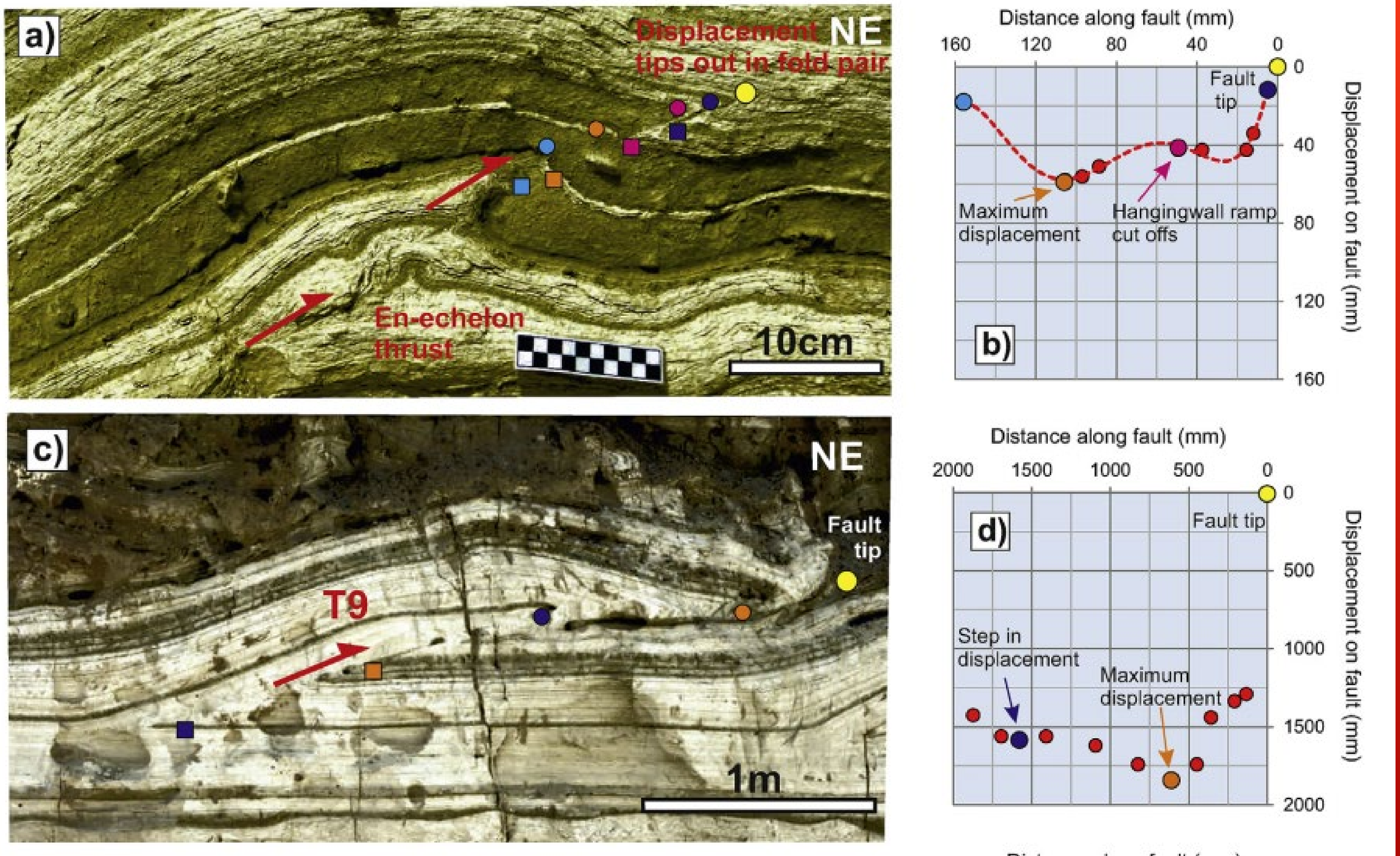
ANALYSIS: DISPLACEMENT-DISTANCE GRAPHS

- Traditionally used to analyze faults cutting lithified rocks
- Distance measured along hanging wall of thrust from fixed reference point to marker bed horizon
- Compare distance with displacement of the same marker bed by measuring offset in footwall

In general, gentle gradients on D-D plots represent rapid propagation of thrust tip relative to slip, while steep gradients represent slower propagation relative to slip



Displacement is greatest where thrust cuts detrital horizon (orange)



Displacement maxima represents site of fault nucleation

TAKE-AWAY

- Relative stretch for soft sediments typically <0.5, lower than expected values for lithified rocks (0.5-0.89)
- Interlimb angles in soft sediment folds => less than predicted
- Thrust ramps initiated in competent (detrital) horizons
- Average spacing of thrust ramps and thickness of thrust sequence => 5:1 ratio
- Thrust systems examined broadly balance with respect to shortening, but exhibit "missing shortening" and top layers, possibly due to lateral compaction
- CD-D graphs w/ "step" show variable slip rate & greater inconsistency compared to thrusts cutting lithified rocks
- D-D graphs => "step" in gradient displays more variability in displacement compared to lithified rocks

OUTSIDE IMAGE SOURCES

Slide 8: http://shaileshchaure.com/Notes/DipIsogon.pdf