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Tectonic Related Lithium Deposits Another Major Region Found North East Tanzania

—A New Area with Close Association to the Dominant Areas: The Fourth of Four

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Abstract

The current "mega" interest in Lithium resources was spurred by the development of Lithium-Ion batteries to aid in restructuring the world's reliance on carbon spewing power petroleum reserves. Current resources of lithium recovery have fallen into two main categories—Pegmatite, found worldwide associated with felsic intrusions and Brine Related, and now with development in the Southwest United States of America (SWUS), a third category—Tertiary Volcanic clays, are specifically associated with Tertiary volcanics and major Tectonic Plate interactions. "Active" Plate tectonics is important as both the SWUS, the Lithium Triangle of South America (LTSA) and the Tibetan Plateau of China (TPC) producing tertiary (Miocene) volcanism that is important to the development of Lithium resources. The Tanzanian part of the East Africa Rift System (EARS) has features of both the SWUS, tertiary volcanic related "playas" and Continental rifting, the LTSA, tertiary volcanic related "Brines" and a major Tectonic plate event (subduction of an Oceanic Plate beneath the Continental South American Plate) and the TPC, tertiary volcanics (?) and major tectonic plate event (subduction of the Indian Continental Plate under the Eurasian Continental Plate). As well as the association of peralkaline and metaluminous felsic volcanics with Lithium playas of the SWUS and the EARS (Tanzania) "playas". These similarities led to an analysis of a volcanic rock in Northeast Tanzania. When it returned 1.76% Lithium, a one-kilometer spaced soil sampling program returned, in consecutive samples over 0.20% Lithium (several samples over 1.0% lithium and a high of 2.24% lithium). It is proposed that these four regions with very similar past and present geologic characteristics, occur nowhere else in the world. That three of them have produced Lithium operations and two of them have identified resources of Lithium clay and "highly" anomalous Lithium clays should

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be regarded as more than "coincidental".

Keywords

Lithium Triangle of South America Southwest United States Tibetan Plateau of China East Africa Rift System Tectonic Continental, Oceanic Plate Subduction Tertiary (Miocene - Holocene) Volcanics Continental Rifting

1. Introduction

In late 2022, while returning from Moshi, in Northern Tanzania, we had a flat tire. While the driver fixed the "flat" with the assistance of a couple of locals, I had the occasion to look at the surrounding terrane and located a felsic looking volcanic rock that was related to the intense Tertiary volcanos located to the north, the tallest mountain in Africa, Mount Kilimanjaro and its east west sister volcanos related to the East Africa Rift System (EARS).

My interest was related to the current "mega" interest in Lithium and my experience in South West United States of America (SWUS) looking at the tertiary volcanic related "playas" that were currently being explored in great anticipation of developing the Lithium resource in the clays of those "playas". I had been in

Photo 1. "The Flat Tire".

Tanzania for two and a half years (mainly to avoid the Covid 19 epidemic, which was only minorly present in Tanzania, ravaging Europe and the Americas) and had often thought of seriously looking at these young Tertiary volcanic associated with the EARS, due to the Tertiary volcanic association I had seen in the SWUS.

This was also spurred by the comment in a paper by Yu-Long Li *et al.* *[1]*, attributed to my old University Professor Steven Kesler: "Interestingly, the principal lithium-rich salt lakes across the globe are found in continental arc-subduction zones or collision environments in arid latitudes, rather than salt lakes which developed in cratons and stable tectonic platform regions (Kesler *et al.*, 2012; …) [2]." The EARS Kilimanjaro area located on the equator of Africa fits this like a "glove", yet little to no analysis of this area had been done or reported.

The sample I took assayed 1.76% lithium, which confirmed that the Lithium association with Tertiary volcanics was valid here in Tanzania.

Undertaking additional sampling of the "downstream" playa from this sample, the Titan 1 prospect was revealed and sampling of additional "playas" identified in the area, identified Titan 2 and other playas of interest (**Figure 1**). This sampling done on very wide (1000 m) spacing returned values in consecutive samples of over 0.20% Lithium including several samples over 1.0% lithium

Figure 1. Location of titan prospects in northern Tanzania.

(with a high of 2.24% lithium).

With this very anomalous surface expression of Lithium, here in Tanzania, I was prompted to look at the current worldwide association of Lithium deposits (brines and Clays) and Tertiary volcanism. This short Article is my humble attempt using my own experiences and research of the current disposition of the three other areas of "Playa Associated" lithium deposits, the Southwest of the United States of America (SWUS), the Lithium Triangle of South America (LTSA) and the Tibetan Plateau of China (TPC)

2. Lithium Deposit Types

Current resources of lithium recovery fall into two main categories, Pegmatite related and Brine related, with development in the Southwest United States of America (SWUS) of the third category, Tertiary Volcanic clays (**Figure 2**).

Pegmatite related deposits/prospects are found worldwide mainly associates with Precambrian rocks (Greenbushes mine in Western Australia, various prospects in Canada, China and Africa) but also with Paleozoic rocks (The Appalachians in USA) so there appears to be no time age association with their presence.

Lithium Brines in SWUS, Lithium Triangle of South America (LTSA) and Tibetan Plateau of China (TPC) are specifically related to the tertiary volcanics associated with their areas. The Lithium clays are also specifically related to these tertiary volcanics.

Presently pegmatite mining operations in Australia, a tailings reclamation operation in Brazil, and both pegmatite and brine extraction operations in Argentina

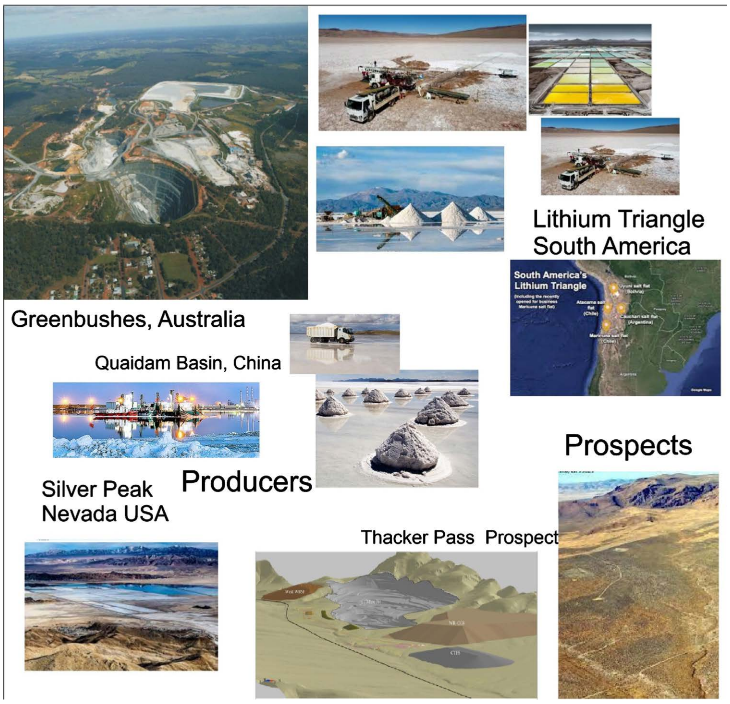

Figure 2. Producers and prospects of lithium ore.

and Chile, and China account for more than 95% of global Li production (Table 1). Additionally, brine operations in the SWUS, additional pegmatite operations in other countries and recovery from the petroleum industry make up the remaining < 5%.

The Worldwide resources identified by the USGS which includes the producing operations above and also the potential of the Lithium Clays is 98 million tons. Brines hold the dominant position with 52 million tons (Bolivia, Argentina, Chile and China), with over 30 million tons, pegmatites is the other source (Australia, China, Europe and the rest of the world) but significantly another about 10 million tons is identified with Clay hosted resources in the USA (total US resources are listed as 12 million tons from “continental brines, claystone, geothermal…[and]oilfield brines and pegmatites” [4] has been adjusted by the author’s knowledge of the Thacker Pass and other Prospects in the SWUS).

The significance of the Clay Lithium resources is that the US has basically surpassed Chile, China and Australia in identified resources. Currently there is significant exploration being carried out in the SWUS through the States of Utah and Nevada looking for these types of deposits. The technology to develop them is available and the advantages of producing a Lithium Carbonate Equivalent (LCE) from the clays suggest that these deposits will become part of the Lithium supply chain in the near future.

When looking at the resources of the world, the Brines of the LTSA are a significant reservoir, when the potential of the Lithium clays is integrated, their potential will be close to if not in excess of two thirds of the world resources. These

Table 1. Worldwide reserves and resources of lithium [4].

Rank	Country	2021 Production (tonnes)	% of total	2023 Reserves (‘000 Tons)	Rank
#1	Australia	55,416	52.2%	7900	5
#2	Chile	26,000	24.5%	11,000	4
#3	China	14,000	13.2%	6800	6
#4	Argentina	5,967	5.6%	20,000	2
#5	Brazil	1,500	1.4%	730	16
#6	Zimbabwe	1,200	1.1%	690	17
#7	Portugal	900	0.85%	270	19
#8	United States	900	0.85%	12,000	3
	Rest of the World	102	0.10%	38,610	
	TOTAL	105,984	100%	98,000	

Bolivia in the #1 position in Resources has no Production. Germany, Congo, Canada (Reserves ranked #7, #8, & #9) have minimal or no production (included in the rest of the world) (100% in rest of the World is due to rounding up).

two categories have two commonalities, the association with Tertiary volcanics and major Tectonic Plate interactions. They have one major production advantage, they produce LCE directly from their “ore”.

The Brine “Lakes” of TPC although not as directly linked to the Tertiary Volcanics as the SWUS and the LTSA are majorly linked to a Tectonic event (the “subduction” of the Indian Plate under the Eurasian Plate) and share the production advantage.

Pegmatites will remain a significant source, due to their wide spread location and association, pegmatites are associated with felsic intrusives which are “prepared” to intrude any age strata. However, they only produce a “concentrate (of lithium bearing minerals, mainly spodumene)” which requires significant processing to extract the lithium for the LCE final product.

Technical Note: In the following sections I delve deeply into the characteristics of the SWUS. Mainly this is a reflection of my experience and that the amount of research and papers on that area dwarf what is available on LTSA, TPC and Tanzania. However, there are similar geological features identified that are/could be present in the other three areas, but will leave that to the reader to determine. Further details that emerge can assist in our understanding of the connections of these four regions.

3. The Tanzanian Situation

Northeastern Tanzania has abundant volcanic action that is not only Tertiary but present (Mount Kilimanjaro, Meru, Ngorongoro, See **Figure 3** for detail) with the African continent’s only active volcano, Oldoinyo Lengai, located about 200 km west of Kilimanjaro. What is also significant about this volcano (last activity June of 2017 which deposited ash up to 48 km distance) is that it is a natrocarbonatite. Natrocarbonatites have high lithium content (211 - 294 ppm) and the lithium mica Taeniolite [5].

Of significant note is that the Sadiman Volcano geology (dating is questionable but greater than 1.7 million years is pretty well confirmed) is reported to be similar to the Oldoinyo Lengai [6]. This suggests that the natrocarbonatite volcanism and its associated Lithium content has been occurring over a long period of the development of the East Africa Rift System (EARS).

The area of the Kilimanjaro volcanos is right on and astride the equator, although lush and green around the volcanos and the Arusha-Moshi area, there are areas to the south and west that see little rainfall and have year-round high temperatures. The famous Serengeti Plain is 250 km to the west.

Geologically being part of EARS, the area has two major geologic “units”. The Tertiary volcanic and the Cambrian Mozambique metamorphic belt (MMB). The east limb of the EARS trends south west along the east side of the Lake Victoria Precambrian Craton dying out after about 200- 300 kilometers. However, a “sister rift”, the Pangani Rift, trends south from Mount Kilimanjaro into the Indian Ocean between Madagascar and Mozambique (**Figure 4**) [7] [8].

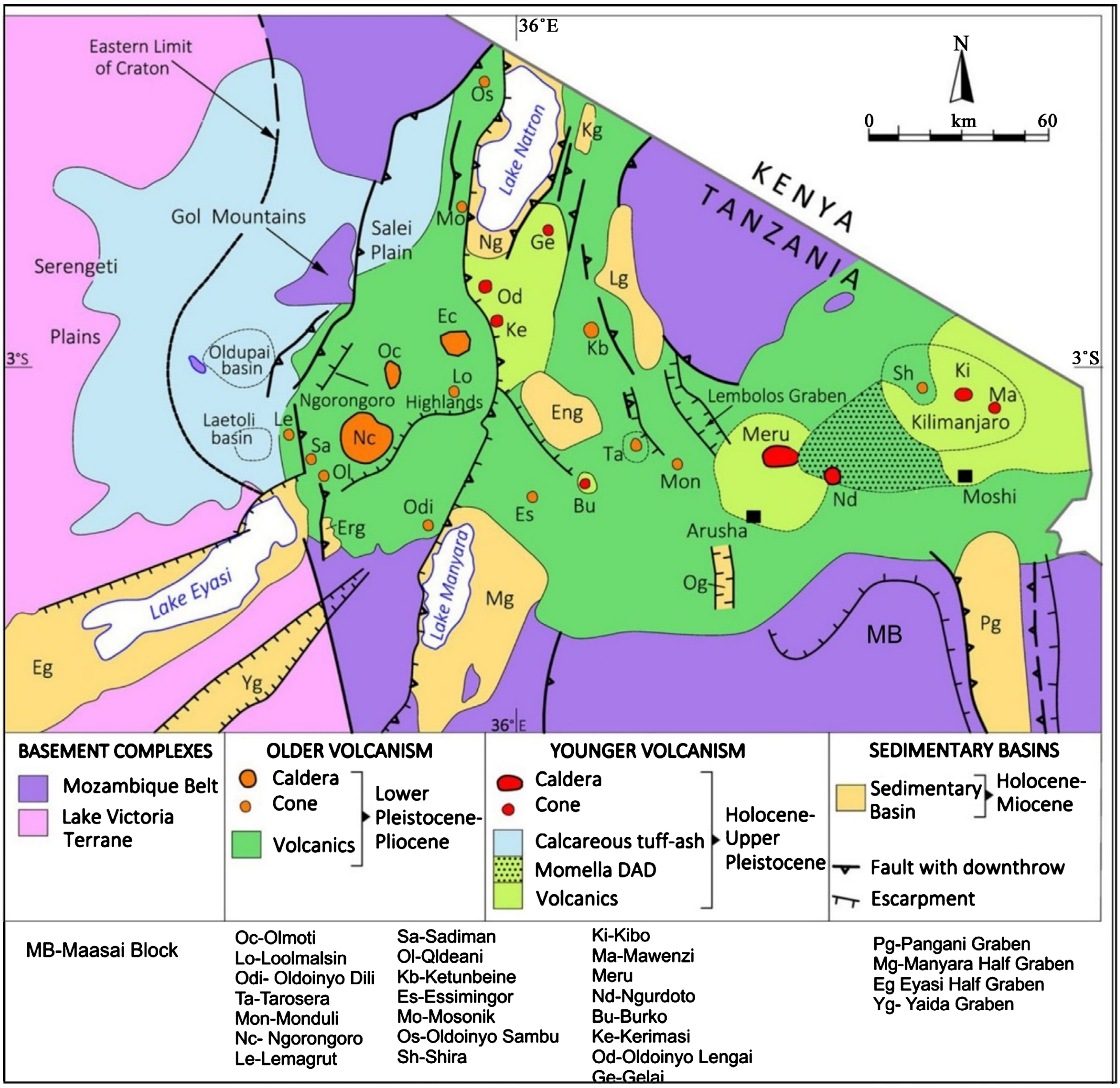

Figure 3. Volcanic province of north east Tanzania (after Scoon 2020) [7].

These rift systems don't add any geological units but represent active and significant structural formations to the Mozambique Metasediments.

The EARS represents the only active continental rift system in the world and has been "speculated" to be opening a new "ocean" as it splits the African continent in two (Albeit in a few million years ± a few million!).

The Pangani Rift separates the Pare Mountains (MMB to the east) from the Maasai Block (a Plateau of MMB to the West) and according to the plate tectonic theory, sits above an uprising Mantle Plume (as evidenced by the Kilimanjaro Volcanics). Dating work has outlined that the Kilimanjaro volcanic belt is younger as it goes east, suggesting the main African continental plate is moving west. While the Somalia Plate is proposed to be moving east away from the African plate, creating the "new" continent and ocean, the Volcanics' aging, younger to the east (**Figure 5**) suggests either that both plates are moving westwardly or the Pangani Rift is now the "new" margin of the African Plate.

In support of that suggestion is that the southwest arm of the EARS, abutting the Lake Victoria (Tanzania) craton appears to be inactive and does not continue much farther south, whilst the Pangani Rift continues to the south southeast through Zanzibar Island and into the Indian Ocean between Madagascar and Mozambique on the African Coast (**Figure 4**).

This "active" Plate tectonics is important in our discussion as both the SWUS, the LTSA and the TPC areas were and/or are active continental Plate margins. These active Plate margins have produced tertiary volcanism that in the SWUS and LTSA is extremely important to the development of Lithium resources. In the TPC the tertiary volcanism association is less obvious however a study by Li Yu-Long *et al.* [1] shows an association with Lithium and the surrounding felsic volcanic, is present.

Our sampling, to date has indicated some of the highest Lithium values found in soil sampling (mainly compared to the SWUS, as most of the data from the LTSA is brine related with few reported soil samples). These high values could be due to the natrocarbonatite volcanism reported above.

Our research has identified possible MMB units on the edges of these rift structures that are carbonaceous and could be, in conjunction with the rifting, adding material to the magmas feeding the recent volcanic action (**Figure 6**) [9] [10].

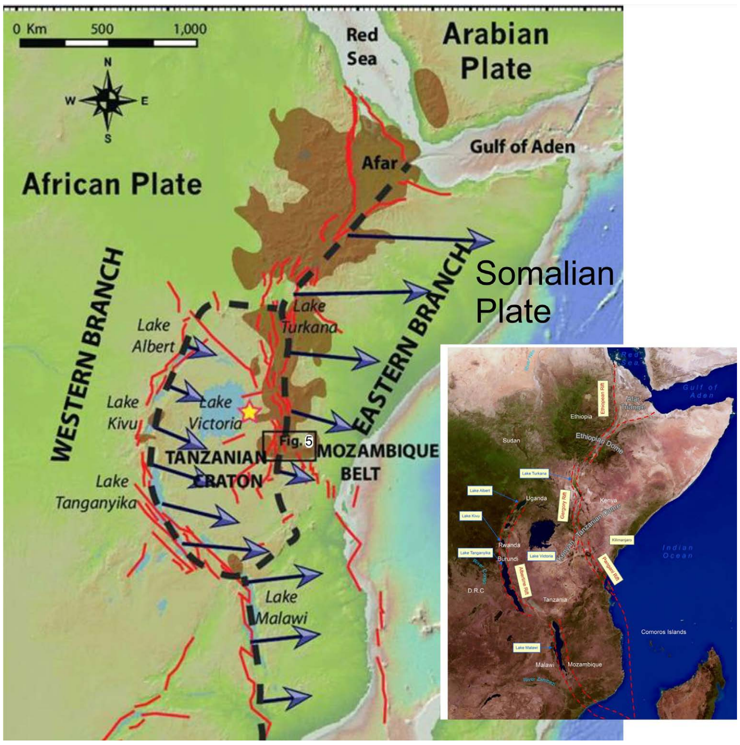

Figure 4. The East Africa Rift System (EARS) (after Mana *et al*; and Scoon) [7] [8].

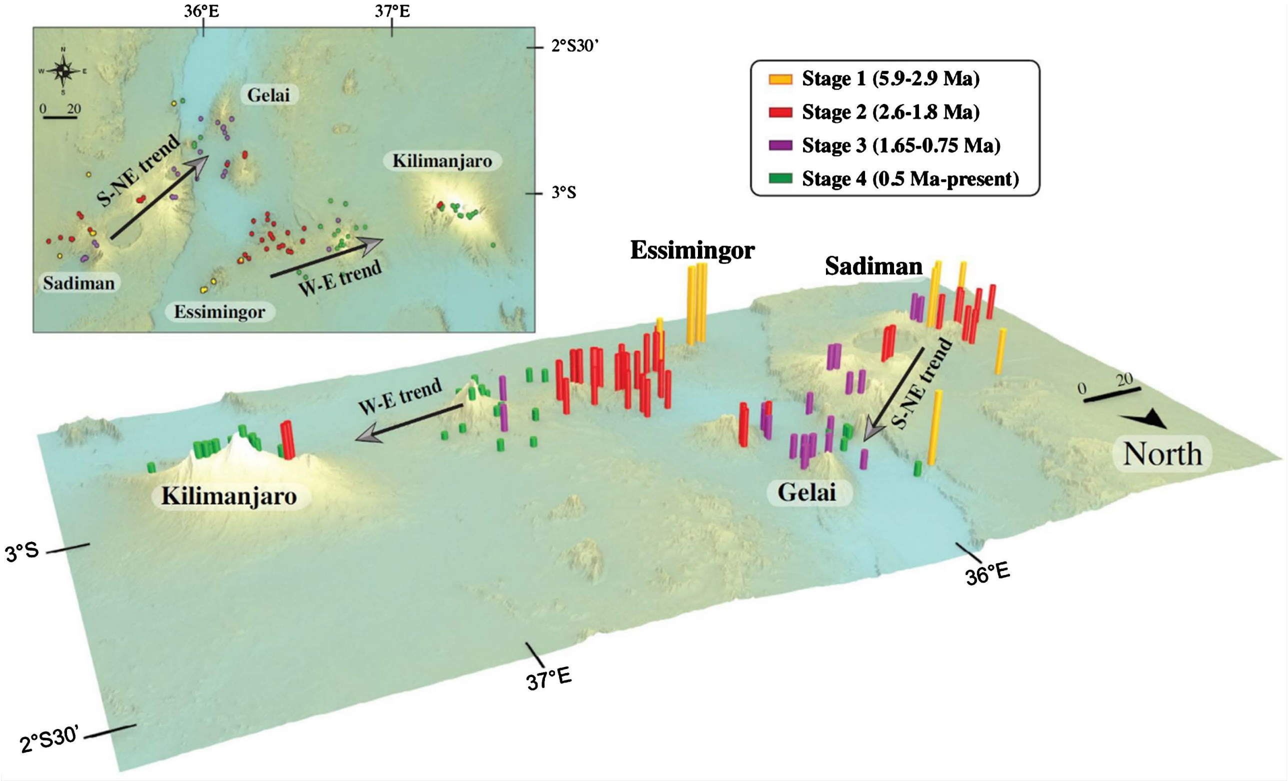

Figure 5. The aging of the volcanos in North East Tanzania (After Mana *et al.*) [8] [9].

4. The South West United States Situation

The SWUS area is located in the Great Basin and Range Geologic Province of Nevada and Utah, approximately 400 to 650 kilometers east of the active plate tectonic boundary of the North American Plate and the San Juan Plate [11]. However, as reported by the US Department of the Interior "The topography of the Basin and Range Province and Rio Grande Rift reveals the full range of characteristics of a continental rift zone" [12].

In Nevada, defined by aeromagnetic surveys, the north-northwest-trending northern Nevada rift zone extends for at least 500 km from southern Nevada to the Oregon-Nevada border (**Figure 7**) [13]. In fact, rifting has occurred episodically in the western United States from the Precambrian to the Cenozoic. Speculation concerning Precambrian rifting has focused on the possibility of major continental rifts about 1450 mya and 900? to 650 mya ago. During the late Cenozoic, extensional faulting produced one of the world's most widespread regions of continental rifting that extends from the United States southward into northern Mexico, a distance of 1500 km [14].

This is of interest in that the 3500 km long EARS system could be an analogous current representation of this "ancient" continental rift system.

This northern Nevada rift is (along with the Columbia River flood basalts in northern Oregon) considered to be part of an enormous lithospheric rift that propagated rapidly south-southeast and north-northwest, respectively, from a central mantle plume [14]. This is part of the "mechanism" that is theorized to

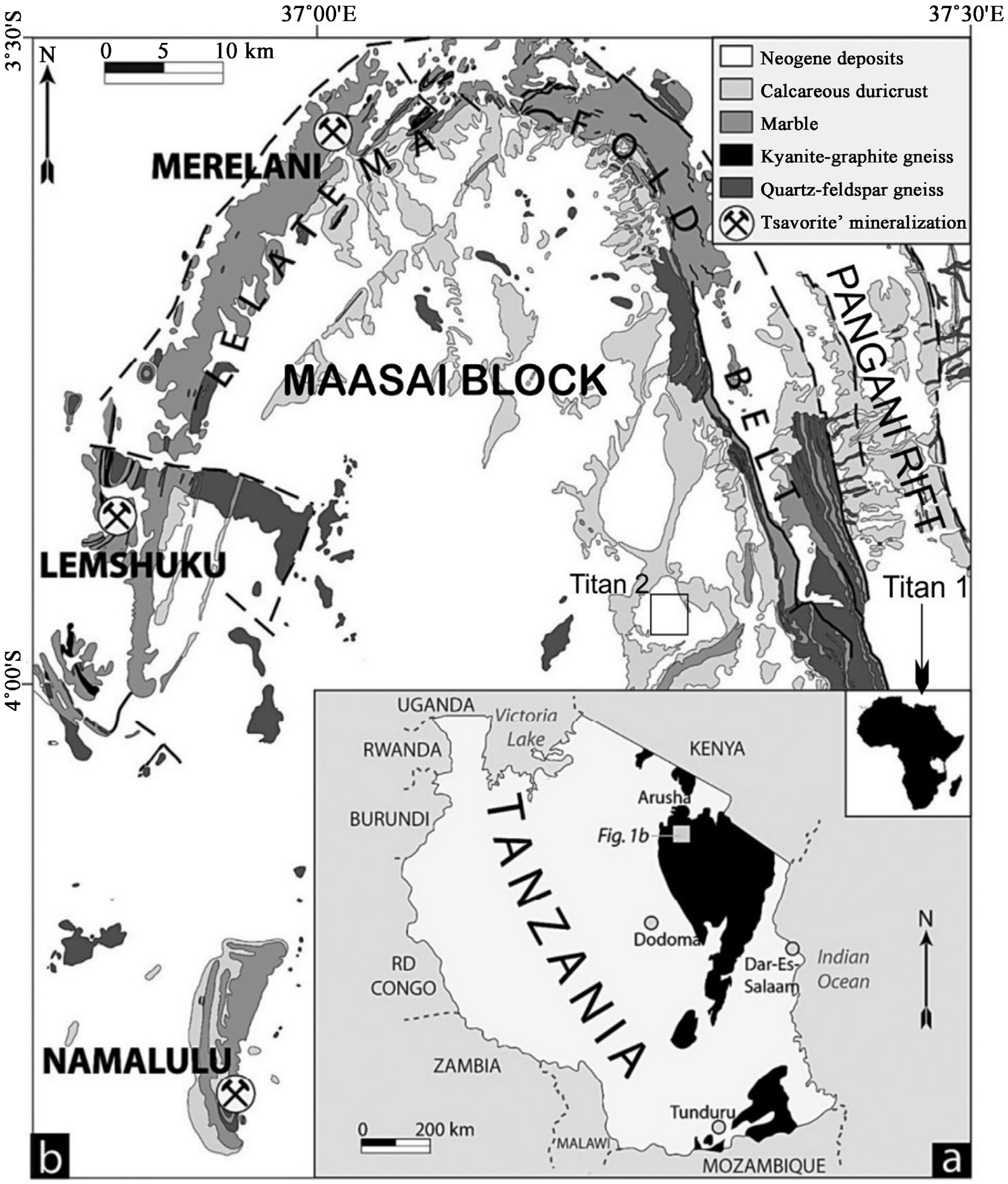

Figure 6. (a) Location of Neoproterozoic metamorphic Mozambique Belt [MMB in text] (in black) in Tanzania (After Pinna *et al.* 2004). (b) Geologic map of the Lemshuku, and Namalulu (modified after Grainger 1964, Macfarlane 1965, unpublished Quarter Degree Sheet a'87 from the Tanzanian Geological Survey) [9].

be behind the EARS (In my research into the TPC there was mention of some "flood Basalt" areas, but I did not follow up on their association).

The tectonic significance of the rift is dramatized by its length, its coincidence in time, 17 and 14 Ma., and space with the oldest silicic caldera complex along the Yellowstone hotspot trend, and its parallelism with the subduction zone along the North American coast prior to the establishment of the San Andreas fault [12]. The subduction association becomes more relevant when we look at the LTSA area which is a more "recent" possible representation. The TPC area

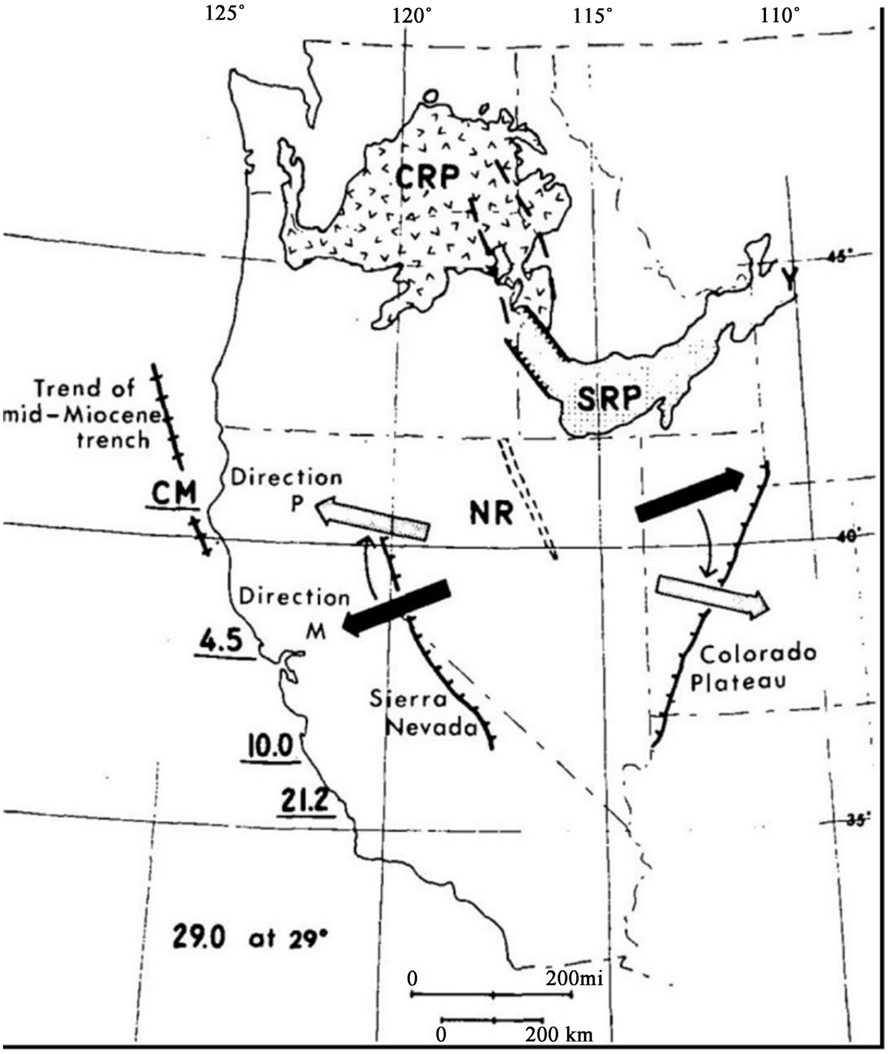

Figure 7. Map of Western United States of America Showing the Mid-Miocene (M) and the present (P) extension direction. CRP= Columbia River flood basalt province, SRP = Snake River Plain, and Y = Yellowstone National Park. Northern Nevada Rift (NR) is outlined by short dashes. Dates (In millions of Years before Present) off coast of California mark the Location of Mendocino triple junction (Atwater and Molnar 1973). CM = Cape Mendocino, Present location of triple junction. Chief Joseph dike swarm is shown approximately by Dashed Lines (From Zoback *et al.* 1994) [15].

subduction is a little more complex as it is Continental to Continental collision but there appears to be a general consensus that the Indian Continental Plate is being "subducted" to the Eurasian Continental Plate (why else would it give rise to the highest mountain range in the world?).

Stewart in 1978 [14] outlined four theories relate extension due to this continental rifting as: 1) oblique tensional fragmentation within a broad belt related to the development of the right-lateral San Andreas transform fault system; 2) upwelling from the mantle behind an active subduction zone (back-arc spreading); 3) subduction of the East Pacific Rise; 4) mantle plumes. Although the first is unique to SWUS, the second, third and fourth would be generally applicable to the LTSA and the upwelling of the second and the fourth to the EARS. All appear to present in the TPC.

This middle Miocene rift of Northern Nevada is important in that the 16.39 ± 0.02 Ma, the McDermitt caldera collapse structure, along the Nevada-Oregon border is located within it. The McDermitt caldera is commonly considered the point of origin of the Yellowstone hotspot [16]. It would be analogous the "younger" Ngorongoro Crater of Tanzania 250 km west of Mount Kilimanjaro on the EARS.

This, "north end of the rift", McDermitt Caldera hosts Lithium America's Thacker Pass Lithium Clay deposit. This multi-billion-dollar project is projected to produce 40,000 tonnes of LCE annually over its 40-year mine life [17].

Exclusively mafic magmas erupted initially. Rhyolite lavas erupted as early as 16.69 Ma, increased steadily until eruption of the McDermitt Tuff. Pre-caldera silicic activity was diverse and almost entirely effusive, including metaluminous to mildly peralkaline, with metaluminous to peraluminous biotite rhyolite lavas and domes emplaced around what is now the caldera wall in four areas. Eruption of the McDermitt Tuff generated the irregularly keyhole-shaped caldera. Collapse occurred mostly along a narrow ring-fault zone of discrete faults with total collapse no more than similar to 1 km, and total erupted volume was similar to 1000 km^3 of which 50% - 85% is intracaldera tuff. Tuffaceous sediments as much as 210 m thick filled the caldera, numerous hydrothermal systems probably related to caldera magmatism produced Hg, Zr-rich U, Ga, and minor Au mineralization. Lithium deposits formed throughout the intracaldera tuffaceous sediments [18].

A study by Macdonald *et al.* [19] identified a central Kenya peralkaline province comprises five young (<1 Ma) volcanic complexes. These volcanos are part of the EARS, north of Tanzania. In the study they outlined the presence of peralkaline trachytes and metaluminous trachyte.

Our research supports the idea that these rock types should be present in the Tanzanian volcanos of the EARS. Similarly, the comenditic rhyolites found in Kenya, that are thought to have formed by volatile-induced crustal anatexis is consistent with our speculation of the composition of Tanzanian Volcanos (See **Figure 6**).

In Tanzania, the involving up to "tens of cubic km of magma" related to these small centres is consistent with the McDermitt total "erupted" volume especially from the main Kilimanjaro-Ngorongoro Volcanic belt.

Farther south along this Nevada Rift, is located the Silver Peak volcanic center, 4.8 to 6.1 m.y. Along the margins of the range, they overlie and interfinger with the various sedimentary sequences. The sedimentary rocks range in age from late Miocene to late Pliocene. The oldest rocks in the Esmeralda Formation are 13.1 mya and an air-fall tuff in the upper part of the section is 4.3 mya [20] [21] [22].

This complex history of late Mesozoic and Cenozoic deformation, magmatism and sedimentation in the Silver Peak region is analogous to other parts of the Basin and Range Province, especially as it is related to the Nevada Rift. The Silver Peak region has a unique history of a supradetachment basin, its deformed basement, experienced Late Cretaceous to Paleogene plutonism rifting and Miocene volcanism [23].

This "younger" Cenozoic section of the rift in western Nevada, and adjacent California consist principally of continental sedimentary and pyroclastic rocks of the Esmeralda Formation and lavas and tuffs of the Silver Peak volcanic center. Lying 80 km west (**Figure 8**), the East Sierra Valley System (ESVS), which comprises the westernmost part of the Walker Lane (Nevada)-Eastern California Shear Zone, marks the boundary between the highly extended Basin and Range Province and the largely coherent Sierra Nevada-Great Valley microplate (SN-GVm) [25] [26].

The Owens Valley is a graben in this part of eastern California (Part of the ESVS) that extends approximately 250 km northward from the Garlock fault to Mono Lake, the rift zone is 10 km wide with a vertical displacement of more than 5 km. The graben contains from 1.5 to 2.5 km of sediments, but the mountain fronts rise 2.75 km above the valley floor to an elevation above 4000 m. This rift valley is thought to have formed within the last 3 million years [25]. Although there is some volcanics associated with this rift they are not of significant size or "volume".

The modern ESVS began to form when the Sierra Nevada-Great Valley microplate (SN-GVm) started moving relatively westward away from cratonal

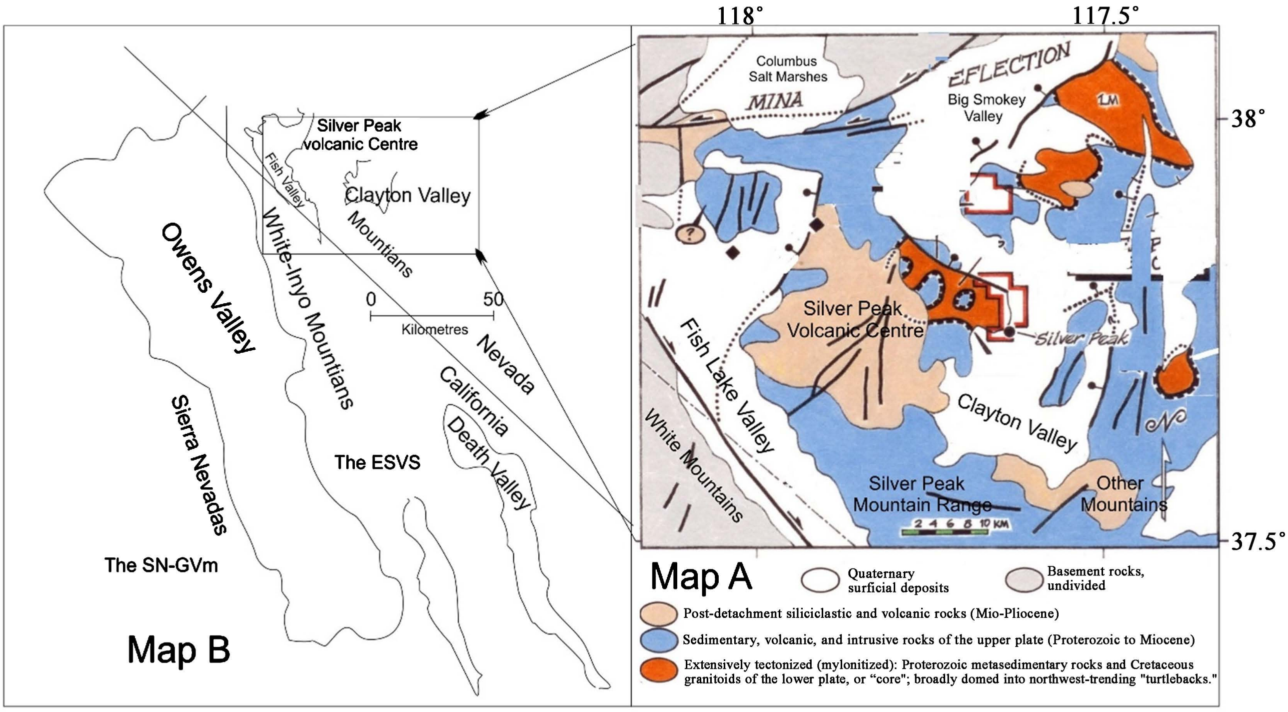

Figure 8. (a) Modified Clayton Valley Geology (After Hulen 2008) Silver Peak Brine Operations [24]; (b) Location of Clayton Valley (Map A), with respects to the West (after Stevens *et al.* 2013) [25].

North America in middle Miocene time. Continued rifting in the ESVS could lead to complete rupture between the SV-GSm and cratonal North America and creation of narrow ocean basin comparable to the Gulf of California [26].

This would be analogous to what is postulated for the EARS and the African Plate (like the SN-GVm) moving away from the Somalian Plate (like the North American Craton).

The Silver Peak volcanics are reported to have up to 228 ppm Lithium associated with its rhyolites and Price *et al.*, have postulated it as the source rocks for the Clayton Valley Lithium Brine which is not only the lone North American producing Lithium Brine operation with resources exceed 700 million kg of Lithium [27], it is the only producing Brine outside of the LTSA.

Significantly, exploration to find additional "brines" has led to the discovery of several Lithium clay advanced Prospects in this region (Tonopah Flats, TLC, Clayton Valley and Rhyolite Ridge).

To date no brines have been located in Tanzania but none have been looked for! However, the initial soil sample results dwarfs any of these USSW prospects' surface expression of the delineated mineralization.

Two other points about the SWUS are: Prior to the Eocene Epoch (55.8 ± 0.2 to 33.9 ± 0.1 Ma) the convergence rate of the Farallon and North American Plates was fast and the angle of subduction was shallow (This would be a "smaller" analogy of the collision of India with Asia around 55 - 60 Ma that built the Tibetan Plateau and Himalayas, versus the Rockies of North America!). During the Eocene, the Farallon Plate subduction-associated compressive forces of the Laramide orogeny ended, and volcanism in the Basin and Range Province flared up. It is suggested that this plate continued to be underthrust until about 19 Ma, at which time it was completely consumed and volcanic activity ceased in part. Although not well defined or researched, possible analogies in the TPC (the Tertiary volcanics of the Songpan Ganzi, including the Hoh Xil volcanics, south of the Qaidam Basin, where the Lithium "lakes" are being developed) exist [28]-[35].

The second point is the characteristic of continental rifts is that their valleys contain most of the deepest lakes in the world. These include the world's deepest, Lake Baikal in Siberia (5387 feet; 1642 meters deep) and the 2nd and 4th deepest, Lake Tanganyika (4323 feet; 1318 meters) and Lake Malawi (2316 feet; 706 meters), in the East African Rift.

The first point of significance is that in the LTSA area, the Nazca Plate is postulated to be currently subducting under the South American Plate at a "shallow" angle. The second is that Death Valley in the ESVS would be a deep lake if it weren't so deficient of water!

5. The Lithium Triangle South America Situation

The Lithium Triangle area of South America is located in the central part of the Andes Mountain Chain just over 300 km from the coast of Chile and over 3500 m above sea level. It is in an active tectonic zone with the Nazca Oceanic plate being subducted beneath the South American plate.

The Central Andes encompass southern Ecuador, Peru, western Bolivia, and northern and central Argentina and Chile [37]. They are characterized by their continental basement rocks and by an absence of oceanic and metamorphic rocks. The formation of the Central Andes was determined by subduction processes that occurred in the absence of major plate collisions during the period when the South Atlantic was opening (**Figure 9**).

Integrated magmatic, structural, and geophysical data provide a basis for modeling the Neogene lithospheric evolution of the high Central Andean Puna-Altiplano Plateau. In the Altiplano and Puna Plateau common processes, including subduction characterized by relatively shallow and changing slab dips, crustal shortening, delamination of thickened lower crust and lithosphere, crustal melting, eruption of giant ignimbrites, and deep crustal flow occurred [38].

Major episodes of ignimbrite eruption were associated with this Neogene lithospheric evolution and occurred over steepening subduction zones in the Late Miocene to Holocene. It gave rise to the Altiplano-Puna volcanic complex (APVC) which is a major caldera and volcanic field located in the southern Altiplano-Puna plateau in the central Andes, including parts of Argentina, Bolivia,

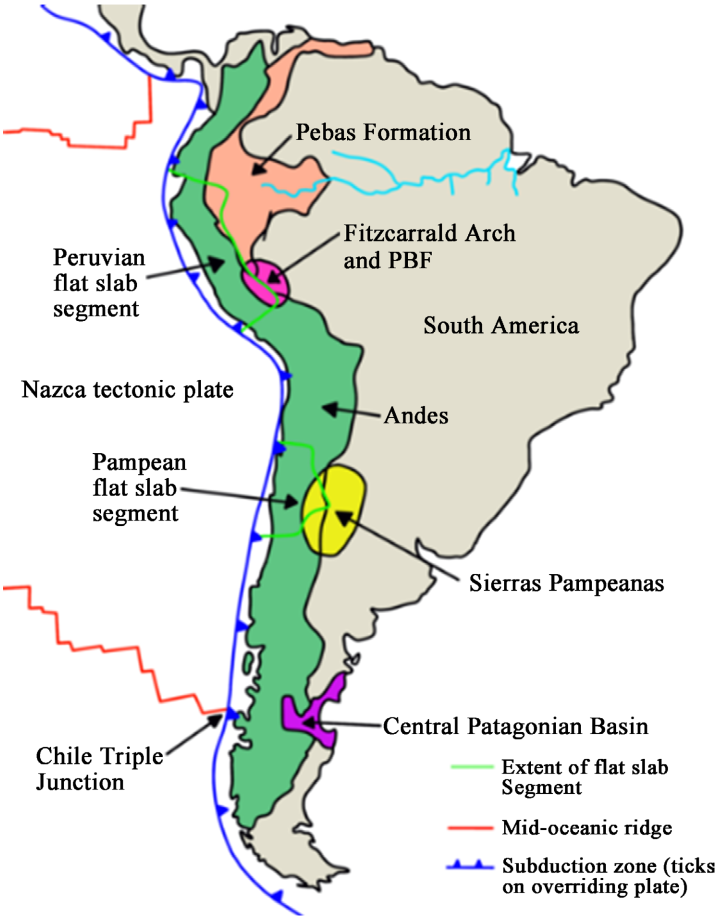

Figure 9. Simplified geology of the Andes of South America and their Western Tectonic Plates [36].

and Chile. It includes two active geothermal areas: Tatio and Sol de Manana. "Cordilleran orogens, such as the Central Andes, form above subduction zones, and their evolution depends on both continental shortening and oceanic plate subduction…Arc and batholith compositions (related to these processes) are consistent with partial melting…whereby felsic melts rise upward through the crust… [39]"

The APVC is a silicic ignimbrite volcanic field located in an elevated dry region in the central Andes. This high plateau region features vast plains punctuated by spectacular volcanoes.

Delamination of the crust has occurred beneath the northern Puna and the southern Altiplano. At approximately 10 - 20 km (6 - 12 mi) depth, seismic data indicate the presence of melts in a layer called the Altiplano-Puna magma body (or Altiplano-Puna low-velocity zone). It is the largest known active magma body on Earth and is probably the source of the regional volcanism (**Figure 10**) [40].

This intense geological feature of the Central Andes as a result of the interaction of the oceanic and continental plate, has not been identified in the SWUS, however, the amount of volcanics suggest that it is not that dissimilar to the LTSA area. Given that the SWUS area is "older" than the LTSA, perhaps it has "migrated", the Yellowstone Hot spot?

Figure 10. The Altiplano-Puna volcanic complex (APVC) Magma [40].

Regional activity variations have been attributed to the southwards moving subduction of the Juan Fernández Ridge (A volcanic ridge in the south part of the Nazca plate). This southward migration results in a steepening of the subducting plate behind the ridge, causing decompression melting. Approximately 25% - 33% of the generated melts erupt to the surface as ignimbrites. Along with the other volcanoes of the region, they are formed from the subduction of the Nazca Plate beneath the South American Plate where the crust is chemically modified and generates large volumes of melts that form the local caldera systems of the APVC [41].

The APVC covers an area of approximately 50,000 sq km (19,300 sq mi) between the Atacama basin and the Altiplano. It is bounded by the Bolivian Cordillera Real in the east and by the main chain of the Andes, the Cordillera Occidental, in the west. There are numerous volcanic cones, some exceeding 16,000 feet (4900 metres) in elevation. Mount Kilimanjaro in Tanzania is 5895 metres and Mount Kenya is 5199 metres with over 10 others between 2300 and 4200 metres (**Figure 4**), so the processes involved are producing similar quantities of volcanic material (this is reinforced by the fact that the EARS Volcanics are closer to a "sea level" base than the Andes' volcanos).

Argentina possesses the world's second-largest identified lithium resources (behind only Bolivia), and the third-largest quantity of commercially viable lithium reserves behind only Chile and Australia. In terms of production sites, it has two commercially operational salt flats in its northwestern provinces of Jujuy and Catamarca: Salar de Olaroz and Salar del Hombre Muerto. Both are located in the APVC "ash shadow".

The dry climate and high altitude of the Atacama Desert (in Chile) have protected the deposits of APVC volcanism from erosion. Still, limited erosion also reduces the exposure of buried layers and structures. A line of low coastal mountains, the Cordillera de la Costa, lies to the west of the desert, and to its east rises the Cordillera Domeyko, foothills of the Andes. The desert consists mainly of salt pans at the foot of the coastal mountains on the west and of alluvial fans sloping from the Andean foothills to the east; some of the fans are covered with dunes, but extensive pebble accumulations are more common. Farther to the east in the western outliers of the Andes, preceded by the Cordillera Domeyko, there are the numerous volcanic cones, described above. Along Chile's northeastern frontier with Argentina and Bolivia extends the Atacama Plateau, which reaches elevations of 4000 metres.

The Salar de Atacama salt flat, hosts the SQM mine in the Atacama Desert in northern Chile [42].

Chile possesses the largest quantity of commercially viable lithium reserves in the world—despite having far fewer potential resources than both Bolivia and Argentina—and is the world's second-largest commercial producer after Australia. While a favorable desert climate and access to the Pacific Ocean augur well, Chile's lithium industry has both a longer history than other countries—

lithium was discovered in its Salar de Atacama in 1962—and the support of a favorable investment climate in the past. Recently the government of Chile has "nationalized" the Lithium production industry, affecting the two main companies controlling Chile's lithium extraction industry: Albemarle, a U.S.-based company that also controls the largest lithium operations in Australia, and Sociedad Química y Minera de Chile (SQM), Chile's largest lithium mining company [43].

Bolivia possesses the world's largest identified lithium resources and is home to the world's largest salt flat—Salar de Uyuni. Nevertheless, Bolivia has struggled to transform its lithium resources into commercially viable reserves, due in large part to the poor investment climate borne of the country's political instability.

Salar de Atacama is part of a larger depression hosting other salt flats. This depression, called "La gran fosa" by Reinaldo Börgel is bounded by north-south structures. At present this larger depression conforms a subsiding sedimentary basin. Comparing with neighboring areas of the Andes the depression is a major topographical anomaly thought to be caused by a lithospheric block that due to its high density has remained at lower position than the rest of the Andes. The high density would derive from the times the Salar de Atacama depression was a westward rift arm of the Salta Rift Basin located further east in Argentine territory [44].

South of Salar de Atacama ancient plutonic rocks of Cambrian and Ordovician age crop out. These rocks are associated with the Famatinian orogeny (an accretionary-type orogeny that took place in the Ordovician along the proto-Andean margin of Gondwana from Patagonia to Venezuela).

From the Late Cretaceous to the Late Eocene volcanic and sedimentary rocks of the Purilactis Group deposited in the basin. During this time, volcanism occurred chiefly west of the basin rather than east as in the present, thus it was back then a back-arc basin. After the Purilactis Group had deposited tectonic movements tilted the strata in the north to east and in the south a thrust fault pushed old Late Paleozoic rocks over the younger Purilactis Group [45].

The presence of a "fossil" rift/west rift arm in this active uprising of the Andes was a startling insight bringing the similarity to the other two areas complete. During the Early Cretaceous, the east side of the Andes Mountains did have an inland sea that had developed from the north (**Figure 11**). A possible "rift valley" or fossil rift? Continuation of the Salta Rift Basin?

The middle of the Cretaceous in the Central Andes was marked by a change in tectonic activity—from crustal extension to crustal compression, which initiated the formation of a series of sub-Andean foreland basins from Colombia to central Argentina, characterized by considerable volcanism along the axis of the principal cordillera. Andesites, basalts, and rhyolites have been the major rock types to result from that activity, with some granitoids as well [46].

A series of Middle to Late Triassic basins in the area of the Brazil Craton, had developed through horizontal crustal extension during the early phases of Pangea's

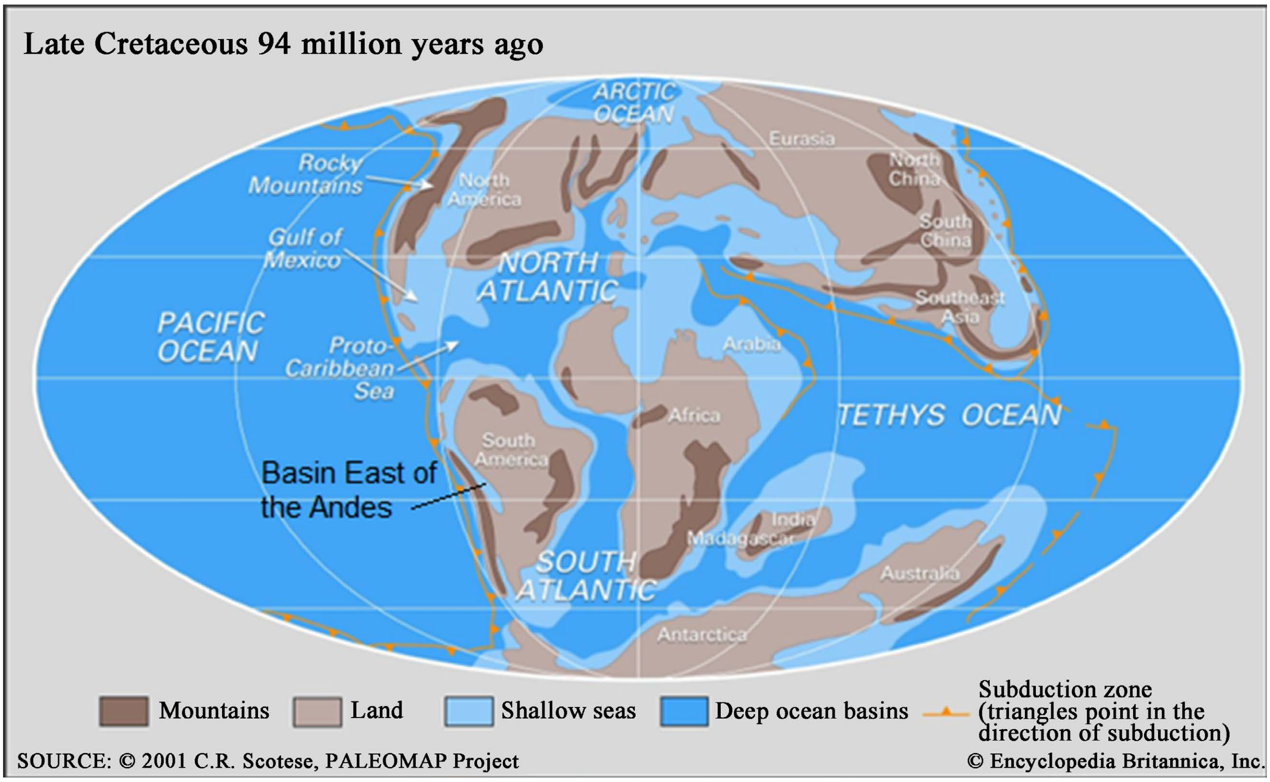

Figure 11. World plate locations late cretaceous, 94 million years ago.

dispersal. Those rifted basins largely followed the previous Paleozoic sutures along the western side of the continent. Crustal extension reactivated the inner part of the supercontinent as well. This long exposure to rifting in South America is analogous to the 1500 km PreCambrian to Cenozoic rifting in the SWUS region and the "recent" development of the 3500 km EARS. The Atacama Plateau is 1600 km in length.

Crustal extension prevailed from the Jurassic Period (about 201 to 145 million years ago) to Early Cretaceous times, when important volcanic piles and plutonic rocks were emplaced and back-arc basins developed in the sub-Andean regions.

As seen in the SWUS the Nevada Rift was active from PreCambrian times, suggesting that this Cretaceous inland sea could be related to these rift basins and the Salta Rift Basin (Columbia to central Argentina is 3200 km!).

Distinctively from the Tanzanian Situation, both the SWUS and LTSA have evidence of accreting island arcs and oceanic/continental plate interactions. Although not apparent in the TPC some mention of some "island arcs" was noted in the research and the continental/continental plate interaction is uniquely developed (although as mentioned above possible analogous in the SWUS) [47]-[52].

A further distinctive difference is that very limited data on soil and volcanic lithium values is available. Most of the reporting is with respects to the lithium Brine values in the TPC and the LTSA and fairly nonexistent in Tanzania.

6. The China Tibet Situation

Continental collision between India and Asia, started circa 55 mya has, and resulted in crustal thickening and uplift of the Tibetan plateau. The timing and mechanisms of the Tibetan plateau growth are still poorly understood but have been occurring during Late Cretaceous-Oligocene time. Often been called the "Roof of the World", the plateau is probably the largest and highest area ever to exist in Earth history, with an average elevation exceeding 5000 m [53].

Whereas the southern part of the plateau may have been created and maintained since the late-Oligocene, the northern plateau would have not attained its present-day elevation and size until the mid-Miocene when the lower part of the western Qiangtang and Songpan-Ganze lithospheres began to founder and detach owing to the persistently northward push of the underthrust Indian lithosphere (**Figure 12**).

The spectacular rift valleys of the Tibetan plateau curve away, some to the east, some to the west, from the point where India is punching into the gut of Tibet [47] [48].

Cenozoic volcanism on the Tibetan plateau, which shows systematic variations in space and time, is the volcanic response to the India-Asia continental collision. It is generally accepted that the Cenozoic potassic volcanic rocks of northern Tibet were derived from a lithospheric mantle source in the Miocene (ca. 18 - 15 Ma). K-rich adakitic volcanic rocks from the Hoh Xil area of the Songpan-Ganzi block in northern Tibet. Wang *et al* contend that these rocks were generated by partial melting of the mafic lower crust, in an intracontinental setting unrelated to subduction of oceanic crust (**Figure 13**) [31].

The terms adakitic (TPC), metaluminous (SWUS), peraluminus (SWUS and Tanzania) all are related to felsic volcanic rocks, in the references in this paper, derived in part form partial melting associated with "island arc" subduction and/or "plate" subduction. In the Wikipedia outline for adakites it refers to them as being due "to when young oceanic crust (less than 25 million years old) is subducted, adakites are typically produced in the arc (closer to the mid-ocean ridge where it formed)". In a 2018 paper [55] in Frontiers in Earth Science, Jeffery *et al.*'s title "*Peralkaline Felsic Magmatism of the Atlantic Islands"* suggests an affinity! Other authors however noted that, the petrogenesis of adakite rocks is controversial and is still debated in the literature. However, until consensus is reached the term is likely to remain "confusing and controversial" [56] and

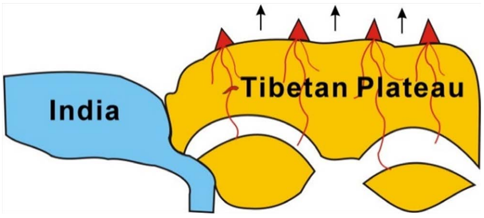

Figure 12. The Indian Continental Plate (India) "meets" (and is subducted) by Eurasian Continental Plate (Tibetan Plateau) [54].

"Existing models for adakitic melt generation are hampered by the scarcity of geochemical and geochronological data" [57].

This geological setting is for the Qaidam Basin (**Figure 14** and **Figure 15**), in the north-western part of China's Qinghai province on the Plateau of Tibet, an area of many brine lakes and salt flats [58]. It has been the source for many commercial "salts" for many years but its lakes were characterized by higher Mg/Li ratios and lower Li values. However, in 2004, a new technology to treat these high-Mg content brines demonstrated the feasibility of commercial production of lithium carbonate and a "2015ish" reserve estimates for deposits in the Qaidam Basin range from 1 to 3.1 Mt [59].

More recently, Qinghai Salt Lake said its new Lithium Carbonate factory was online [60]. Qinghai invested nearly CNY7 billion (USD1 billion) to build the lithium salt processing plant at Qarhan Salt Lake with a yearly output of 40,000 tons. It is also teaming up with electric car and battery manufacturer BYD on another lithium carbonate plant with an annual capacity of 30,000 tons. It is estimated to contain reserves 12 million tons of lithium chloride and other salts [61] [62].

As well other developments in the Qaidam Basin have identified sulfate lithium resources [62].

These recent resources will add/have added to China's resource of LCE cited above in **Table 1** and have/will replaced the original Lithium lake producer in the Southwest of Tibet as the dominant source of Brine Lithium in China.

The Zhabuye Salt Lake in Southwest Tibet had a reserve of 1.53 million tonnes Li claimed [59], but the estimate was considered overly optimistic. Kesler *et al.* identified it as the main Lithium Brine resource in 2012 [2].

The industry had an annual output of 10,000 tonnes in 2016 of lithium carbonate and hydroxide, so the addition of these Qaidam Basin resources and production targets outlined above should be quite significant.

The Qaidam basin (with altitudes ranging 2600 - 3200 m) is surrounded by significantly higher ranges mountains (altitudes > 4000 m) favors the formation of salt deposits with more than 20 salt lakes and an abundance of salt–brine resources distributed throughout the basin (**Figure 14**) [63].

Because of this position, Qaidam forms an endorheic basin accumulating lakes with no outlet to the sea. The area is among the most arid non-polar locations on earth, with some places reporting an aridity index of 0.008 - 0.04 [35].

Although there are no "rifts" associated with the Qaidam basin, the tectonic activity is deemed to be excessive related to the impact of the Indian Continental Plate being "subducted" under the Eurasian Continental plate (**Figure 13**). This tectonic activity has been identified as a four-stage surface uplift which led to the developing into a plateau similar to the modern Tibetan Plateau since the Middle Miocene.

The presence of Miocene volcanics in the mountains to the south is possible contributors to the basin's sedimentary deposits. Volcanism migrated northward and became quite active in the Hoh Xil and West Qinling during the Miocene

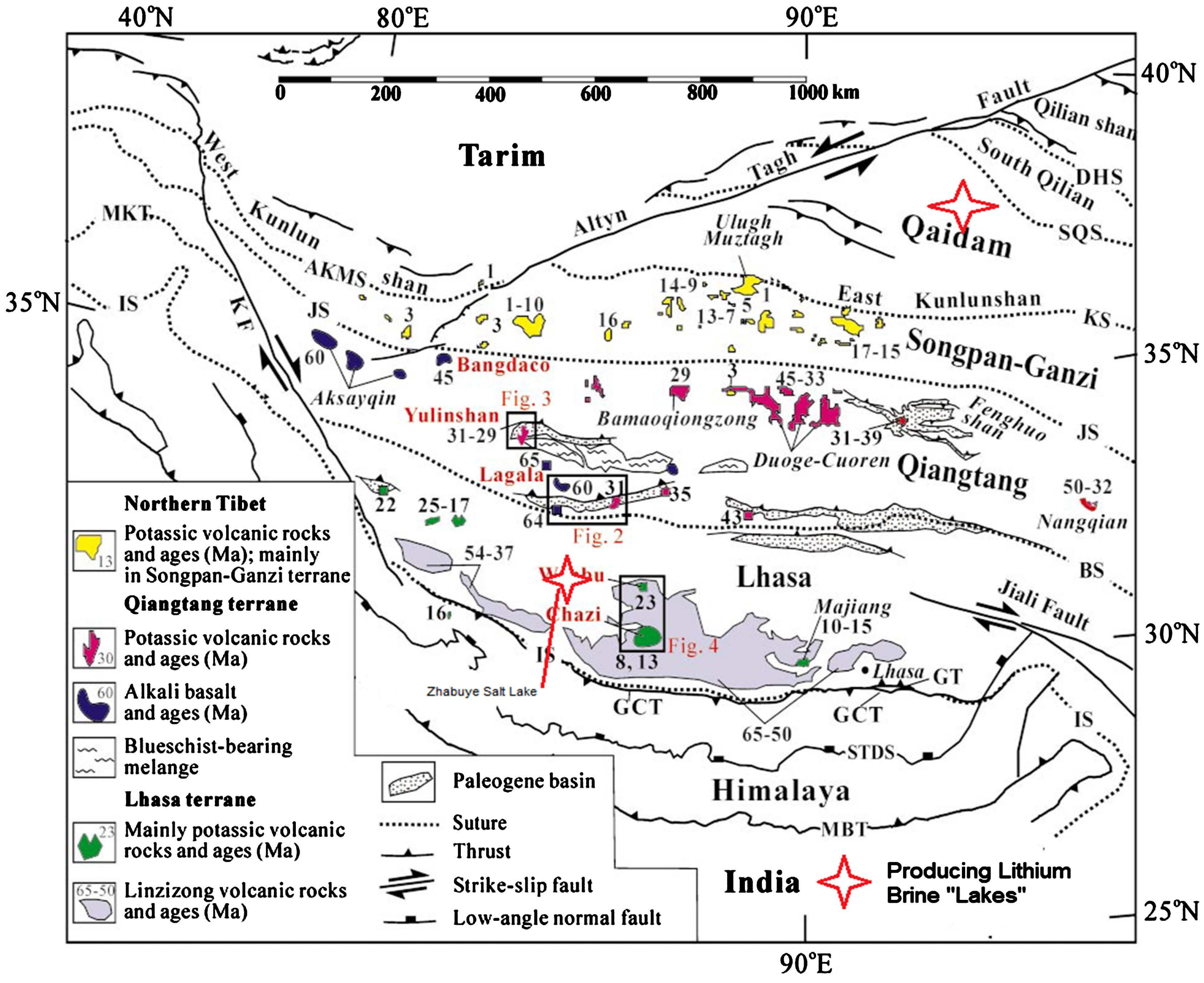

Figure 13. Map of the Tibetan Plateau showing the major terranes and temporal—spatial distribution of Cenozoic volcanic rocks (modified from Yin & Harrison (2000)). Ages compiled from Coulon *et al.* (1986), Burchfiel *et al.* (1989), Deng (1989, 1998), Turner *et al.* (1996), Zheng *et al.* (1996), Chung *et al.* (1998), Miller *et al.* (1999, 2000), Deng *et al.* (2000), Hacker *et al.* (2000), Tan *et al.* (2000), Horton *et al.* (2002) and Kapp *et al.* (2002, 2003a). From north to south, the main suture zones between the terranes are: DHS, Danghe Nan Shan; SQS, Southern Qilian; KS, Kunlun; JS, Jinsha; BS, Bangong; IS, Indus. Major faults: GT, Gangdese thrust system; GCT, Great Counter thrust; STDS, Southern Tibet detachment system; MKT, Main Karakorum thrust; MBT, Main Boundary Thrust; KF, Karakoram fault [29].

(Figure 15), as manifested by diverse volcanic lava dated at ~ 23 - 7 Ma. Miocene potassic-ultrapassic and mafic-ultramafic volcanics in the Hoh Xil and West Qinling suggest a crucial role of deep thermomechanical processes in generating crust- and mantle-sourced magmatism. Also noticeable are the continuity of mid-Tertiary successions and absence of volcanics in the Qaidam basin [33] [34] [35].

On the other hand, the original brine source, Zhabuye Salt Lake in Southwest Tibet is located at over 4400 m and is surrounded by 5000 m + mountains, located in the Lhasa Terrane (Figure 13).

This southern margin of Eurasia has been tectonically active throughout the

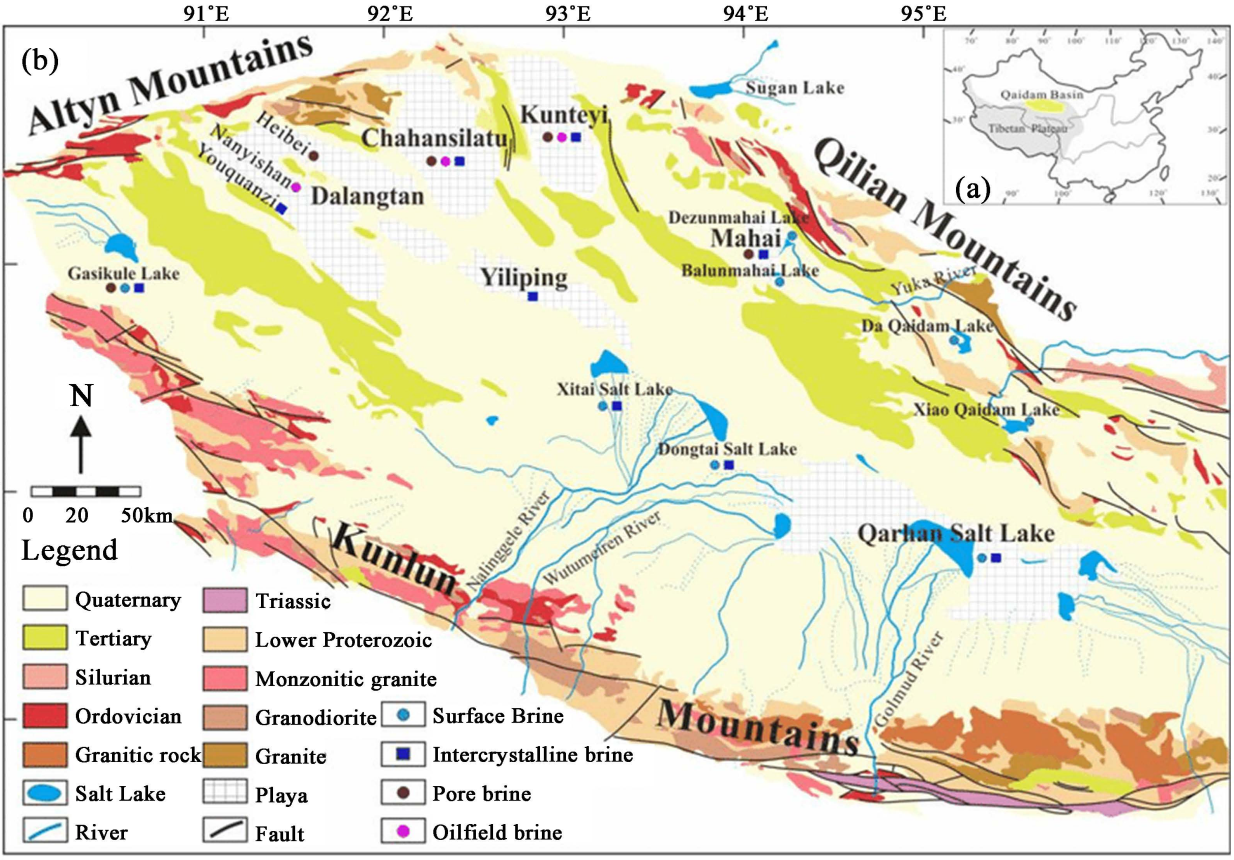

Figure 14. Geological map showing the geological map of the Qaidam Basin and its surrounding ranges [64].

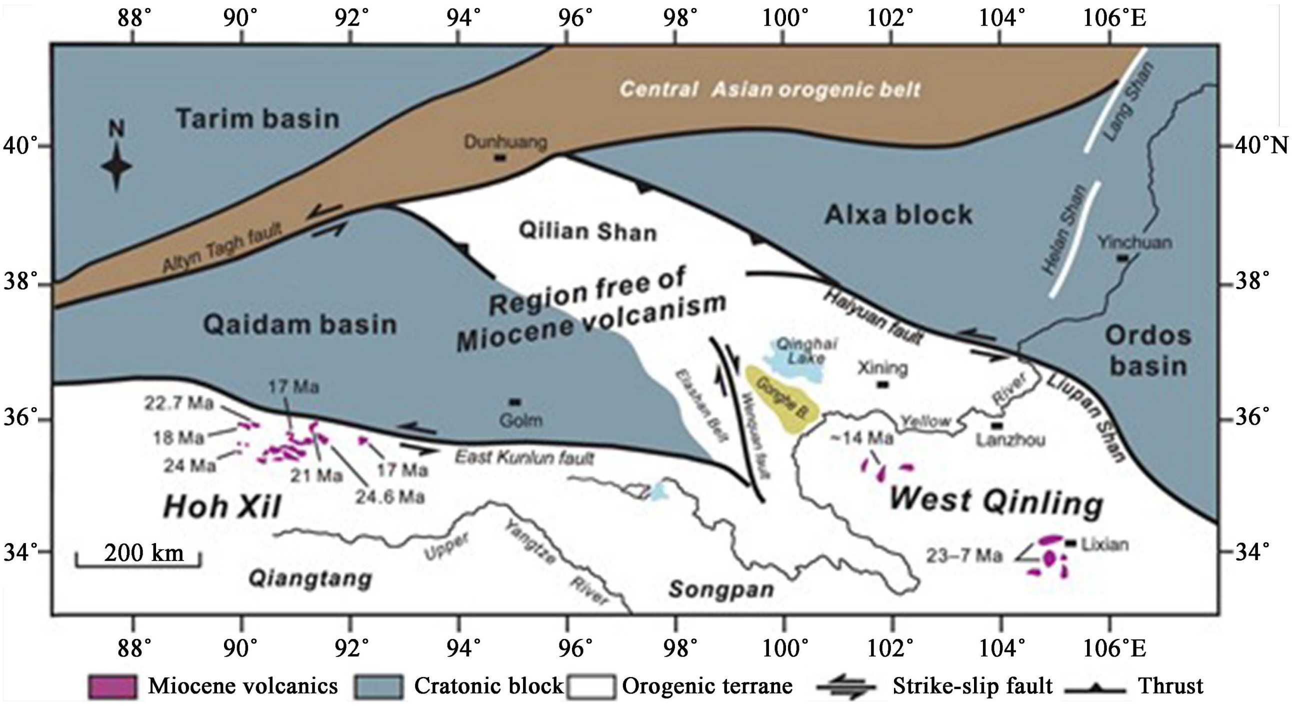

Figure 15. The Miocene Volcanism south of the Qaidam Basin (Wei, H-H, *et al.*) [48].

Phanerozoic. This activity mostly consists of the successive accretion of multiple terranes that now compose the Tibetan plateau. Accretion of these terranes is generally assumed to young southward, with docking of the Qilian and Kunlun terranes in the Paleozoic, the Qiangtang terrane in the early-mid-Mesozoic, and the Lhasa terrane in the mid-late Mesozoic (forming the Bangong-Nujiang Suture Zone; BS on **Figure 13**). The late Cretaceous to early Eocene saw the beginning of India's ongoing collision with the Lhasa terrane along the Indus-Yarlung Suture Zone (IS on **Figure 13**), creating much of the crustal shortening observed today [29].

Shortening, accompanied by magmatism, continued throughout the Lhasa terrane until the Paleocene giving rise to the local Lhasa volcanism outlined (Green and Grey on **Figure 13**, in the Lhasa Terrane) [65]. Its relationship to this salt lake is not clear but Cretaceous volcanics are noted on the Lunggar Rift Valley map (**Figure 16**).

Several geodynamic models may explain the timing of rift initiation in the South Lunggar Rift in the early to middle Miocene, none so far explain the onset of rapid extension at 8 Ma. A model of rift evolution that invokes upper-crustal thinning, supradetachment basin subsidence, and subsequent isostatic rebound along the more-evolved central segments of Tibetan extensional systems is present [66].

This significant rift valley just west of the Zhabuye salt lake is interesting in comparison to what I have outlined for the SWUS, LTSA and Tanzania and the "rapid extension of 8 Ma" coincident in timing of a lot of the volcanism delineated in the SWUS and LTSA (and Tanzania?) but further comment is up to the reader.

The relationship between pegmatite and brine-type lithium deposits and the potential multi-source of lithium in the lithium-rich salt lakes in the Tibetan Plateau has not been sufficiently investigated, in the few studies on the area. The recent expansion of the Lithium resources suggests more studies are warranted.

7. The Jadar, Serbia Situation

Although not necessarily a comparable situation, the sedimentary and clayey nature of this deposit needs some comment. The Mineral Resources comprise 85.4 Mt of Indicated Resources at 1.76% Li_2O and 16.1% B_2O_3 with an additional 58.1 Mt of Inferred Resources at 1.87% Li_2O and 12.0% B_2O_3 [67].

From a stratigraphic point of view, it is observed that sedimentation in the basin is associated with a low energy environment for large periods with widespread distribution of stratigraphic units in the basin. There were periodical influxes of coarser clastics that are interpreted to be sourced mainly from the slopes of the basin to the north and northwest. Contribution from the west-southwest seems to be important during certain periods of basin fill [68].

Although, the area is part of the tectonic plate collision of Europe and Africa/Arabia, that gave rise to the European Alpine Ranges and others, there is little

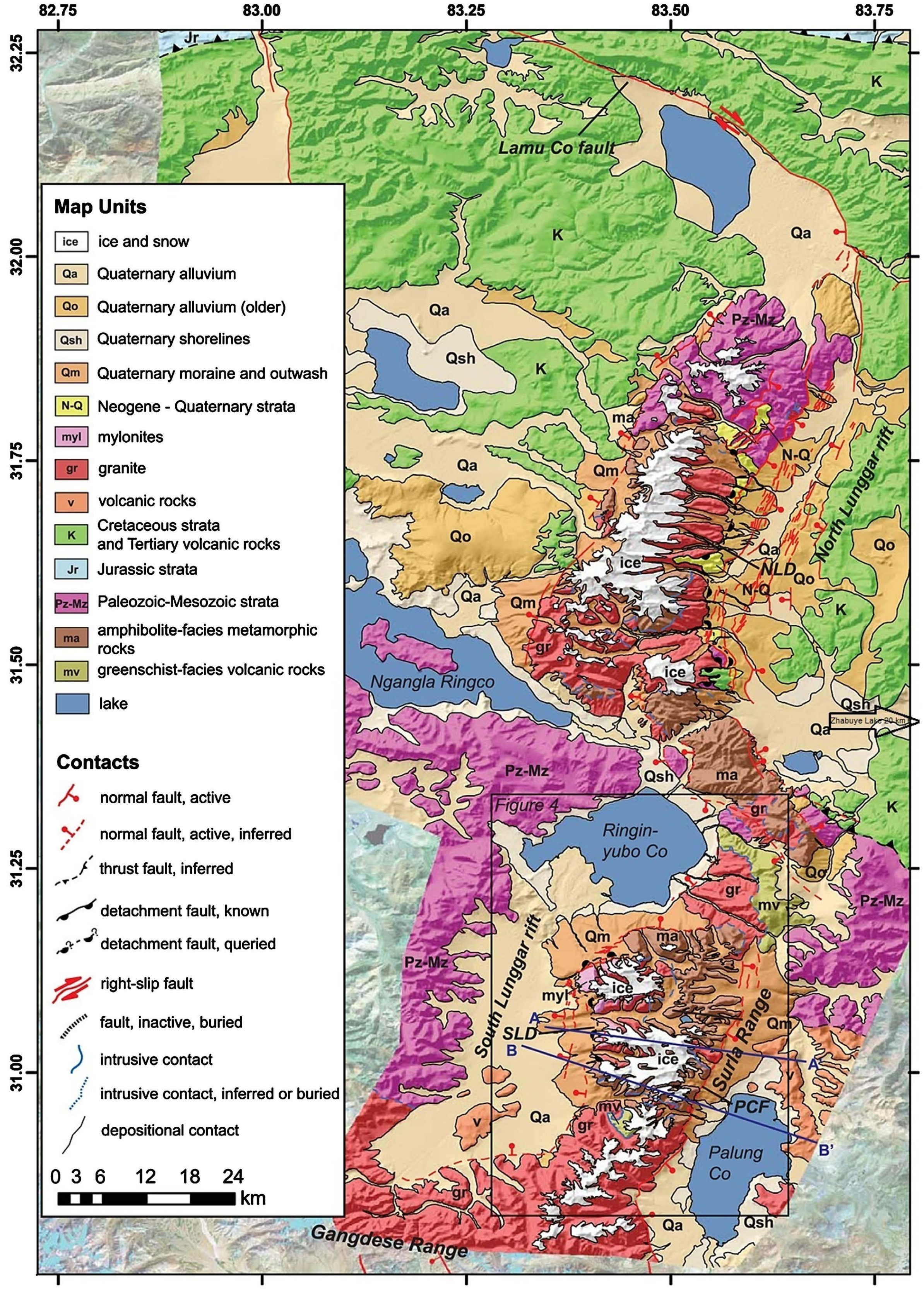

Figure 16. Lunggar Rift Valley Southwest Tibet, China [66]. The Zhabuye Salt Lake mine is located 20 kms to the east of the Valley (see Arrow).

to no locally identified Tertiary volcanism in the area, and no readily identifiable major "rift" structures associated with the deposit. Ergo it is not a real fit to the model.

The presence of Jaderite as the new Lithium ore mineral in this locale only suggests that the deposit is unique. The minerals of this deposit contain significantly more silicon dioxide than the other boron-bearing minerals, most notably colemanite, within which they occur. The absence of these minerals in other intermontane lacustrine evaporite-type deposits suggests that the Jadar deposit was formed by atypical mineralization processes.

8. Concluding Remarks

The four areas discussed have "anomalous" amounts of Lithium. Three of the areas have produced "Lithium Brines" (LTSA, SWUS and TPC) while another two (possibly 3 or 4) have "lithium clays", one with identified resources (SWUS) and the other with prospective exploration targets (Tanzania). There appear to be some possible Lithium clays in the TPC and we could infer some in the LTSA but no one is really looking for them in those areas.

The main similarity of all four areas is the presence of Recent (Tertiary) volcanism from the Miocene (LTSA, SWUS and TPC) to the Pleistocene (Tanzania). This "active" volcanism is due to major tectonic events, Spreading centres (SWUS and Tanzania) and Subduction (LTSA, SWUS and TPC).

There appear to be "generous" amounts of Lithosphere material being incorporated into the volcanic magma feeding the volcanic systems of all four areas. From the limited data available all the volcanics in these areas have high lithium values in their rocks (TPC is inferred as no real data for lithium in volcanics analysis was observed in my research). Also, three areas (SWUS, LTSA and Tanzania) have had volcanic ash falls/weathering of these volcanic rocks contributing to the "liberation" of the Lithium into brines and the deposited clays. The TPC area could have ash fall and certainly weathering of the volcanics but there are no real indications of this from the literature that would relate to the Lithium areas.

All four areas had "restricted" internal inflow basins (In Tanzania, the Titan 2 basin is an obvious inflow restricted basin, while Titan 1 due to its size and extent is theorized to have been an inflow restricted basin in part before filling up). The age of the volcanics is Miocene (SWUS, LTSA and TPC) through to Pleistocene (Tanzania and LTSA) with Tanzania basically starting at the end of the other two (SWUS and LTSA) eruptive periods. The TPC volcanism that is related to the Qaidam Basin has starting timings older than the SWUS but similarly continued through most of the Miocene. During this same time period all four areas have been sites of major tectonic interactions between tectonic plates with one still active (Tanzania) and three having adjacent activity (SWUS, LTSA and TPC).

Finally, these four regions are distinct with very similar past and present geologic characteristics, that occur nowhere else in the world. That three of them have producing (LTSA, SWUS and TPC) Lithium operations and two of them have identified resources of Lithium clay (SWUS) and "highly" anomalous Lithium clays (Tanzania) should be regarded as more than "coincidental".

More research and investigation are required!

Acknowledgements and PostScript

During the initial exploration of the Titan 1 and Titan 2 prospects, the author had several discussions with and several references, from fellow Geologist Craig Alford, and although not direct, with his experience in the Southwest United States of America, the author would like to acknowledge his contribution.

I have a fairly extensive list of references as we are dealing with four separate world area geologies, to which the author had limited to very limited background. As the quest for lithium continues, my hope is that this list will aid other researchers develop more refined analysis.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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