Subducted Ridges, Magmas, Differential Uplift, and Gold Deposits: Examples from South and Central America

David Shatwell

INTRODUCTION

Magmatic-related Au-Ag deposits of similar age and type in magmatic arcs along convergent margins are not uniformly distributed, but are longitudinally grouped in "gold-rich" regions separated by segments containing few deposits. The nature of the oceanic lithosphere which is being subducted at a convergent margin may influence the rate of uplift and hence the topography of the overlying magmatic arc, through changes to the angle of the subduction zone. Subducted young/warm/light oceanic lithosphere will tend to flatten at about 100 km depth, cause rapid uplift of the overlying crust, modify magma chemistry, and eventually close down magmatic activity. It may result in destruction (by erosion) of existing Au-Ag deposits, and exposure of underlying porphyry systems; conversely, erosion during the cooling cycle of magmatic bodies may promote the formation of large magmatic-related gold deposits at higher levels. This paper examines such processes in Costa Rica and in the Central Andes

COSTA RICA

Metallic mineralisation in Costa Rica and other Central American countries is associated with a Miocene magmatic arc emplaced above Cocos Plate oceanic lithosphere which is being subducted eastward below the Caribbean Plate. Mineralisation in Costa Rica is hosted by ca. 6 Ma calcalkaline volcanics and related domes and plutons, overlain in western Costa Rica, by <2 Ma post-mineral volcanic rocks and active volcanoes (Bagby et al., 1987).

The mineralised belt is divided longitudinally into three zones with contrasting metallogenic characteristics.

1. An 80 km low sulfidation gold belt in western Costa Rica. Deposits have been in intermittent production since 1824, mostly from single-vein underground mines. In recent years, large low grade resources have been delineated at the Bellavista and Las Crucitas deposits – in the latter case, 93 Mt, 1.03 g/t Au. Bagby et al. describe the gold veins as "Sado" type, but the association with vein Mn-Mg carbonates and the lack of adularia places them in the (subsequently-defined) carbonate-base metal class, formed by mixing of magmatic fluids with near-surface CO_2-rich water (Corbett and Leach, 1998).
2. Adjoining the gold belt to the south east there is a 120 km belt of subeconomic polymetallic vein deposits, in which vein minerals include galena, sphalerite, pyrite, chalcopyrite, pyrrhotite, magnetite, and barite, but no significant gold.
3. South east of the polymetallic zone there is a region of porphyry-style mineralisation at high elevations on the Talamanca Cordillera, extending into Panama. Bagby et al. list 24 porphyry-style occurrences, some of which contain chalcopyrite, molybdenite, secondary biotite, quartz-sericite-pyrite alteration, and sphalerite-galena-barite veins. The large Cerro Colorado deposit in Panama (1300 Mt, 0.8% Cu) may be part of this zone.

In the Osa Peninsula on the Pacific coast of Costa Rica, there are a number of small gold placers whose position is consistent with derivation from a primary gold source in the Talamanca Cordillera.

The metallogenic subdivisions 1-3 above correlate closely with tectonic subdivisions which can be identified both offshore in the subducting Cocos Plate, and onshore in the over-riding Caribbean Plate. These include contrasts in bathymetry, topography, seismicity, and dip of the subduction zone (eg Fisher et al. 1998; Protti, 2002):

The gold belt (1) coincides with a region of relatively subdued landscape (except where modified by recent volcanism) at low elevation in the magmatic arc. The volcanic arc is still active, shallow earthquakes are relatively infrequent, and the Wadati-Benioff zone dips steeply. The large Lake Nicaragua, in neighbouring Nicaragua, is in a back-arc position and in outline resembles a pull-apart basin resulting from back-arc extension. Offshore, the subducting Cocos Plate exhibits “smooth” ocean-floor topography.
The polymetallic belt (2) is a region of more elevated terrain, in which the Plio-Pleistocene volcanic arc terminates. There is increased shallow seismicity, and the subduction zone flattens. There are at least six inbound seamounts offshore. Back-arc extensional features are absent, and instead, arc-parallel thrusts are present between the Miocene arc and a Cretaceous-Eocene oceanic sequence which lies between the trench and the arc.
The “porphyry” belt (3) contains the highest part of the Talamanca Cordillera, with elevations above 2000m. There are no Plio-Pleistocene volcanoes, and a Late Miocene batholith is exposed. Offshore, there are no seamounts, but there is an area of shallower water, where the Cocos Ridge and the Panama Fracture Zone are both being subducted. The Wadati-Benioff zone is absent in this segment (Johnson and Thorkelson, 1998).

The boundaries between these three divisions are defined by pronounced arc-normal features, including elongated sea-floor ridges in the Cocos Plate, which extend onshore as topographic discontinuities and normal faults in the Caribbean Plate. The boundaries coincide with concentrations of shallow seismicity in both plates.

In segment 1, “smooth” ocean floor was generated at the north-trending East Pacific Rise. In contrast, the inbound seamounts (segment 2) and the Cocos Ridge (segment 3) originate at the site of an active mantle plume crest centred on the Galapagos Islands, situated just south of the east-west trending Nazca-Cocos ridge-transform system.

The seamounts and the relatively warm and buoyant Cocos Ridge first arrived at the Middle America Trench at <2 Ma, flattening the subduction zone and extinguishing volcanic activity. Segment 2 was uplifted and eroded to expose the polymetallic roots of the carbonate-base metal gold systems, while uplift in segment 3 was sufficient to unroof a large batholith and associated porphyry systems. Gold from the eroded Talamanca vein systems was re-deposited to the SW as placers in low-lying coastal regions of the Osa Peninsula.

I infer that ridge and seamount subduction played no obvious part in the origin of the gold deposits, but caused their subsequent destruction by erosion.

CENTRAL ANDES

Eastward subduction of the Nazca Plate below the South American Plate has resulted in gold deposits whose ages range from Jurassic to Pliocene. Resources are dominated by Miocene high sulfidation and porphyry deposits, grouped in two regions:

I North-Central Peru, between 6° and 13° S.
II Northern Chile and Argentina, between 27° and 30° S.

Miocene high sulfidation and porphyry deposits in each of these regions contain approximately 90-100 Moz gold, in terms of current resources and past production. In contrast, Miocene deposits elsewhere in the Central Andes contain only about 17 Moz, largely but not exclusively in low sulfidation epithermal deposits. All of the large Miocene gold deposits in Regions I and II are either high sulfidation or porphyry style, and there are no known world-class high sulfidation Au-Ag deposits outside these two regions. Regions I and II lack Quaternary or modern volcanic activity, but are flanked by the Northern, Central, and Southern Volcanic Zones of Neogene and Quaternary volcanism.

Region I – North-Central Peru, 6-13° S (Figure 1)

The region contains at least fifteen large magmatic-related copper and/or gold deposits (Shatwell, 2002). Among these are the world-class Yanacocha, Pierina, and Alto Chicama high sulfidation deposits, and the Minas Conga and Michiquillay porphyry copper-gold systems. Some porphyry and high sulfidation systems are associated with enargite-cored lead-zinc-silver limestone-replacement deposits. The large high sulfidation deposits were formed between 14.5 and 11 Ma, whereas porphyry systems span the range 20 Ma to 7.4 Ma. High sulfidation deposits are typically hosted by the Oligocene-Miocene Calipuy Volcanics, and exhibit zoned alteration systems with a core of massive or vuggy silica ± alunite, an intermediate zone of kaolinite and other clays ± alunite, and an outer zone of clay, sericite, and chlorite.

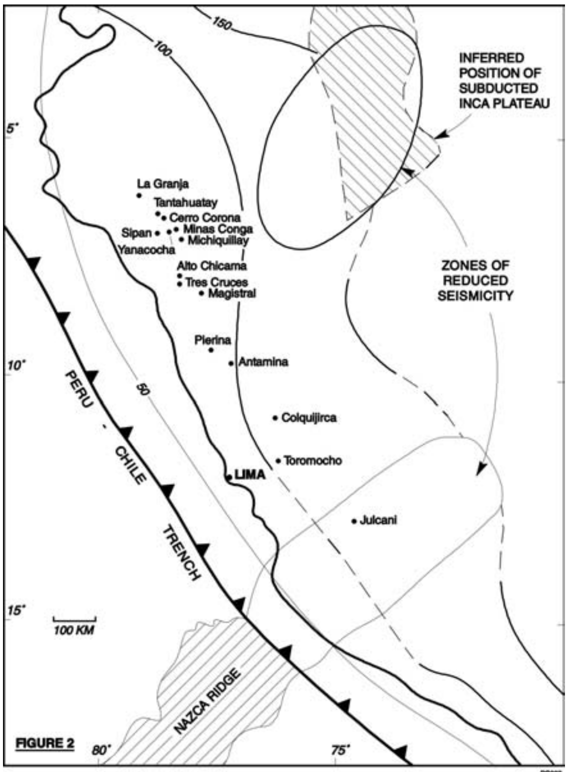

Figure 1. "Flat-slab" region of northern and central Peru, showing the Nazca Ridge, areas of reduced seismicity, and inferred position of the subducted Inca Plateau, based on Gutscher et al., 1999, Figure 2A, p.338, with permission from Elsevier Science. Contours are depths in km to the Wadati- Benioff zone. The named deposits are Miocene Cu ± Au porphyries (La Granja, Cerro Corona, Michiquillay, Minas Conga, Toromocho), Au-Ag high sulfidation systems (Tantahuatay, Sipán, Yanacocha, Alto Chicama, Tres Cruces, Pierina, Colquijirca, Julcani) and Cu ± Zn skarns (Antamina, Magistral). Deposits enclosed by the dotted line contain 88 Moz Au.

In Region I, Noble and McKee (1997) recognise three Miocene compressive events: Quechua 1 (19 Ma), Quechua 2 (9.5 Ma), and Quechua 3 (6 Ma). The large high sulfidation deposits were emplaced between Quechua 1 and Quechua 2 deformations, during which time the Andes of central and northern Peru underwent several stages of uplift (Noble and McKee, 1977). Peneplanation resulted in the mature Puna erosion surface by 10 Ma.

The subducted Nazca Plate in Region I is sub-horizontal below about 100 km depth, but is not a planar surface: Gutscher et al. (1999) point out that there are two “spurs” or salients in the flat section, each corresponding to an area of low seismicity. The southern spur coincides with the onshore (subducted) part of the incoming Nazca aseismic ridge (Figure 1), but there is no offshore ridge corresponding to the northern spur.

Gutscher et al. consider that the northern spur is the “missing” mirror image of the volcanically-active Marquesas Ridge in the western Pacific, and refer to it as the Inca Plateau. According to their kinematic reconstruction, the Inca Plateau would have arrived below northern Peru at 10-12 Ma; all major Miocene Au-Ag high sulfidation deposits and Cu-Au porphyries in Peru lie immediately outboard of its inferred present position (Figure 1), and have production and/or resources totalling 88 Moz Au. I propose that the arrival of the Inca Plateau below northern Peru at 10-12 Ma, and uplift and erosion resulting in the Puna surface, were linked events. These events played a key role in the emplacement of high sulfidation deposits between 14.5 and 11 Ma,, and perhaps unroofed older Cu ± Au porphyries such as Michiquillay and Minas Conga.

Region II – Chile-Argentina 27-30° S

The magmatic-related Miocene gold deposits in Region II occur in three sub-regions (Figure 2):

(a) The Maricunga district in Chile at 27°-28° S, dominated by porphyry gold ± copper deposits, but also containing the important Ag-Au La Coipa high sulfidation district. Deposits are estimated to contain 45 Moz Au, and their ages range from 24 to 13 Ma (Sillitoe et al., 1991).

(b) The Pascua-El Indio district at 29°-30° S on the Chile-Argentina border, containing the now-closed El Indio-Tambo Cu-Au intermediate-to-high sulfidation district (Chile), and the undeveloped high sulfidation Pascua-Lama-Veladero Au-Ag district straddling the Chile-Argentina border. All mineralisation was emplaced between 9.4 and 6.2 Ma (Bissig et al., 2002), and total gold content is estimated at 40 Moz.

(c) The Sierras Pampeanas region in the eastern Andes of Argentina, containing isolated 7-5 Ma Cu-Au porphyries and associated high sulfidation mineralisation at Nevados del Famatina, Bajo la Alumbrera, and Agua Rica, with 20 Moz Au in total.

In sub-regions (a) and (b), mineralisation is hosted by late Oligocene to early Miocene volcanics (plus underlying Triassic sediments at La Coipa). In sub-region (c), the host rocks are late Miocene volcanic-subvolcanic complexes intruded into Precambrian-lower Paleozoic metamorphic basement.

The subduction zone south of 27° S flattens to form a southward-broadening plateau between 100 and 125 km depth, terminated abruptly by the onshore projection of the Juan Fernandez Ridge at 32°-32.5° S (eg Ramos, 1994). All of the deposits in sub-regions (a), (b), and (c) are located between 27° and 30° S, on the “flat-slab” plateau. Flattening is thought to have commenced at 18 Ma and accelerated between 11 and 7 Ma. (Vila and Sillitoe, 1991).

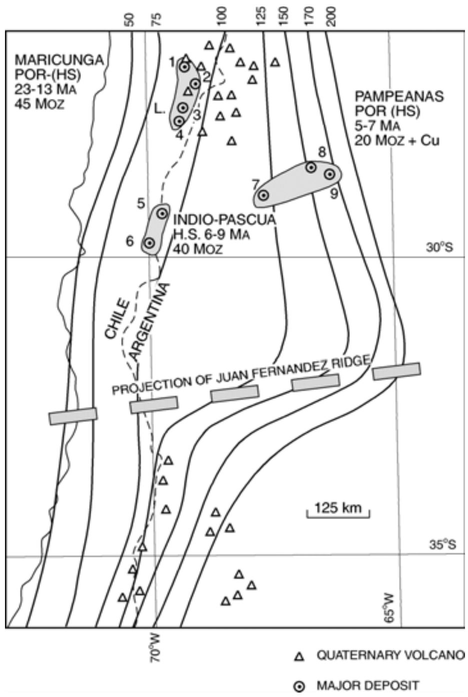

Figure 2. Flat-slab Region of Chile-Argentina, showing Quaternary volcanoes (triangles), projected position of the subducted Juan Fernandez Ridge, and depth contours in km to Wadati-Benioff zone, after Ramos (1994). Numbered deposits/districts are: 1, La Coipa; 2, Marte-Lobo; 3, Refugio; 4, Cerro Casale; 5, Pascua-Lama-Veladero; 6, El Indio-Tambo; 7, Nevados del Famatina; 8, Bajo la Alumbrera; 9, Agua Rica. Deposits 1, 5, 6, and 7 are high sulfidation Au-Ag; 2, 3, 4, 8, and 9 are porphyries; and 7 includes both types. Por = porphyry. HS = high sulfidation.

Bissig et al. identified three pediment surfaces in sub-region (b): Frontera-Deidad (17-15 Ma), Azufrera-Torta (14-12.5 Ma), and Los Ríos (10-6 Ma). These developed within the inferred period of slab flattening. The youngest (Los Ríos) surface coincides approximately with the 11-7 Ma period of accelerated flattening, and with the 9.4-6.2 Ma age range of the predominantly high sulfidation Au-Ag-(Cu) deposits in the Pascua-El Indio region.

CONCLUSIONS

In general terms, any process that removes overlying rock from an active, gold-rich hydrothermal system may extract gold from the intrusive and deposit it at higher levels. Such processes may include the sector collapse of an overlying stratovolcano, and there can be no better example of this than the Ladolam gold deposit on Lihir Island, Papua New Guinea.

Slab-flattening accompanied by erosion and peneplanation or pediment formation may destroy existing gold deposits (Costa Rica), but may also be an ore-forming process (Andes). For this to happen, several hundred metres of cover would have to be stripped off a porphyry intrusion while the associated hydrothermal system is still active, typically around 500,000 years or less. Evidence in support of high rates of erosion in the Peruvian Andes is provided by the Cordillera Blanca Batholith, for which radiometric ages as young as 2.7 Ma have been obtained (Petford and Atherton, 1994). It has been estimated that the batholith was unroofed when the Cordillera Blanca was uplifted on a major fault along its western margin by over 4 km in the last three million years, following Quechua 3 compression.

An active hydrothermal system will initially be subject to lithostatic pressures below the brittle-ductile transition at approximately 400° C and several km depth (Einaudi 1994). A vapour phase may separate, cross the brittle-ductile transition, rise to the near-surface, and condense to form a barren silica-alunite alteration zone. The liquid phase would remain at depth until the system cools sufficiently for hydrostatic conditions to be established, during which time gold may be deposited in the cooling porphyry environment. Under hydrostatic conditions, the gold-depleted liquid would rise convectively and may deposit silver in shallow low sulfidation veins.

On the other hand, if the ground surface is rapidly lowered during the cooling cycle of the intrusive, the transition from ductile to brittle conditions will be accelerated. Instead of circulating for an extended period in the porphyry environment, the liquid phase may cross the brittle-ductile boundary before it has deposited much of its gold content. Gold-silver deposition may then occur in the epithermal environment, typically in porous, leached rocks of the silica-alunite alteration zone formed earlier by the vapour phase.

These two scenarios may explain the contrast between high sulfidation Au-Ag deposits in north-central Peru and in Chile-Argentina, and low sulfidation Ag-rich veins in southern Peru and Bolivia.

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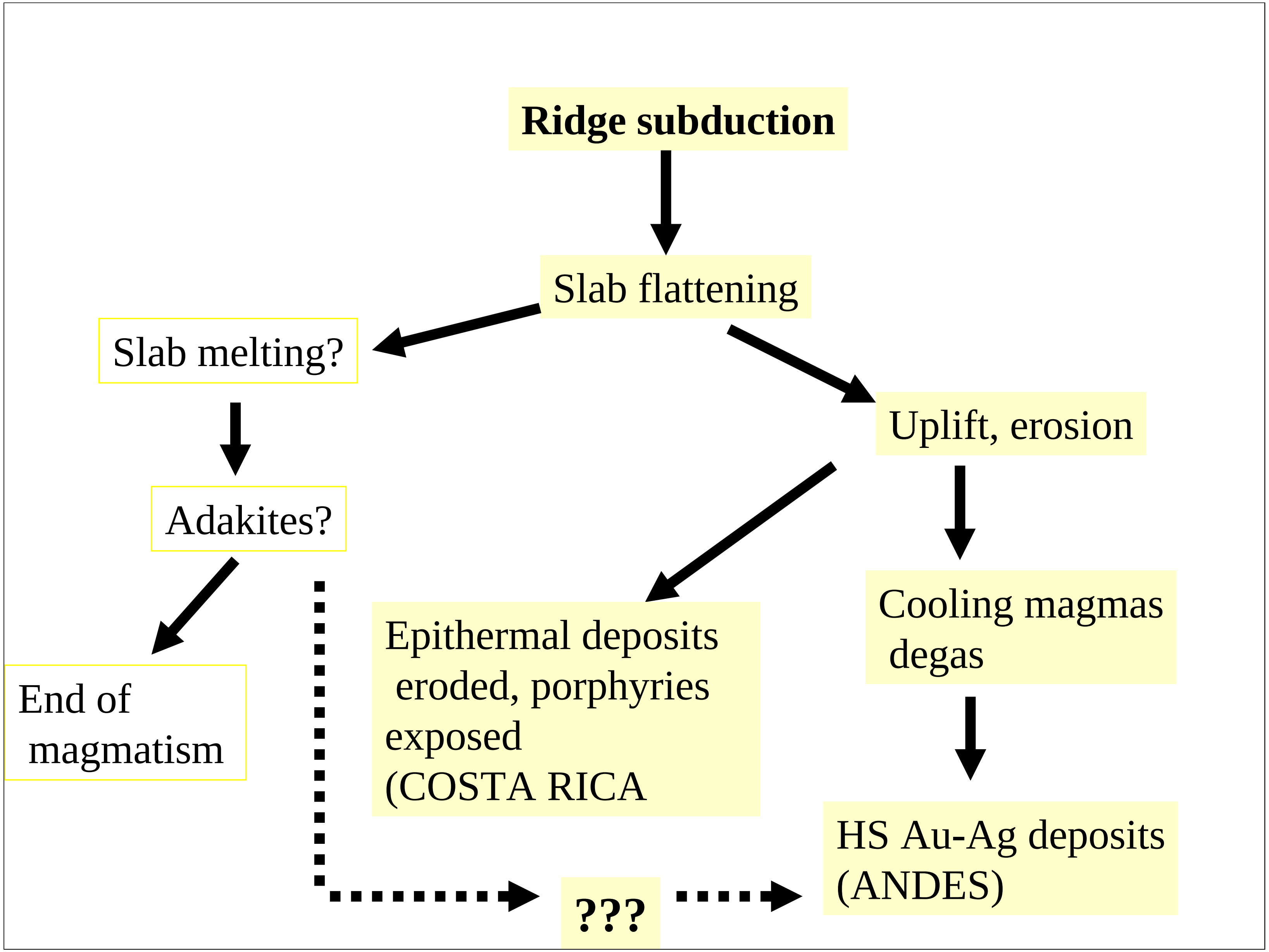
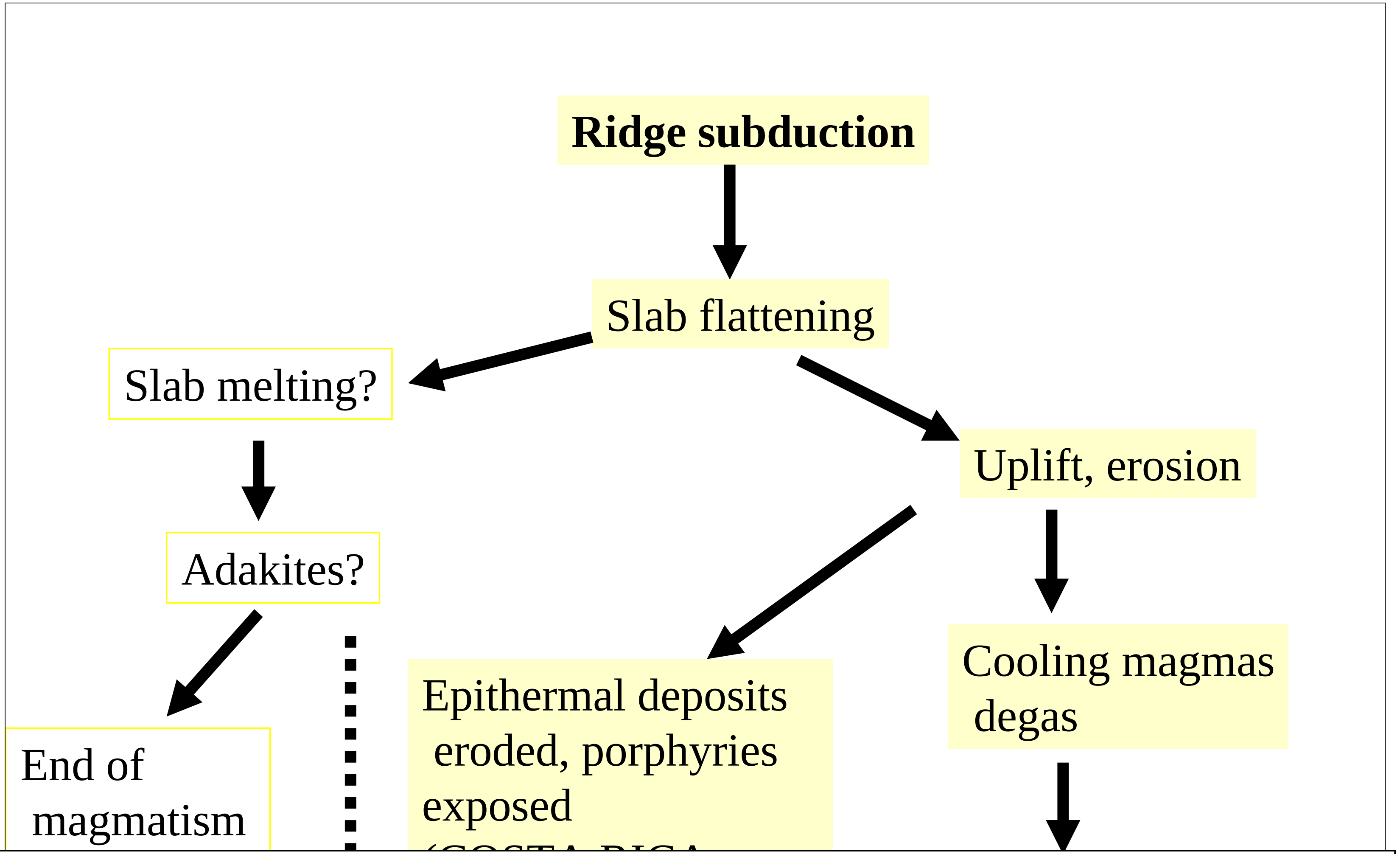
Subducted ridges, magmas, differential uplift, and gold deposits

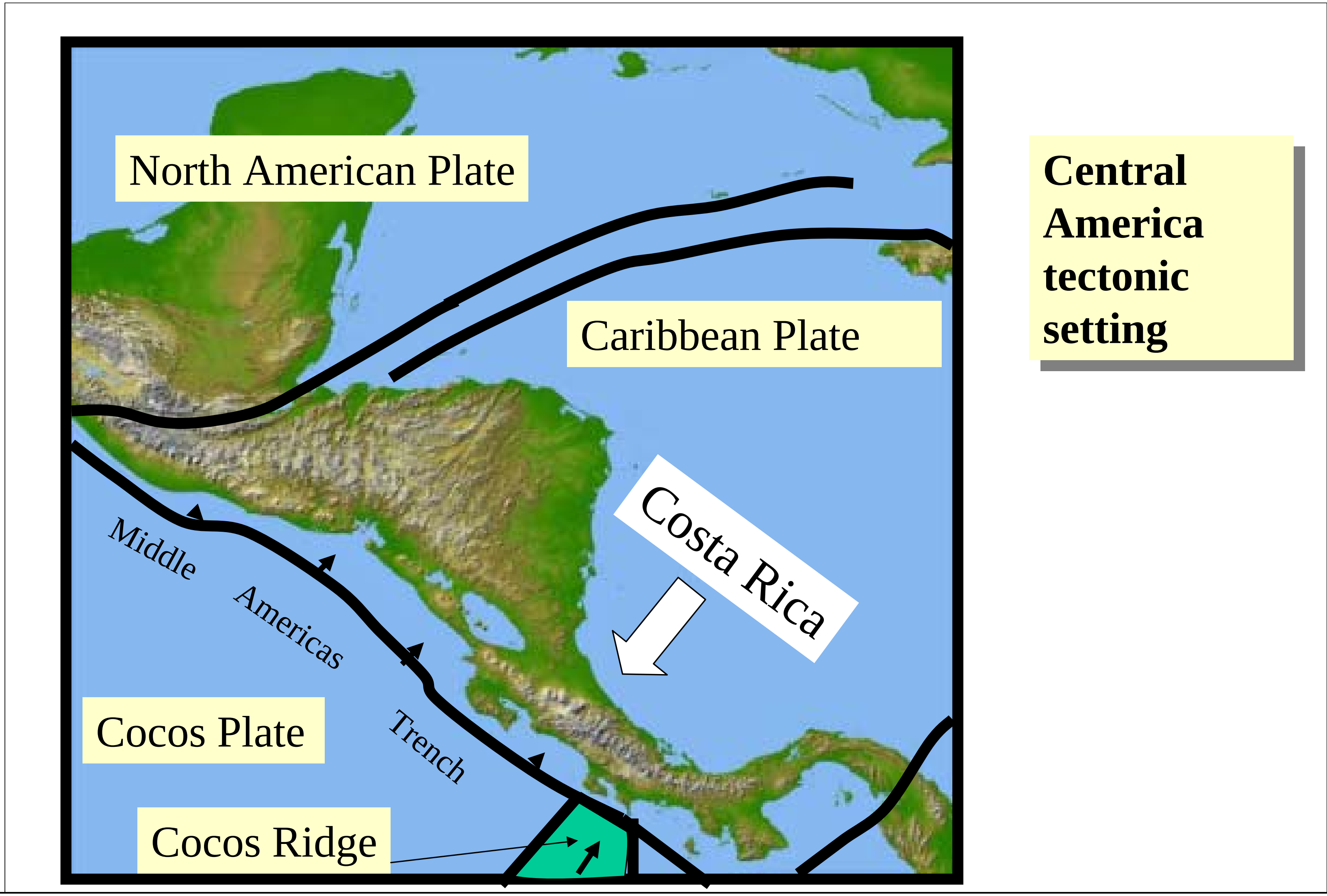
Examples from Central and South America

Presented by David Shatwell


Ridge subduction
Slab flattening
Slab melting?
Uplift, erosion
Adakites?
Cooling magmas degas
Epithermal deposits eroded, porphyries exposed (COSTA RICA
End of magmatism
HS Au-Ag deposits (ANDES)
???

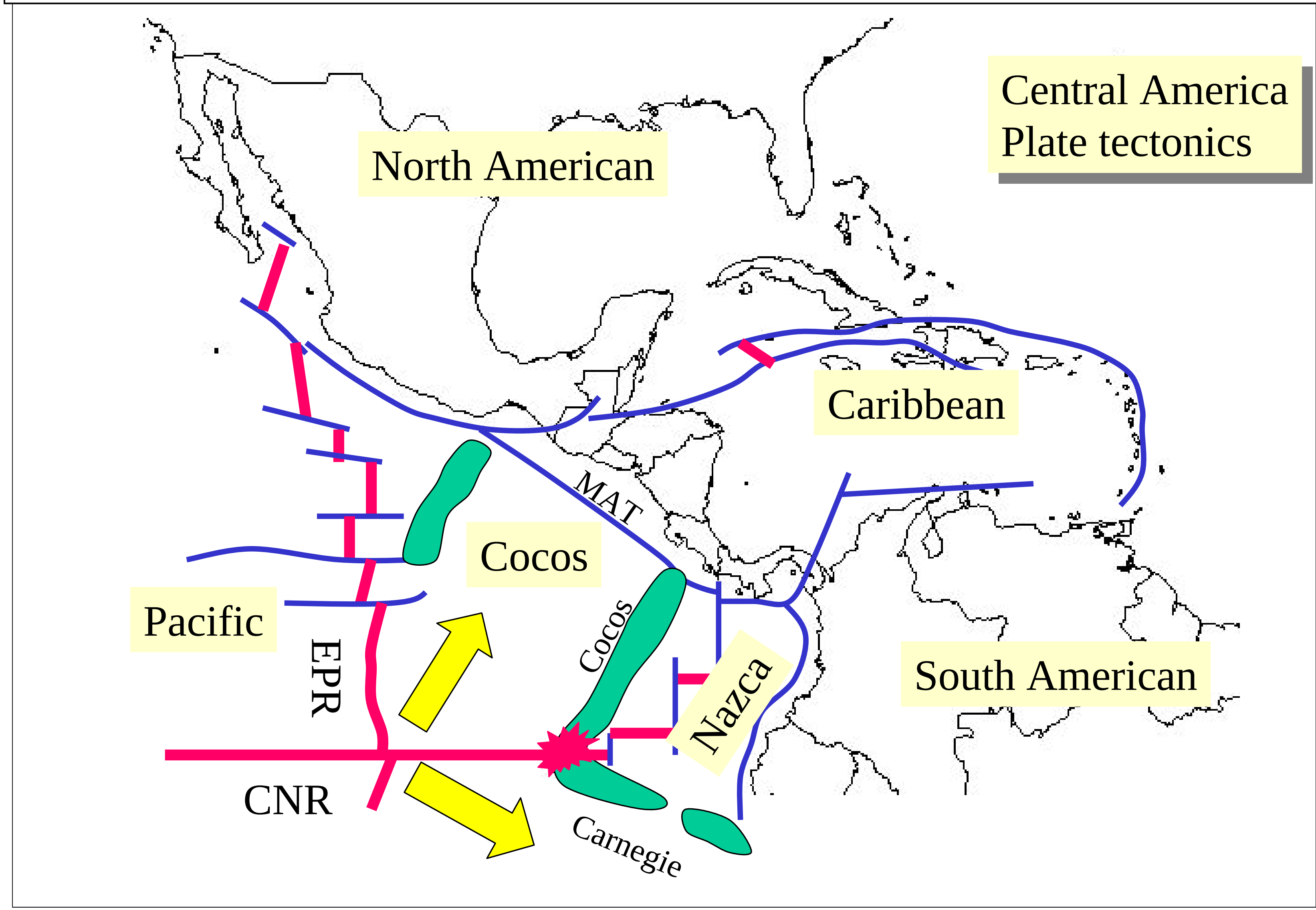


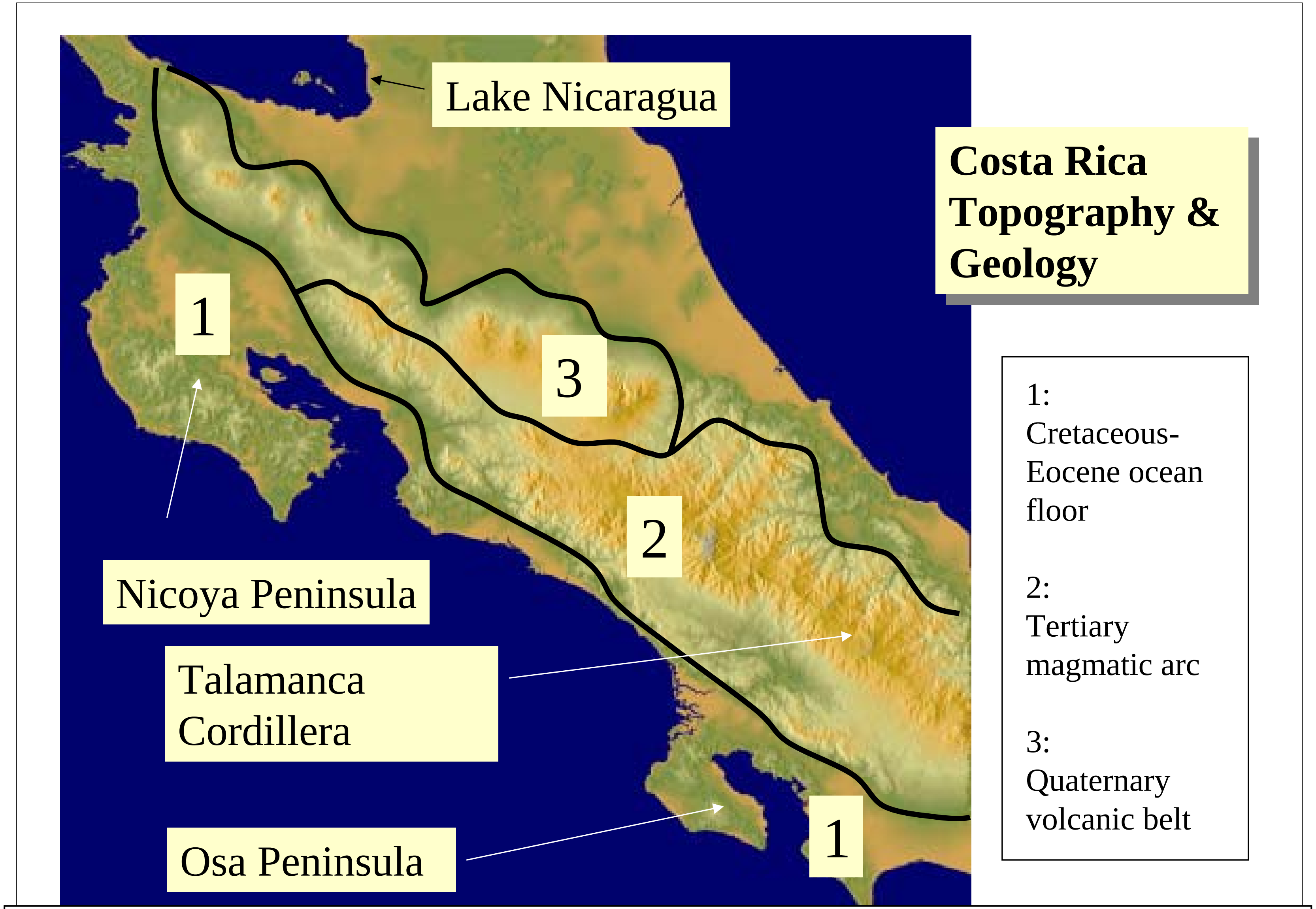
Slide 1: Outline of talk. Aseismic ridges propagate from mantle plume crests and are eventually subducted at convergent margins. Being younger and more buoyant than "normal" oceanic lithosphere, they cause the subducted slab to flatten. One effect of this is to modify the magma chemistry by slab melting, (adakites) and ultimately extinguish magmatism. The other effect is to cause topographic uplift of the magmatic arc, which is the subject of this talk (right side of the diagram, yellow boxes). Uplift may erode pre-existing epithermal deposits and expose porphyries (Costa Rica). But it may also be part of the magmatic ore forming process (Andes), especially in relation to high sulfidation gold-silver deposits.



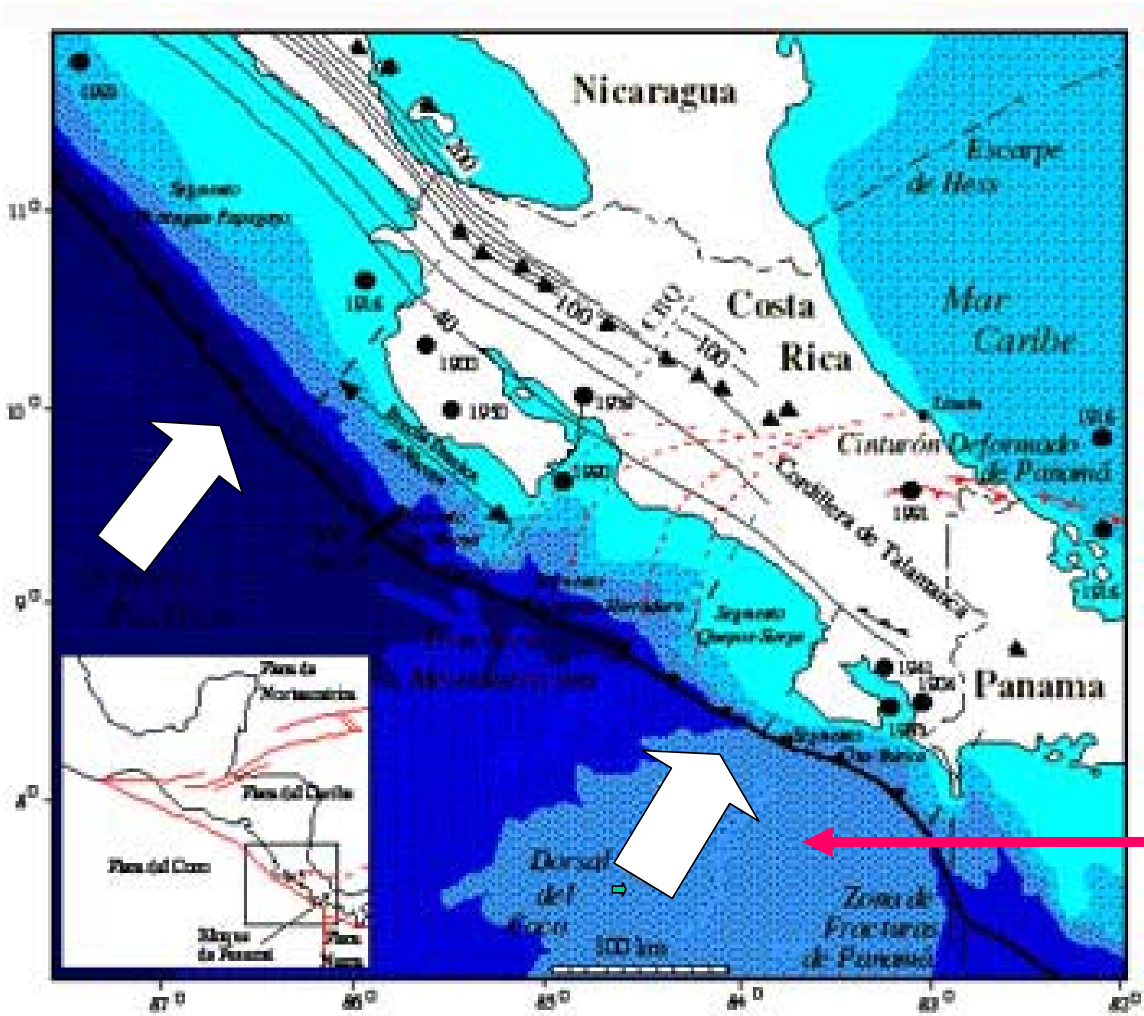
Slide 2: Central America. Central America is a Cenozoic island arc joined on to two continents. It formed as a result of NE subduction of the Cocos Plate below the Caribbean Plate. In the last 3 My or so the Cocos Ridge has been subducted below Costa Rica. Note extensional features (Lake Nicaragua) below Nicaragua, outside of the influence of the Cocos Ridge.

Slide 3: Cocos and Carnegie Ridges. Cocos and Carnegie Ridges originate at the Galapagos – Cocos Ridge is being subducted below Costa Rica. Its mirror image, the Carnegie Ridge, is subducted below Ecuador.



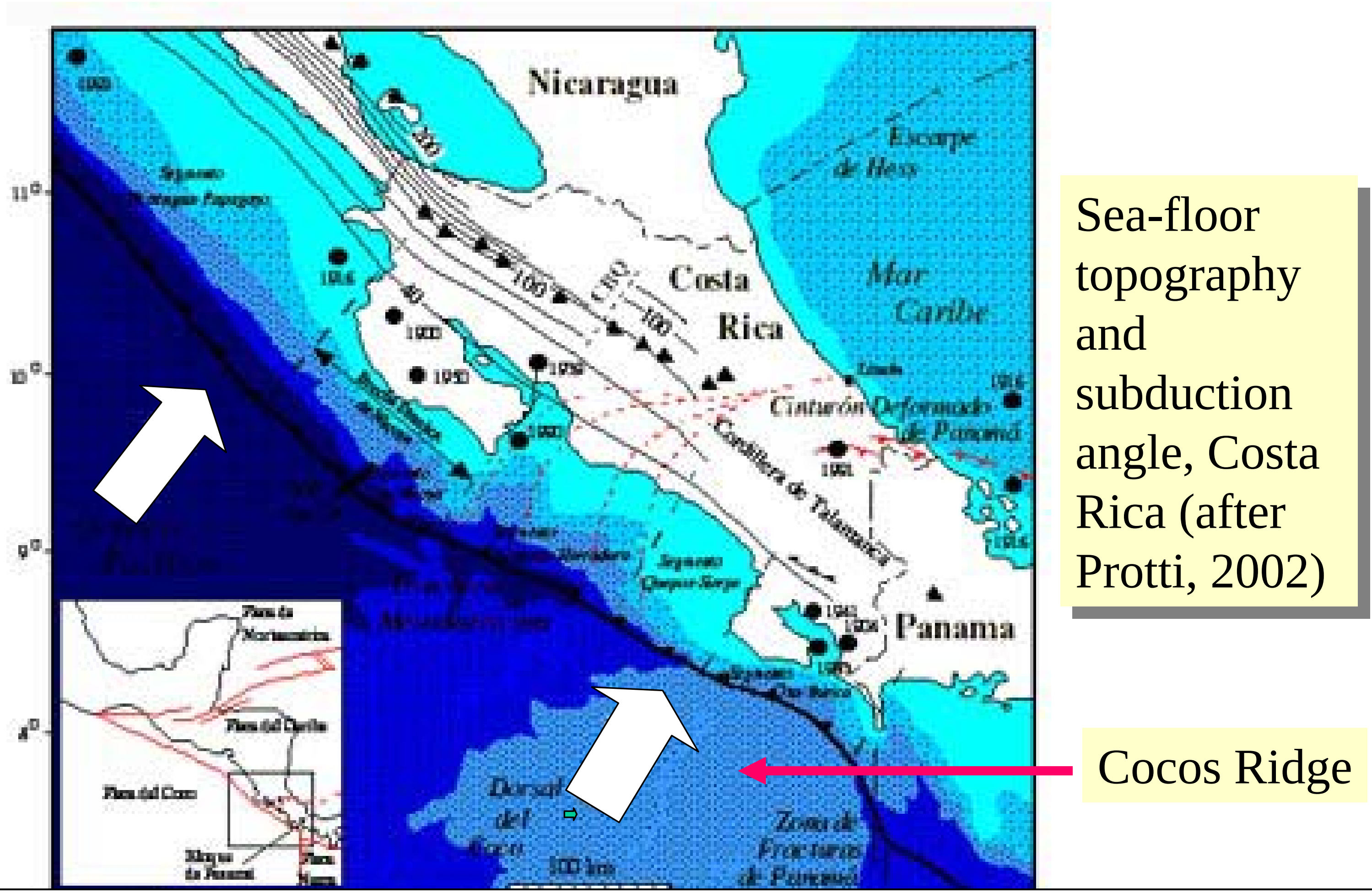


Slide 4: Costa Rica geology. Cretaceous-Eocene ocean floor on the Nicoya and Osa Peninsulas, the Eocene-Miocene magmatic arc with elevated terrane in the Talamanca Cordillera, and the active Quaternary arc in NW Costa Rica.

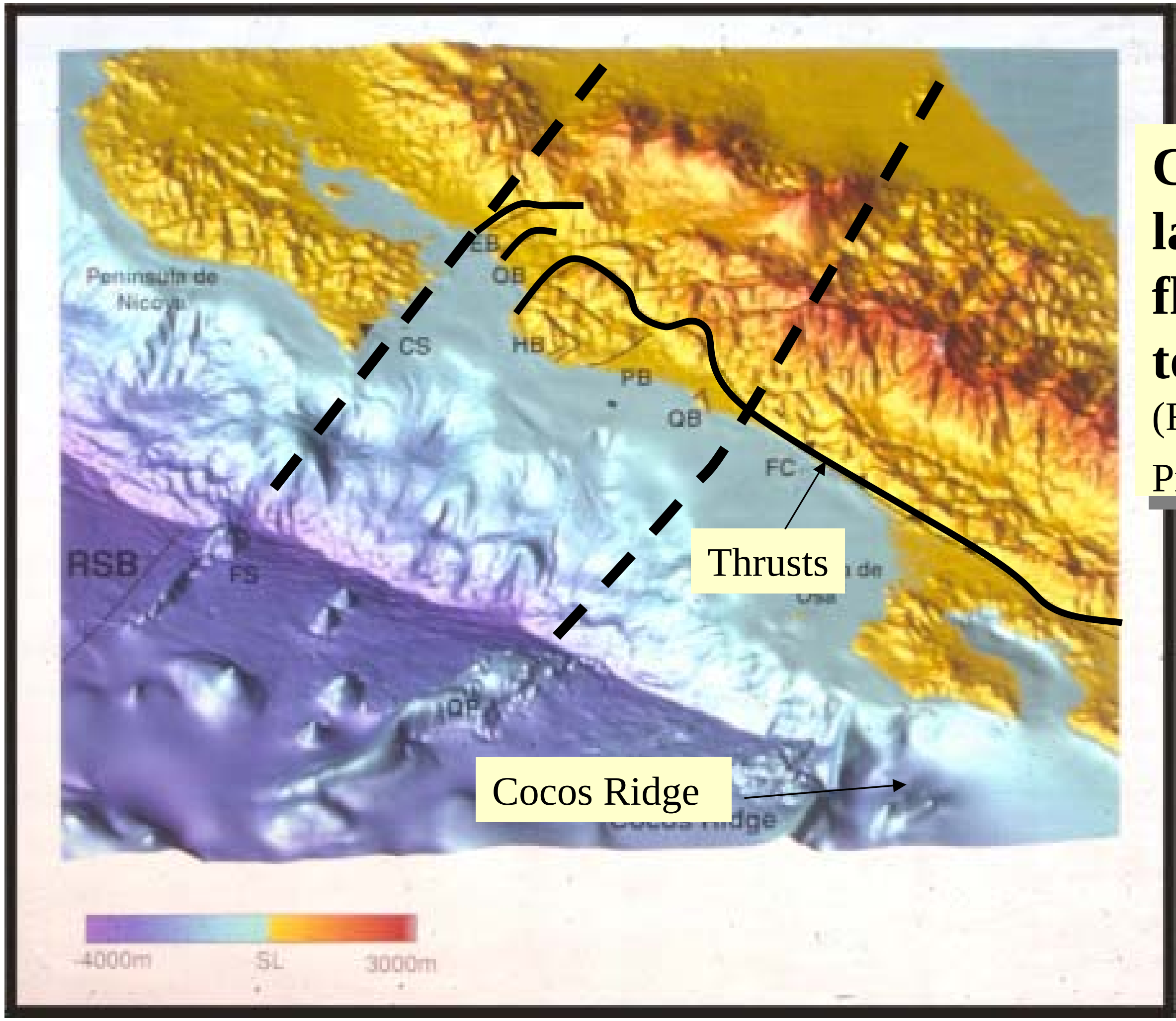


Sea-floor topography and subduction angle, Costa Rica (after Protti, 2002)

Cocos Ridge



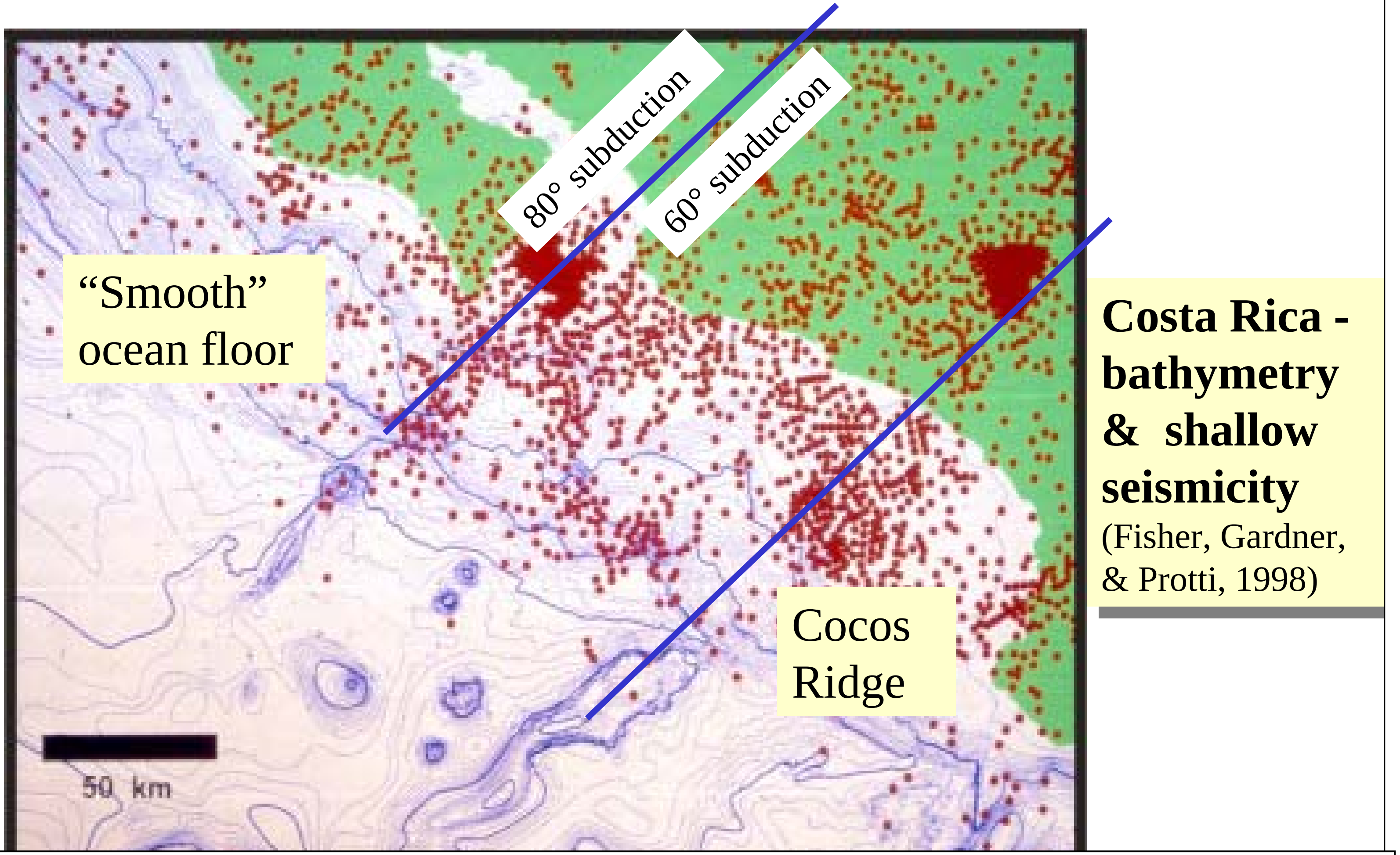
Slide 5: Bathymetry and plate tectonics, Costa Rica. Deep water off NW Costa Rica, shallower water to the SE, coming under the influence of the Cocos Ridge. The Wadati-Benioff zone dips at about 80 deg off NW Costa Rica, flattening below central Costa Rica, and is not detectable below SE Costa Rica, where the Cocos Ridge is being subducted – slab thought to be horizontal here. Note linear truncation of Nicoya Peninsula at boundary between steep and flatter subduction



Costa Rica land and sea-floor topography

(Fisher, Gardner, & Protti, 1998)

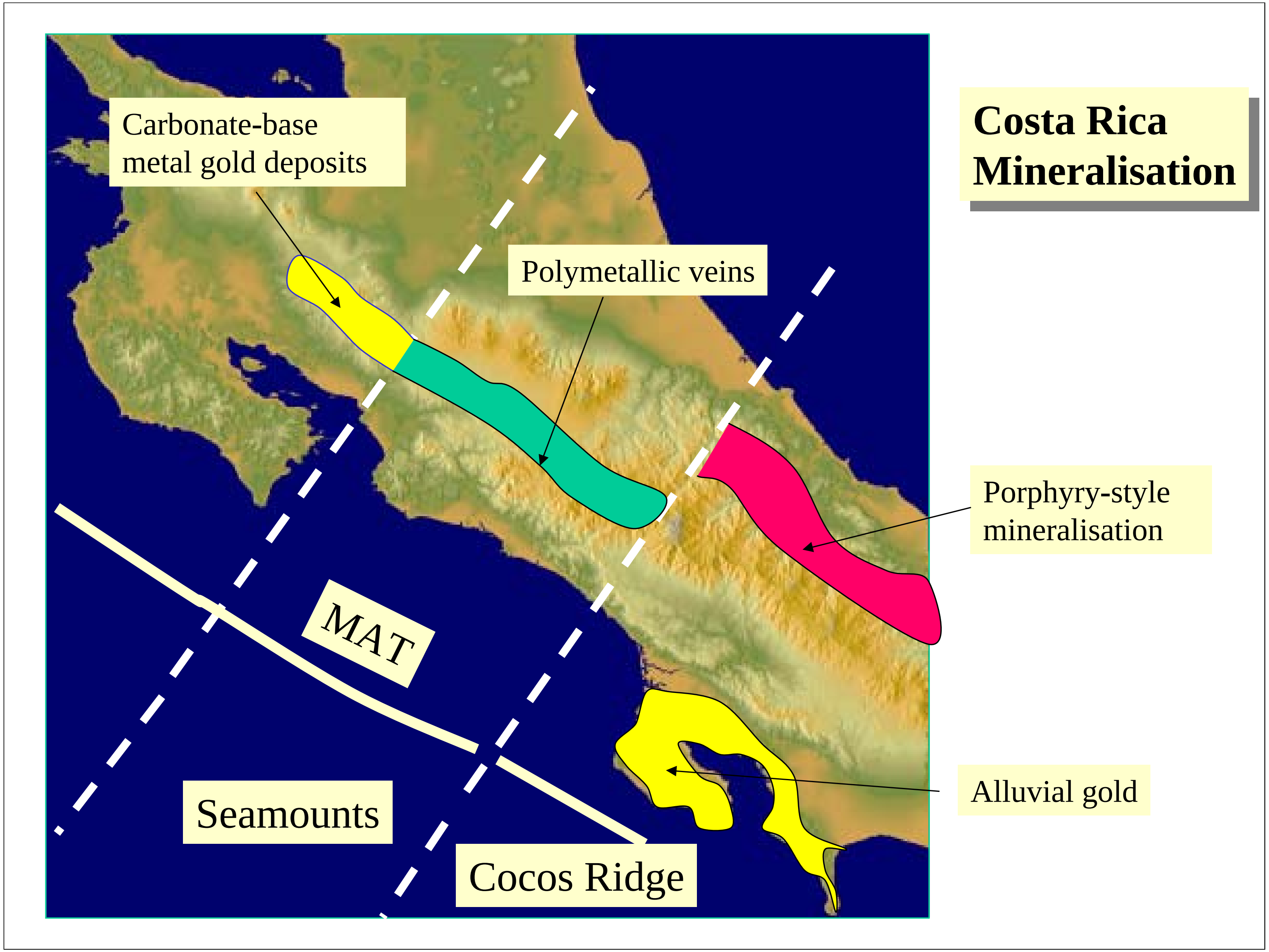
Slide 6: More Costa Rica bathymetry. The region of intermediate depth water and flattening subduction corresponds to subducted seamounts, the shallower water to the SE is the Cocos Ridge. Thrusts in the fore-arc region are restricted to the latter two. Recall Lake Nicaragua – a back arc basin – inboard of the region of “normal’ subduction.

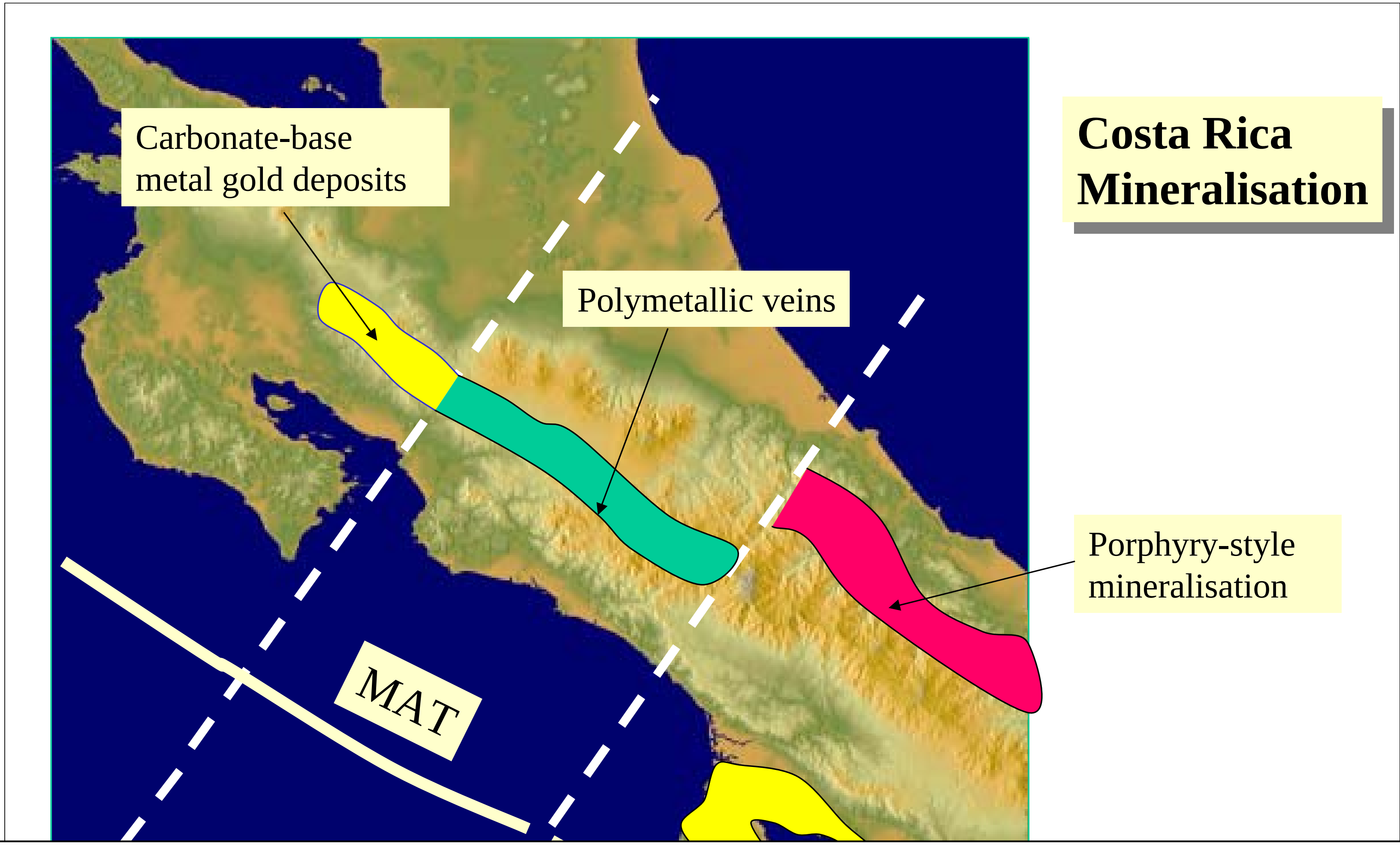


Slide 7: Costa Rica seismicity. Again, the three regions are reflected by shallow seismicity – few shallow earthquakes in the region of smooth ocean floor, more where the seamounts and Cocos Ridge are being subducted. Boundaries between regions marked by intense shallow seismicity.

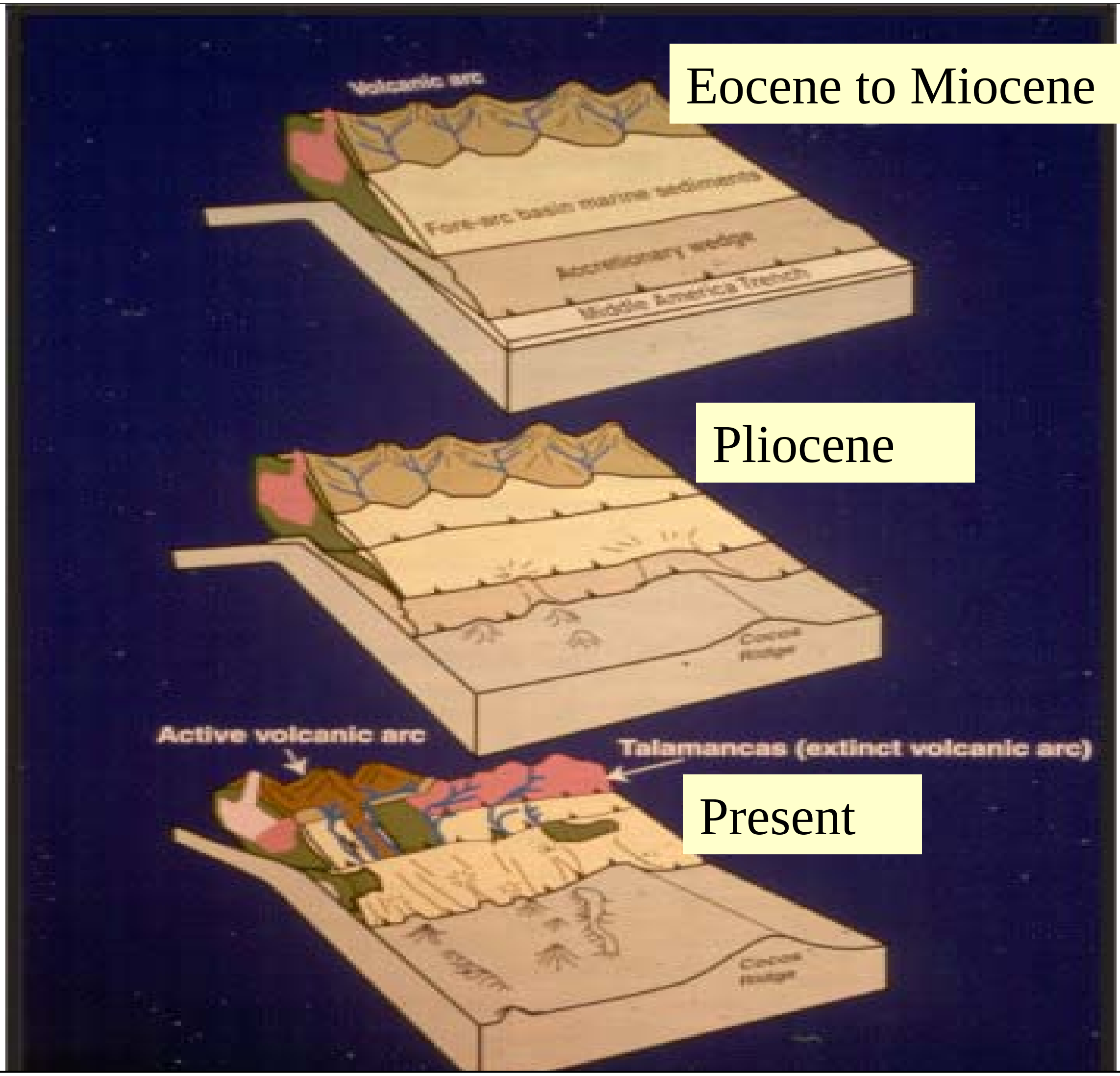
Slide 8: Arc-normal faults in Costa Rica. Aerial shot of a fault looking NE across Costa Rica.

Active arc-normal fault scarp, NW Costa Rica


Costa Rica
Mineralisation
Carbonate-base
metal gold deposits
Polymetallic veins
Porphyry-style
mineralisation
Alluvial gold
MAT
Seamounts
Cocos Ridge

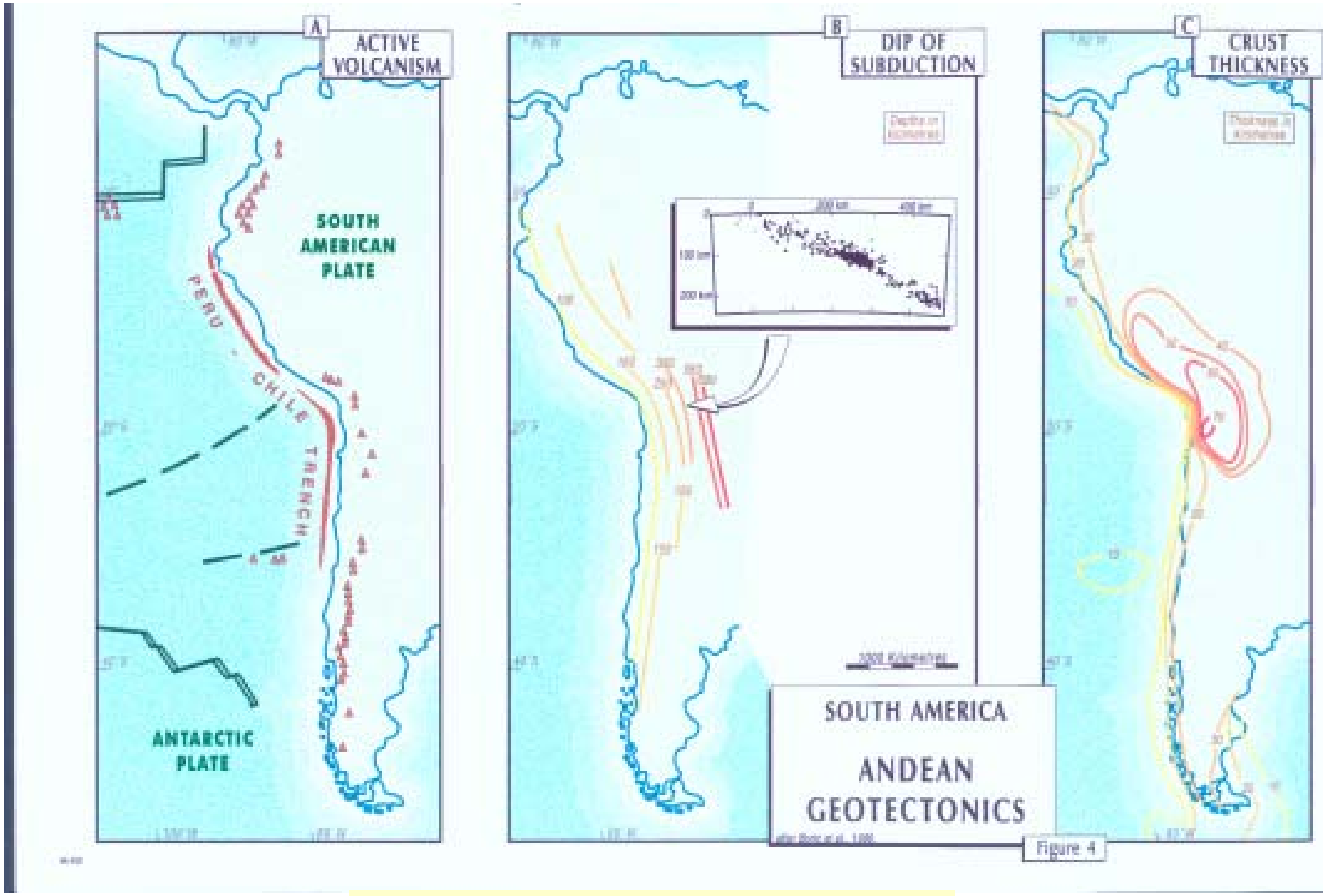


Slide 9: Metallogenic subdivisions of Costa Rica. A late Miocene (ca 6 Ma) epithermal or carbonate base metal gold belt in NW Costa Rica – production since about 1820. To the SE, subeconomic polymetallic vein deposits, and then porphyry systems in the Talamanca Cordillera, extending SE into Panama. These correspond to differing degrees of uplift and erosion – the low-lying gold belt overlies "smooth" ocean floor, the polymetallic roots of these systems are exposed where seamounts are being subducted, and the porphyry systems are exposed in the Talamanca Cordillera, which is the region of strongest uplift above the subducted Cocos Ridge. The gold eroded from the former epithermal deposits in the Talamanca Cordillera now forms alluvial deposits on the Osa Peninsula

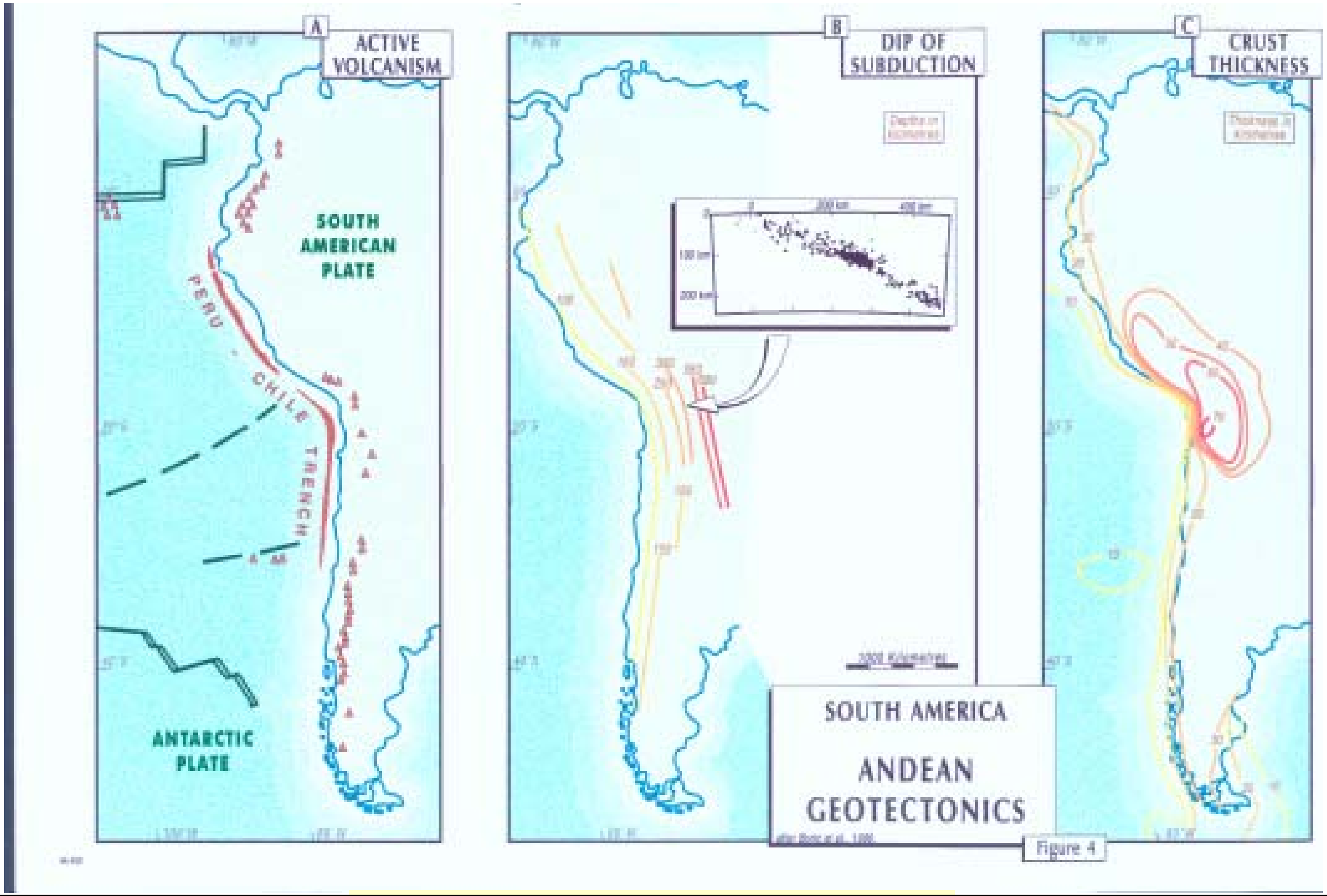


Subduction of the Cocos Ridge below Costa Rica in the Plio-Pleistocene

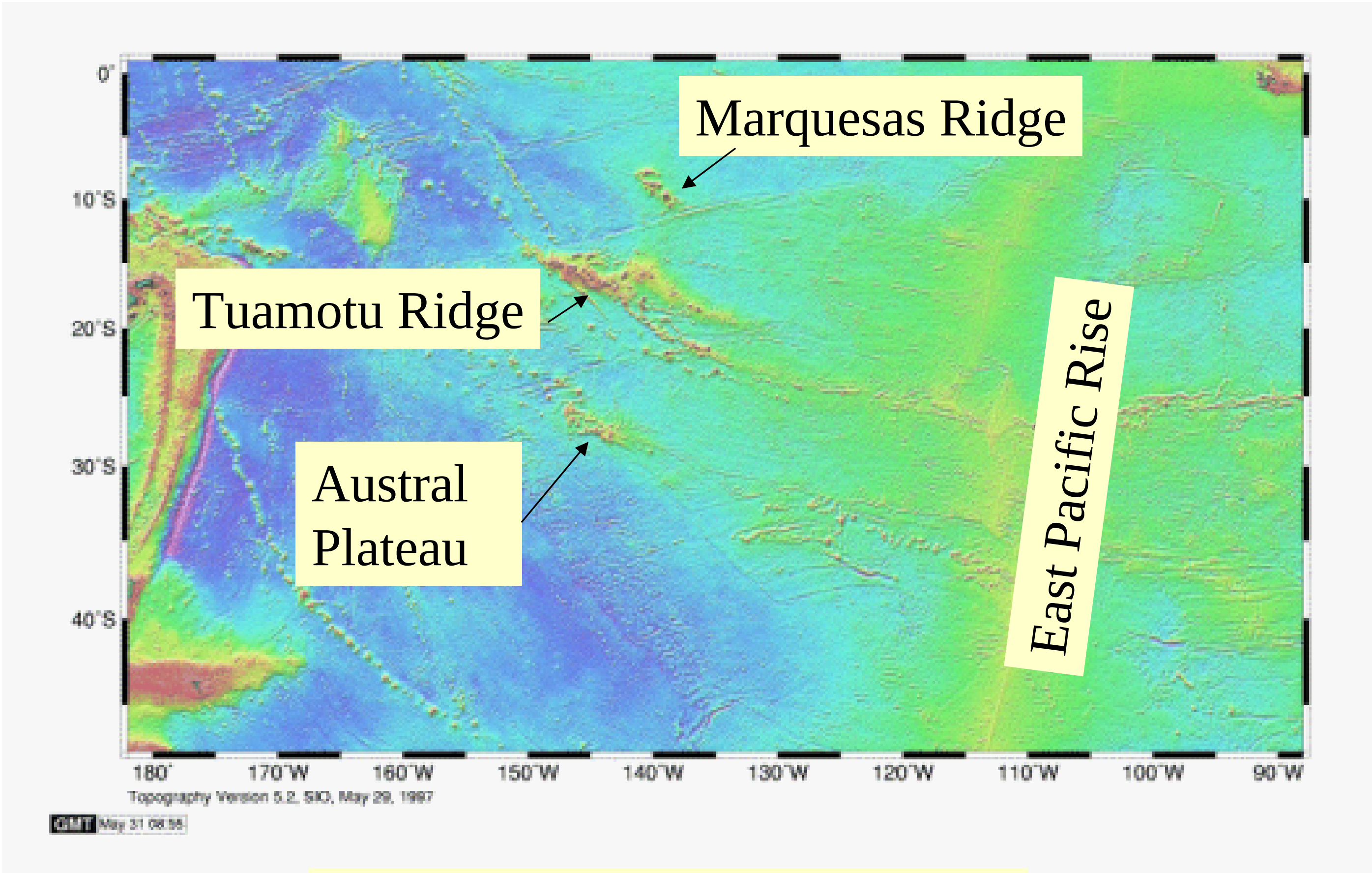
Slide 10: Costa Rica synthesis. Normal subduction in the Eocene to Miocene – porphyry systems and epithermal gold deposits form in the arc during the late Miocene. Seamounts and Cocos Ridge arrive at the trench off SE Costa Rica in the Pliocene, causing uplift and exposure of granites and associated porphyries in SE Costa Rica, erosion of epithermal gold deposits. The magmatic arc is extinguished here but continues to be active in NW Costa Rica and Nicaragua



Andes - Regional Tectonics

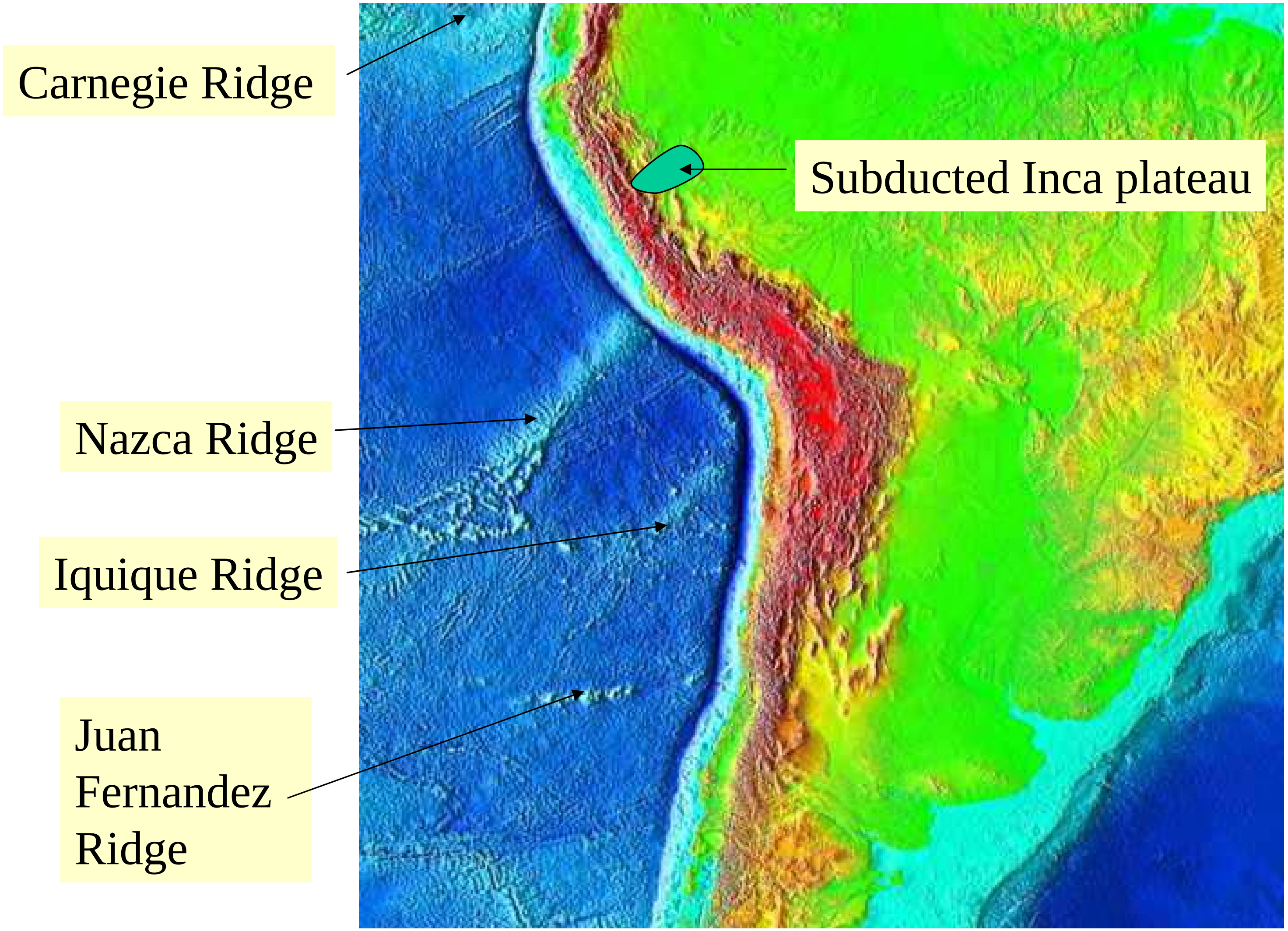


Slide 11: Andean tectonics. Turning now to the Andean region, we have the Nazca Plate being subducted below S America at least since the Jurassic. There are regions of flat subduction below N Peru and Chile-Argentina, separated "normal" subduction below S Peru-Bolivia – a region of thickened crust (70 km). The regions of flat subduction have no Quaternary volcanoes. The next slides will discuss metallogeny of the three regions of contrasting subduction geometry.

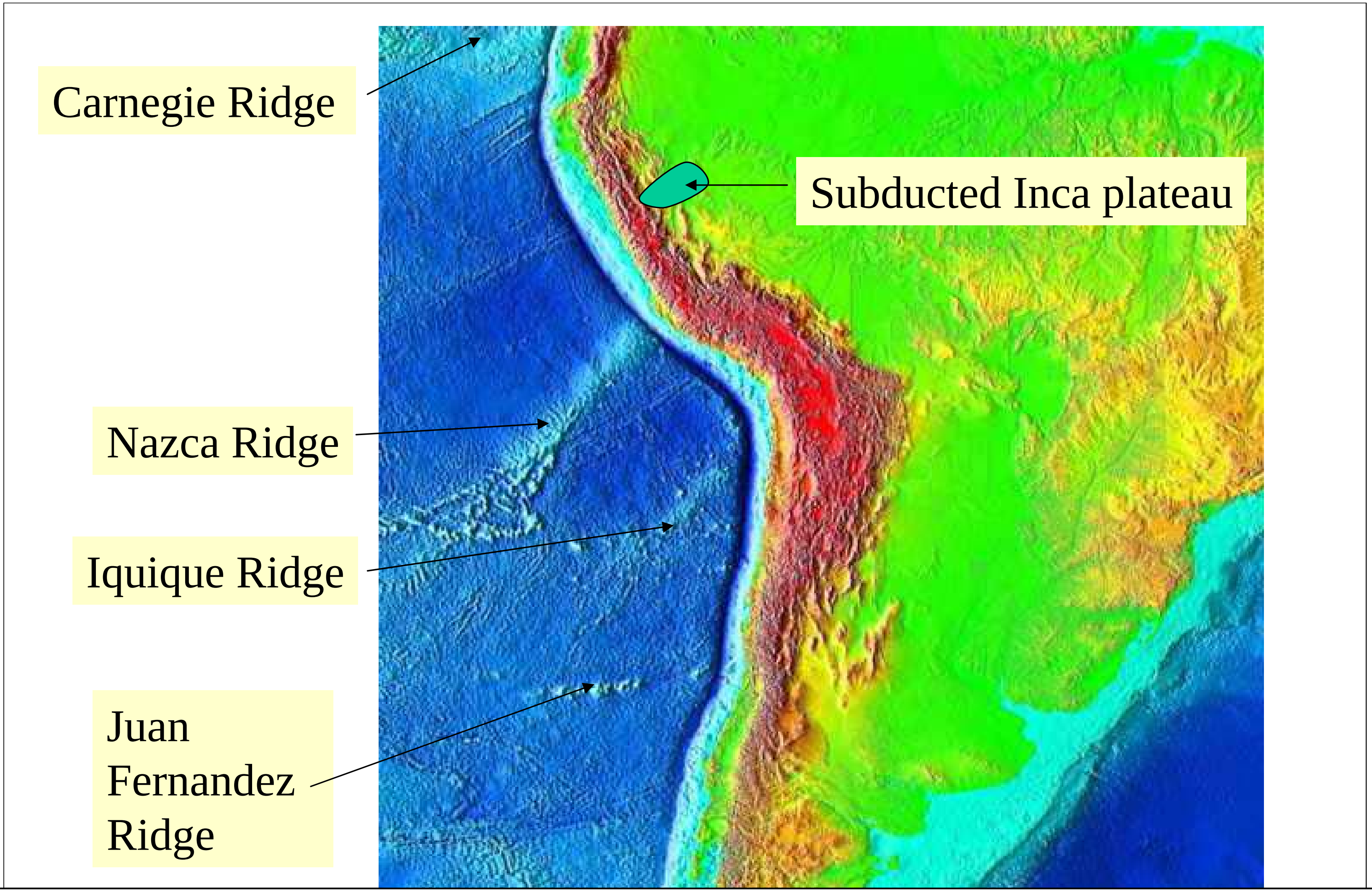


Aseismic ridges in the Pacific

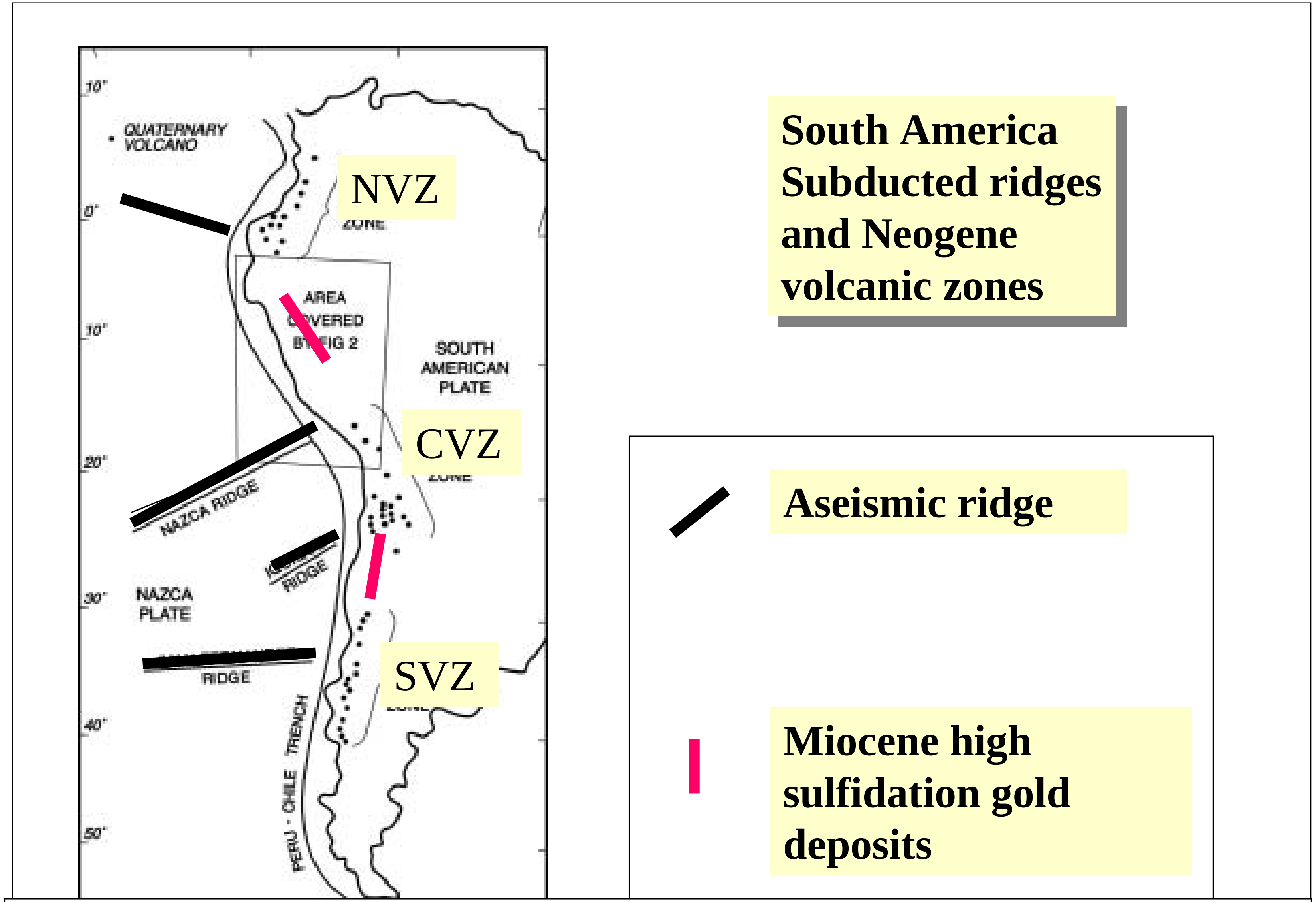
Slide 12: Aseismic ridges in the W Pacific. But first, a diversion to the W Pacific, where three aseismic ridges (Marquesas, Tuamotus, and Austral Plateau) are the dissected parts of an area of thickened crust comparable to (but much older than) the Cocos Ridge. They originated at the East Pacific Rise 30-40 MY ago.



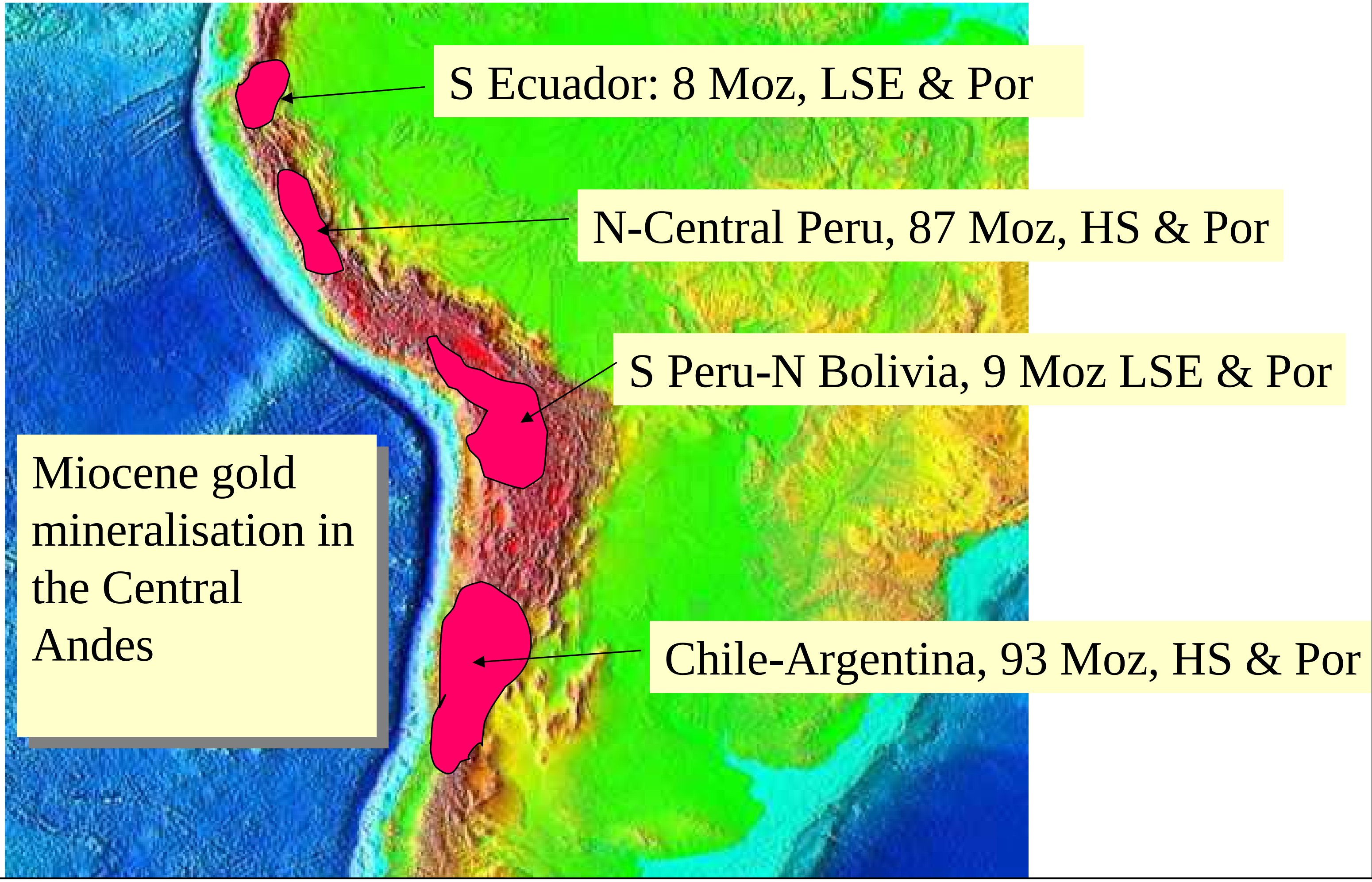
S America - subducted ridges



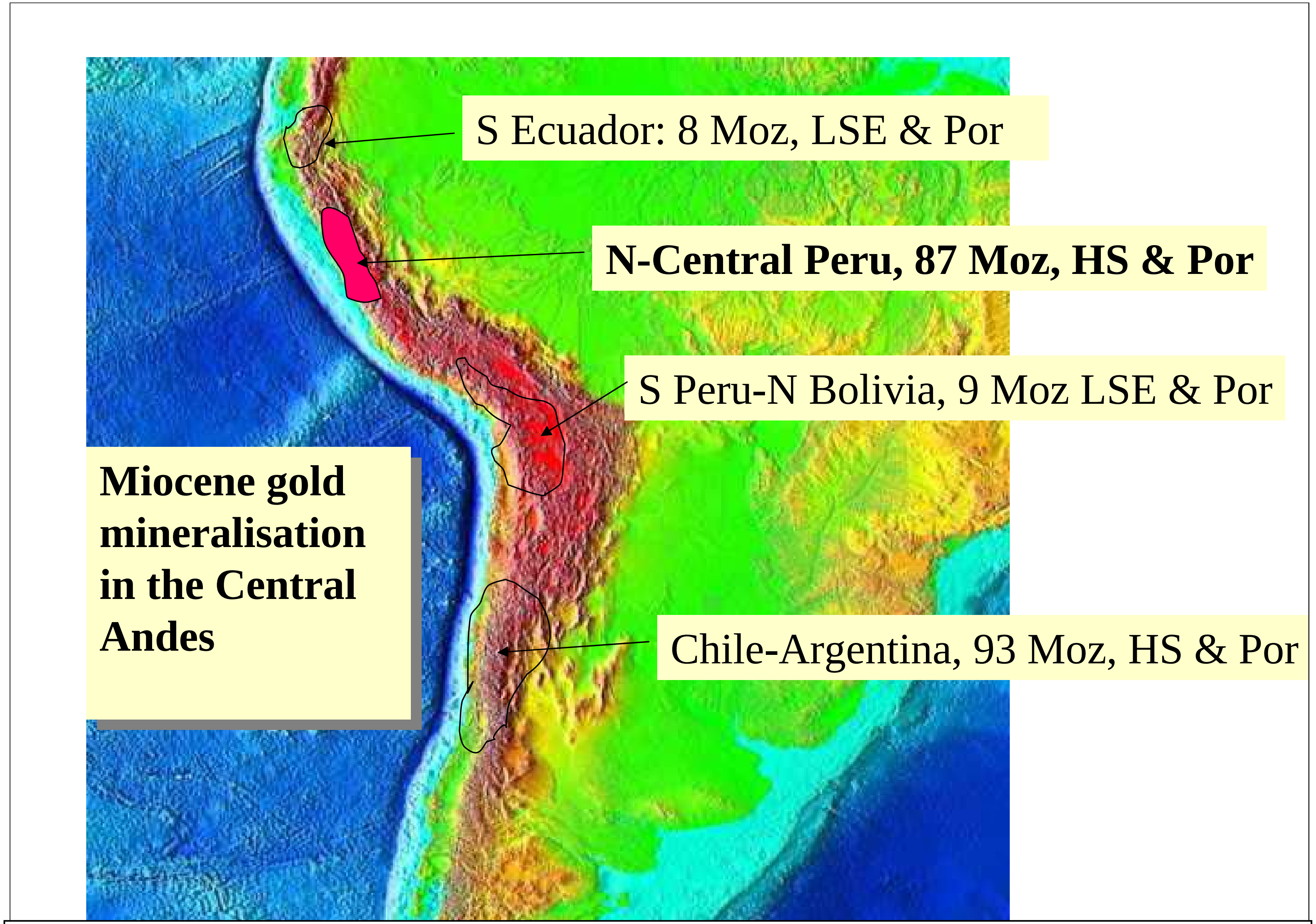
Slide 13: Their counterparts in the Eastern Pacific. Just as the Coco and Carnegie ridges are mirror images of each other, the three W Pacific ridges must also have E Pacific equivalents. Gutscher et al. (2000) say the equivalent of the Tuamotus and Austral Plateau are the Nazca and Iquique ridges respectively – the Nazca Ridge is half subducted at the Peru-Chile trench, and the Iquique Ridge has not yet reached it. The "missing" Marquesas has already been subducted and now lies below eastern Peru. Gutscher et al identify it as an region of reduced seismicity in eastern Peru. They call oit the Inca Plateau.



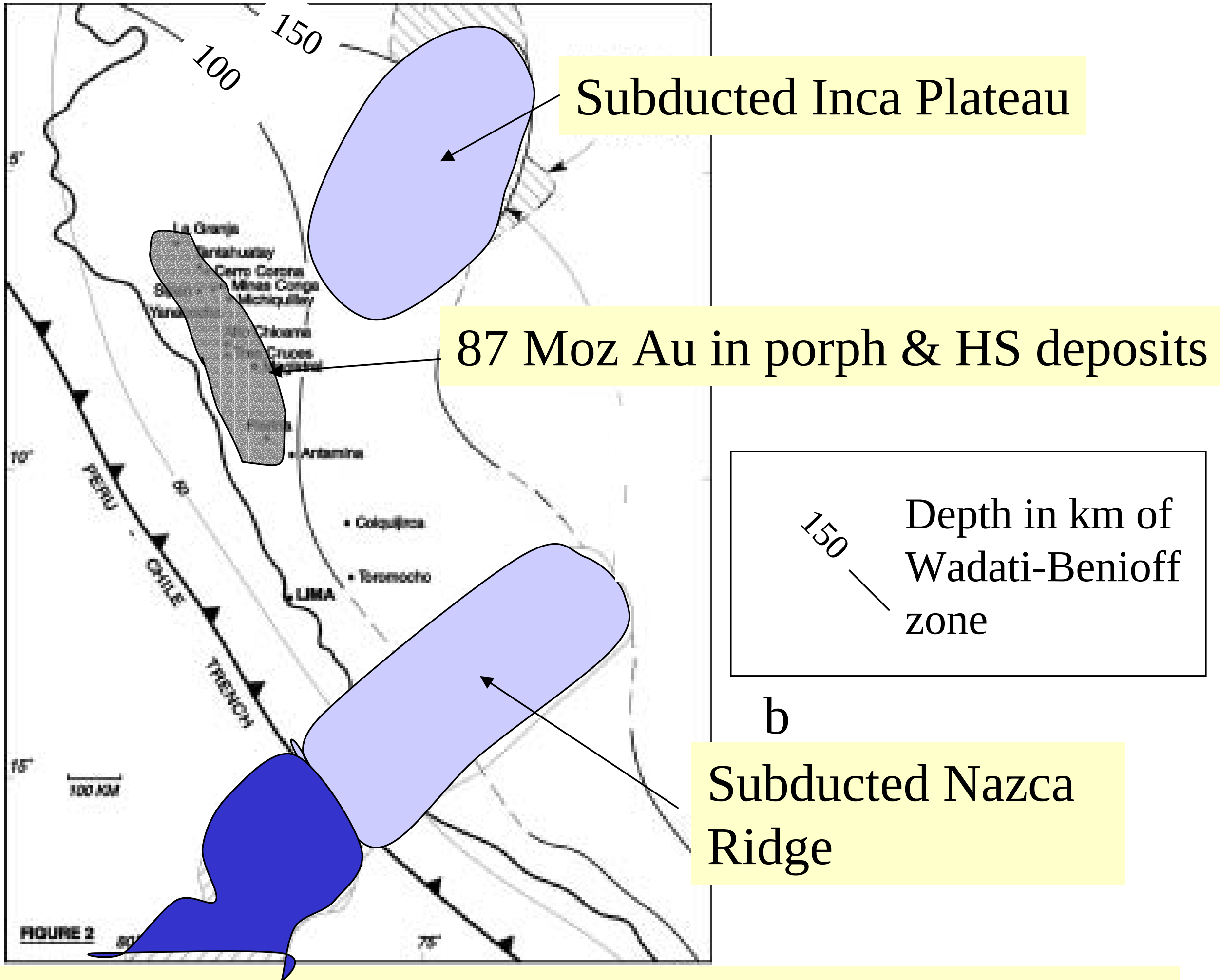
Slide 14: Another look at Andean volcanism and mineralisation. The slide shos the two regions where Miocene high sulfidation gold deposits are concentrated in the Andes, thjeir relationship to the Northern, Central, and Southern Volcsanic zones of Neogene volcanism, and their relationship to subducted ridges.



Slide 15: Miocene gold in the Andes. Miocene gold deposits are concentrated in the two flat subduction regions, N-Central Peru and Chile-Argentina. Both have a known resource + production of about 90 Moz, in high sulfidation and porphyry deposits. Flanking them are regions of much lower Miocene gold content which include both high and low sulfidation deposits.

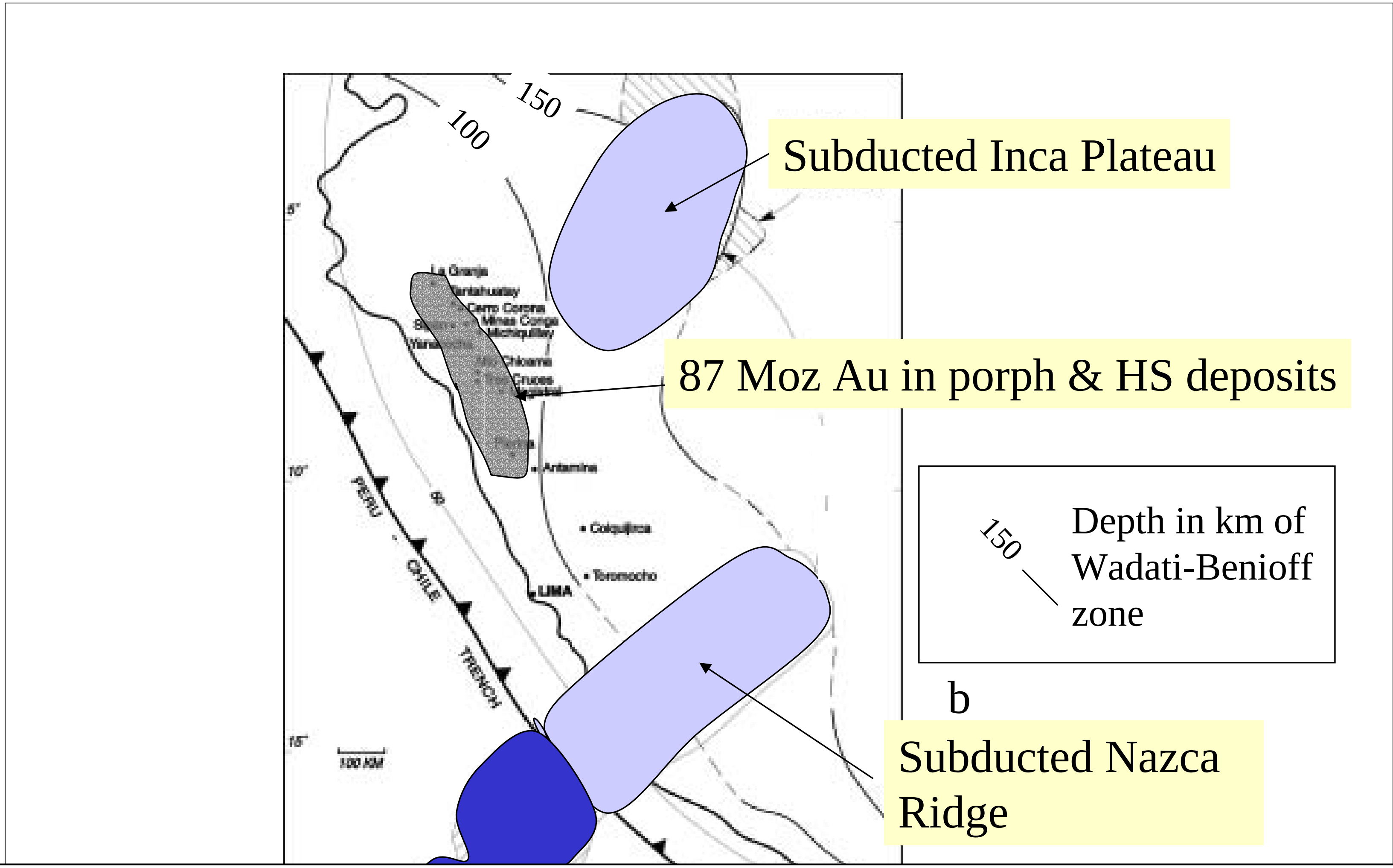


Slide 16: North-Central Peru deposits

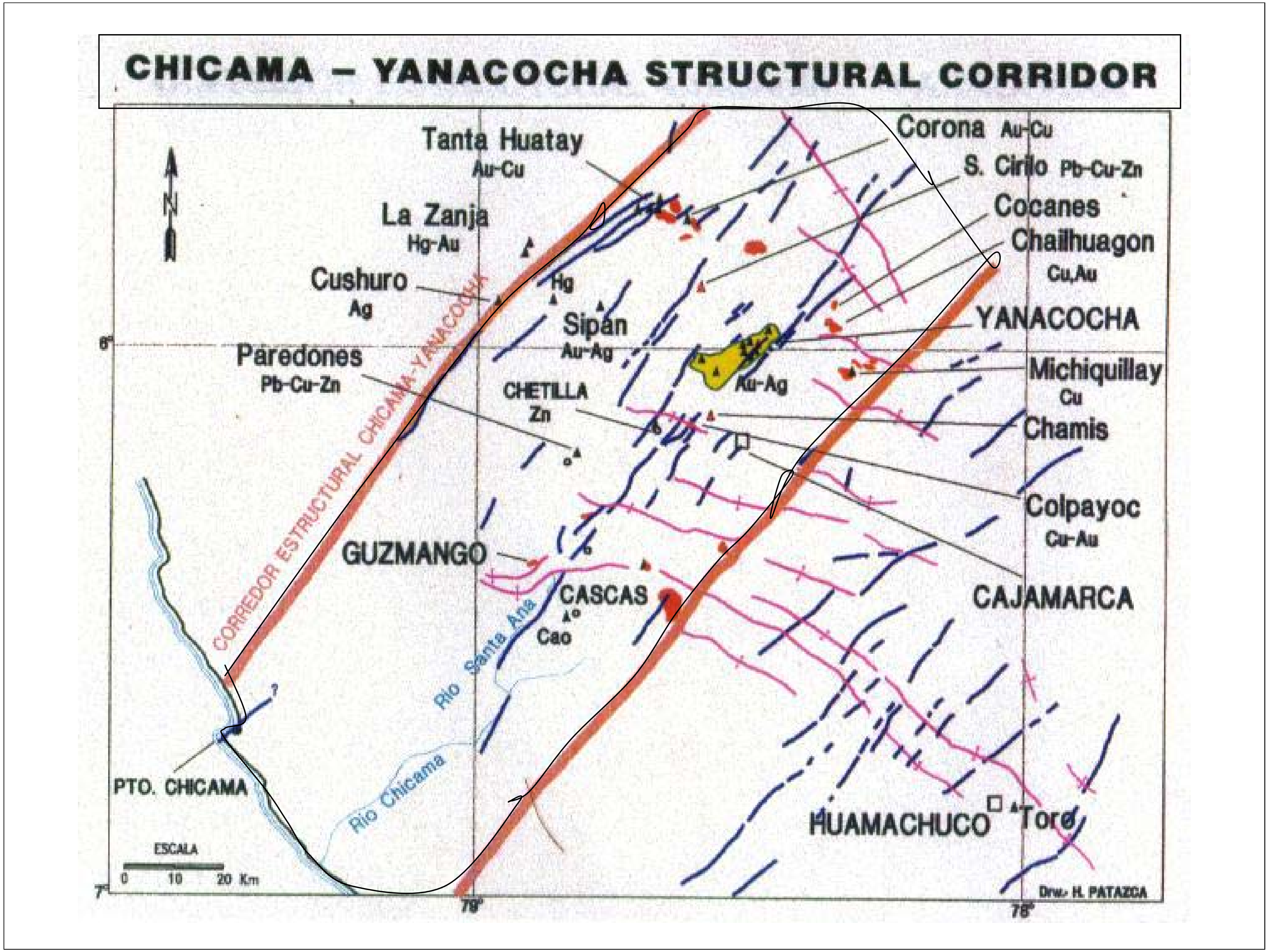


North-Central Peru - Subducted ridges & mineralisation

(based on Gutscher et al., 1999, with deposits added)



Slide 17: Relation between subducted ridges, subduction angle, and Miocene gold deposits in Peru. The inferred subducted Inca Plateau supports a "spur" in the subduction zone, and outboard of it lie some of the largest high sulfidation gold deposits in South America – Yanacocha (40 Moz), and also Pierina and Alto Chicama, each with over 7 Moz. There are also large Au-Cu porphyries, such as Minas Conga. The HS deposits range in age between 15 and 11 Ma, some of he porphyries may be up to 20 Ma. The subducted Nazca Ridge to the south seems not to be associated with major gold mineralisation.


CHICAMA – YANACOCHA STRUCTURAL CORRIDOR
N
Tanta Huatay
Au-Cu
La Zanja
Hg-Au
Cushuro
Ag
Hg
Sipan
Au-Ag
Paredones
Pb-Cu-Zn
CHETILLA
Zn
CORREDOR ESTRUCTURAL CHICAMA-YANACOCHA
GUZMANGO
CASCAS
Cao
Rio Santa Ana
Rio
Rio Chicama
PTO. CHICAMA
ESCALA
0 10 20 Km
Corona Au-Cu
S. Cirilo Pb-Cu-Zn
Cocanes
Chailhuagon
Cu,Au
YANACOCHA
Au-Ag
Michiquillay
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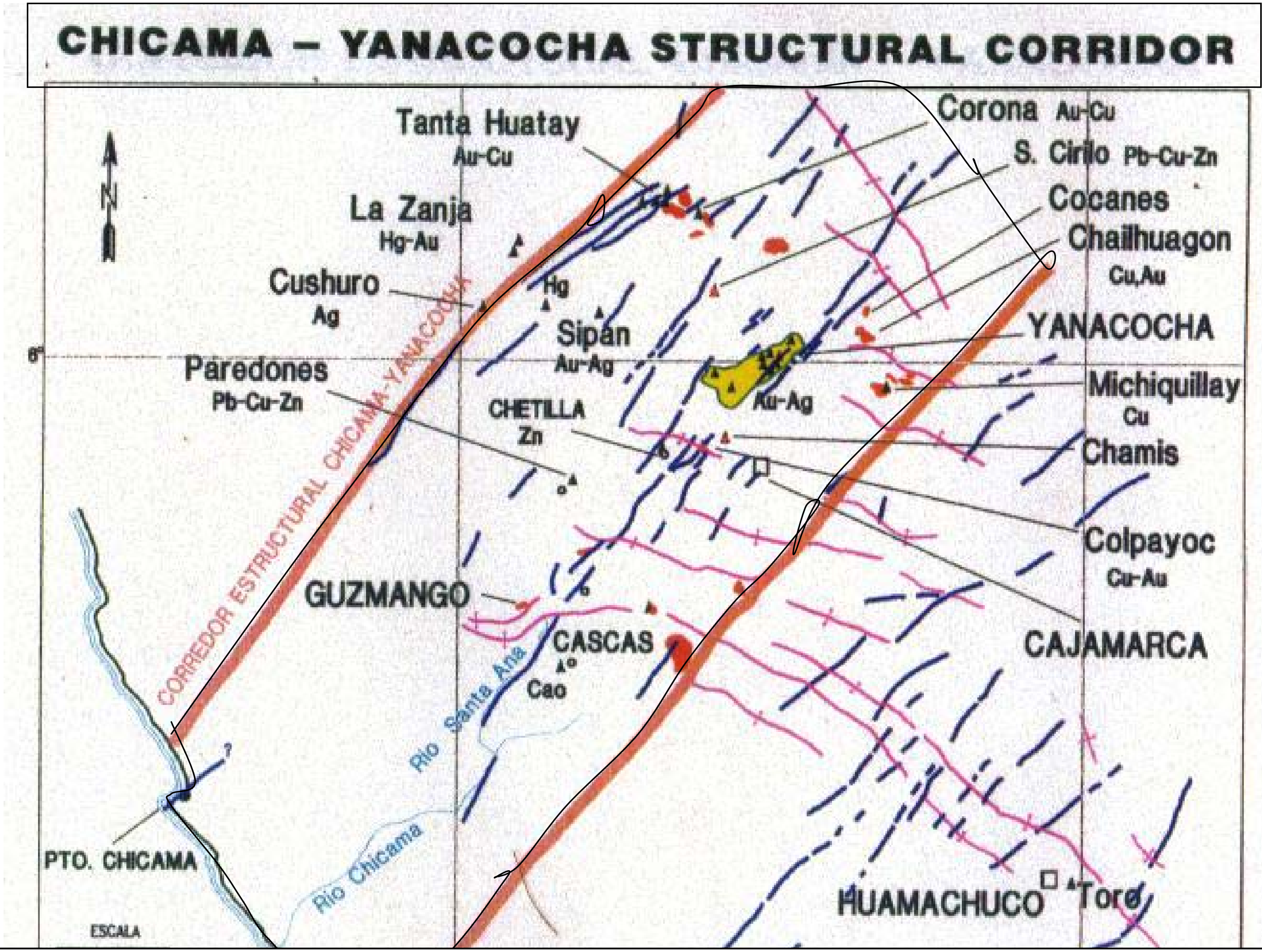
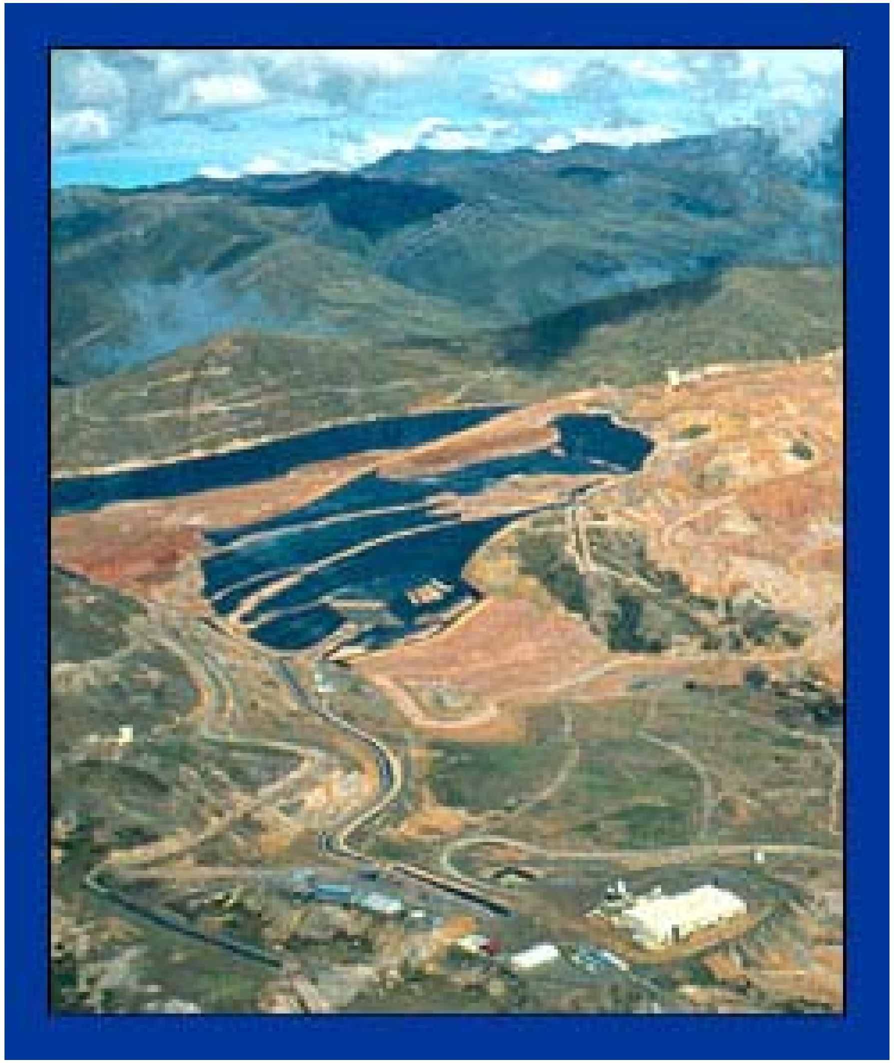
79°
78°
Drw.: H. PATAZCA



Slide 18: The Chicama-Yanacocha structural corridor. A system of arc-normal structures along the inferred track of the Inca Plateau has been identified, and is associated with the porphyry and high sulfidation systems. It is referred to as the Chicama-Yanacocha structural corridor.

Slide 19: The Yanacocha deposit. Note the relatively flat topography, which is becoming flatter before the eyes of these campesinos. 8 Moz Au produced, 34 Moz left.

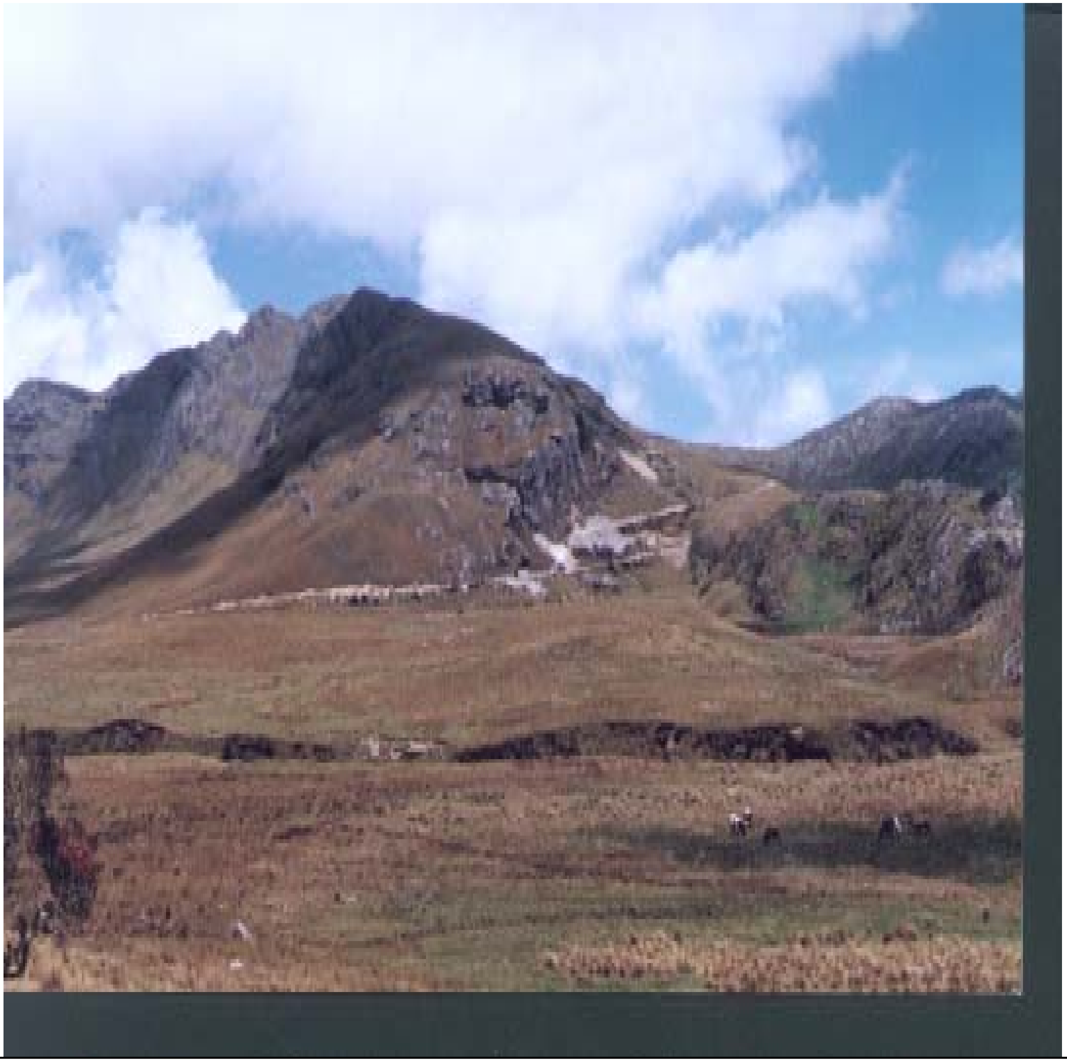
Yanacocha high sulfidation deposit, Peru



PIERINA HIGH SULFIDATION DEPOSIT, PERU

14.5 Ma HS deposit
3.5 Moz produced
4.7 Moz remaining

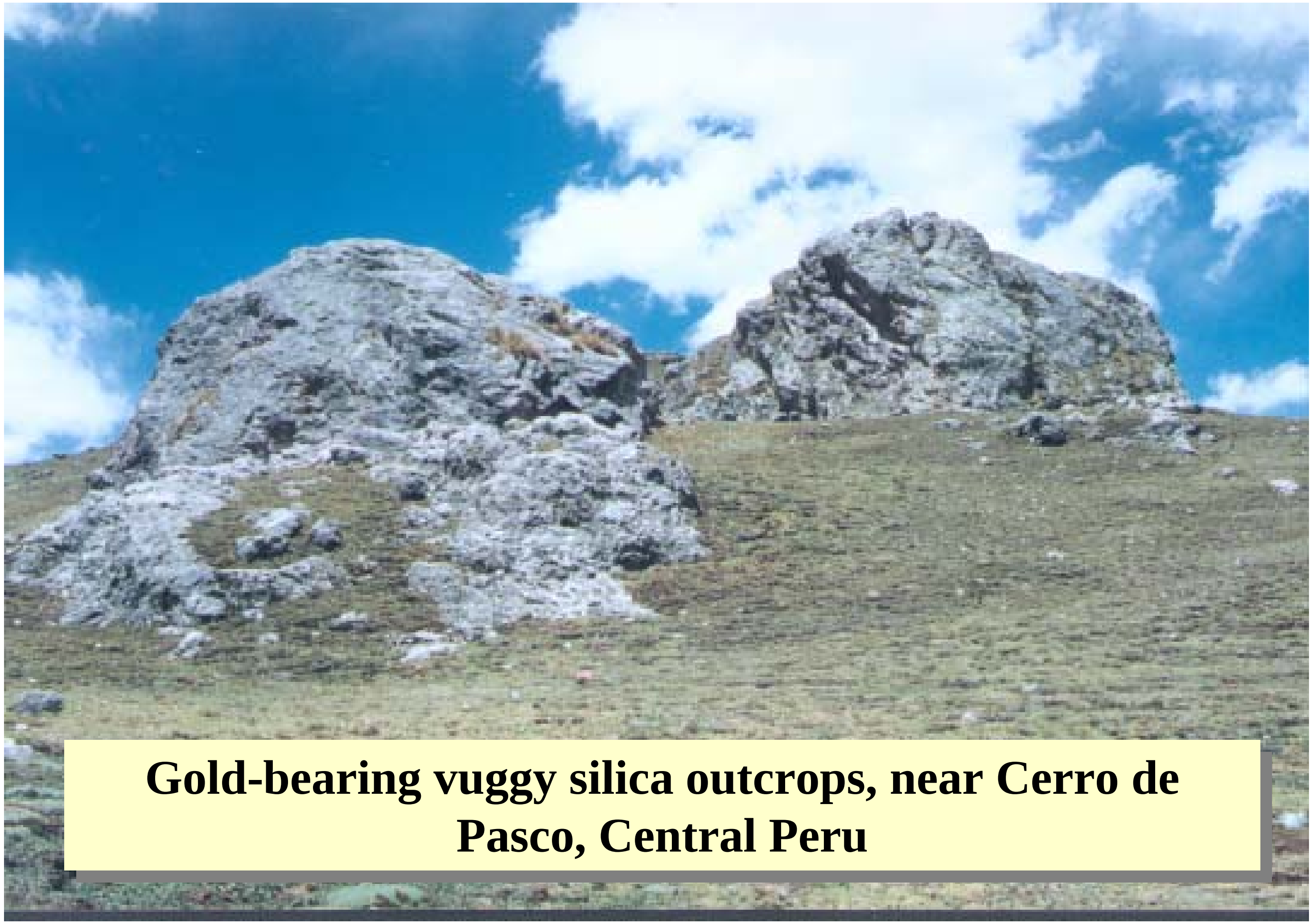
Slide 20: Pierina. Not so flat. 3.5 Moz produced, 4.7 left. 14.5 Ma.



Colquijirca, Central Peru Miocene HS system associated with polymetallic mineralisation

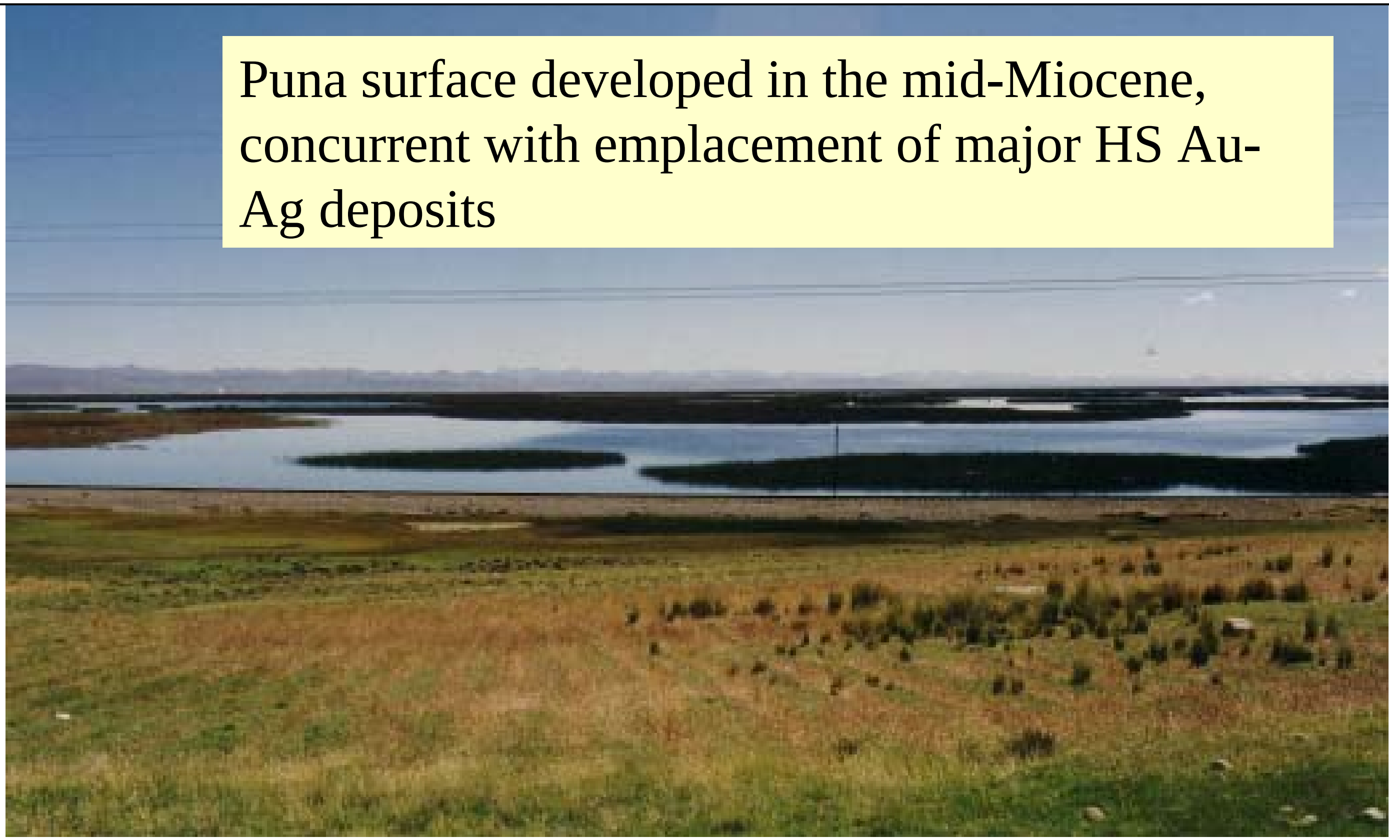
Slide 21: Colquijirca. A Cu-rich HS deposit, associated with polymetallic mineralisation, near Cerro de Pasco. Subdued topo again.

Slide 22: Quicay. Small HS system also near C de P – may be older than Miocene, but gives a good idea of the alteration – central vuggy silica flanked by argillic alteration (horizon on the left). Subdued topo.



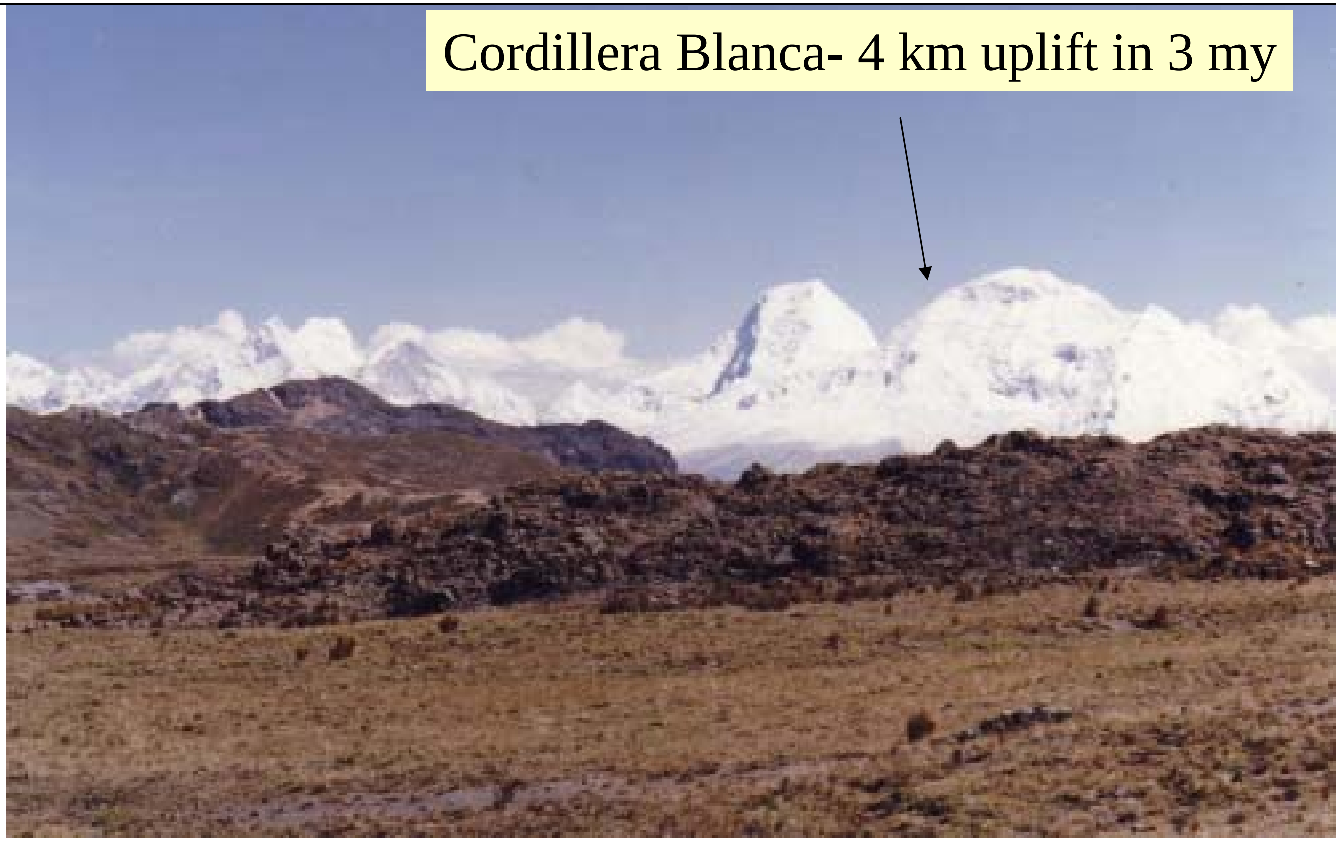
Slide 23: Quicay close up. Gold bearing vuggy silica outcrops at Quicay

Slide 24: Puna surface. This is the surface (at lake Junin) which I suggest formed when the subducted Inca Plateau arrived below N Peru at about 12 Ma. This surface developed between the Quechua 1 (19 Ma) and Quechua 2 (10 Ma) compressive pulses. I maintain that the high sulfidation deposits such as Yanacocha and Pierina formed as a result of this uplift and erosion, and I will suggest later how this could have occurred.

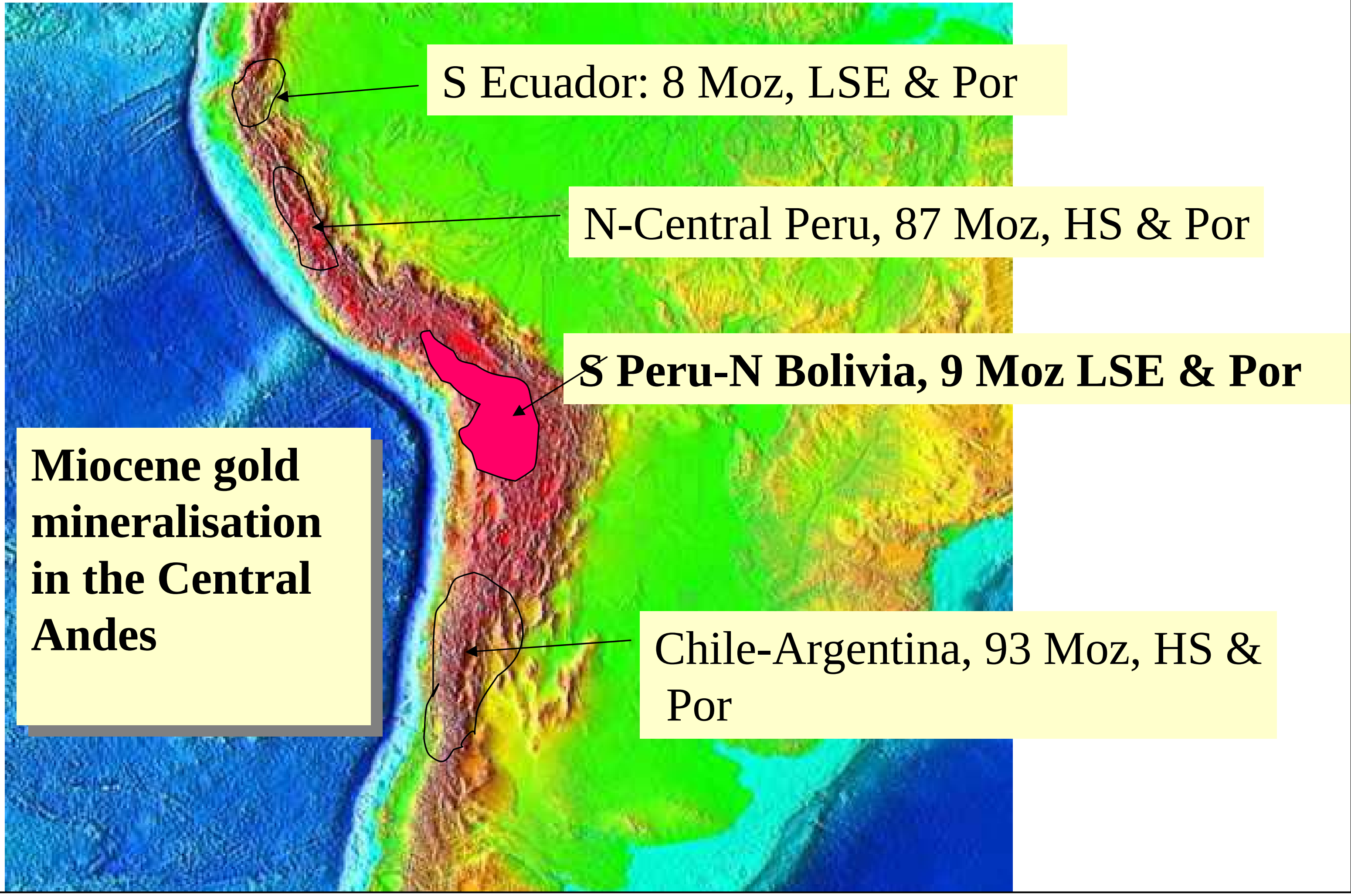


Miocene Puna Erosion surface, Lake Junin, central Peru

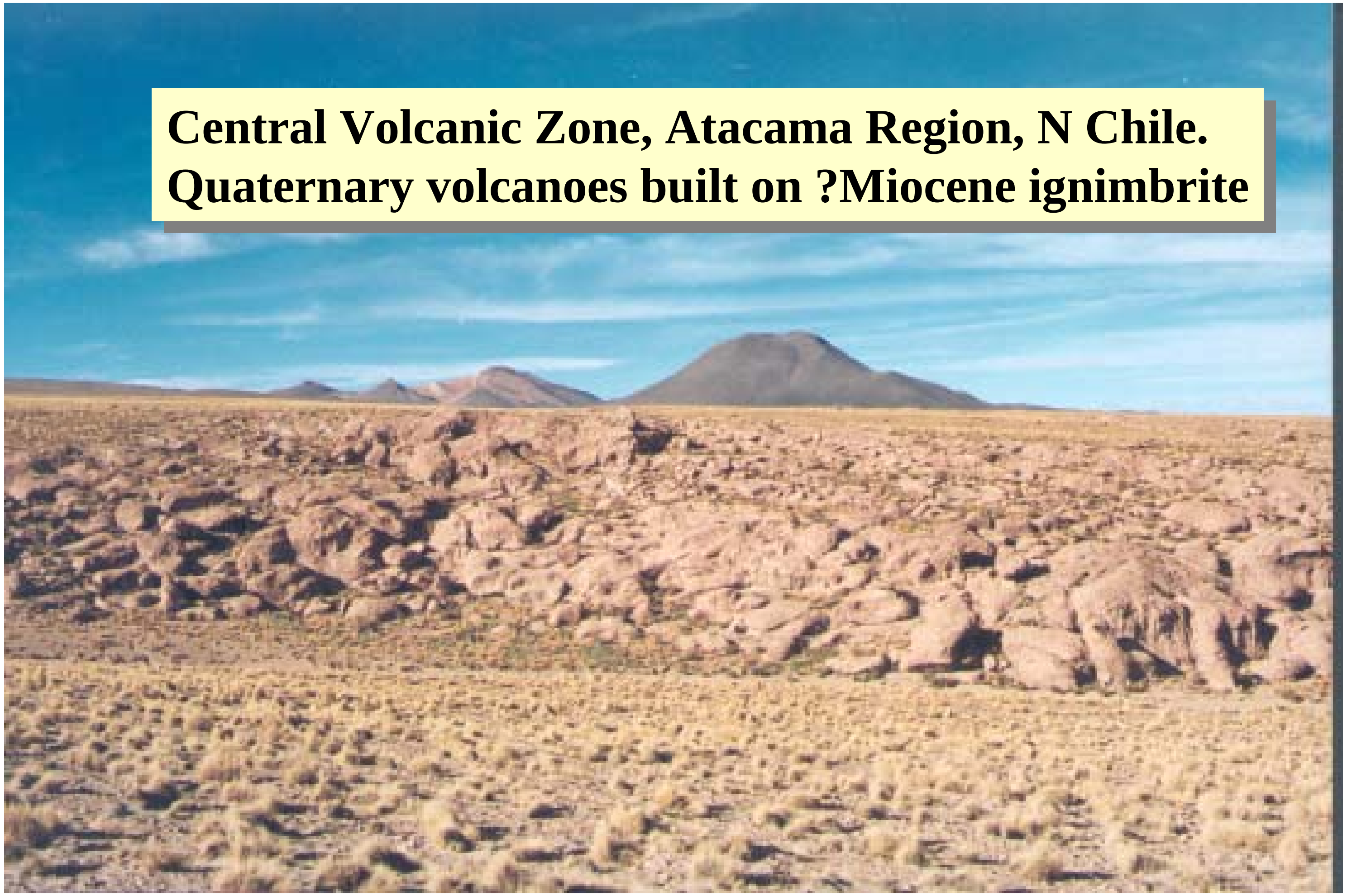
Slide 25: The Cordillera Blanca. This shot of the CB is taken not far from Pierina. Its relevance is that it consists mostly of granite, as young as 3 Ma, which has therefore been unroofed during that time. I believe this unroofing is an expression of the passage of the Inca Plateau during the late Miocene, but the point is it illustrates how rapid uplift and erosion can be in this region. This translates to about 4 km of erosion in the last 3 My, which is equivalent to 100s of metres during the cooling cycles of magmatic systems – a point I will come back to later.



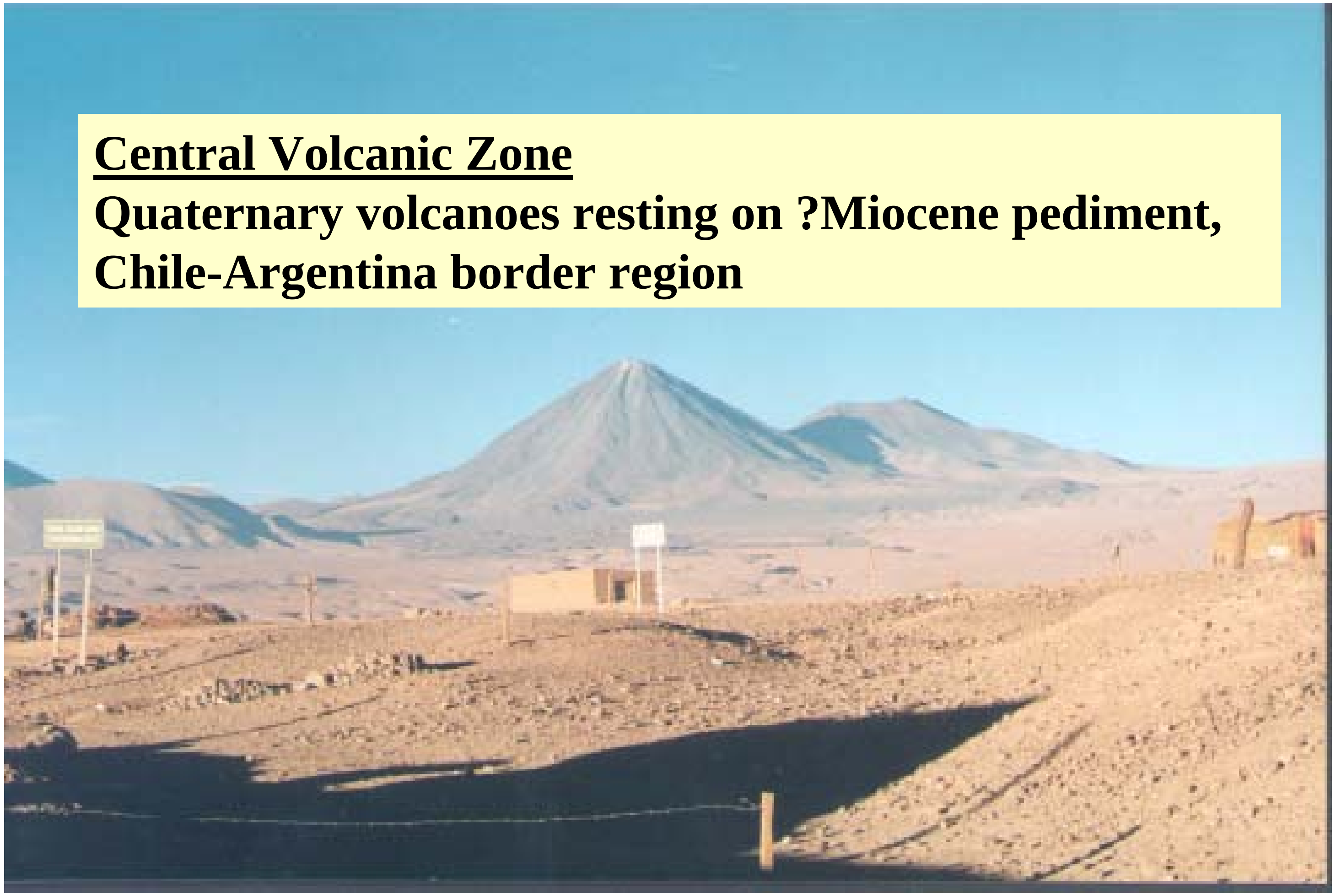
Cordillera Blanca, seen from near Huaraz, Central Peru



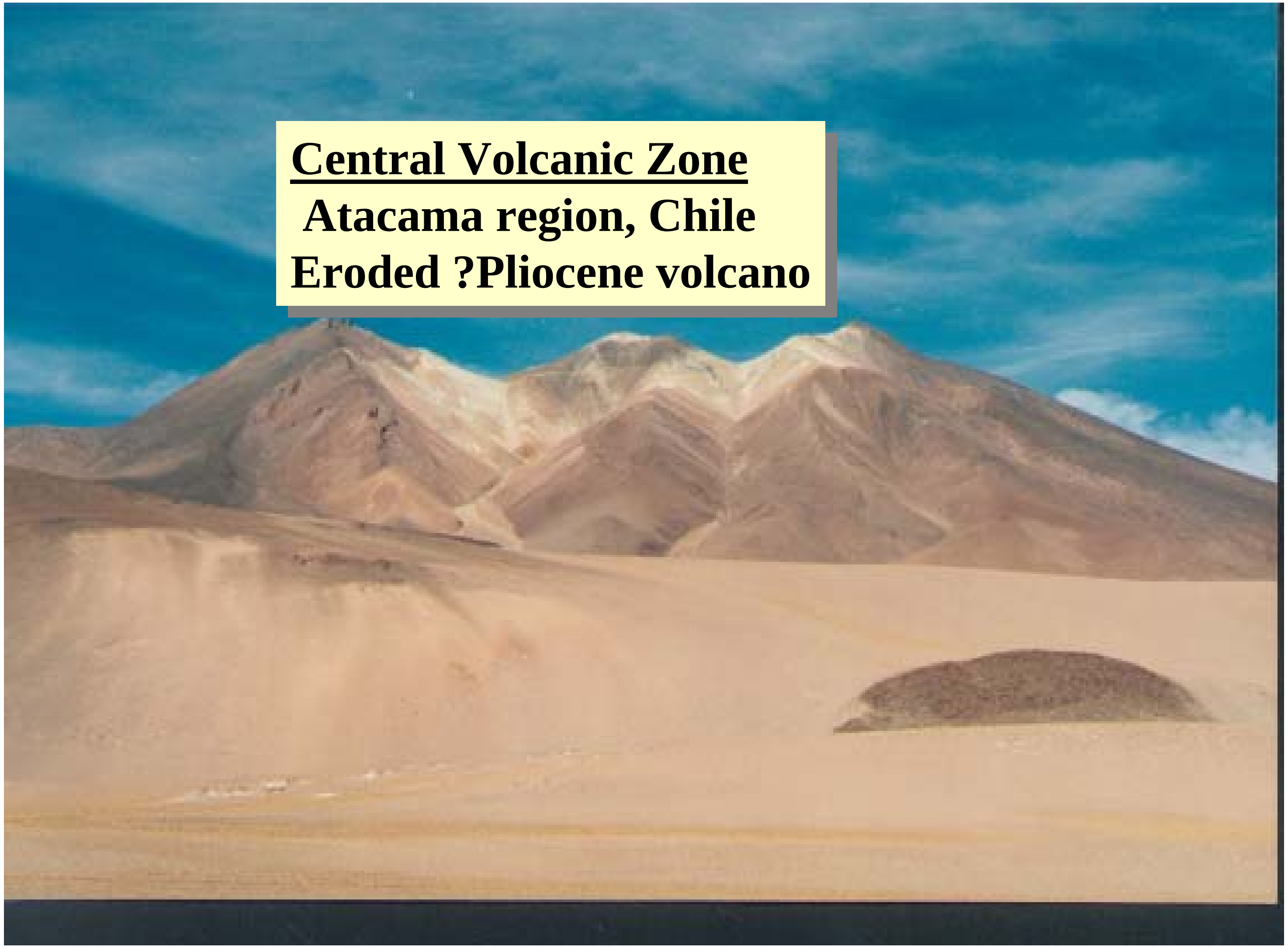
Slide 26: The Central Volcanic Zone. That conclude what I have to say about N-central Peru for the moment, and we move down to southern Peru and Bolivia, out of the influence of flat subduction and subducted ridges, and into the Central Volcanic Zone. (Remember the absence of modern volcanic features in previous slides).



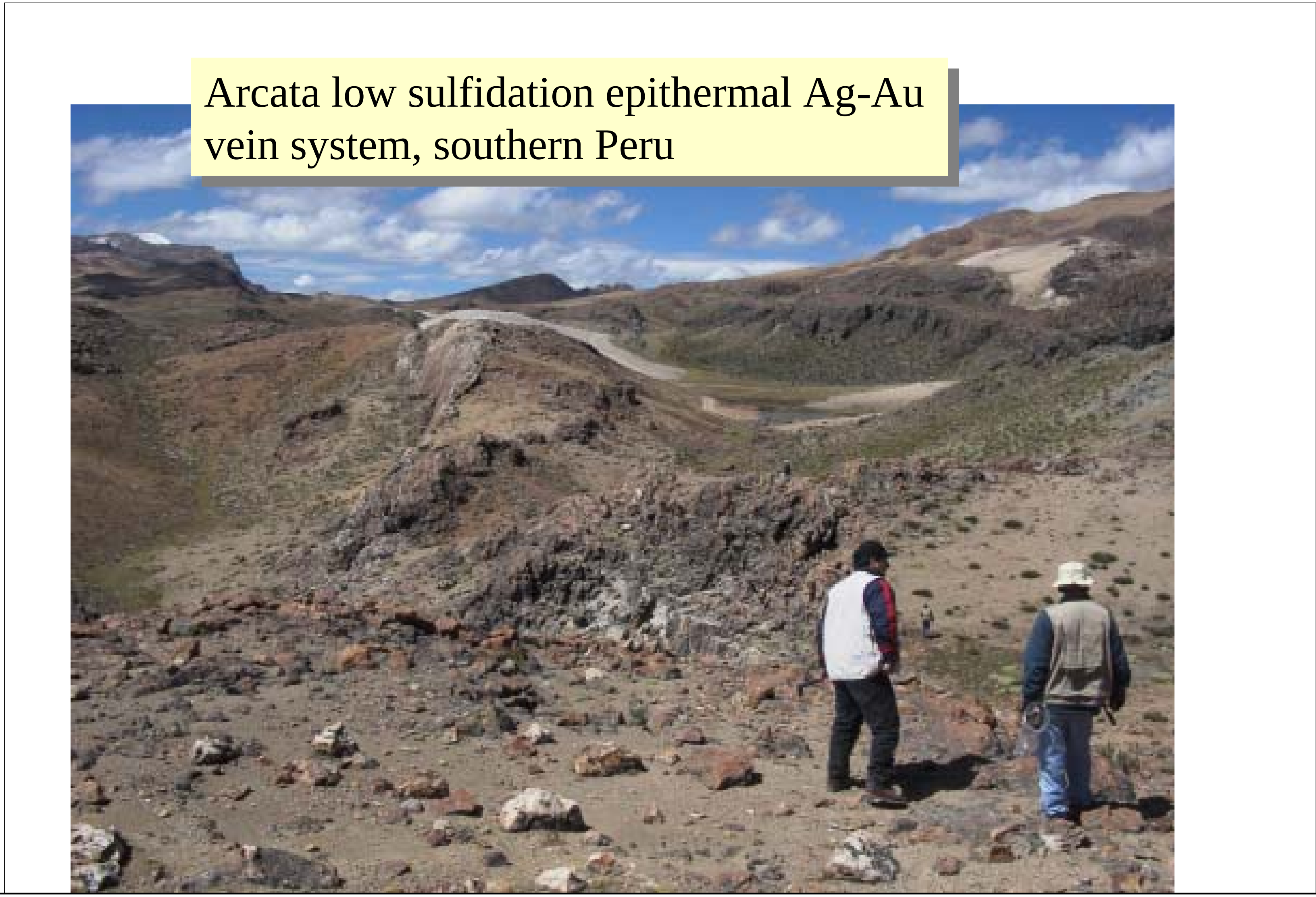
Slide 27: CVZ landscapes. This and the next few slides show the contrast in landscape between N Peru and the central part of the Andes. Here, in N Chile, Quaternary volcanoes rest on Miocene ignimbrite sheets.



Slide 28: and more volcanoes. Intact Quaternary volcanoes rest on gravel pediments (Bolivia).



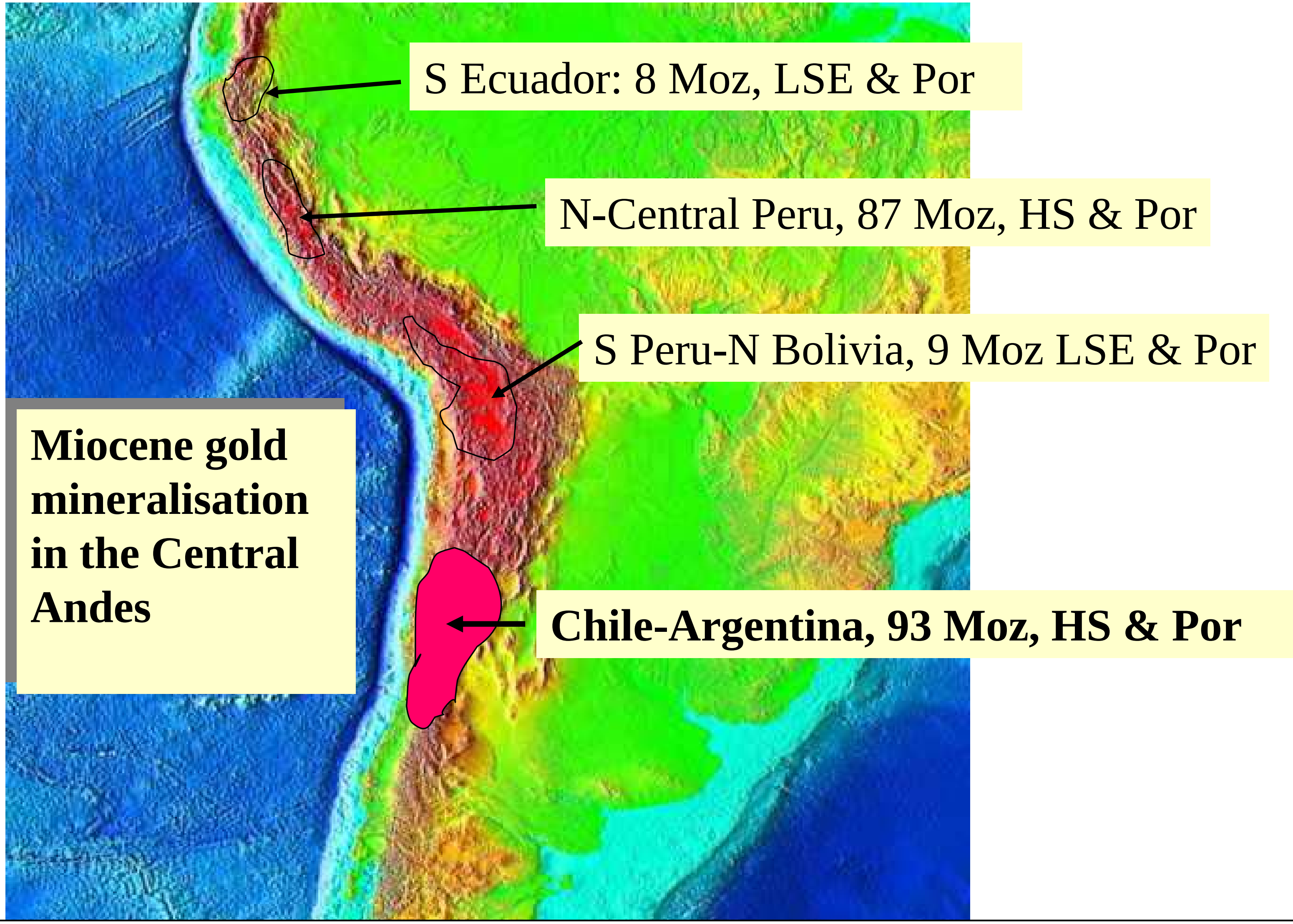
Slide 29: and more. A Pliocene volcano reveals the alteration in its eroded core (N Chile).



Slide 30: Arcata. This is a late Miocene epithermal Au-Ag mine, Arcata, in the CVZ of southern Peru. It shows the Baja vein, a low sulfidation Ag-rich vein with Au credits. Such deposits were mined by the Spaniards in the Colonial era, and remain in production today.

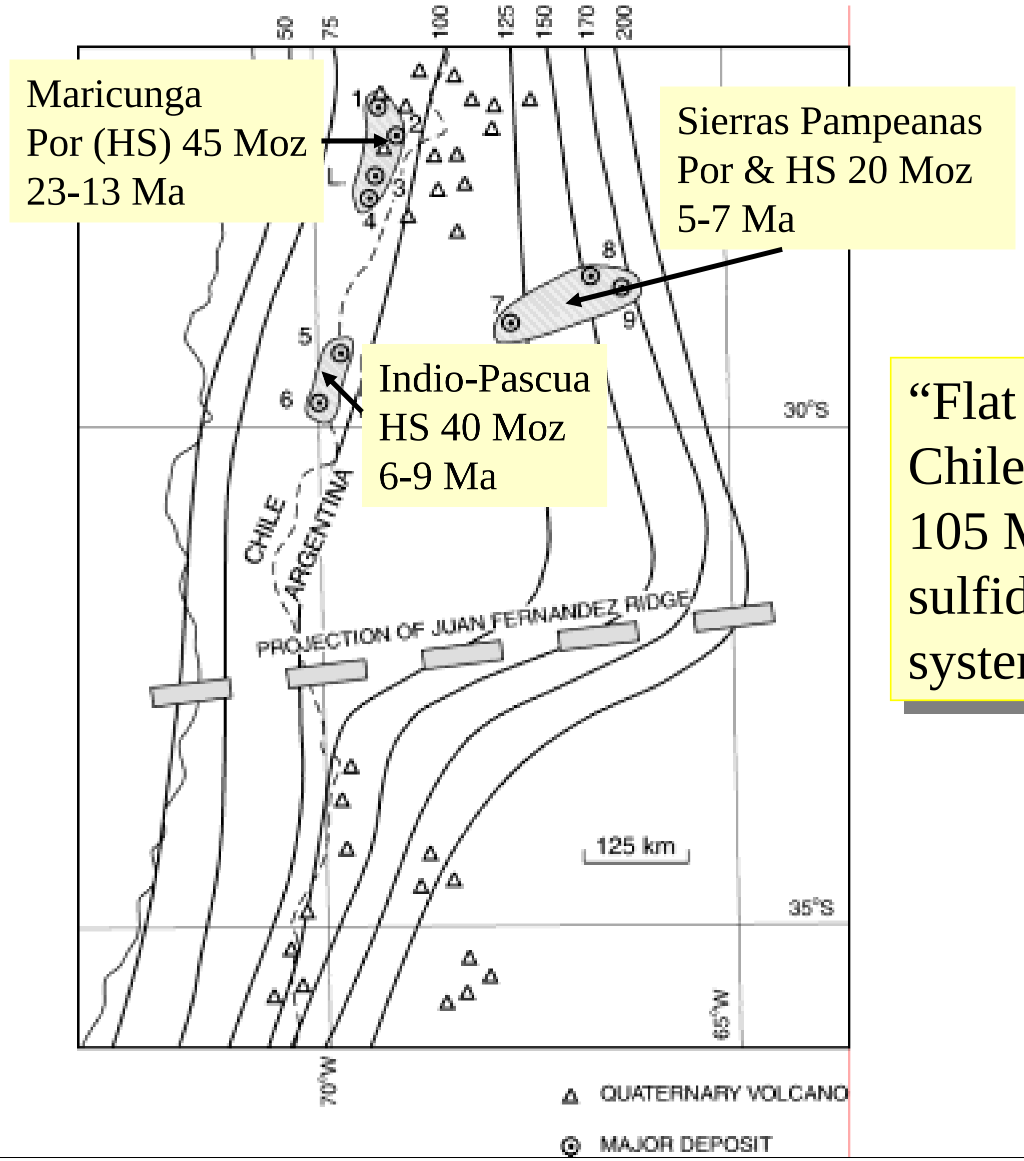
Slide 31: San Antonio de Lipez, Bolivia. Another low sulfidation Ag vein system in S Bolivia, mined by the Spaniards in the 16th century. The remains of the town and cathedral still exist, unfortunately ransacked and gutted.

San Pablo de Lipez epithermal silver deposit, southern Bolivia

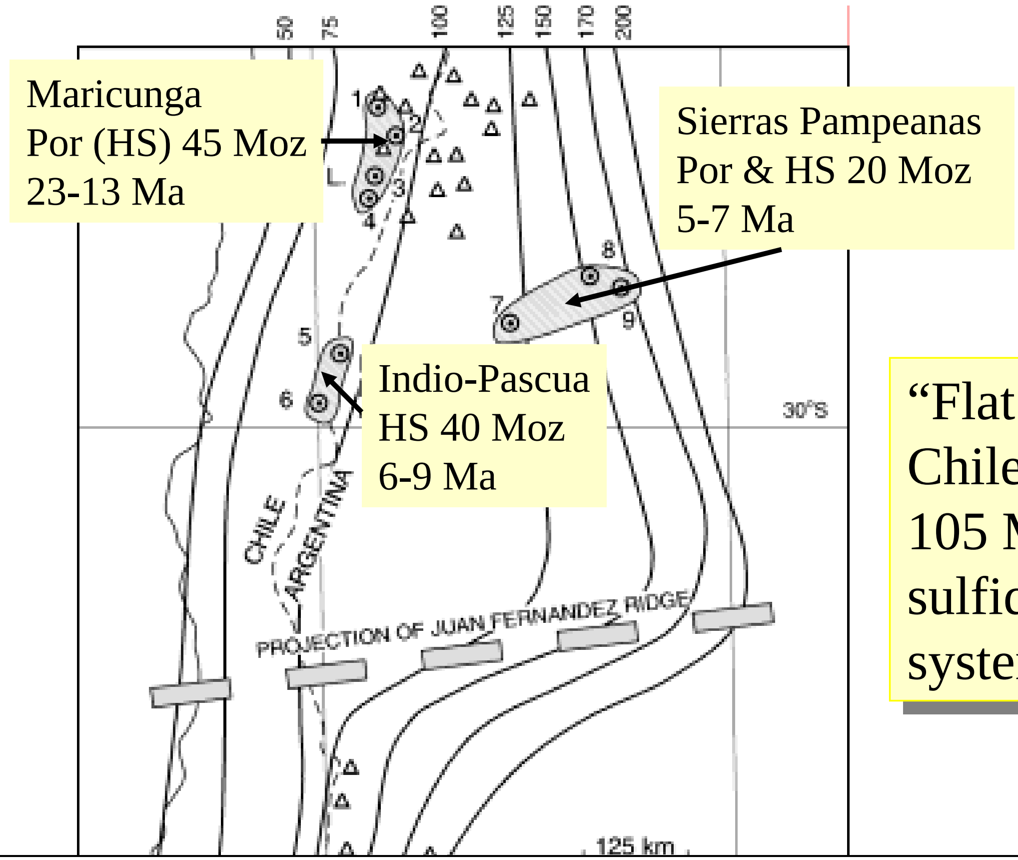


Slide 32: The flat slab region of central Chile and N Argentina. 93 Moz in Miocene HS and porphyry systems.

Shatwell, D., Subducted ridges, magmas, differential uplift, and gold deposits. Ishihara Symposium



"Flat Slab region of Chile & Argentina 105 Moz Au in high sulfidation & porphyry systems

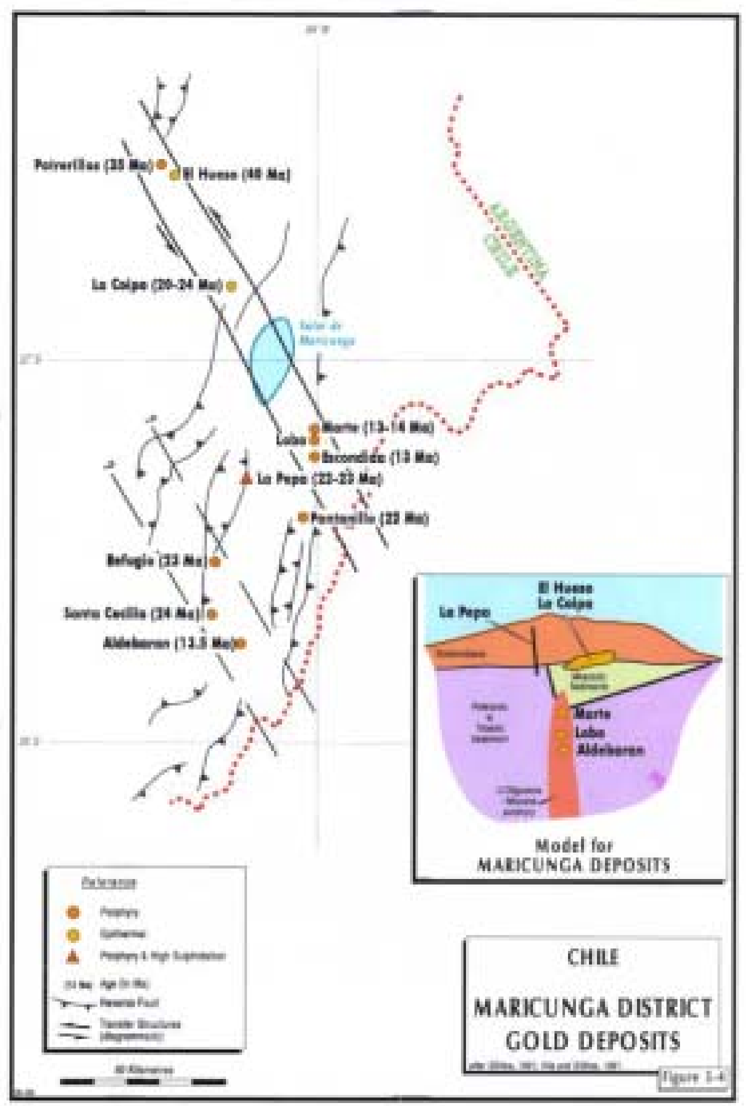


"Flat Slab region of Chile & Argentina 105 Moz Au in high sulfidation & porphyry systems

Slide 33: Subduction geometry and some deposit examples. The Juan Fernandez Ridge seems to form a discontinuity between flat subduction, to the N, and steep subduction, to the S. Gold deposits are concentrated in three regions:

- the Ag-rich high sulfidation La Coipa deposits and Au-rich porphyries of the Maricunga district in Chile (20-13 Ma)
- the El Indio-Pascua district on the Chile-Argentina border (9-6 Ma), and
- 7-5 Ma porphyry dominated systems in the Sierras Pampeanas. These include Bajo la Alumbrera (in production).

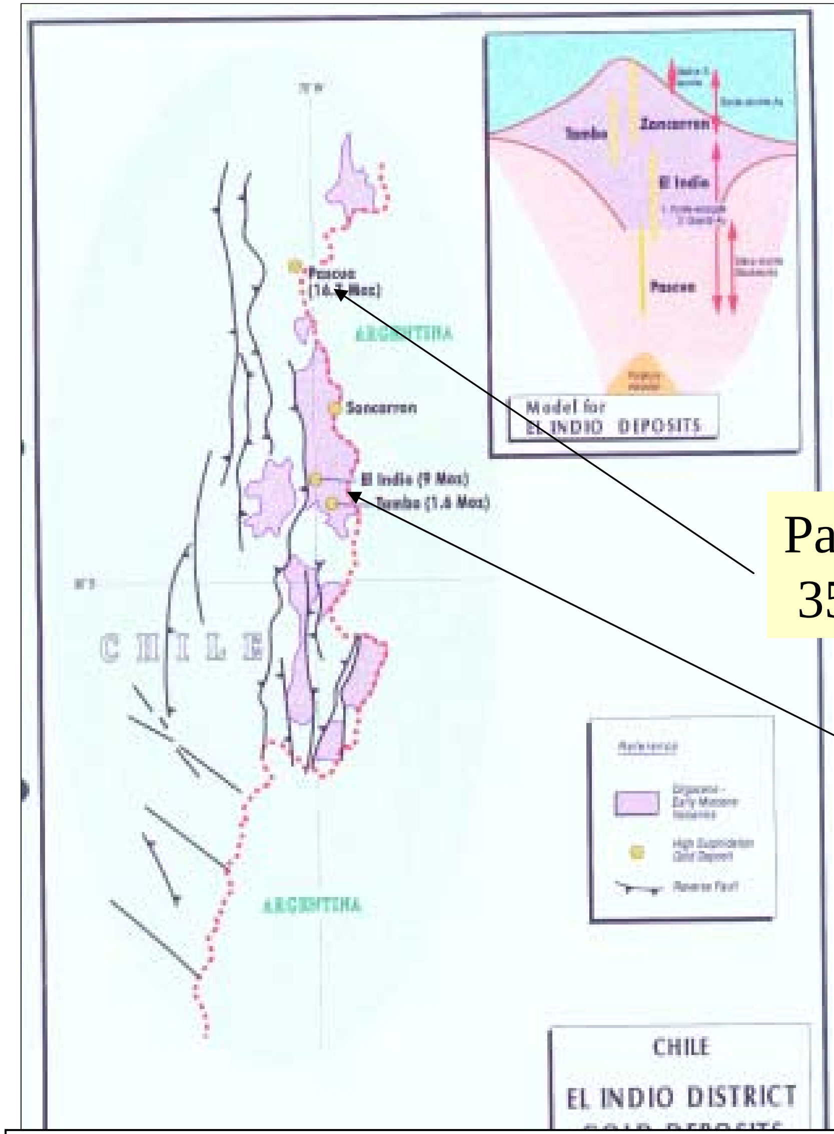
Slide 34: Maricunga district, Chile. Porphyry deposits contain 30 Moz Au, including Cerro Casale with 23 Moz. Only one of them, Refugio, has been put into production, the others remain on the drawing board.



Maricunga district, Chile

La Coipa HS - 23 Ma
Porphyries - 24-12 Ma
Total 34 Moz Au

Slide 35: La Coipa. Landscape shot near La Coipa, a commercially successful HS Ag-Au deposit in the northern part of the Maricunga district.



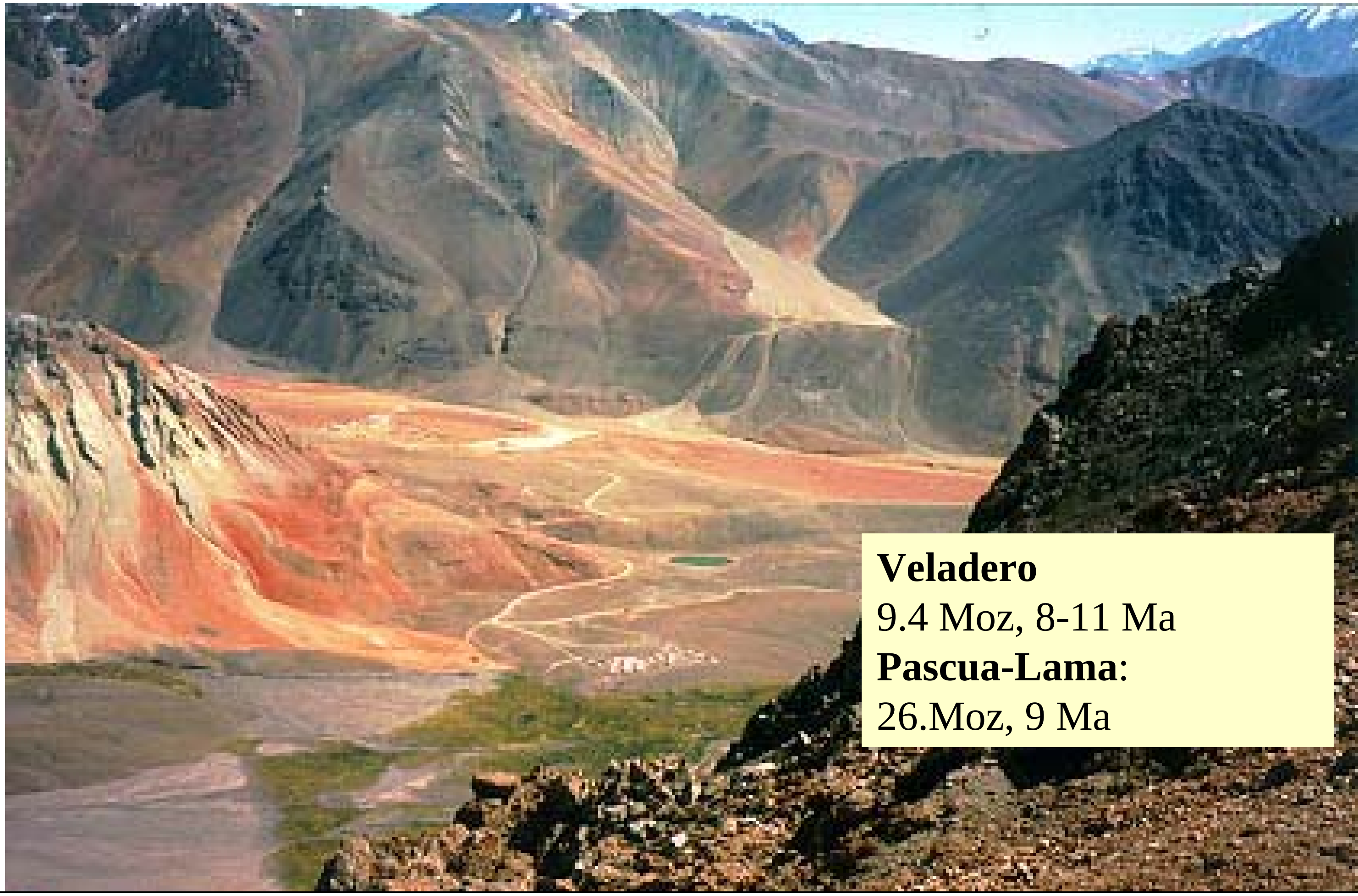
El Indio-Pascua HS District, Chile-Argentina: Deposit ages 9.5-6 Ma

Pascua-Lama-Veladero: 35.5 MOz

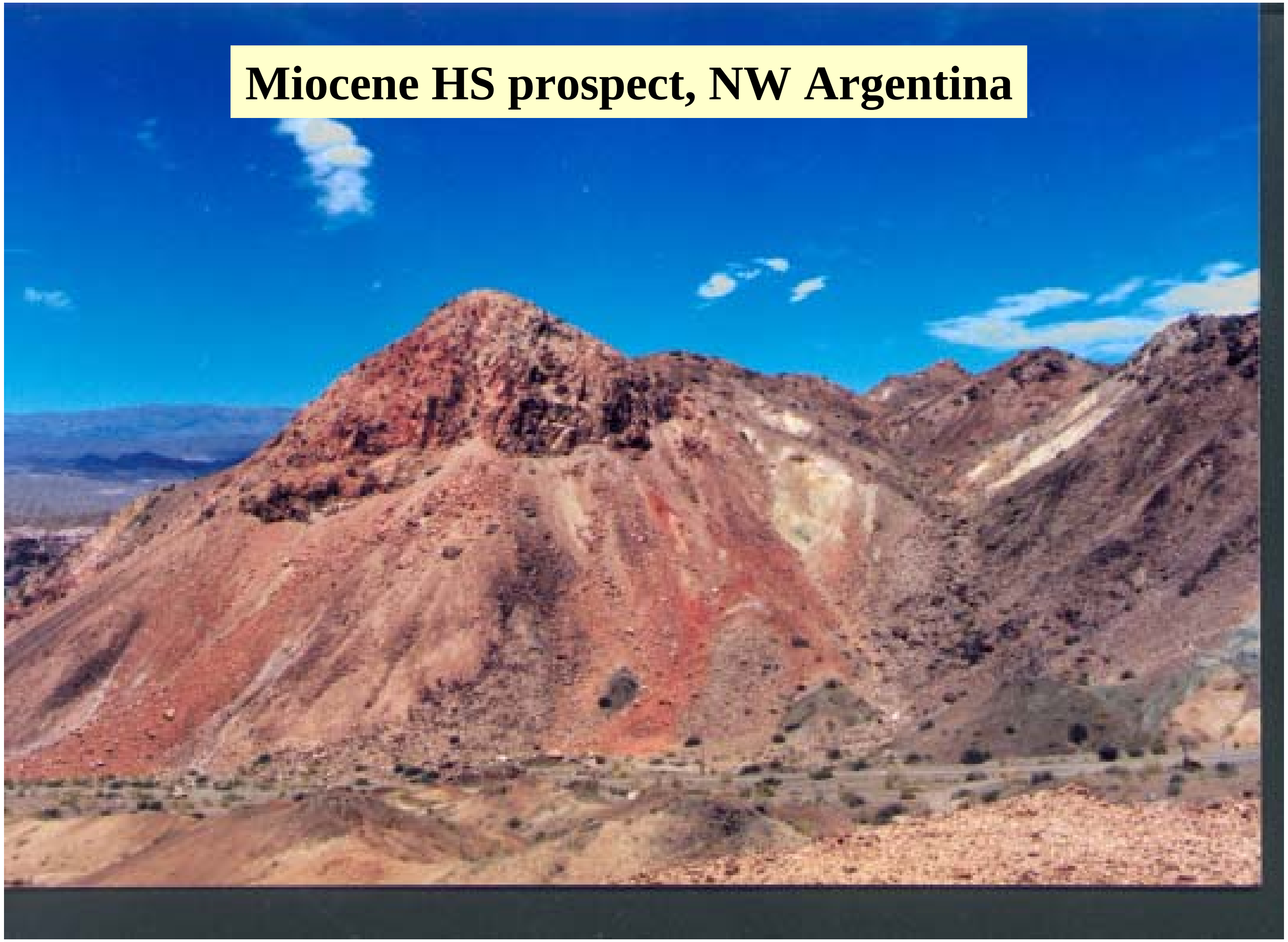
El Indio-Tambo: >5 Moz

Slide 36: El Indio-Pascua district. HS deposits include El Indio-Tambo, now closed, which produced 5 Moz Au plus Cu and Ag. The new projects are Pascua-Lama-Veladero, a 35 Moz HS district on the Chile-argentine border. All deposits are in the age group 9-6 Ma

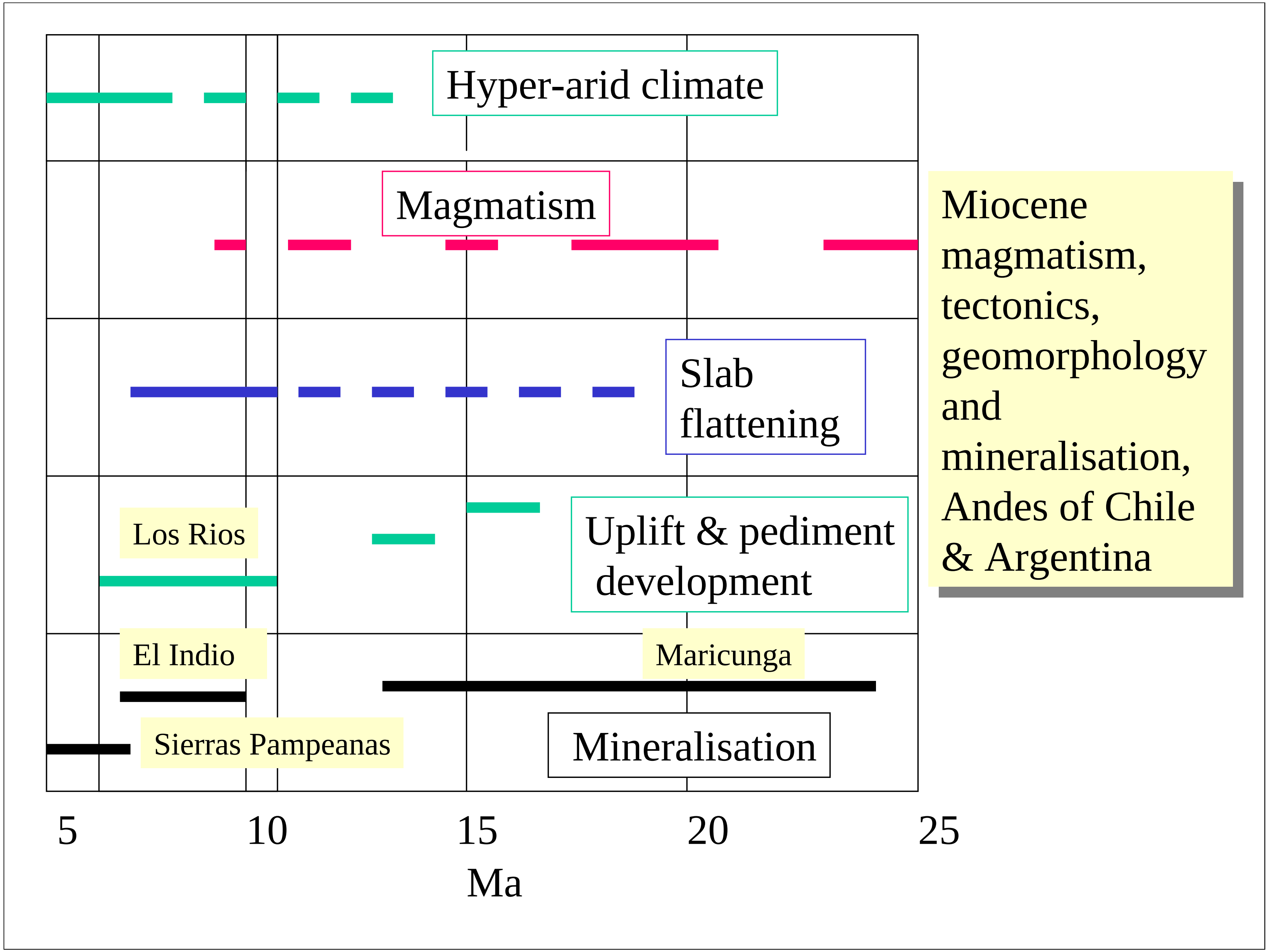
Veladero-Pascua-Lama high sulfidation district, Chile-Argentina

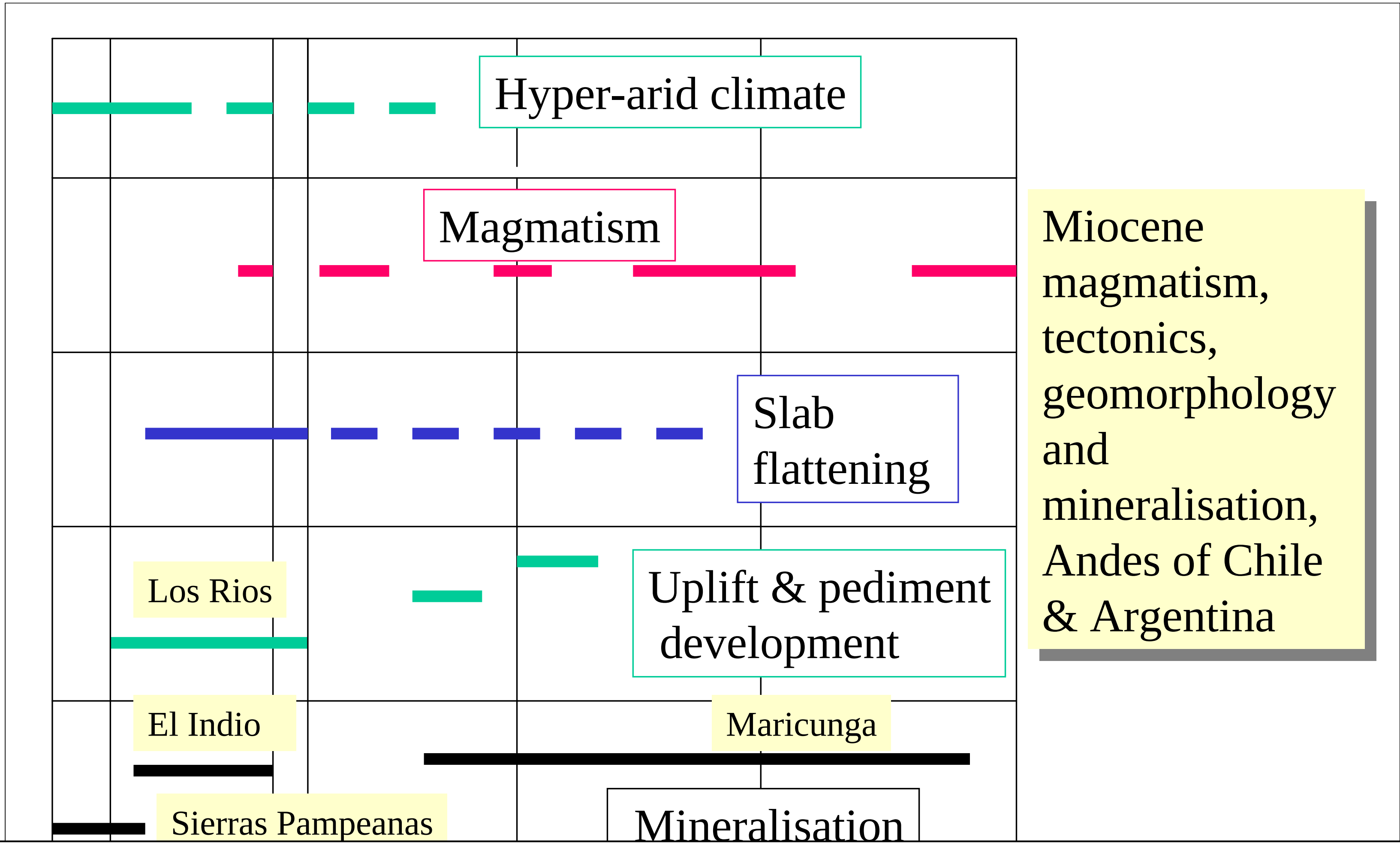


Slide 37: Veladero and Pascua-Lama. Landscape shot of the Pascua-Lama district, in the high of the Chile-Argentina border, taken from near Veladero.



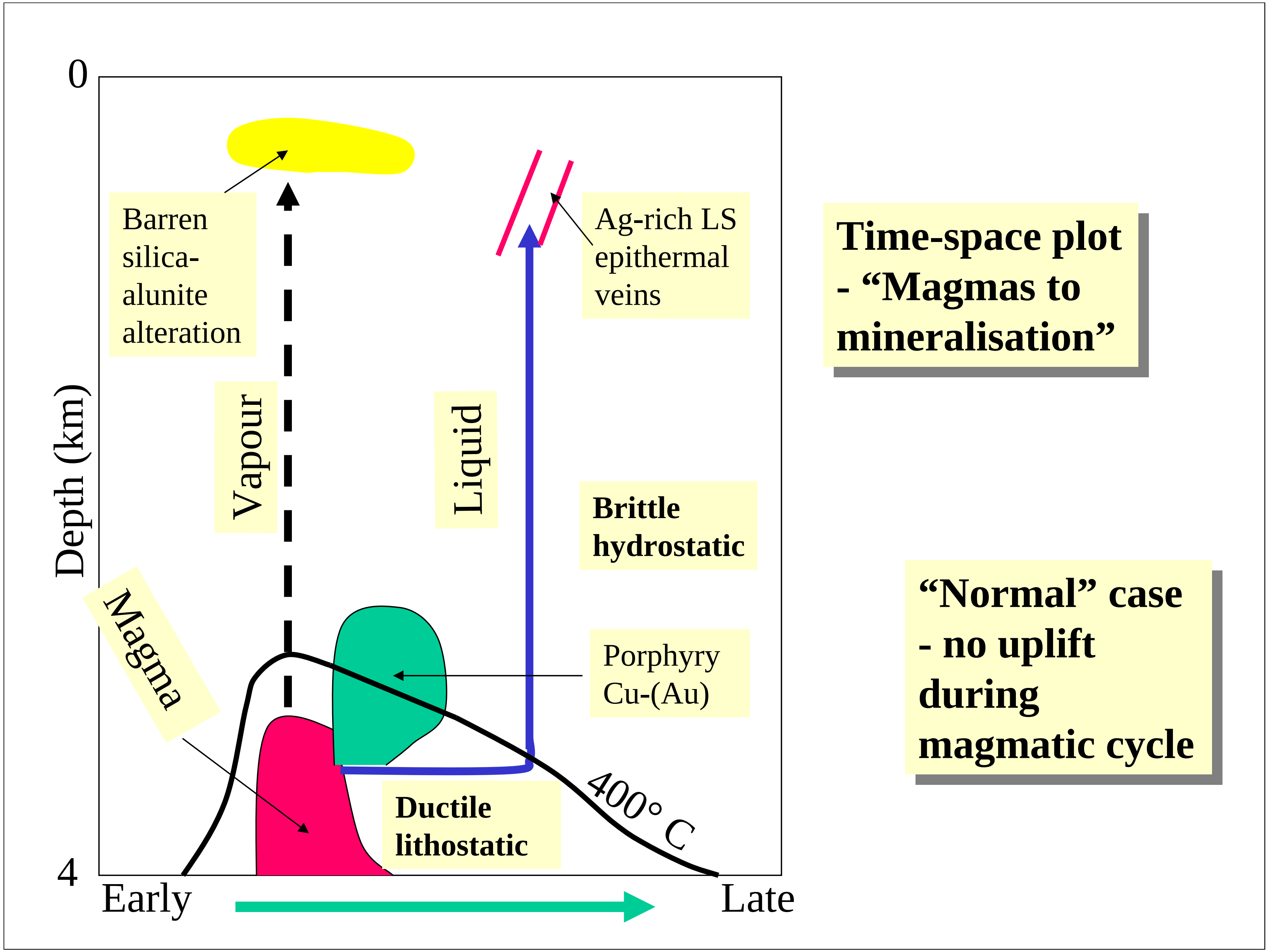
Slide 38: Castano Nuevo HS prospect. Another HS prospect in this part of Argentina – silica alteration and hypogene alunite.

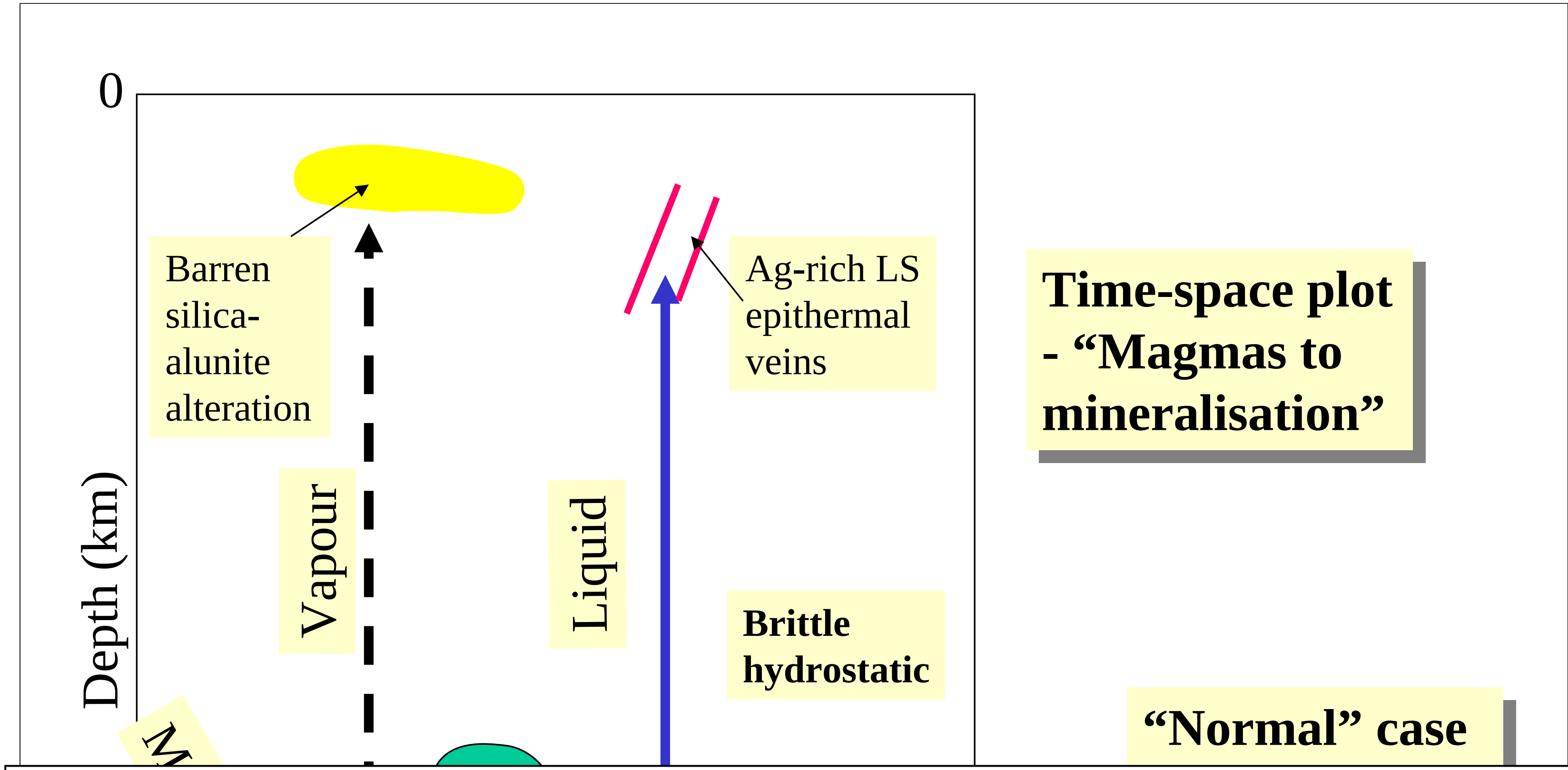

Hyper-arid climate
Magmatism
Miocene magmatism, tectonics, geomorphology and mineralisation, Andes of Chile & Argentina
Slab flattening
Los Rios
Uplift & pediment development
El Indio
Maricunga
Sierras Pampeanas
Mineralisation
5
10
15
20
25
Ma



Slide 39: Summary of events in the Chile-Argentina flat-slab region.

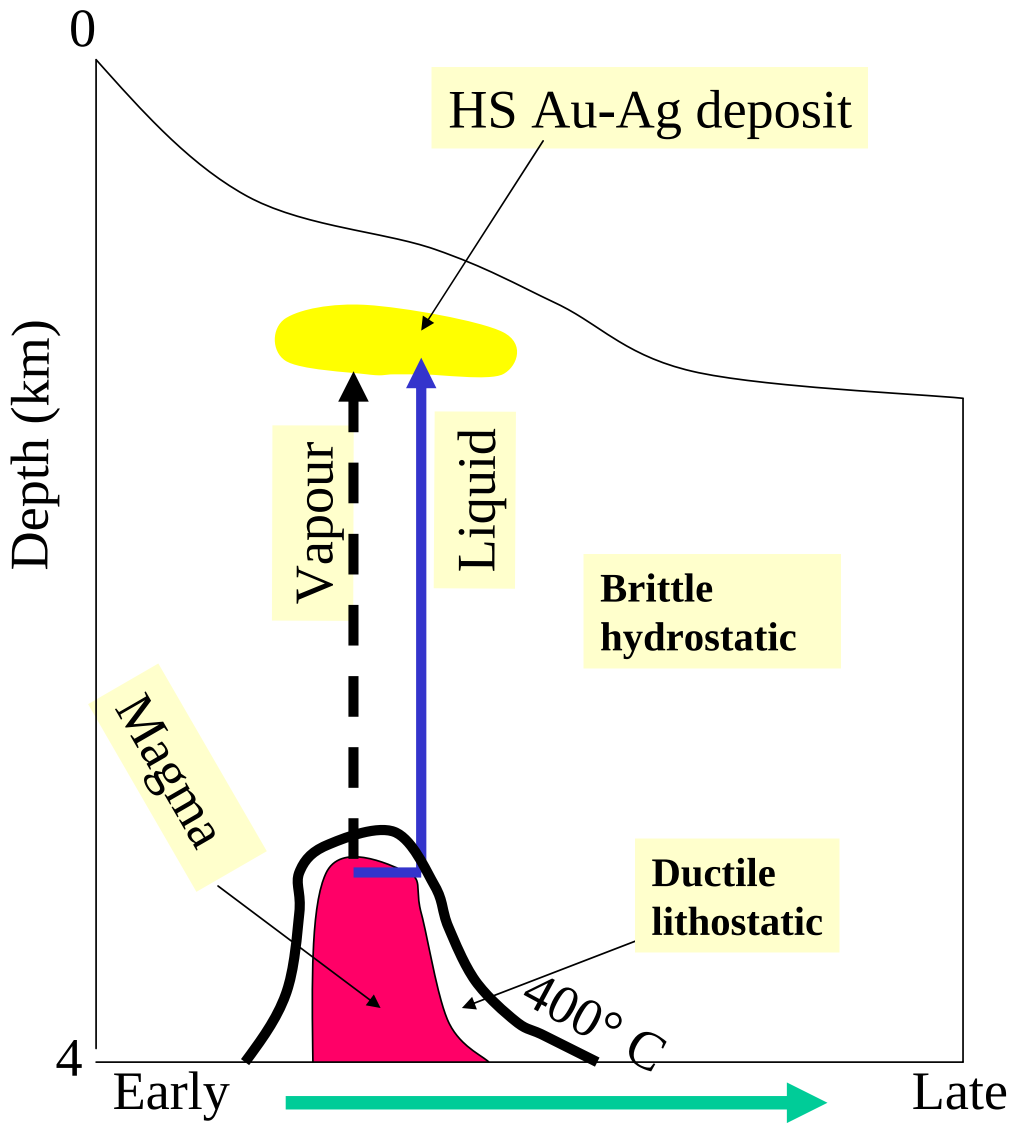
- Slab-flattening, 18-7 Ma, accelerated 11-7 Ma.
- Erosion surfaces 17-6 Ma – Los Rios surface 10-6 Ma.
- HS deposits 9-6 Ma
- Hyper-arid climate in the last 13 My?


0
4
Depth (km)
Early
Late
Barren silica-alunite alteration
Vapour
Magma
Liquid
Ag-rich LS epithermal veins
Brittle hydrostatic
Porphyry Cu-(Au)
Ductile lithostatic
400° C
Time-space plot - “Magmas to mineralisation”
“Normal” case - no uplift during magmatic cycle



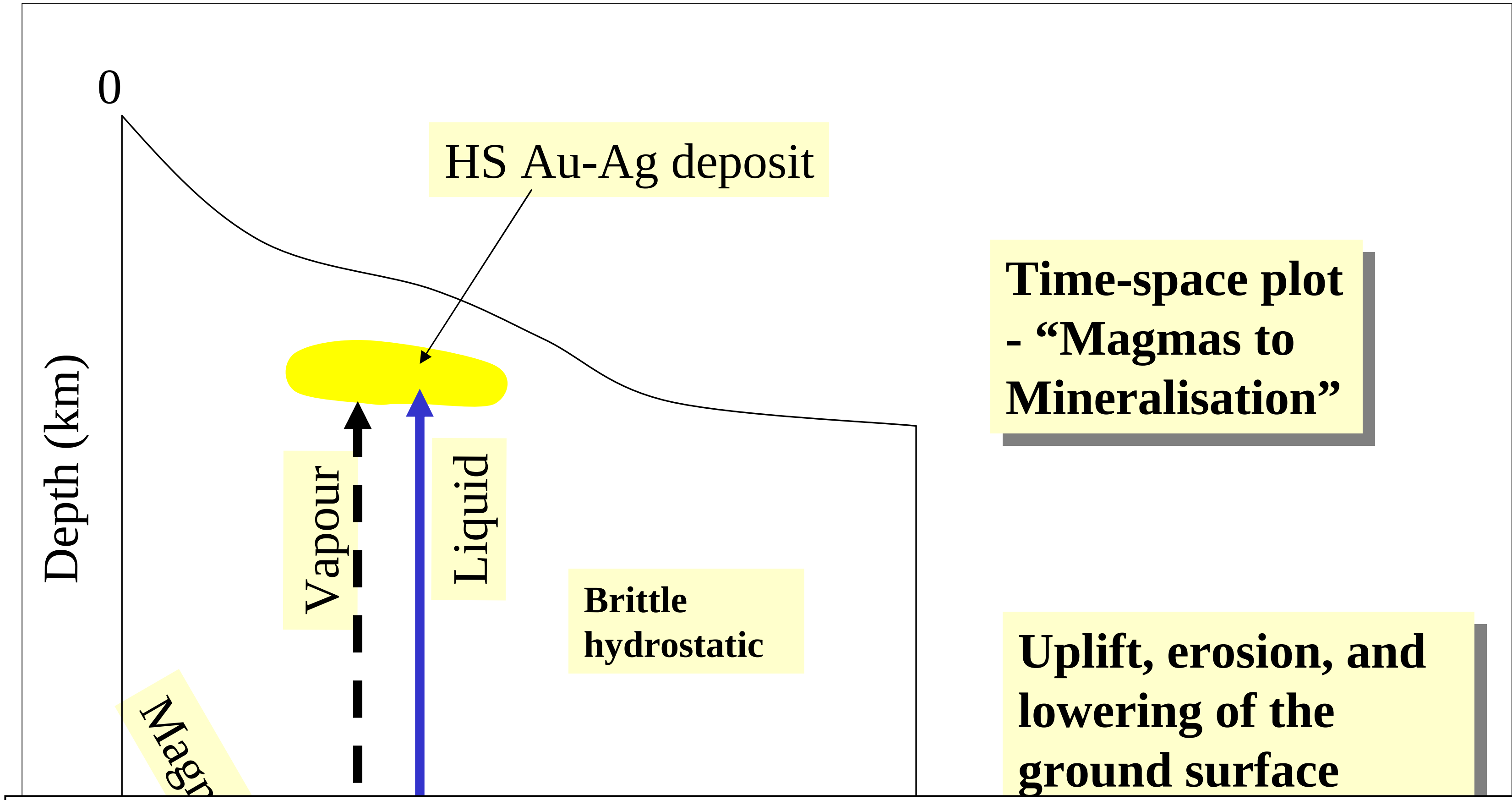
Slide 40: Possible mechanisms – the "normal" situation. There is an apparent coincidence between large HS gold deposits, ridge subduction, and specific episodes of uplift and erosion. This time-space diagram (based on one by Marco Einaudi) and the next one suggest a possible mechanism.

In this slide, a cooling magma (red) is intruded at a depth of a few km. The brittle-ductile boundary, at about 400 deg. C, is also a boundary between lithostatic (deep) and hydrostatic(shallow) pressure. A porphyry system (green) develops and a magmatic fluid separates, evolving a vapour phase. This vapour is able to pass across the brittle-ductile interface, and forms a barren, acid-stable alteration zone near the surface. The liquid phase remains at depth, and deposits most of its copper and gold content in the porphyry system. As the system cools, the brittle-ductile boundary collapses and the gold-depleted liquid rises into the epithermal environment, forming a distal, low sulfidation Ag ± Au epithermal deposit.



Time-space plot - "Magmas to Mineralisation"

Uplift, erosion, and lowering of the ground surface during the magmatic cycle



Slide 41: uplift and erosion. The slide shows the effect of rapid erosion during the cooling cycle of the magma. Rapid removal of overburden accelerates the lowering of the brittle-ductile interface and the transition from high lithostatic to low hydrostatic pressure. A liquid phase is able to "escape" from the system early, with most of its gold content intact, and form a high sulfidation deposit in the acid leached alteration formed by the vapour phase.

Rapid removal of overburden and lowering of hydrostatic head by any means, including sector collapse of an overlying volcano, can suck gold out of porphyry systems and deposit it at higher levels (eg the Lihir deposit PNG). Erosion as a result of ridge subduction seems to be another way this can occur.