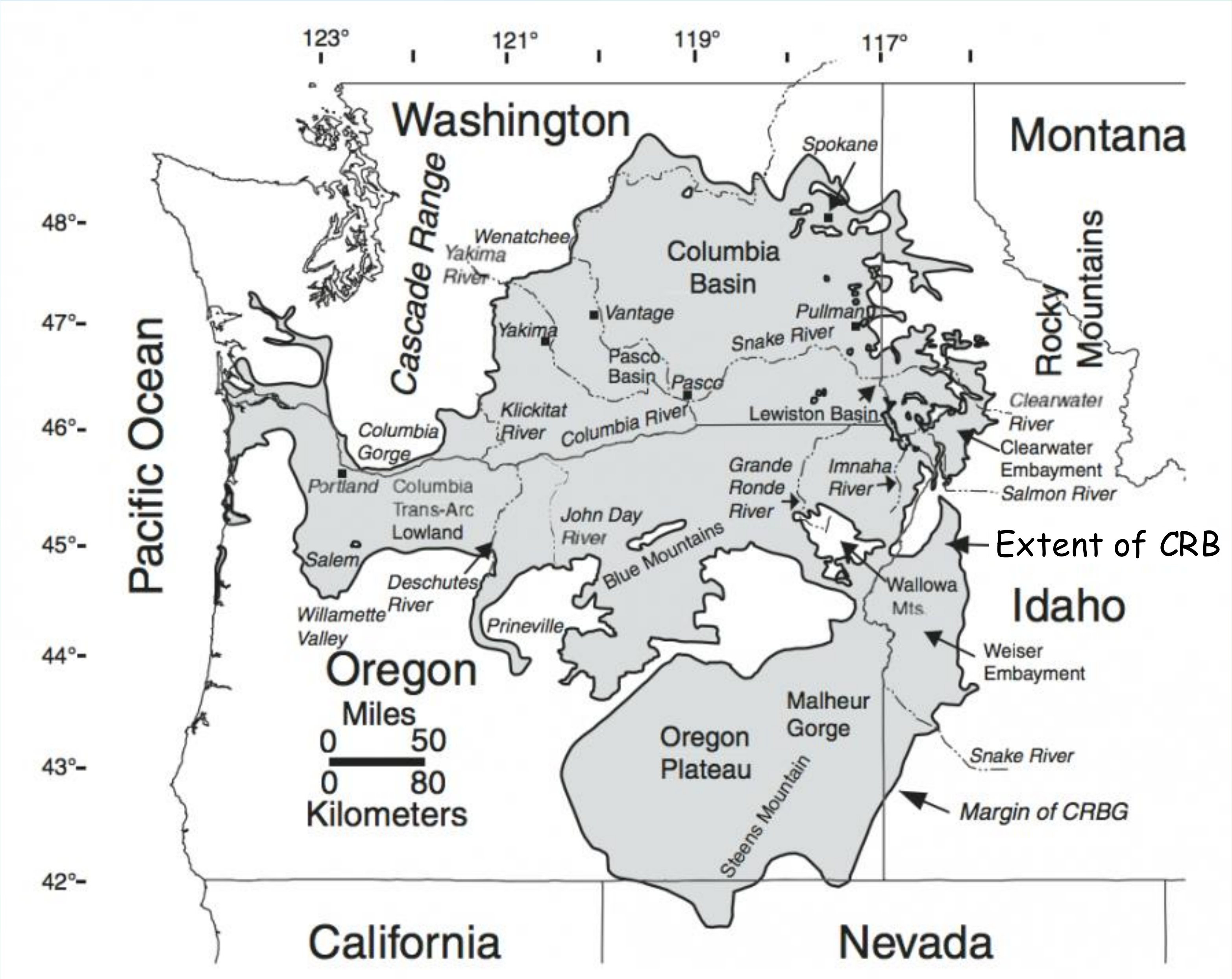

Columbia River Flood Basalts

# Introduction

- Columbia River Basalt (CRB) province → large flood-basalt province in NW USA
- large areas of igneous rocks are called LIPs (Large Igneous Provinces)
- the CRB province covers large areas of Oregon, Washington State and western Idaho with total area ~210,000km$^2$
- the CRB province comprises a thick sequence of dominantly tholeiitic basalt composed of >350 individual flows
- youngest and best preserved flood-basalt province in the world

# Areal extent of Columbia River Basalt province



# Flood basalts

- Result from a giant eruption or series of eruptions → widespread lava flows cover vast areas quickly
- caused by combination of continental rifting in conjunction with a mantle plume undergoing decompression
- produce vast quantities of low viscosity tholeiitic basalts from a series of fissures rather than a central volcano
- dark areas on the Moon (maria) → flood basalts also cover much of the surface of Venus

# Flood basalts on the island of Hawaii

# Sheet lava flow

Active sheet lava flow, 1984 eruption of Mauna Loa, Hawaii

# Fissure eruptions

- Flood basalts flow out of fissure eruptions where there is usually no actual central volcano
- fissure eruptions produce extensive sheets of lava that flood the landscape, fill valleys and produce broad, flat plains
- basalt is supplied to fissures through a series of dykes
- difficult to pinpoint where lavas were originally erupted because there is no central volcano e.g. Western Victoria

# Flood basalt - fissure eruptions

Fissure eruption - Kilauea 1983

# Fissure eruptions

Fissure eruption – Kilauea, Hawaii 2011

# Fissure eruptions

Fissure eruption , Iceland

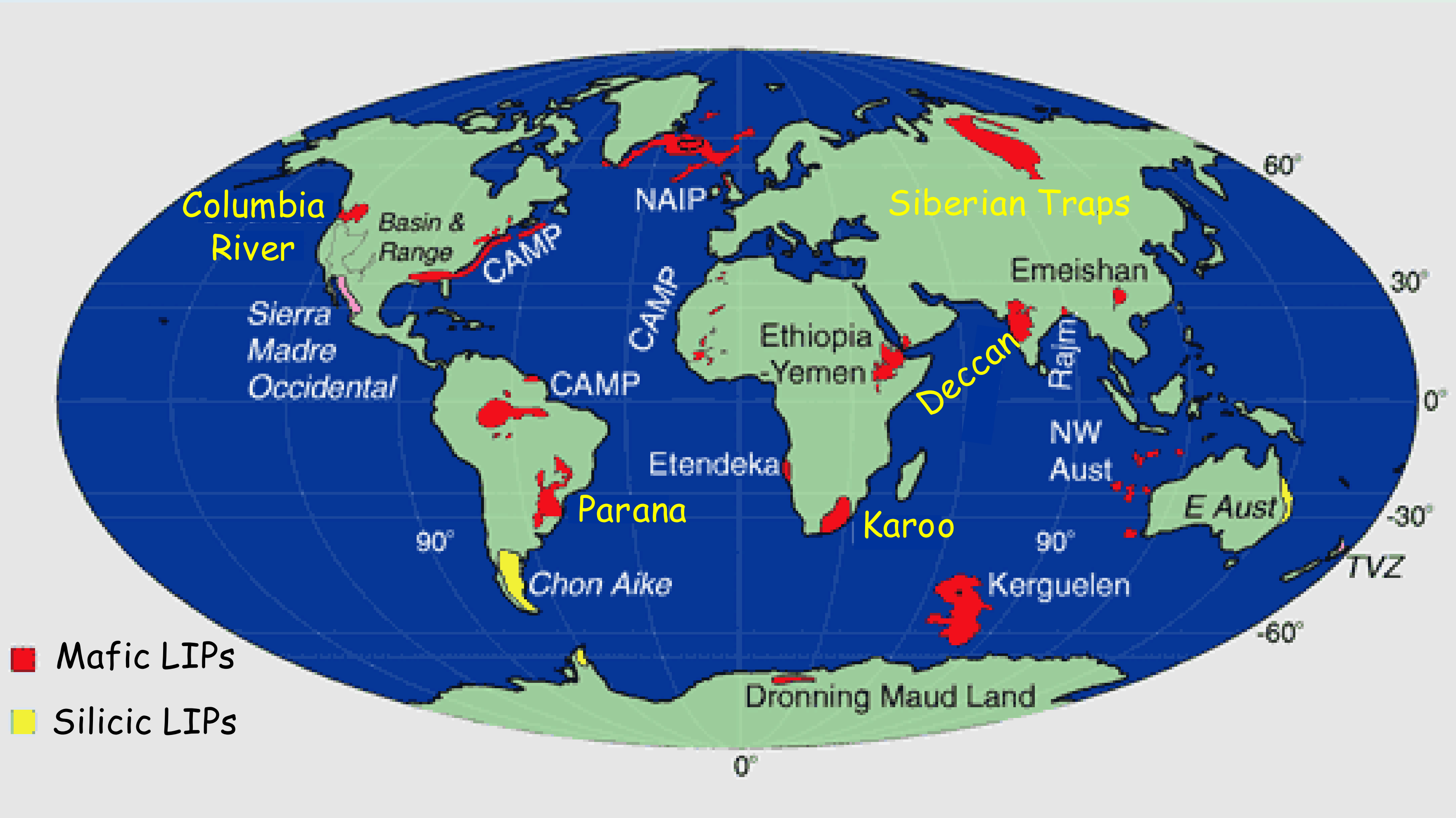
# Fissure eruptions

Lava flowing from a fissure eruption, Grindavik, Iceland March 2024

# Large igneous provinces (LIPs)

- LIPS → Extremely large accumulations of igneous rocks emplaced at or below the Earth's surface
- large volcanic provinces → created by flood basalts
- most have formed accompanied by major climate changes
- strong correlation with major extinctions
- LIP examples: Deccan Traps (India), Siberian Traps (Russia), Columbia River Basalts (USA), Karoo (S.Af), Parana (Brazil)
- flood basalts associated with hot spots → rapid, massive accumulation of basalt with high rate of extrusion

# Large igneous provinces (LIPs)



# Formation of LIPs

Several theories as to how they form:

## Plume formation

- convective plumes originating from deep in the mantle → form hotspots unrelated to plate boundaries

## Plate stress formation

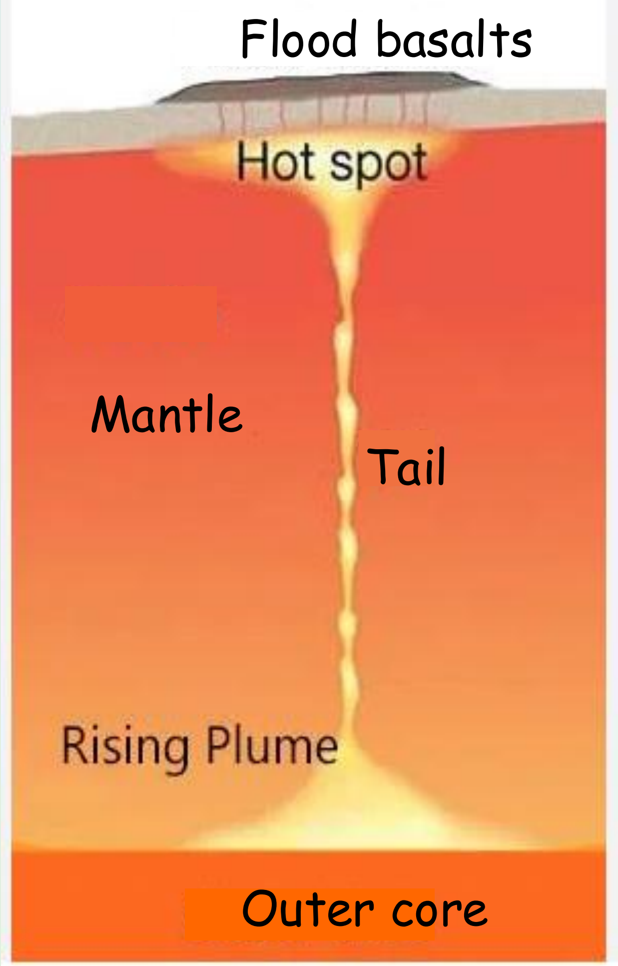
- ruptures caused by plate-related stress → fractures lithosphere → allows melt to reach the Earth's surface

## Meteorite induced formation

- large body impacts may trigger flood basalts (?) e.g. Sudbury

# Hotspot

Hotspot → region of Earth's mantle that upwells to melt through the crust to form a volcanic feature



# LIP examples

| Province | Locality | Area | Volume | Age (Ma) |
|---|---|---|---|---|
| Columbia River Basalt | NW USA | 210,000km$^2$ | 234,000km$^3$ | 17-6 |
| Deccan Traps | India, S Pakistan | 500,000km$^2$ | 1,000,000km$^3$ | 66 |
| Siberian Traps | Siberia, Russia | 7,000,000km$^2$ | 1-4million km$^3$ | 250 |

# Siberian Traps

- Siberian Traps → largest continental flood basalt province in the world
- triggered by asteroid impact in Wilkes Land Antarctica (?) or plate movement over Iceland plume
- basalt flow sequence is up to 3.5km thick
- one year of erupting introduced > 2Gt of $CO_2$ into the atmosphere
- in total >1,200 billion tonnes of methane gas and ~4,000 billion tonnes of $SO_2$ could have evolved from Siberian Traps eruptions

# Siberian Traps

- Eruptions lasted ~2million years spanning the Permian-Triassic boundary (251-250Ma)
- correlation with major extinction (95% of all species)

# Flood-basalt flows, Taymyr Peninsular, Russia

# Deccan Traps

- Deccan traps in Western India and south Pakistan consist of many flows with total thickness of >2,000m
- originally covered ~1,500,000km$^2$, reduced to current size by erosion and plate tectonics
- thought to have been produced by still active Reunion hotspot
- formed at end of Cretaceous (contemporaneous with Chicxulub impact)
- Deccan Traps eruptions actually began before Chicxulub impact
- Chicxulub asteroid impact on Yucatan Peninsula may have increased Deccan Traps eruptions through strong seismic shaking

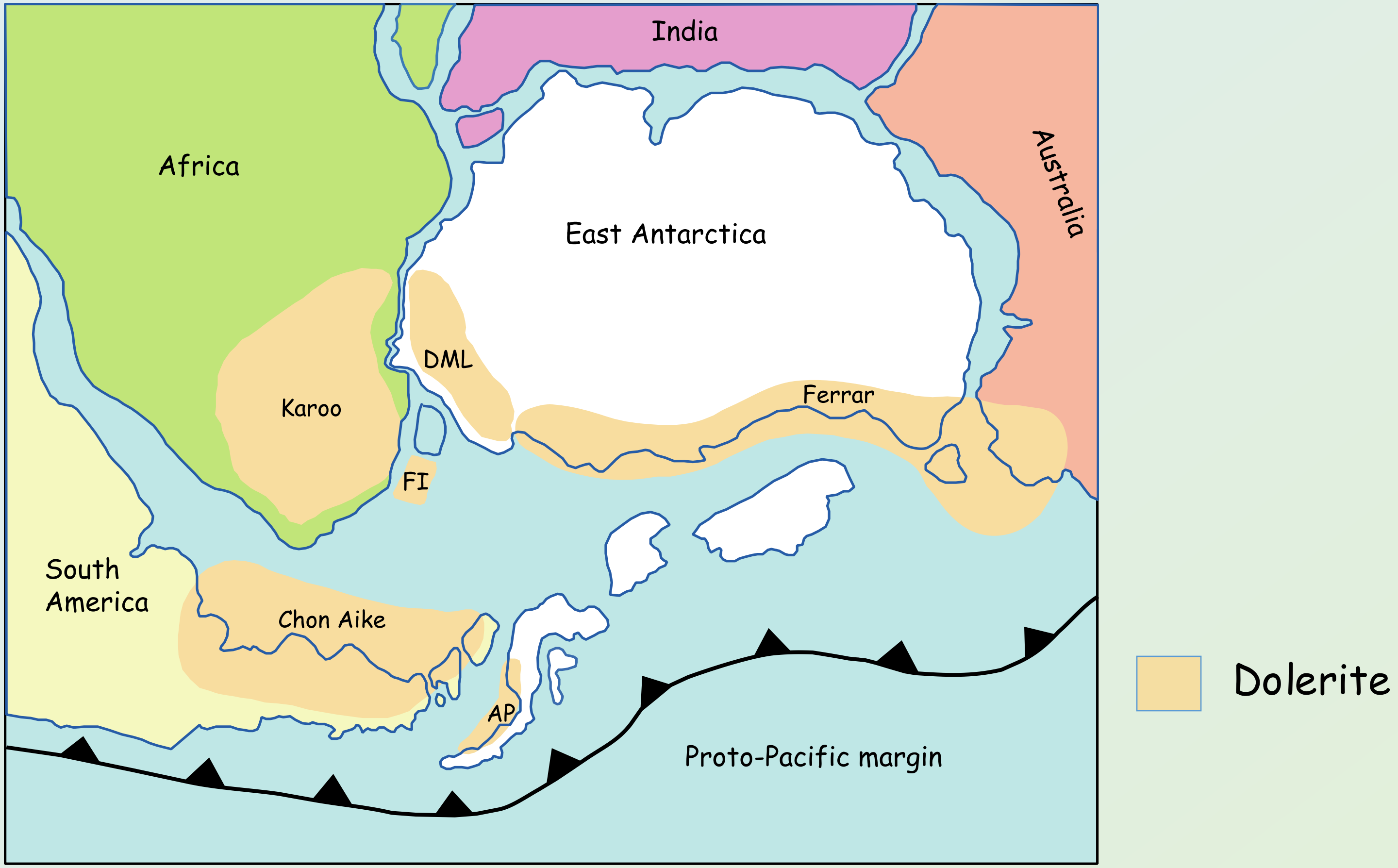
# Deccan Traps

- Eruptions lasted ~30,000years
- thought to have contributed to K-T extinctions (~75% of organisms)

# Deccan Traps lava flows, Mahabaleshwar, India

# Karoo-Ferrar LIP

- Formed at the time of the onset of the break up of Gondwana
- covered an area of about 3million $km^2$ with an original volume of 2.5million $km^3$. Subsequently reduced to ~600,000$km^2$



# Effect on climate and mass extinctions

- LIPs in geological record have formed contemporaneously with marked climate changes → correlation with mass extinctions
- 11 distinct flood basalt episodes in the last 250Ma have coincided with mass extinctions including major extinctions at the Permian-Triassic and Cretaceous-Tertiary boundaries
- vast amounts of sulphurous gases are released during LIP eruptions → react with water in atmosphere to produce sulphuric acid → absorbs heat → may cause substantial cooling
- e.g. it is estimated that one year of erupting Siberian lava could introduce 1.5million tonnes of $SO_2$ into the atmosphere

# Columbia River Basalt (CRB) province

- CRB province lies within the states of Oregon, Washington and Idaho in NW USA
- fifth largest continental flood basalt province after the Deccan and Siberian Traps the Parana Basalt and the Karoo Province
- area of basalts: ~210,000km$^2$

  volume of basalts: 234,000km$^3$

  number of flows: >350

  maximum thickness: 3.5km (near Pasco,Wa)

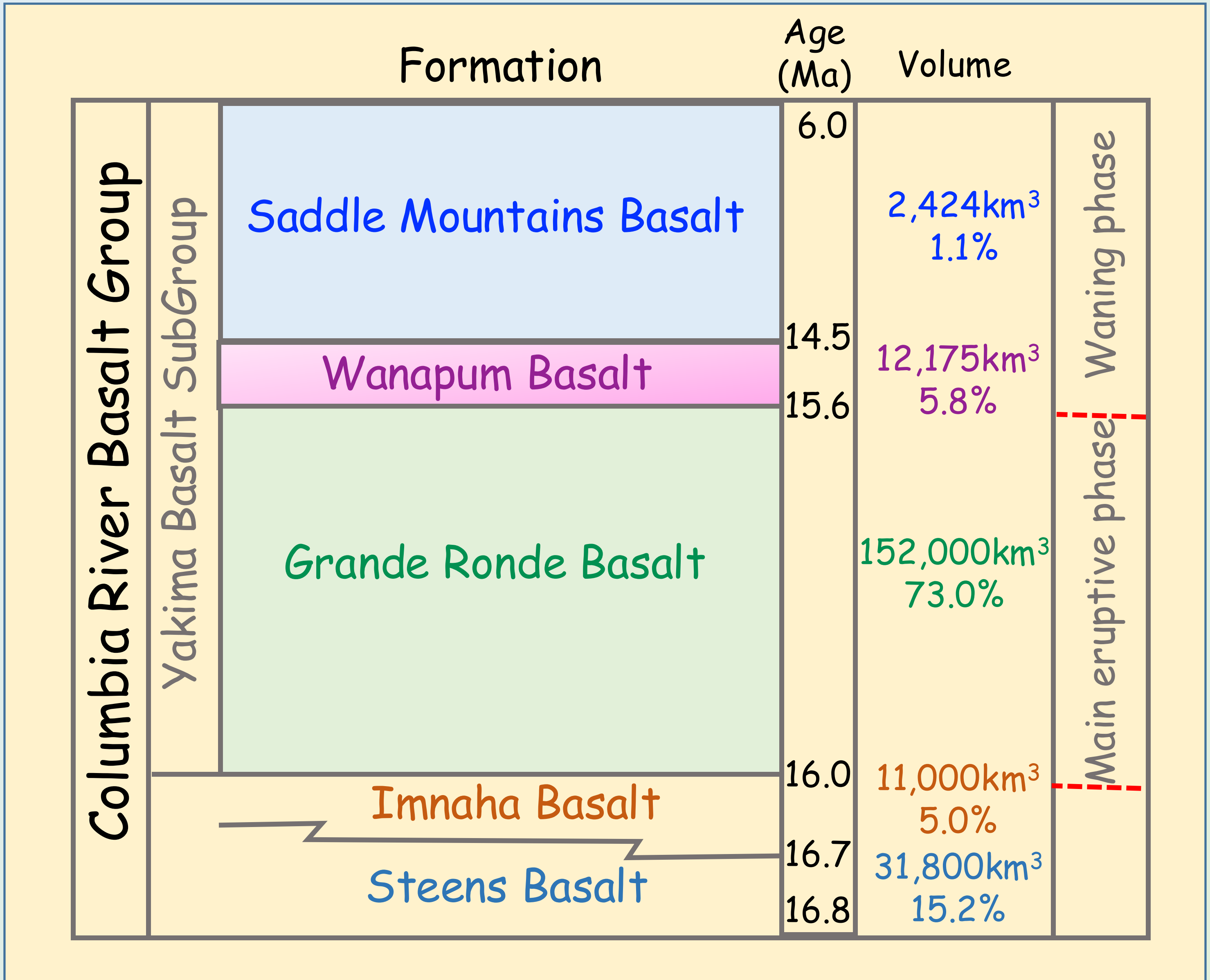
  ages of basalts: 16.8 – 6million years
- beginning 16.8Ma, basalt lavas of the CRB group erupted from long fissures in SE Washington State, NE Oregon and W Idaho

# Columbia River Basalt (CRB) province

- Initiation of CRB volcanic activity coincided with emergence of the Yellowstone hotspot
- some eruptions covered thousands of $km^2$ (mostly in Columbia River Basin) some lavas flowed down Columbia River to the coast
- mountains are buried beneath lava flows with a few peaks of the older rocks protruding through the flows
- in Washington, the crust was depressed ~3000m forming a depressed lava plain → the Columbia River Plateau
- basalts were overlain by Palouse loess during last ice age → erosion by Missoula floods exposed large areas of basalt

# Basalt lava flows along Columbia River

# Columbia River Basalt Group - stratigraphy



# Columbia River Basalt Groups

## Steens Basalt

- Covers ~32,000km$^2$
- ~1km thick in western Idaho and eastern Oregon and Washington
  → roughly contemporaneous with Imnaha Basalt

## Imnaha basalt

- composed of 26 major flows, some older than Steens basalt
- mostly buried below younger flows in CRB province
- interfingered with upper flows of the Steens basalts

# Columbia River Basalt Groups

## Grande Ronde Basalt

- Comprises ~73% of total flow volume erupted over 400,000years
- characterised by a large number of dykes including Chief Joseph dyke swarm
- individual fissures in the swarm are 5-10 m wide, up to 16km long
- dozens of flows reached the Pacific coast resulting in much of Oregon coast being composed of basalt

## Wanapum Basalt

- emplaced between 15.6-14Ma
- accounts for only 5% of total volume of Columbia River basalts
- commonly overlies Grande Ronde basalts in most areas
- more silica-rich than older basalts (58% c.f. 56%)

# Columbia River Basalt Groups

## Saddle Mountains Basalt

- Flooded areas where subsidence occurred due to weight of Grande Ronde basalts
- flows are widely distributed → one flow crops out along Columbia River → reaches Pacific Ocean
- basalt occurs as very thin layers and comprise only 1% of total volume of CRBs, more Si rich than Wanapum basalt

## Picture Gorge and Prineville basalts

- limited to areas of central Oregon
- interfingered with Grande Ronde and Wanapum basalts

# Evolution of Columbia River basalt province

- Volcanic evolution of CRB can be divided into three phases:

  Initial phase 16.8 - 16.0Ma

  Main phase 16.0 – 15.6Ma

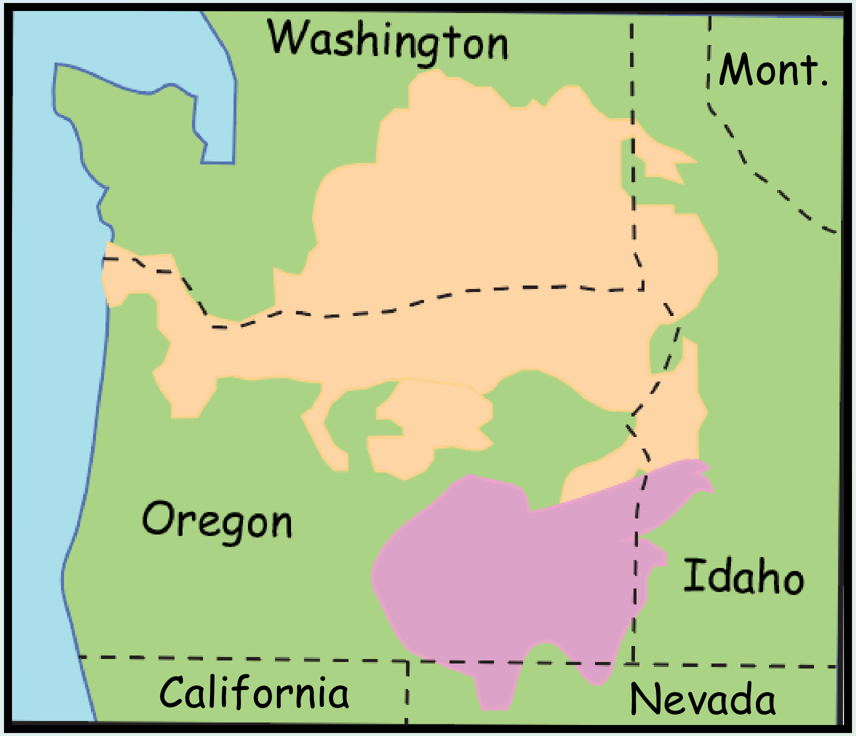
  Waning phase 15.6 – 6Ma

- initial phase occurred in south-east Oregon extending in to south-west Idaho and northern Nevada → produced ~20% of total volume of CRB

- main phase produced ~73% of total volume covering 152,000$Km^2$ in eastern Washington, northern Oregon and western Idaho

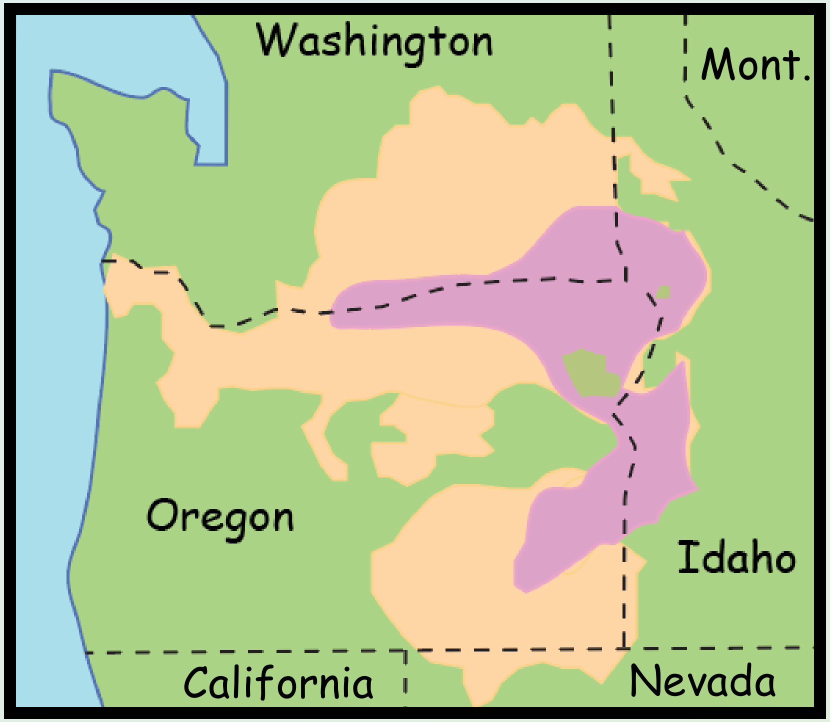
- waning stage produced 6.1% of the total volume of CRB in northern Oregon and south to central Washington

# Columbia River Basalts - Initial phase




Steens Basalt

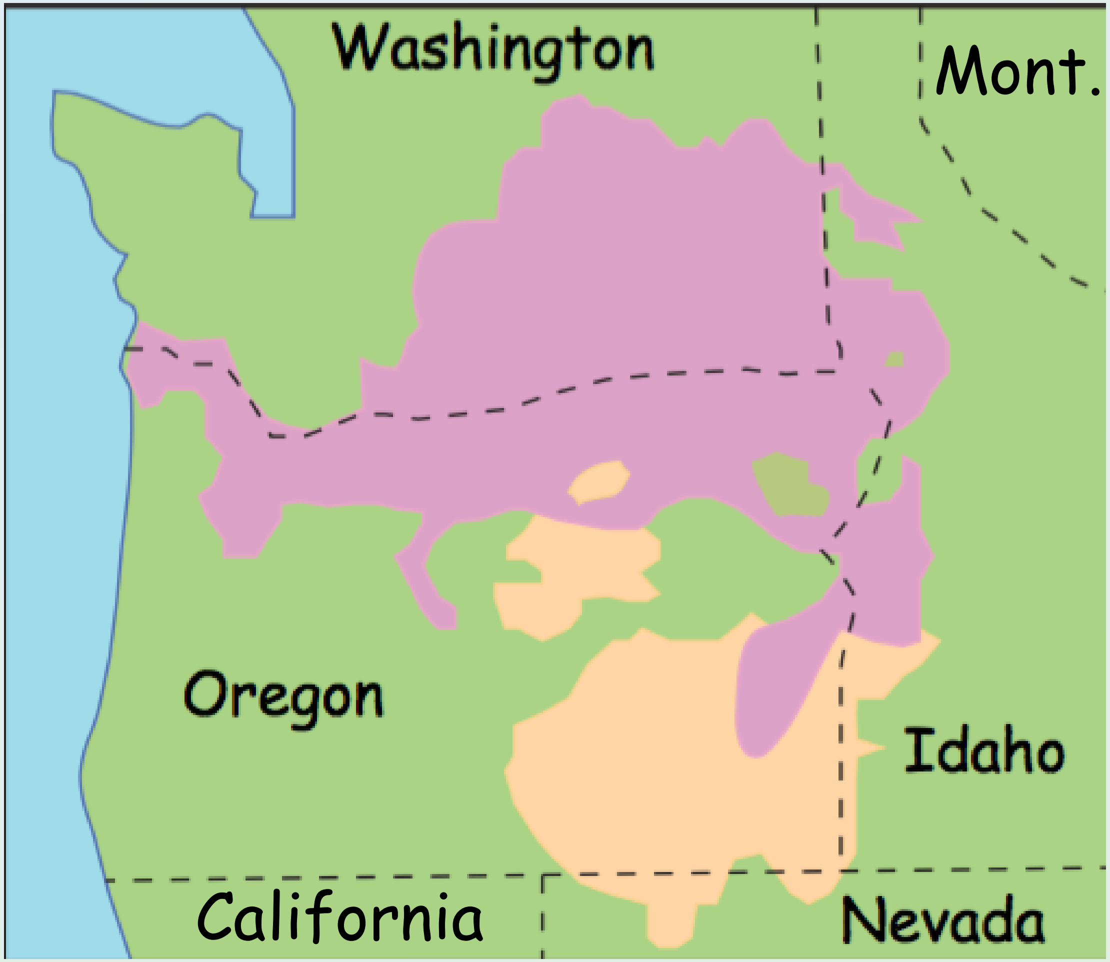
16.8 - 16.6Ma




Imnaha Basalt

16.7 - 16.0Ma

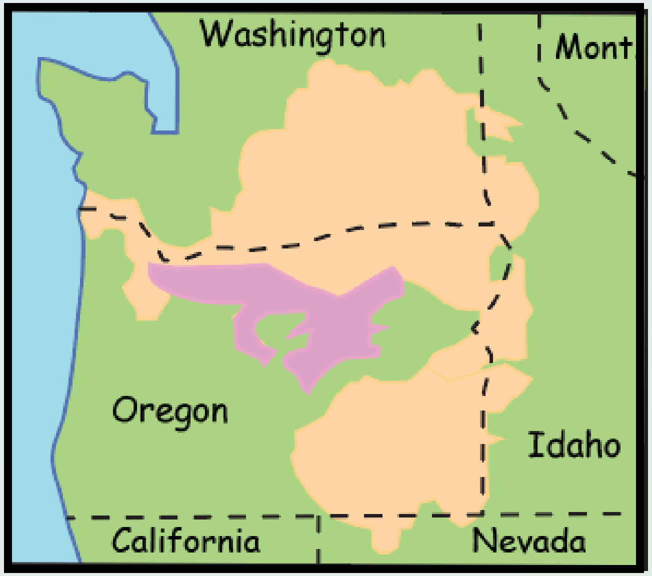
# Columbia River Basalts – Main phase



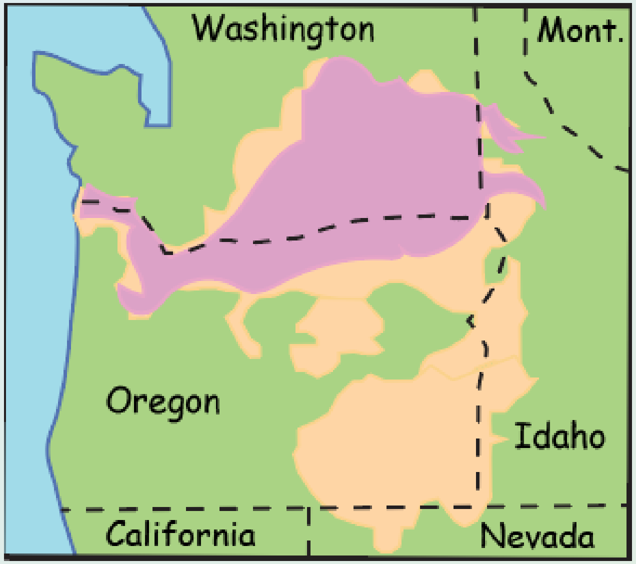

Grande Ronde Basalt

16.0 – 15.6Ma

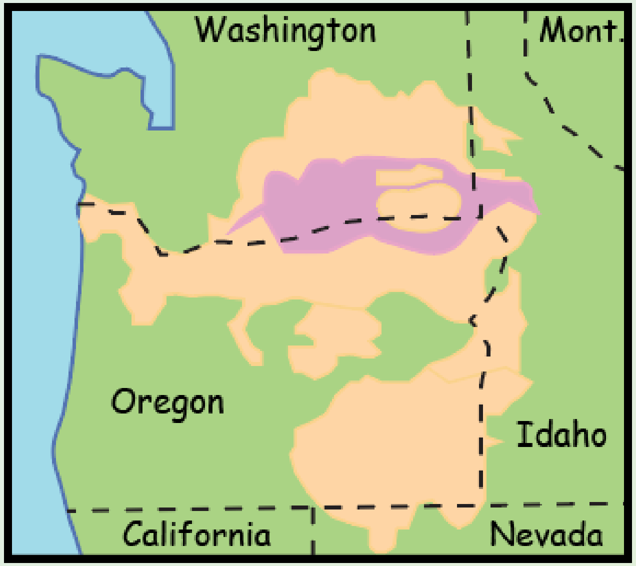
# Columbia River Basalts - Waning phase




Prineville and
Picture Gorge Basalt
16.4 – 15.2Ma




Wanapum Basalt
15.6 – 14.5Ma




Saddle Mountains Basalt
14.0 – 6Ma

# Tectonic origin of Columbia River Basalts

Hooper (1997) identified 3 major factors contributing to the origin of CRB:

(1) Location of Yellowstone hotspot → temporal and spatial correlation with initial eruptions of CRB

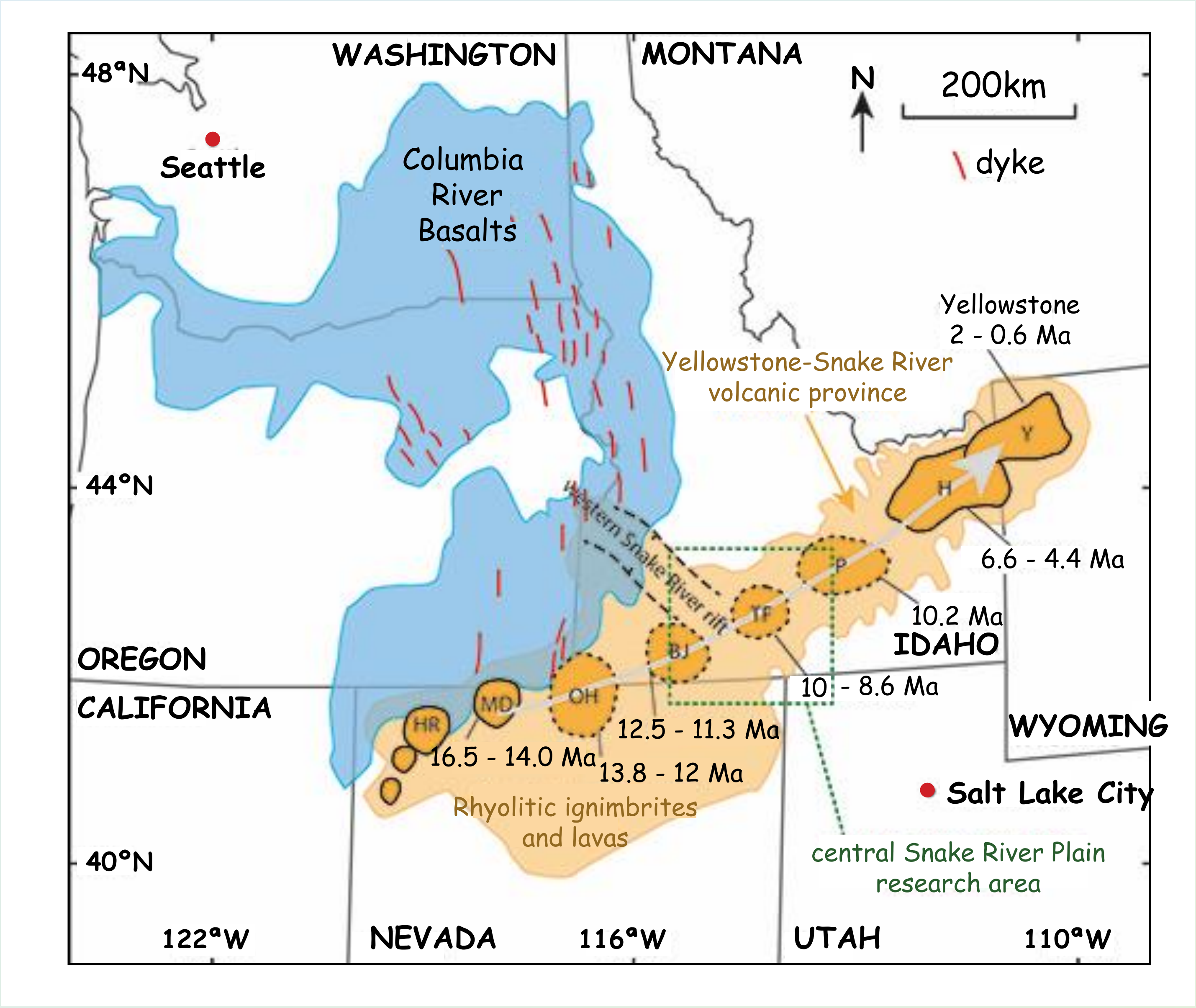
(2) Thinning of continental lithosphere as a result of spreading behind Cascade arc

(3) Proximity of fissure vents to the tectonic boundary between accreted terranes → contrasting competency

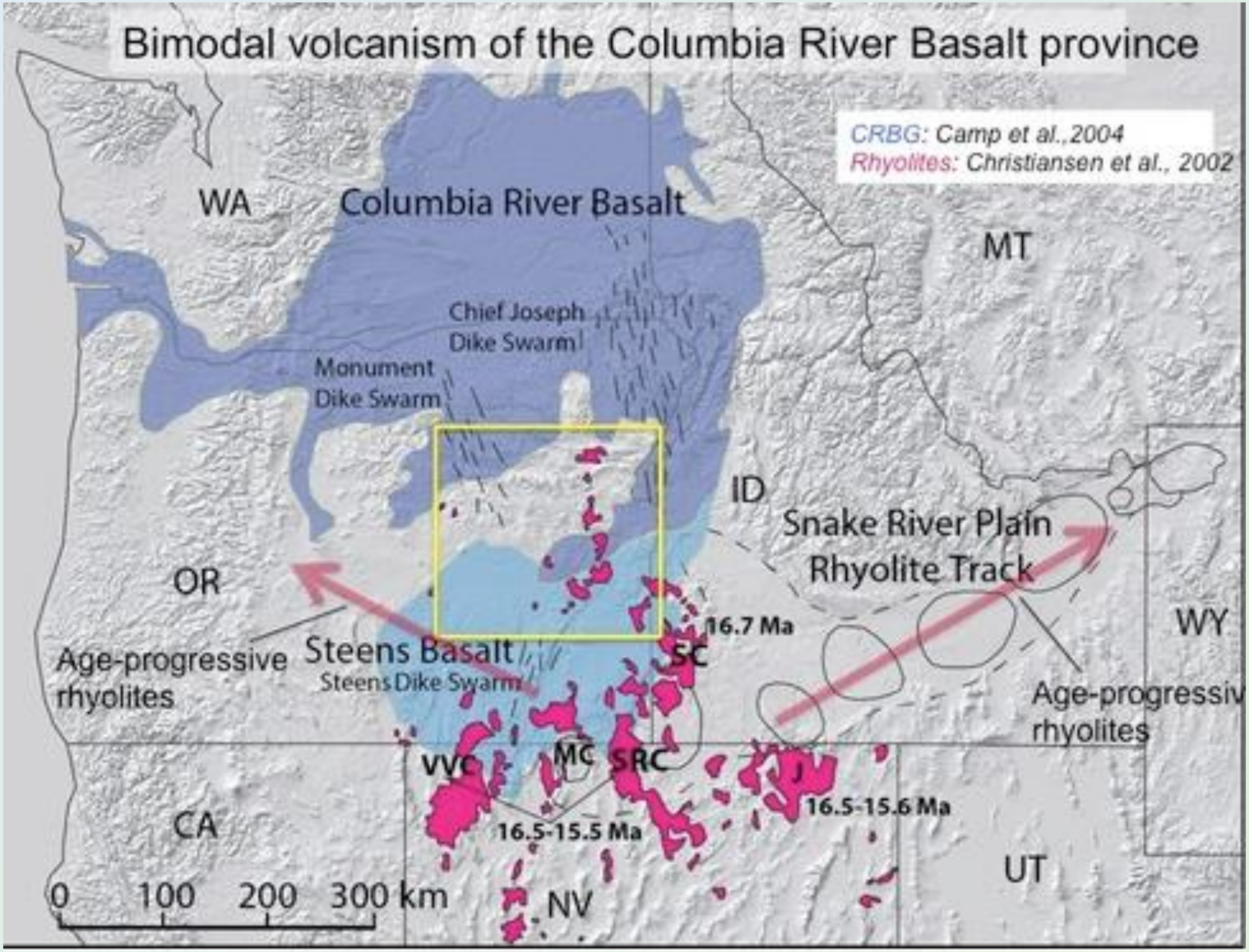
# Relationship between CRBs and Yellowstone hotspot

- Dating of rhyolites in the same area as Steens Basalt gave similar ages (16.7 – 15.5Ma) to Steens and Imnaha basalts
- dyke trends consistent with tension opening created by hot spot eruptions
- mafic globules of same composition as Grande Ronde Basalts found as inclusions in rhyolites (Portland University study)
- it appears that basalt magma flowed into rhyolite magma chamber

# Yellowstone hot spot track



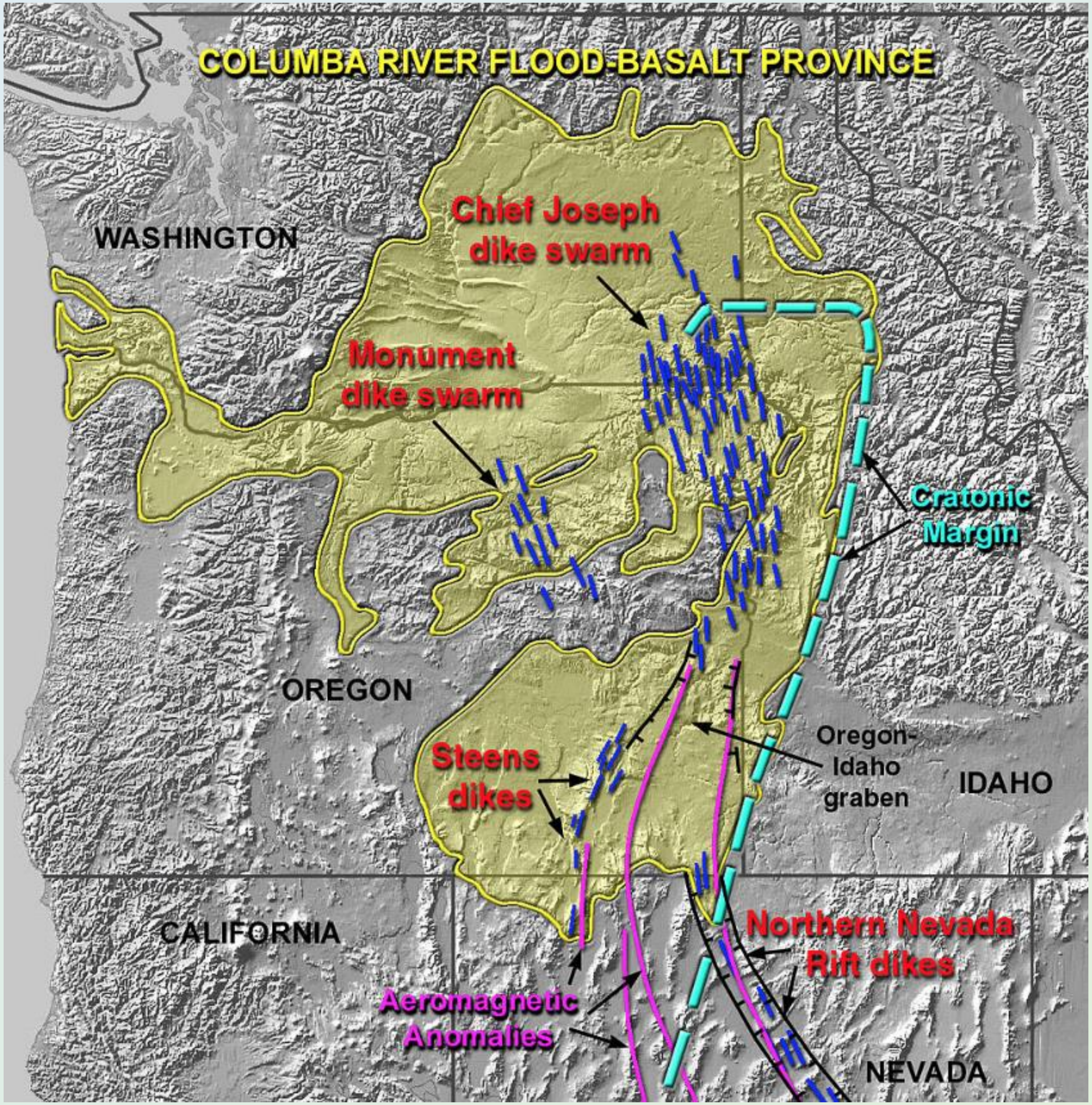
Close spatial relationship between contemporaneous Miocene CRBs and Miocene rhyolites → poorly understood



# Feeder dykes for Columbia River Basalts

- Eruptions of CRB originate from a series of north-northwest trending fissures → feeder dykes
- there are three main dyke swarms:
  (1) Chief Joseph swarm
  (2) Monument swarm
  (3) Steens swarm
- more than 20,000 dykes are associated with the CRBs
- dykes average 8m in width but vary from a few cm up to 60m, individual dykes are up to 16km long
- fissures propagated northwards over the period of evolution of the flood basalts

# CRB feeder dykes



# Columbia River Basalt feeder dykes

Sub-vertical feeder dykes cutting through older Columbia River Basalt

East Washington State

# Columbia River Basalt feeder dykes

Multiple thin feeder dykes for CRBs

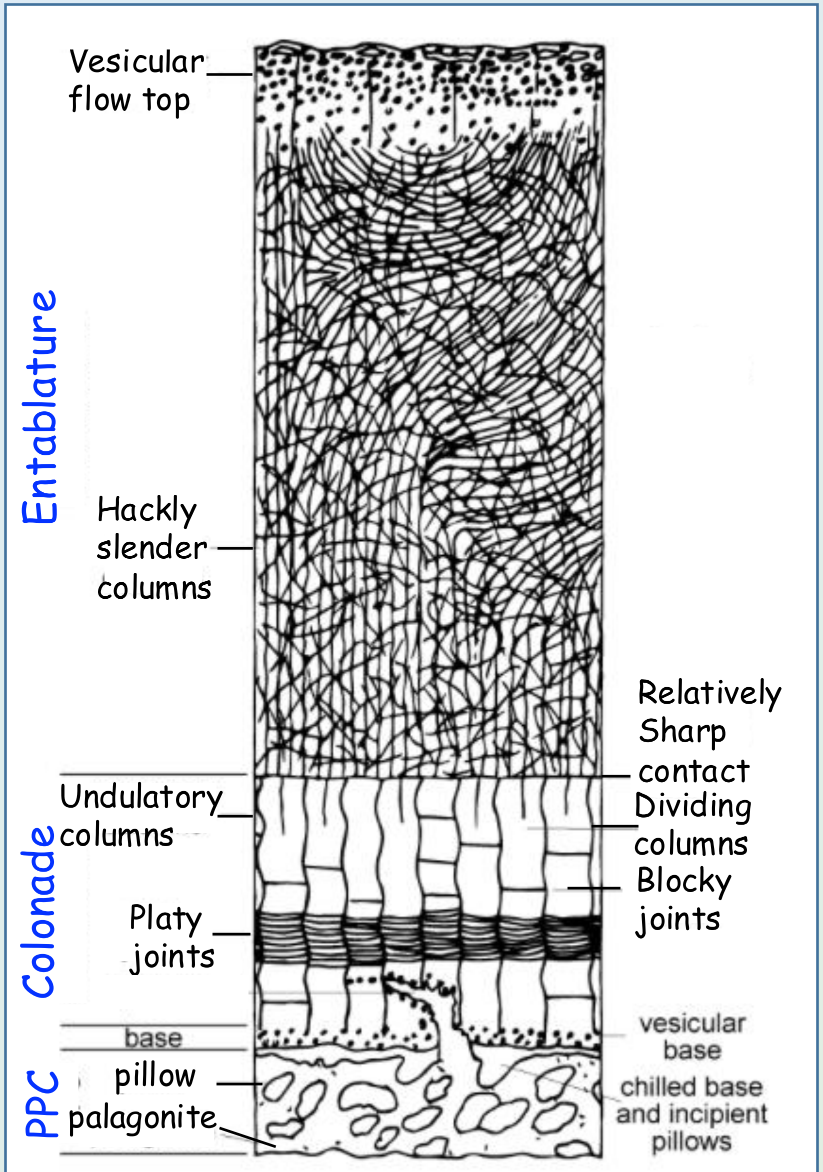
# Morphology of lava flows

- Flows within the CRB range from a few 10s cm to >100m thick
  average thickness 30–40m
- individual flows show zonation → different styles of jointing
- layers of columns → colonnade → form at base of flows
  irregular jointing towards top of flow → entablature
- basalt columns imply that basalt ponded while solidifying → only form under static cooling conditions
- at the base of many flows → pillow-palagonite zone
- vesicular flow tops → analagous to frothy tops of aerated drinks

# Morphology of lava flows

- The entablature consists of columns with diameters generally less than 25cm with less consistent orientation
- columns of many entablatures are bundled into fans, tents or other unusually shaped arrangements
- many flows enter water and formed pillows some of which are localised
- individual flows within CRB commonly show distinct zoning with different styles of jointing and sometimes vesicular flow tops
- columnar jointing has a more regular pattern than entablature and is found at base of flows

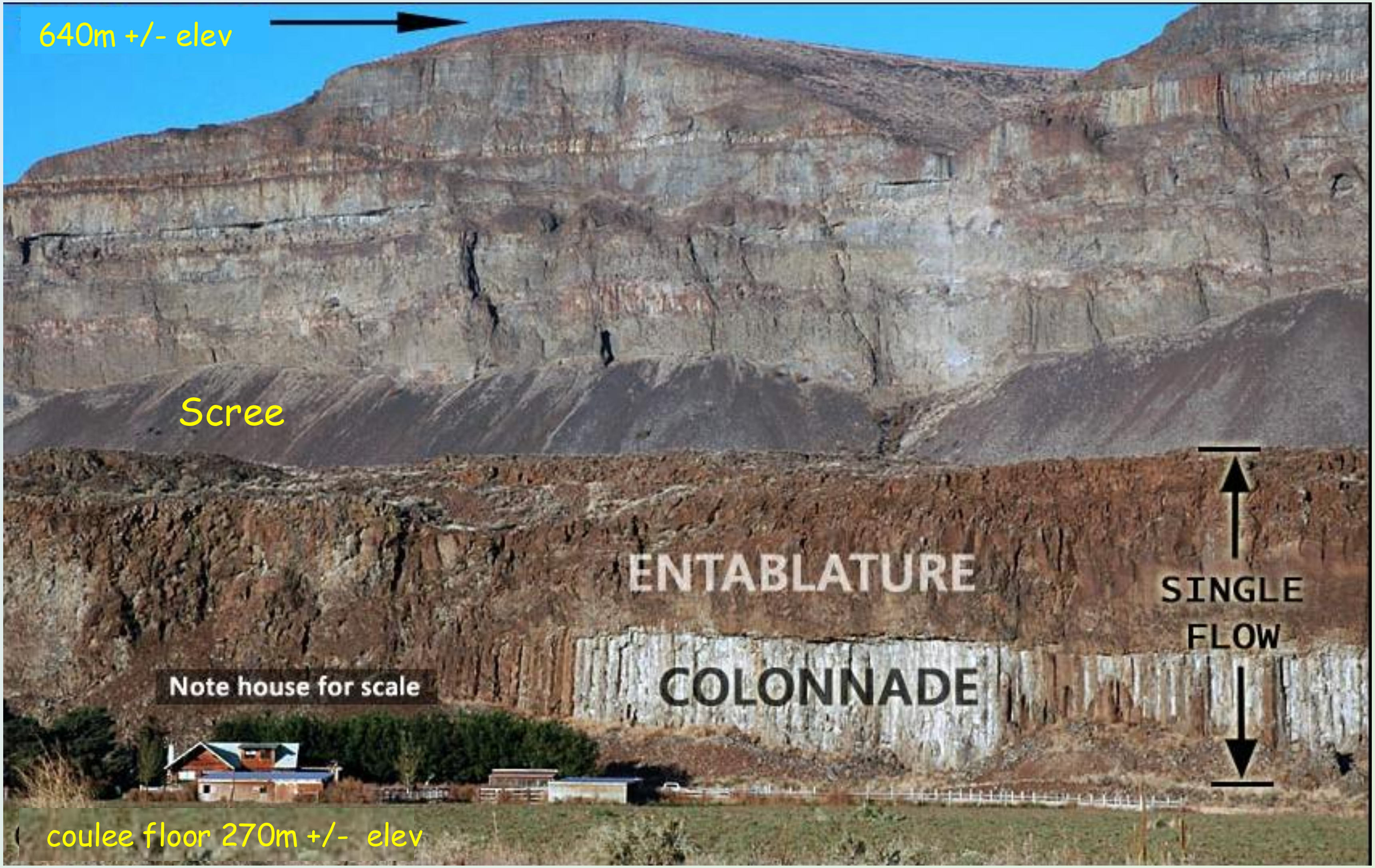
# Zonation in CRB lava flows




Vesicular top of Columbia River Basalt

Entabulature overlying colonnade, CRB

# Zonation in CRB lava flows



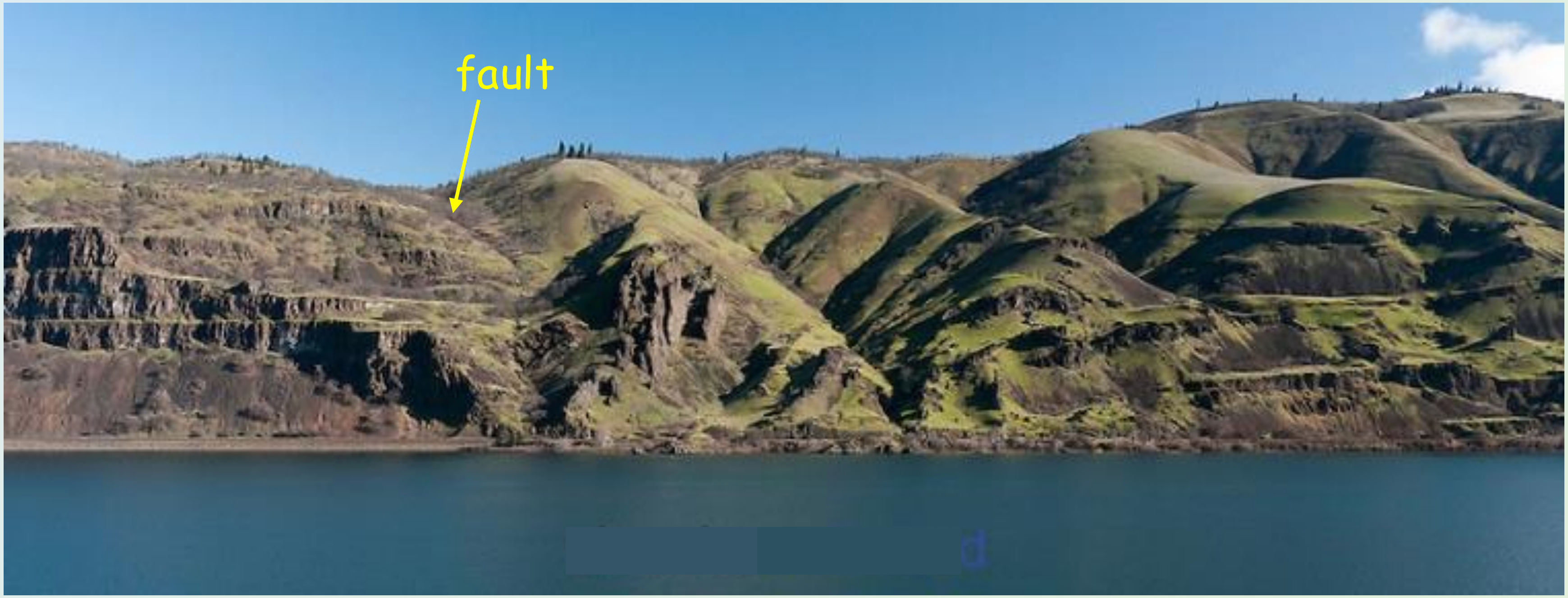
# Entablature forms in CRB lava flows

Complex entablature, Devils Canyon, Scablands, Washington

Palagonite  interstitial to pillow basalts, Columbia Plateau, USA

# Deformation of Columbia River Basalts

- Folding and faulting occurred contemporaneously with formation of CRBs and continued after end of volcanic events
- basalts are gently folded to form narrow ridges (anticlines) and broad valleys (synclines)




Folded and faulted CRB lava flows along Columbia River, Oregon

# Evolution of Columbia River Basalt magmas

The eruption of the Columbia River Basalts progressed through 6 overlapping stages, each  with characteristic chemistry:

Stage 1: 16.7 -15.9Ma produced the Imnaha and Grande Ronde basalts

Stage 2: ~16.0 – 15.5Ma fissure eruptions of icelandites

Stage 3: ~ 16.5 – 14.7Ma caldera –forming eruptions of ash flow tuffs and rhyolite lava flows

Stage 4: 14.7 -13.7Ma fissure eruptions produced olivine basalts

Stage 5: 13.5 – 10.0Ma calc-alkaline basaltic andesite, andesite and dacite lavas

Stage 6: 7-6Ma  small volume alkali eruptions

# Composition of Columbia River Basalts

- Columbia River Basalts are mostly tholeiitic in composition
- later stage basalts tend to be calc-alkaline
- tholeiitic basalts are more enriched in Fe and Mg and less enriched in Al than calc-alkaline rocks and lower in ($Na_2O$ + $K_2O$) than alkali basalts
- basalts are characterised by containing clino and orthopyroxenes and olivine (rarely) as the dominant mafic mineral phases
- the composition of basalts varies from low silica basalts through to intermediate basaltic andesites

# Geochemistry of CRBs