Basins in Motion: Tectonic Inversion and Evolution of Migrating Releasing Step-Overs*

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Abstract

Bends and step-overs along strike-slip faults create localized basins or push-up ridges. The basins created by releasing bends can be source and reservoir for hydrocarbons. The current working model for the evolution of releasing bends does not correlate with field observations. The traditional model states that a bend or step-over grows in structural relief with progressive slip on the principle strike-slip fault. Such a relationship cannot explain basin deposits outside the current basin, the average 1:3 ratio of basin width to length, nor the fact that fault boundaries change with time.

Wakabayashi (2004, 2007) recently proposed that the location of bends and step-overs migrate along strike of the primary strike-slip fault. The migrating step-over hypothesis proposes that at a step-over, one fault tip propagates in one direction faster than the relative far field motions, whereas the other side of the fault dies out. Thus, the step-over basin migrates at a different rate than regional crustal velocities. When the bend or step-over migrates it creates a new active basin and abandons former basin deposits. This model predicts that when migration occurs, this leaves a 'tectonic wake' of former basin deposits that are no longer in the active bend or step-over.

We conducted a field test of a suspected migrating releasing and restraining bend pair in Fish Lake Valley, California/Nevada. Uplifted and shortened playa deposits demonstrate that the southern Fish Lake Valley transitioned from extension and subsidence to shortening and uplift. The localized tectonic inversion is a result of a releasing bend and a restraining bend to its southeast, both migrating northwest. Hypsometry of drainage basins draining the upland area southeast of Fish Lake Valley shows progressively more mature topography southeastward of Fish Lake Valley over 7 km of the Sylvania Mountains. This is consistent with northward migration of a restraining step-over, causing progressive uplift and shorting during northward migration. The migrating step-over

hypothesis proposes that many pull apart basins may have evolved differently than traditionally thought, predicting different relationships between fault slip, basin geometry, and time-burial history of sediments. This implies that areas of petroleum reserves may exist where not currently sought. This could open up new reserve opportunities in petroleum-bearing pull-apart basins.

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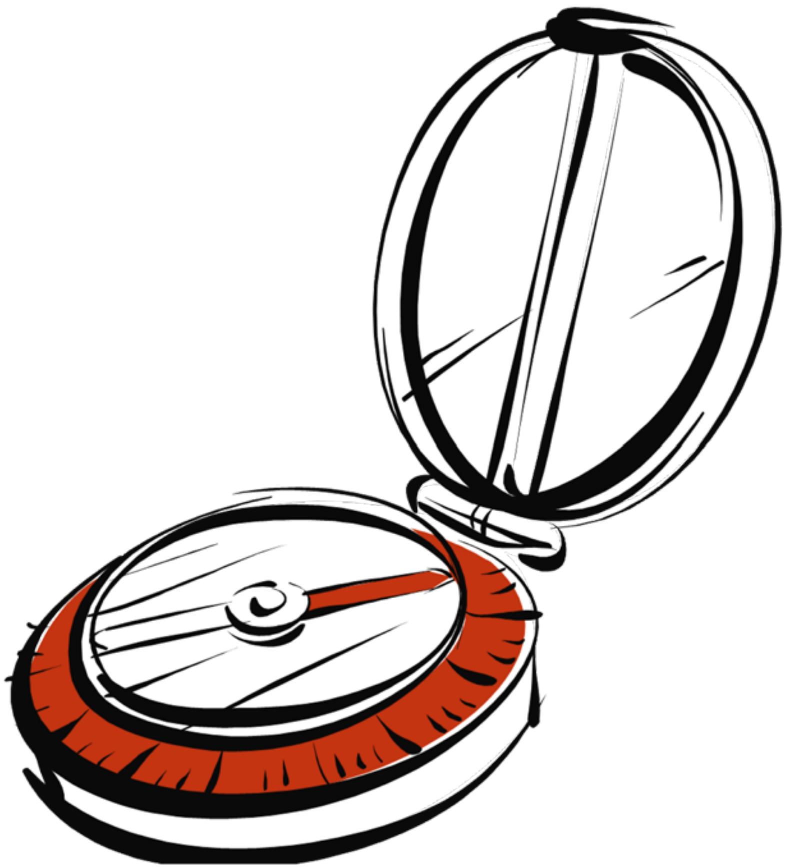
Outline

- Models
  - Traditional
  - Migrating step-over hypothesis
- Field Area- Fish Lake Valley (FLV)
  - Geologic Background
- Methods
  - Field mapping- Structural Analysis
- Conclusions
  - Fish Lake Valley evolution
  - Reactivation of transverse features
  - Implications for petroleum



Intellectual Merit

- Pull-apart basins can be petroleum reservoirs.
- The traditional model of bend and step-over evolution doesn't match field observations.
- Wakabayashi proposes the migrating step-over hypothesis.
- The new model implies that basins associated with releasing step-overs may be larger than previously thought.

Wakabayashi et al, 2004 & Wakabayshi 2007

Traditional Model

- Original faults remain the same.
- Releasing bends increase in length at the same rate as crustal velocity.
- Restraining bends increase throw on the same transverse structures by either pure thrust or oblique-reverse movement.
- Horizontal slip is directly correlates to vertical relief.

$$\mathbf{z = x \sin(\tan\text{-}1\,(\sin\theta \tan\delta))}$$

z= vertical component of displacement

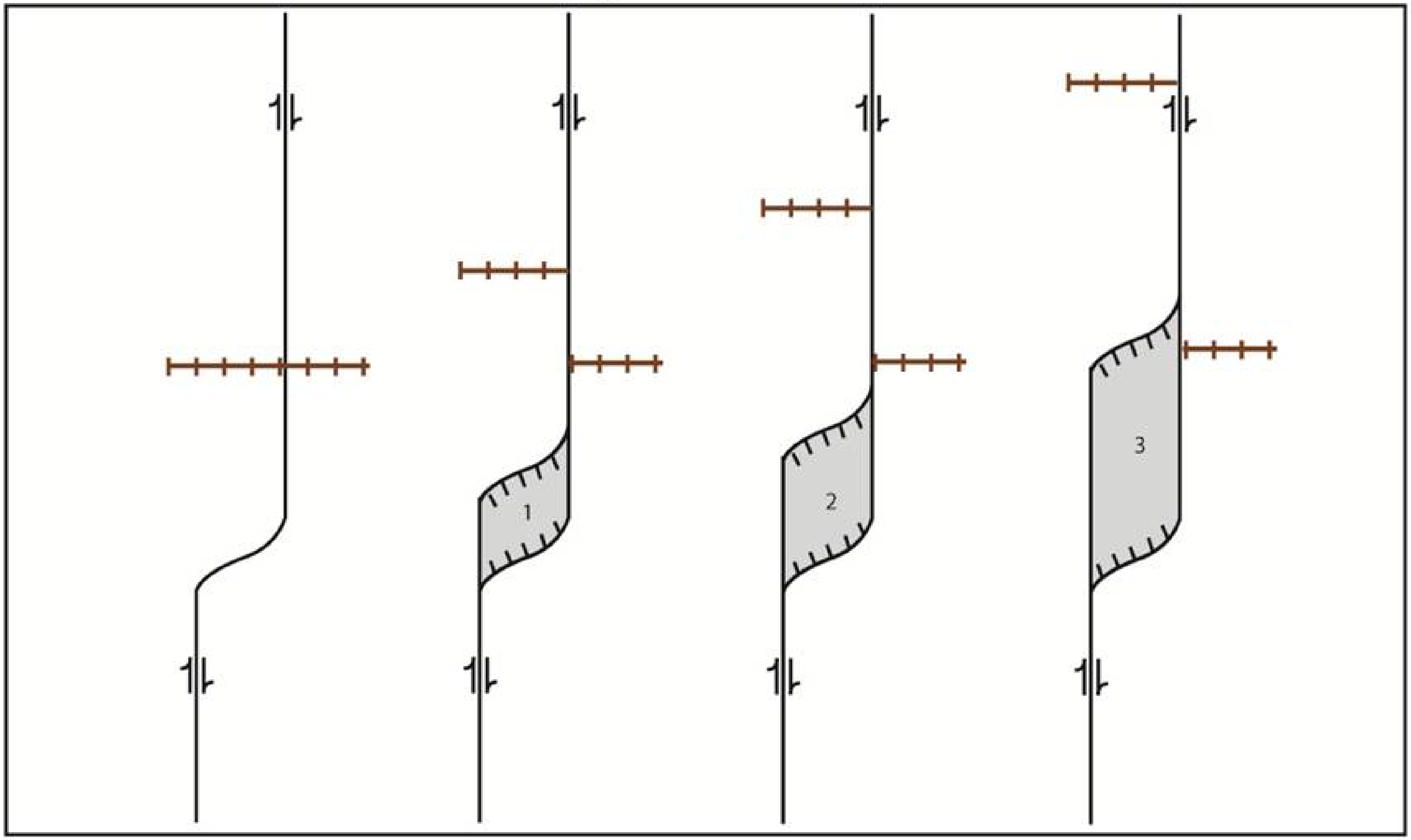
x= strike-slip displacement

θ= angel between transverse structure strike and PDZ

δ= dip of the transverse structure

Notes by Presenter: The equation is from Wak 2004.

Traditional Step-over Model



Notes by Presenter: Step-overs and bends.

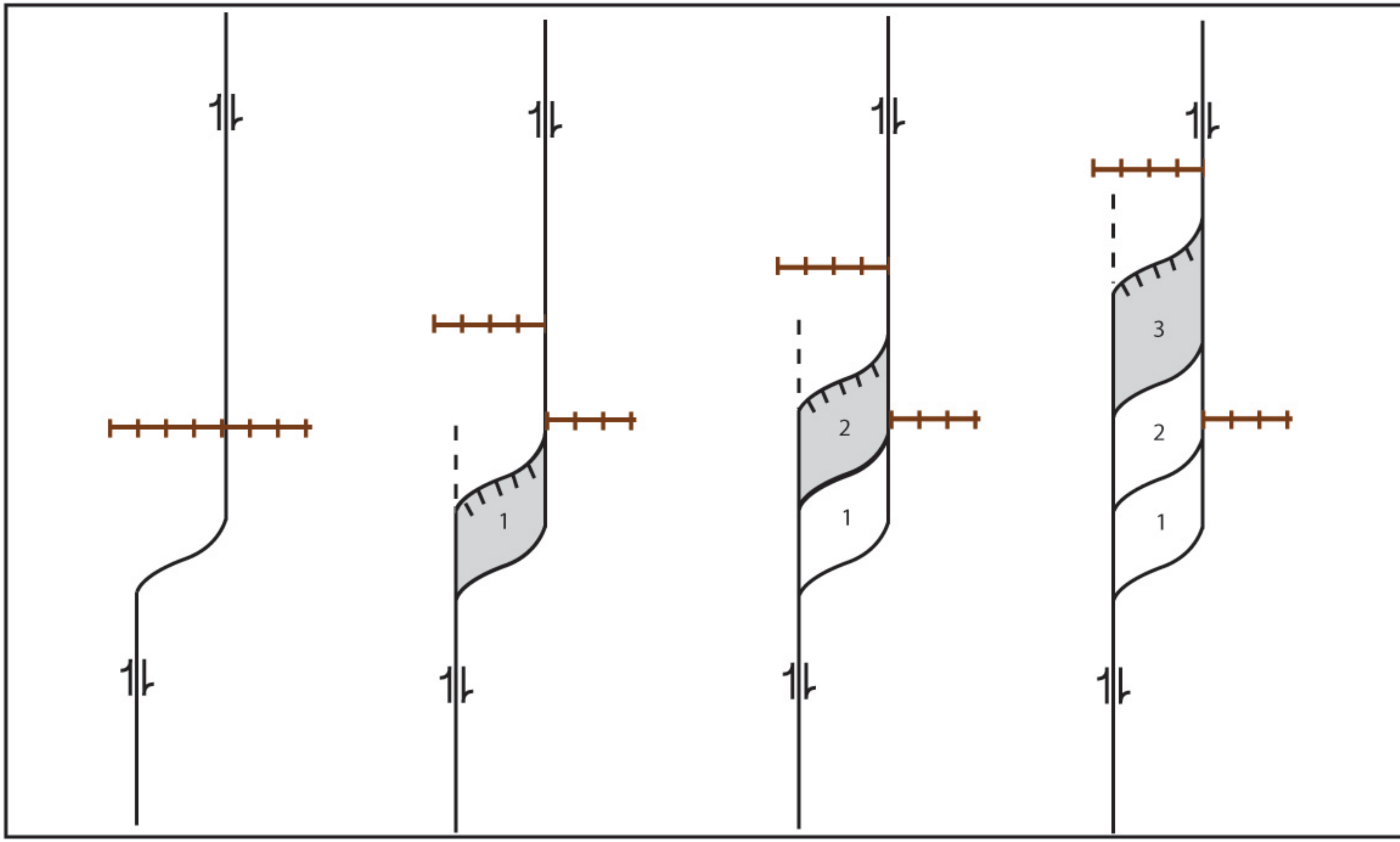
Problems with Traditional Model

1. Pull-apart basin age and rate of motion do not correlate with its length to width ratio (Aydin and Nur, 1982).
2. The basin-bounding faults are not the permanent boundaries of the main fault segment of the step-over (Dooley and McClay, 1997; McClay and Dooley, 1995; Smit et al., 2008).
3. Transpressional welts do not display the high amounts of vertical relief that would be caused by the amount of strike-slip displacement on their faults (Wakabayashi, 2004).
4. Strike slip faults appear to initiate as en-echelon strands that straighten with time (Wilcox et al., 1973), not as straight faults with bends that open over time.

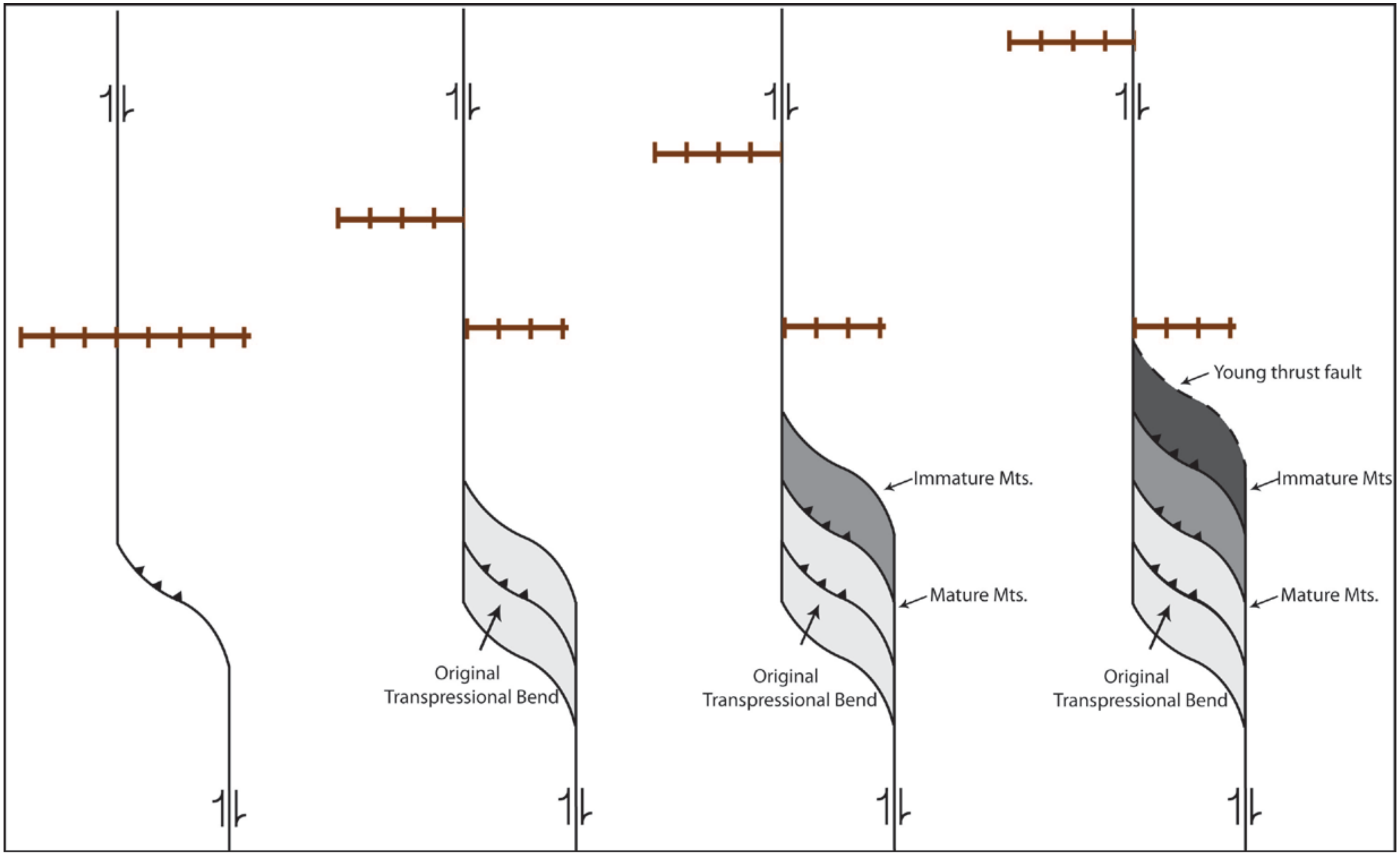
Migrating Step-over Hypothesis

- In the migrating step-over hypothesis the active step-over region migrates with respect to deposits that were once within the active step-over.
- The step-over may migrate at a rate greater than, equal to or less than the relative crustal velocities defined by strike-slip fault rate.
- When a migration occurs, this leaves a ‘tectonic wake’ of former basin deposits that are no longer in the active bend or step-over. A localized tectonic inversion may occur in an abandoned basin if the regional strain is compressional or if a restraining bend migrates into the wake of a migrating releasing bend.

Migrating Releasing Step-over

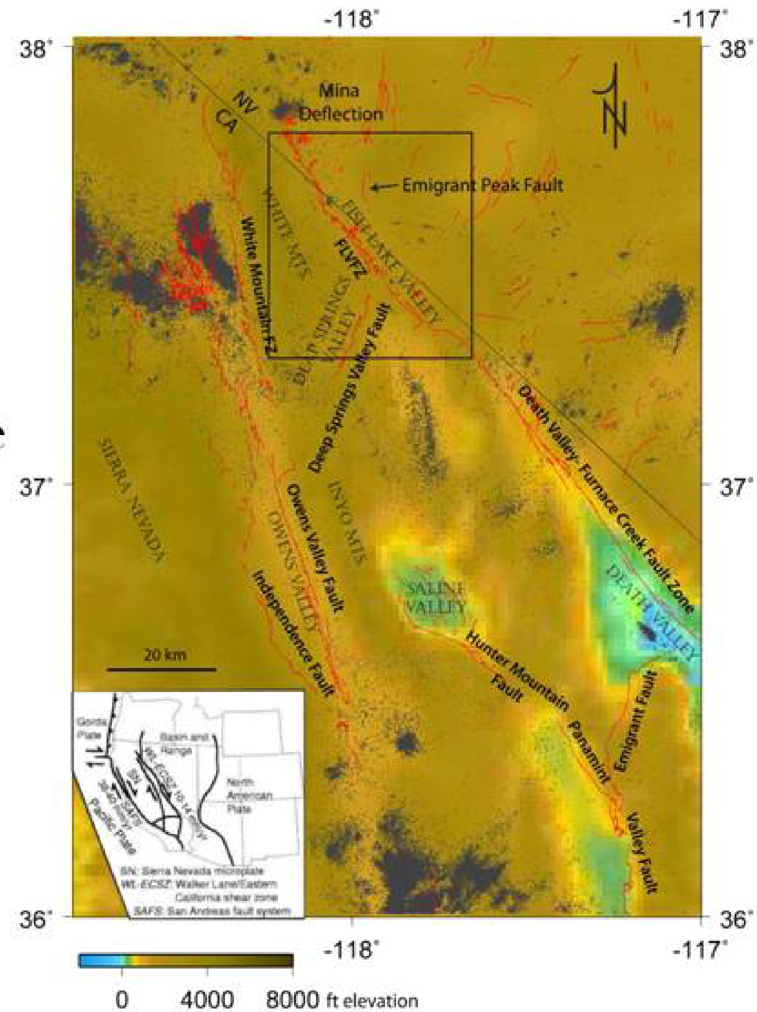


Migrating Restraining Bend



Eastern CA Shear Zone Regional Motion

- FLV is located in the East California Shear Zone (ECSZ)
- Fish Lake Valley Fault Zone (FLVFZ) is the northern continuation of the Furnace Creek-Death Valley Fault Zone
- FLVF accounts for half of motion on the ECSZ
- Arid climate results in surface exposure



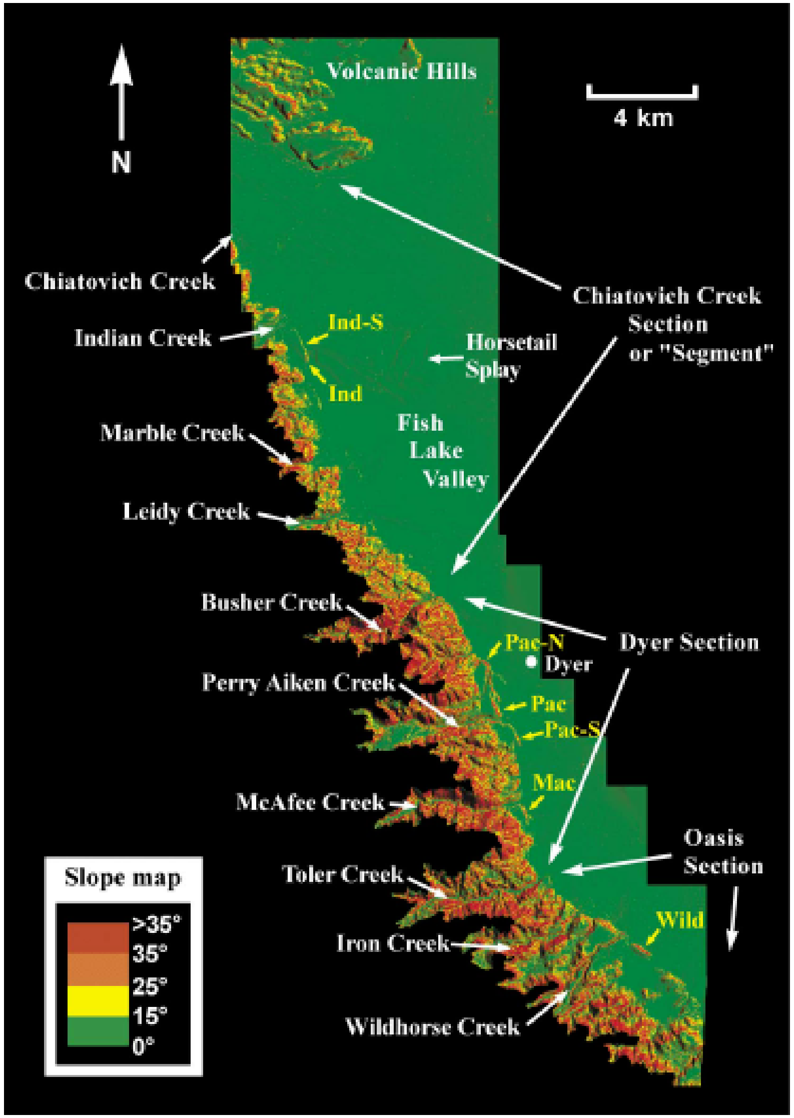
Notes by Presenter: FLVFZ movement is from a combination of Death Valley (3.3 ±2.2 mm/yr) and Owens Valley (3.9±1.1 mm/yr)- Dixson et, al 1995 and then goes into the Mina deflection to the north and Walker Lane (Oldow et al 1994).

Fish Lake Valley

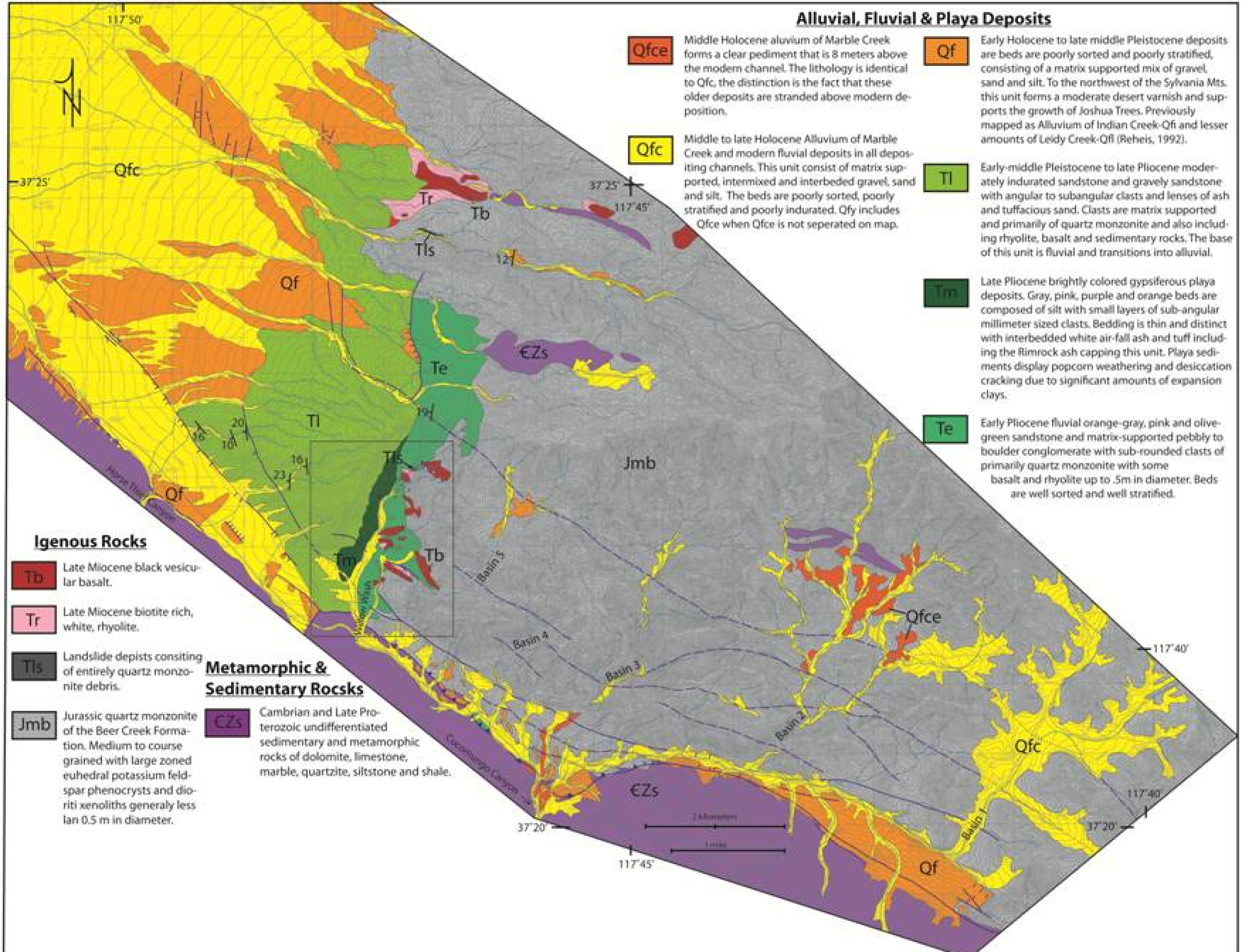
- FLV is a pull apart basin from a step-over from FLVFZ to Emigrant Peak Fault
- 8-25km wide, 25km long
- Average 5mm/yr slip-rate (Reheis, 1997) agrees with geodetic 6.2±2.3mm/yr (Dixson et. al, 1995)
- South of the Sylvania Ranges is a left (transpressional) bend on the FLVFZ

Fault Maturity

- Digital Elevation Model in West Fish Lake Valley
- Fault scarps progressively more youthful northward
- The northern tip of the Fish Lake Valley Fault Zone is younger and shows less displacement because it is the propagating tip.



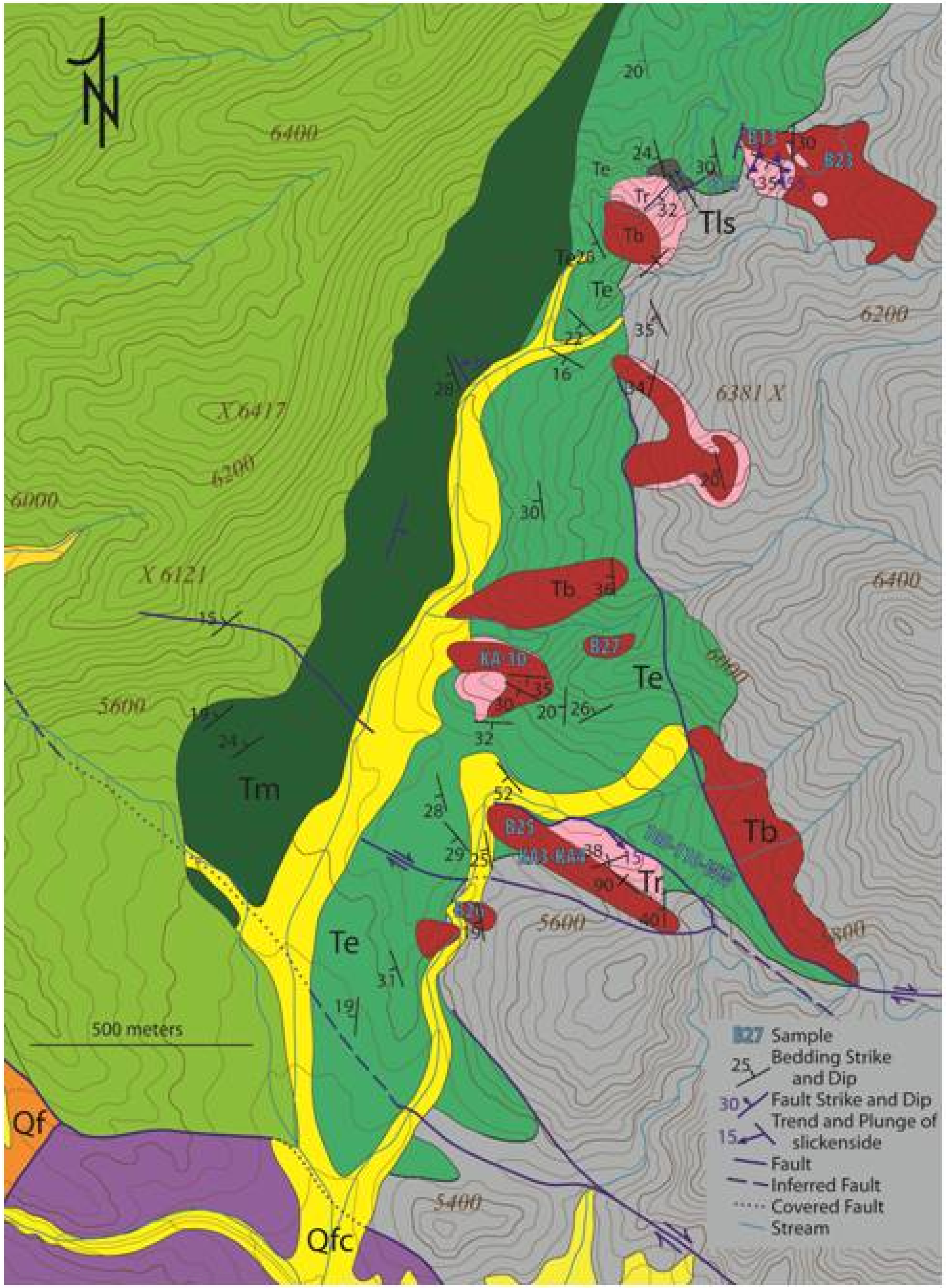
Hooper et al., 2003



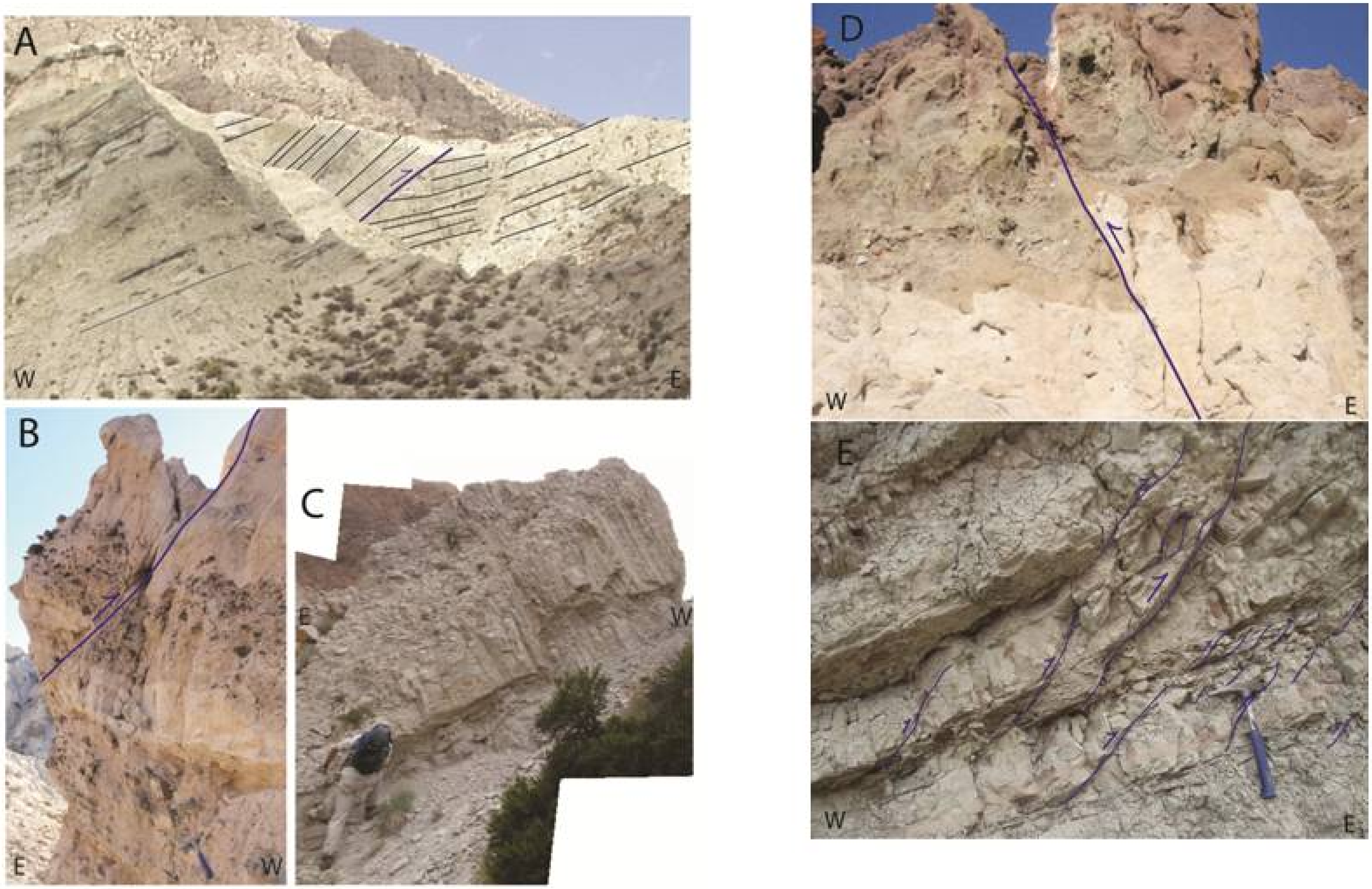
Alluvial, Fluvial & Playa Deposits
Qfce
Middle Holocene aluvium of Marble Creek forms a clear pediment that is 8 meters above the modern channel. The lithology is identical to Qfc, the distinction is the fact that these older deposits are stranded above modern deposition.
Qfc
Middle to late Holocene Alluvium of Marble Creek and modern fluvial deposits in all depositing channels. This unit consist of matrix supported, intermixed and interbeded gravel, sand and silt. The beds are poorly sorted, poorly stratified and poorly indurated. Qfy includes Qfce when Qfce is not seperated on map.
Qf
Early Holocene to late middle Pleistocene deposits are beds are poorly sorted and poorly stratified, consisting of a matrix supported mix of gravel, sand and silt. To the northwest of the Sylvania Mts. this unit forms a moderate desert varnish and supports the growth of Joshua Trees. Previously mapped as Alluvium of Indian Creek-Qfi and lesser amounts of Leidy Creek-Qfl (Reheis, 1992).
Tl
Early-middle Pleistocene to late Pliocene moderately indurated sandstone and gravely sandstone with angular to subangular clasts and lenses of ash and tuffacious sand. Clasts are matrix supported and primarily of quartz monzonite and also including rhyolite, basalt and sedimentary rocks. The base of this unit is fluvial and transitions into alluvial.
Tm
Late Pliocene brightly colored gypsiferous playa deposits. Gray, pink, purple and orange beds are composed of silt with small layers of sub-angular millimeter sized clasts. Bedding is thin and distinct with interbedded white air-fall ash and tuff including the Rimrock ash capping this unit. Playa sediments display popcorn weathering and desiccation cracking due to significant amounts of expansion clays.
Te
Early Pliocene fluvial orange-gray, pink and olive-green sandstone and matrix-supported pebbly to boulder conglomerate with sub-rounded clasts of primarily quartz monzonite with some basalt and rhyolite up to .5m in diameter. Beds are well sorted and well stratified.
Igenous Rocks
Tb
Late Miocene black vesicular basalt.
Tr
Late Miocene biotite rich, white, rhyolite.
Tls
Landslide depists consiting of entirely quartz monzonite debris.
Jmb
Jurassic quartz monzonite of the Beer Creek Formation. Medium to course grained with large zoned euhedral potassium feldspar phenocrysts and dioriti xenoliths generaly less lan 0.5 m in diameter.
Metamorphic & Sedimentary Rocsks
€Zs
Cambrian and Late Proterozoic undifferentiated sedimentary and metamorphic rocks of dolomite, limestone, marble, quartzite, siltstone and shale.
N
117°50'
37°25'
37°25'
117°45'
117°40'
117°40'
37°20'
37°20'
117°45'
Qfc
Qf
Tr
Tb
Tls
Te
€Zs
Tl
Jmb
Tm
Qfce
Basin 5
Basin 4
Basin 3
Basin 2
Basin 1
Horse Thief Canyon
Cucomungo Canyon
Willow Wash
2 kilometers
1 mile

Willow Wash

- Field mapping focused on Willow Wash because of it's lithologic diversity and complex structure.
- This area demonstrates tectonic inversion.

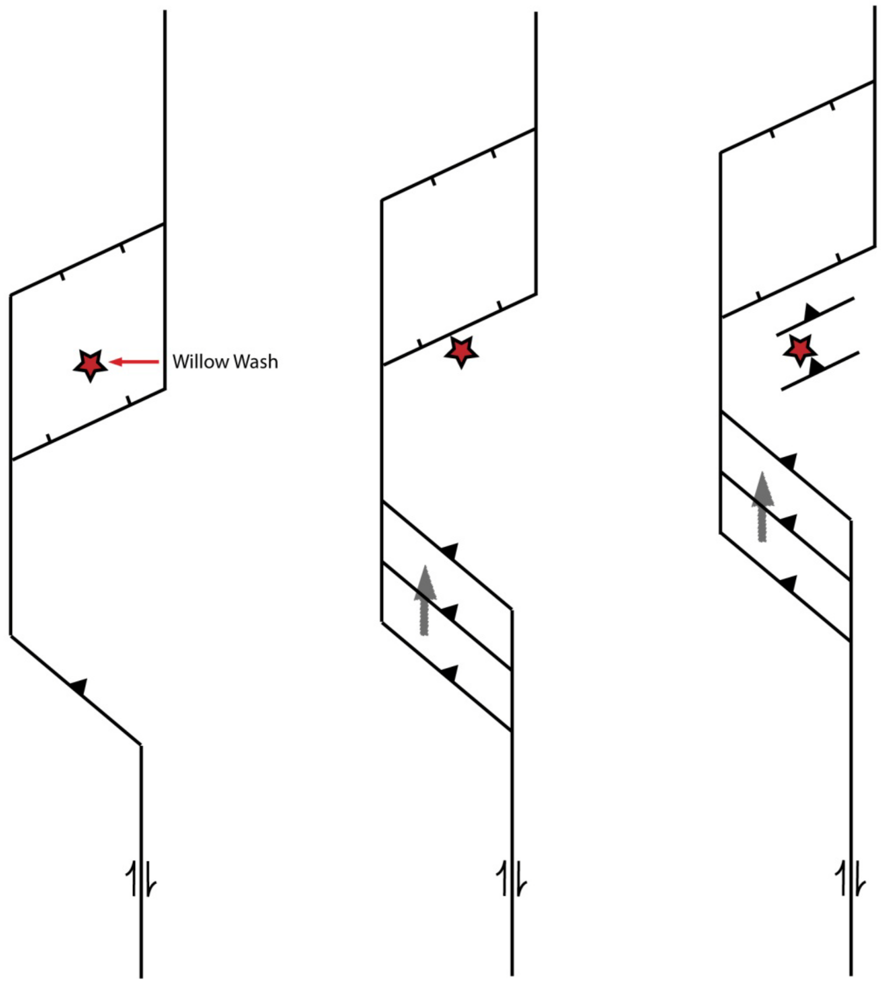


Thrust Features



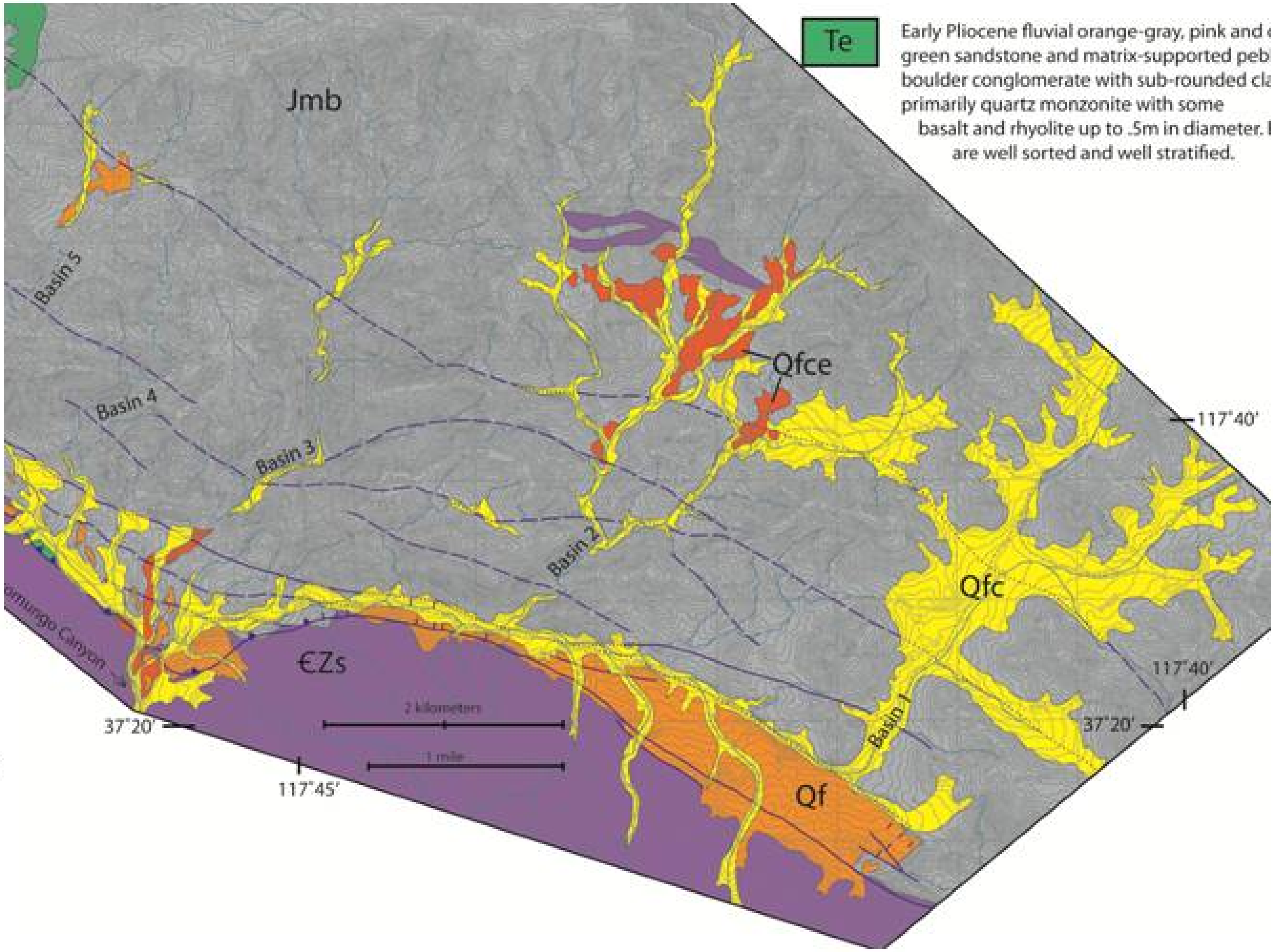
Fish Lake Valley Evolution

The area of Willow Wash was once in a releasing step-over of Fish Lake Valley. The step-over migrated further north abandoning the basin deposits of Willow Wash in its tectonic wake. A restraining bend migrated into Willow Wash causing a localized tectonic inversion.



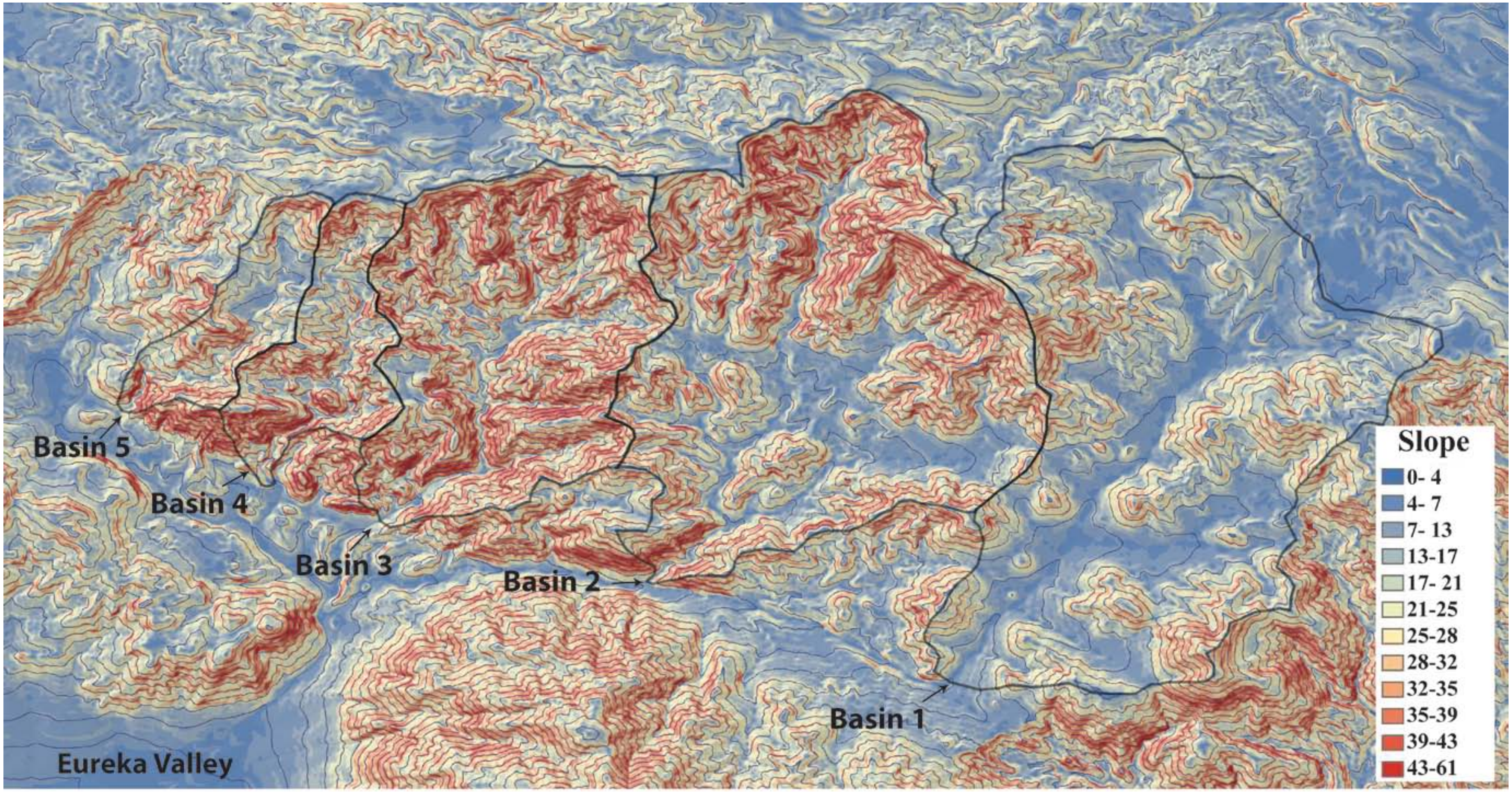
Progressive uplift of Sylvania Mts.

- The Sylvania Mountains have progressively uplifted from southeast to northwest.
- The transitional nature of change implies that migration of the restraining bend moves progressively and not by a serious of 'jumps.'



Click to View Notes by Presenter

Slope Map



- The Sylvania Mts. consist entirely of homogenous quartz monzonite meaning that changes in topography are tectonic.

Notes by Presenter (for previous slide):

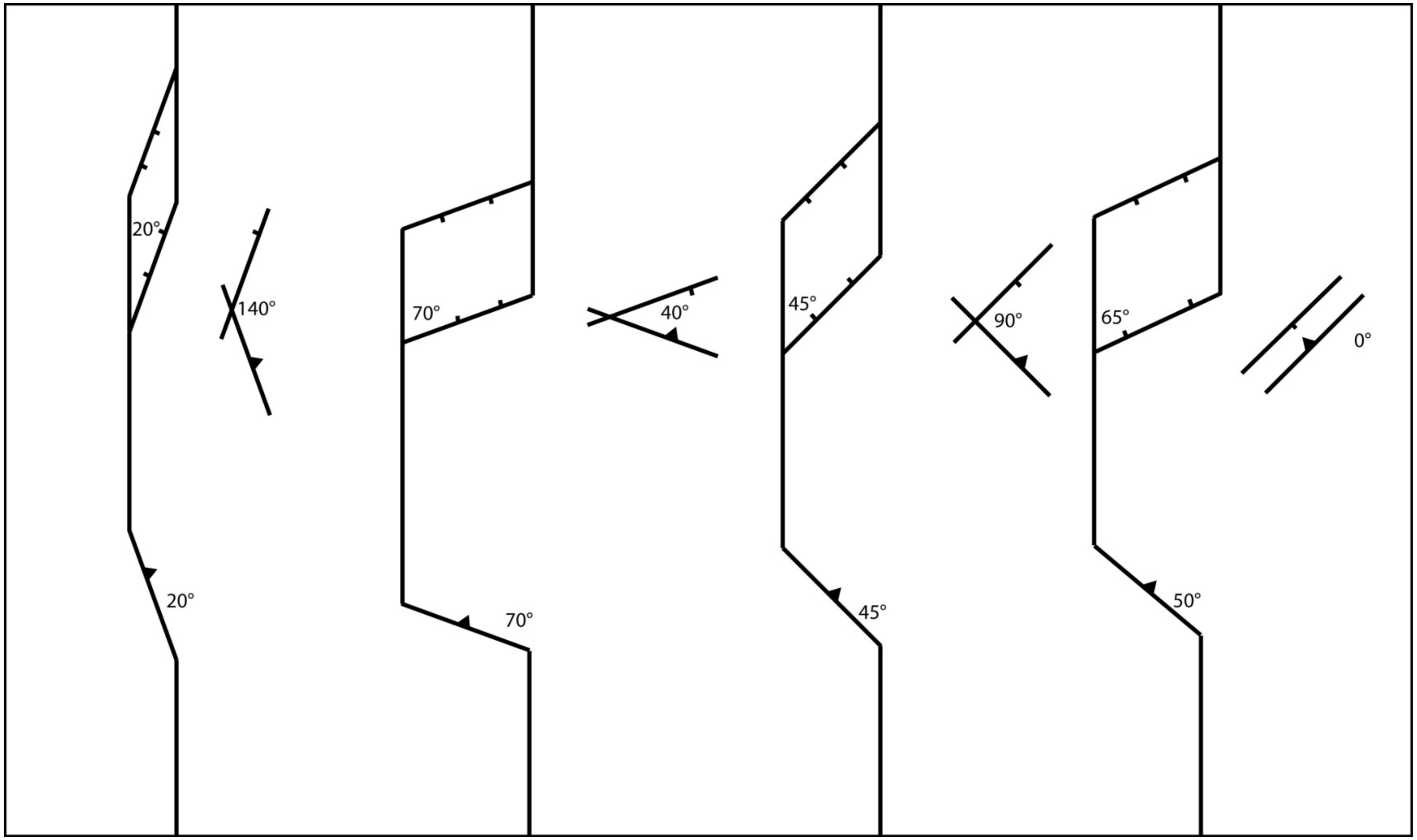
1) the areal extent of the basins 2) scale of drainage basins 3) stream order within basins. But, when drainage basins are smaller the hypsometric integral is greater and approaches .45 (Chen et al., 2003; Hurtrez et al., 1999). The hypsometric integrals in this area are within this range (.42-.48). The terminal stream in Basin 1 has a stream order of 4, compared to Basin 5 which has a stream order of 1. It is debatable what effect the stream order has on hypsometry. Merritts and Vincent (1989) determined that lower stream orders are more sensitive to tectonism and Walcott and Summerfield (2008) state that basins of different stream order have little relation to hypsometric integral.

Styles of Sedimentation or Erosion

NW- Cliff Forming Erosion

SE- Broad Depositional Basin

Kinematic Mechanisms of Migration



- In Fish Lake Valley, the normal faults created during extension were preferentially reactivated during compression although this is not the preferred angle for faulting.

Petroleum Applications

- Producing pull-apart basins maybe larger than previously thought; opening up more reserves along strike.
- The migrating step-over hypothesis would create a localized tectonic inversion unrelated to the regional tectonic setting.

Questions?