SUBDUCTION POLARITY REVERSAL: ANCIENT EXAMPLES

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ABSTRACT

Subduction polarity reversal refers to change in the direction of a subducting lithospheric plate into the mantle. The mechanism for this has been attributed to both a slab break off and slab roll back driven by collision of tectonic plates especially when arc and rifted continental margins collide. Magmatic and metamorphic event related to and postdating the collision are major characteristic of subduction polarity reversal and if collision continued much more deformation my results in seismicity. The integration of geologic data and seismic are used to delineate and make model to understand how it occurred. Ancient examples and geographical area of subduction polarity reversal have been enumerated. Some of the geological ages associated with subduction polarity reversal include; Proterozoic. Mid-proterozoic and Ordivician–Early Siluria. Also presented is case study of the Farwell Mountain - Lester Mountain suture zone of the southwestern united state continental lithosphere.

INTRODUCTION

In plate tectonic subduction of lithopheric plate occurred when two tectonic plates are converging. The denser plate tends to bend and moved downward into the asthenophere and same time the lighter one overrides the subducting lithopheric plate. However, certain tectonic activities may result in the reversal (flip) of the polarity of the subducting plate. Recent studies of continental lithosphere have showed the existence of subduction polarity reversal or flip (Solomon, 1990; Mckenzie, 1969; Konstantinovskaia, 2001).

A clear understanding of this concept may be achieved through an insight to the concept of subduction, which is the term use to describe the downward movement of a denser plate when two plates of different densities converged. This scenario occurs when the two plates are moving towards each other and the point of convergence the denser plate sinks downward into the mantle. The area where this occurred is called subduction Zone and it is characterized by mountain ranges, island arc, volcanism and earthquakes.

When the subducting slab breaks, subduction polarity reversal is given rise to, which is the termination of one subduction zone and the formation of another one in opposite direction. That is, a switch from initially subducting lithopheric plate to another lithopheric plate. For instance, if an oceanic plate (Laurentina) is subducting at southeastern direction it then immediately switched to another (Baltica) that is in the direction of northeast (Fig1). The caused of this polarity reversal has been attributable to the difficulty that aroused when a buoyant continental lithosphere is trying to subduct, (Himiton, 1978), and since it couldn't subduct, it collides, which produces subduction polarity change. This seems to be the hypothesis that explains such process and collision that result in slab break off. As subduction of slab is in progress coeval rocks of igneous, metamorphic and sedimentary origin do record changes associated with this process. The analysis of these rock in which clocks triggered on and switch off events associated with subduction can be obtained in terms of the integration of geologic study, which include mapping of structures, unconformity, seismic data, geochronology, isotope data and heavy minerals of sediments in a nearby basin will assist in deducing changed in directions and the mechanism responsible for their formation.

The paper is aimed at giving insights to the concepts of subduction polarity reversal, as subduction polarity reversal and subduction literatures are lacking in Nigeria's geological literature. Ancient examples of subduction polarity reversal are also cited and how some integration of geological attributes such as seismic, petrography, geochronology, geochemical, stratigraphy and heavy minerals can be use to constrain and explains subduction polarity reversal are highlighted.

CAUSES OF SUBDUCTION POLARITY REVERSAL /FLIP

That subduction occurred when two plates of different densities converged and one overrides the other and the one experiences downward movement is no longer debatable, this has already be constrained by geologic , seismic and geochronology data.

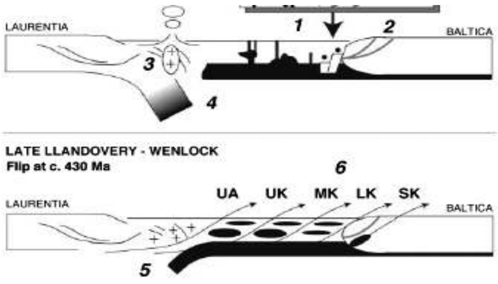

Fig 1: proposed evolution of subduction polarity reversal and the closure of laptus ocean adopted from Andreasson et al. (2003).

1. Back –arc fill at Halti-Birtavarri; arkose, limestone, shale, pillow lava, calcareous turbidites intrusion
2. Margin imbricated and eroded during Early-Ordivician (seve0.
3. Magmatic arc(batholiths) one of the uppermost allochtton.
4. Subduction and high –p metamorphism of the Laurenrian margin; eclogite of NE Greenland.
5. Flip of subduction polarity at c.430ma
6. Derivation of the allochtton; UA=upper allochtton; UK= upper koli Nappes; MK=middle Koli Nappes; LK=lower koli Nappes.

But there is a controversy as regards the occurrence of subduction polarity reversal as a compromised has yet been reached. In this section as we found out later that there are two schools of thoughts on the process that governs subduction polarity reversal. These thoughts demonstrate that subduction polarity reversal is cause by slab roll back and slab break off. Which of them that dominates the process may not be necessary, but it worthwhile to emphasize that subduction polarity reversal is caused by collision of arc with a rifted continental margin.

One hand, the slab break off occurred when the subducting slap break off to discontinued subduction, this emanates from of the impact, arising from collision of the a continental margin or an arc with the margin of the plate that is subducting (Fig.1), while on the other hand, roll-back is a situation where the subducting slab is retreating backward and the overriding plate moving forward. The subducting slab thereafter occupies the space created by the retreating subducting plate. The subducting slab is pushed backward by the upper mantle movement; the top plate is moved downward. The movement of the top plate is caused by the movement of the upper mantle and its subducting causes the top plate to turn into the subducting plate, causing reversal in subduction. In addition, subduction polarity reversal may also results when a subducting continental margin experienced difficulty. This is succinctly explained by Dewey *et al.* (1989) that at the incipient stage of continental collision, collision of island arc and with rifted continental margin is common and when subduction roll back drives collision, the arcs bend and wrap themselves into remnant oceanic holes.

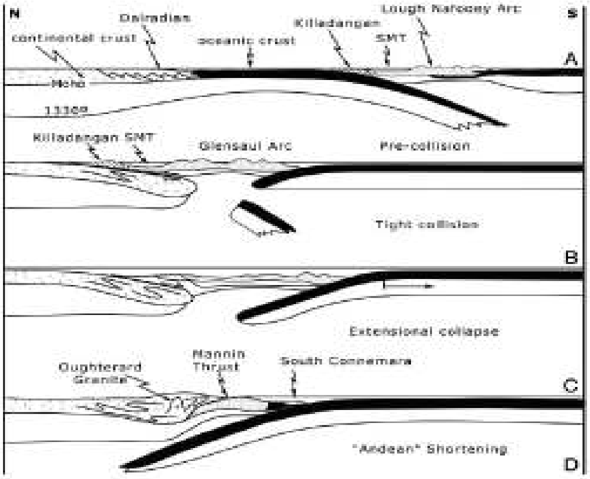

Fig.2: Slab break off due to collision and the evolution of the Ordovician sectional evolution of the Grampian orogeny (Dewey, 2002)

During arc and rifted margin collision the subduction zone is blocked by a weak and buoyant continental crust, which is followed by subduction polarity reversal (Dewey *et al.,* 1970; McKenzie, 1969). For subduction polarity reversal to occurred the initially subduction slab must be terminated by slab break off (Dewey *et al.,* 1970)

CHARACTERISTICS OF SUBDUCTION POLARITY REVERSAL

Subduction polarity reversal is characterized by closure of an ocean. A good example is the closure of the Lapatus Ocean. Andreasson *et al.* (2003) demonstrated that the final closure of Lapatus Ocean was immediately prior to Baltica- Laurentia collision and, the subduction of the Baltoscandian margin. A major characteristic of subduction polarity reversal is the formation of magmamtic events, which may caused either by dehydration or melting of slab or inflow of mantle as subduction slows or during slab rollback (Solomon, 1990). The mechanism of subduction polarity reversal often generates very short Orogeny (Dewey, 2000). This he attributed to the fact that restive forces associated with collisional shortening are relieve by the reversing subducting slab.

DELINEATING EVIDENCE OF SUBDUCTION POLARITY REVERSAL

In order to understand and show evidence of the occurrence of subduction polarity reversal, it is pertinent therefore to study areas/ regions that are characterized by the product of subduction activities. We know that certain subduction products like magmatism, igneous activity, sediments that are deposited in closed basin, orogens and mountains are good starting point. Hence in this section, effort should be focused on how the use of intergraded geologic data, seismic and telseismic images, geochronology, (pressure-temperature data) P-T data, heavy minerals, sedimentological data and tectonic model have contributed to the delineation of subduction polarity reversal.

DEEP SEISMIC AND TELESEISMIC IMAGE

Reflection seismic has been used to study the lithospheric properties of the crust and mantle. This method relies on the time taken for seismic pulse to travels through the lithosphere and recorded at the surface. Though the deep seismic and teleseismic images are not as straight forward as reflection seismic employs in exploration for hydrocarbon, the reflection of the lithosphere is quite chaotic, thus making interpretation of deep seismic difficult due to weak signal that may render density contrast of reflectors unclear because of the chaotic nature of deep seismic.

The subducting slab is often denser and as such, it possesses high reflective contrast that made it to be distinctive from the low reflective contrast of the surrounding crust. This has been used by Morozova *et al.* (2002) who interpreted the Archean-Proterozoic boundary to be linked to a set of dipping reflectors, which correspond to a high reflective crust to the north and a low reflective to the south as showed in (Fig.3). In addition, Tyson *et al.* (2000) interpreted the Cheyenne belt and Farwell Mountain stopped and the Green mountain arc crust was wedged into the Archean crust along the conjugate thrust, as a highly reflective body across the Archean-Proterozoic boundary as the underthrust slab. On seismic section (Fig 3), while tomography image of the highly reflective body has also been used to differentiate between the denser subducting slab from the rest of the crust as shown in (Fig 3) as blue being dense and yellow light dense.

GEOLOGY AND GEOCHRONOLOGY

It has already be ascertained that occurrence of subduction results in some products which can be studied geologically in terms of structures, magmatism and igneous complex and even coeval sediments. These products can be dated since most rocks like time clock records the activities of subduction in terms of the time when the initial subduction and the subsequent reversal events were happening.

The occurrence of subduction polarity reversal should produce a parallel zone which is different in terms of when they are formed. Prior to subduction polarity reversal, subducted rocks from the mantle can be brought to the surface through exhumation and thrusting. When these rocks are dated, they can give ages different from those formed by changed in subduction polarity due to temporal difference. This can be link to subduction polarity reversal when we considered two cases of magmatism associated with subducting slab and the melting of slab, or inflow of hot mantle as subduction slows or during slab rollback. No doubts this will give different ages when dated.

Mid-Proterozoic subduction polarity reversal was interpreted by Davidson and Van Breenman (2001) from both geology and geochronology of the granitoid rocks in the North Bay area, Greenville Province, Ontario. The underthrusting of Laurentia by Baltica is another example of subduction polarity in which the age of Ordovician- early Siluria was also obtained by Andreasson *et al.* (2003) from the U-Pb dating of the Halti igneous province in the Scandinavian Caledonides (Fig. 3). Dewey (2005) also dated igneous and metamorphic rocks of the Grampian Orogeny and obtained age of 467 Ma for the subduction polarity reversal in British and Irish Caledonides.

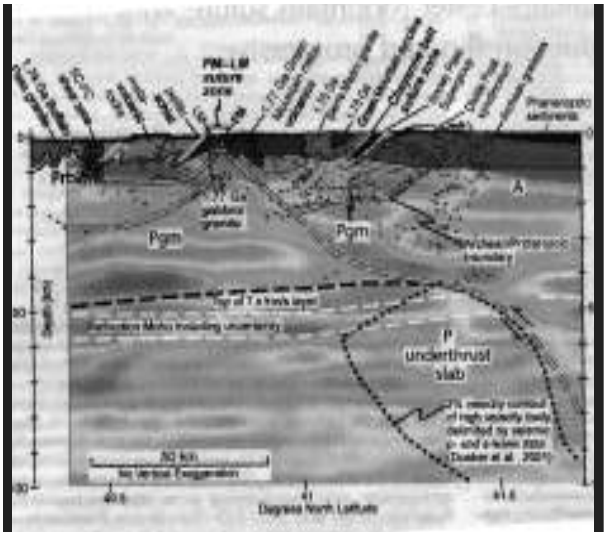

Fig 3: *Seismic interpretation and p and s wave tomography.*
Tan areas-positive impendence contrast, blue = negative impedance contrast,
Dashline = highly velocity body image by p and s wave tomography, p=proterozoic lithosphere, pgm= proterozoic Green Mountain Block, prb= proterozoic Rawah block, FM=Farwell Mountain, LM=Lester block, A =Archean lithosphere and SC-FC = Soda creek – Fish Creek shear zone. From Morozova et al., (2002) and Drucker et al., (2001)

SEDIMENTARY FACIES AND HEAVY MINERAL ANALYSIS

Sedimentary facies and heavy mineral analysis can be integrated with geochronology data to delineate subduction polarity reversal. This is possible as a result of the fact that when subduction does occurred there is the formation of basins where sediments may be deposited and such sediments may records the subduction that is taking place.

THE ROLE OF MODEL IN UNDERSTANDING SUBDUCTION POLARITY REVERSAL

Model helps to understand the mechanism behind subduction that is taken place some km of depths subsurface of continental lithosphere. The use of seismic data-seismic reflection and tomography as well as geologic data has contributed in assisting to understanding how subducting slab behaves and have been represented in the laboratory as analogue and numerical models respectively. Note however that all subduction diagrams on paper and text books are model representations as in Figures 2 and 3 respectively.

ANCIENT EXAMPLES OF SUBDUCTION POLARITY REVERSAL.

A lot of studies based on reliable seismic, isotopic, geology and P.T data of the upper crustal rocks that have been brought to the surface records subduction polarity reversal that gave rise to them. And thus they have shown the existence of the subduction polarity change. The following are some of the examples found in literatures.

PROTEROZOIC

The geologic evidence obtained from, deep seismic reflection data and P and S wave tomography image (Fig.3). Tyson *et al.* (2002) gave another ancient example of subduction polarity reversal of Proterozoic age for the Farwell Mountain-Lester Mountain suture zone, Northern Colorado. The reason given in support of their hypotheses was attributed to the closure of the ocean-basin via the south-dipping subduction system that built the Green Mountain arc at 1.79-1.77 Ga. In support of this, is the absence of Paleoproterozoic felsic intrusion to the north, Craton margin moving towards the trench at 1.77 -1.76 Ga and the abrupt stopped of the south dipping subduction and the subsequent collision of the Green Mountain with the Craton margin.

The remaining ca 2.1 Ga, oceanic lithosphere was underthrusted northward. By 1.75 Ga (age of the Sierra Madre granite), movement at the Cheyenne belt and Farwell Mountain backthrust stopped and Green Mountain arc was wedged into the Archean crust along conjugate thrusts.

THE MID- PROTEROZOIC

Subduction polarity change has been recorded from the evidence of geological study and isotope dating of the rocks of the North Bay area Grenville province, Ontario. The use of U-Pb to date granitoid rocks from the northwestern part of the Grenville province of Ontario and, the ages obtained from the region were subsequently correlated with those obtained from coeval plutonic rocks of the southeastern part of the province. Three ages of mid to late Proterozoic were assigned to three suites: Elzevir (1.27-1.23 Ga), Frontenac/Chevreuil (1.18-1.15 Ga) and Tamaatta/Kensington suites (1.09-1.06 Ga). The Elzevir suites were made abundantly of Calc-alkaline and Metavolcanic rocks and they combined to represent Arc-back. Arc magmatism and terranes amalgamation (Carr *et al.,* 2000) occurred prior to closure of the basin at 1.2Ga (Hanmer and McEeachem, 1992; McEeachem and Van Breenman, 1993; Wasteneys *et al.,* 1999; Van Breenman, 2000) identified two younger A-type characters. The A –type character depicted that it was developed in a different crustal regime for the coeval predominantly calc-alkaline plutonic rocks of the composite Arc belt of the central Metasedimentary Belt.

However, Davidson and Van Breenman (2001) attributed the relationship between the two A-type character as Mid-proterozoic plutonism in the Grenville parautochothon as a distal, and intraplate consequences of arc or back-arc magmatism along the margin of Laurentia at that time (prior to continental collision at ca 1.2 Ga)

Model was used to interpret the southeastern edge of the Laurentia by Rivers (1997); Hanmer *et al.* (2000); Rivers and Corrigan (2000) during the early and middle Mesoprotoerozoic (1.5-1.2 Ga) as convergent margin and the plutonic rocks as the result of long-lived continental magamatic arc. The occurrence of marine volcanic suites and plutonic at various locations within the southeastern Grenville province was traced to the time, the margin had a retreating subduction given rise to extensional back – arc / marginal (Rivers and Corrigan, 2000) and splitting of the magmatic arc (Hanmer *et al.,* 2000). This situation can only be explained by subduction polarity reversal and, this made Davidson and Van Breenman (2001), to conclude that the subduction polarity in the Mesoproterozoic prior to closure at 1.2Ga was toward the present day -northwest.

ORDIVICIAN - Early Siluria

Anderson *et al.* (2003) used U-Pb to date the Halti igneous complex located at the border between the Finland and Norway (Figures.4 and 4a) resulted in new evidence that supported the condition surrounding the occurrence of the igneous complex as being due to the subduction polarity reversal.

The evidence obtained also support the closing of the Lapetus in the northern part of scadandivian caledonides were controlled by the Eastern -subduction system. The Eastern-subduction was said to be responsible for the contemporaneous occurrence of Island arc along the Luarentia and back-arc basin along the Baltica margin. Underthrusting of the Laurentia continental margin beneath the island arc, along the outer margin of Baltica, crystallization of eclogite occurred before the collision that gave rise to subduction polarity reversal and thereafter underthrusting of Laurentia by Baltica.

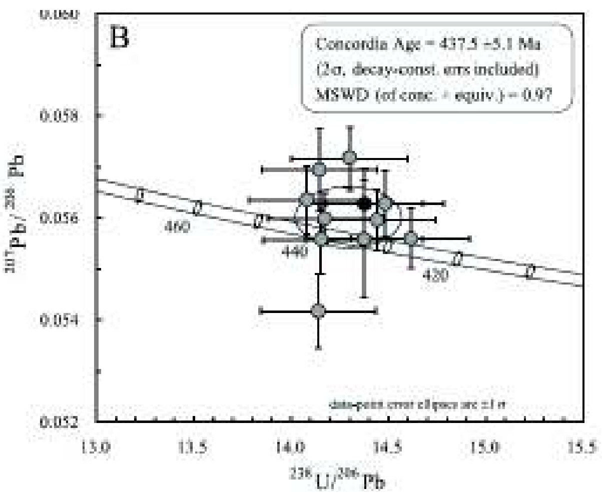

Fig.4a. *the use of isotope data for the constrain of subduction polarity reversal adopted from Andreason et al, 2003.*

The changed in subduction polarity was adduced to the collision of arc thickened by batholic emplacement with the continental margin. Subduction polarity reversal occurred at 435 Ma would allowed the subduction of Baltica to 100km deep, which composed of eclogite at 425 Ma (Griffin and Brueckner, 1980)

AN INSIGHT INTO THE PROTEROZOIC FARWELL MOUNTAIN-Lester Mountain suture zone, Northern Colorado: subduction flip and progressive assembly of arc

The geology of the area was highlighted by the paper to deciphered where the tectonic boundary have been misconstrued, because according to the paper, the history and the process of the crustal growth of continental lithosphere of the southwestern of the united state has not been made clear, In spite of the numerous works that have been carried out.

In the light of this, the paper assembled data that consists of structural, geology, geochronology, seismic and teleseismic image to attempt to unravel where there has been variation in the work of others and also make clarification. The first attempt was to delineate the tectonic boundary of the Farwell-Mountain (FM)-Lester Mountain (LM) suture zone from the geology of the area combined with geochronology (Fig.5).

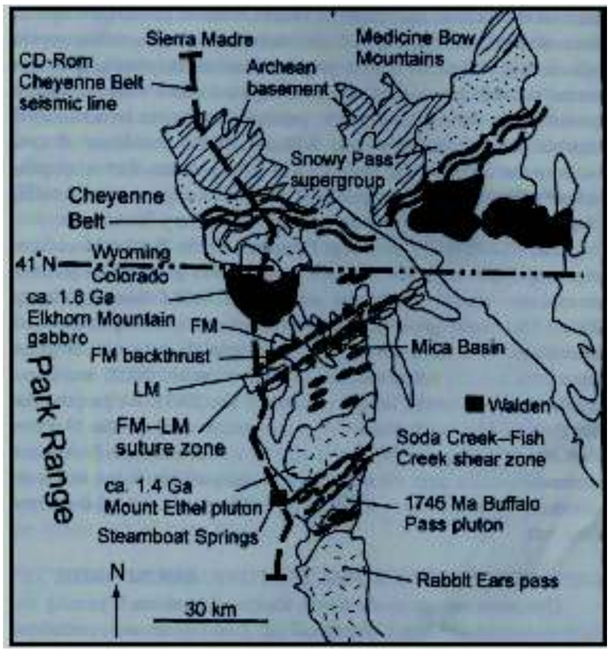

Fig.5. *Geologic map of Farwell mountain-Lester Mounain suture zone (Tyson et al., 2002).*

The FM-LM is bounded in the north by the Archean Wyoming, which consists of >2.7-2.5 Ga basement rocks overlain by 2.4-2.1 Ga, Miogeosyncline Snowy pass super group, preserved in the Sierra Madre as a wedge of subvertically foliated rocks at the south edge of the Archean block (Fig.5). The Miogeosyncline rocks and those of Archean and Proterozoic gneisses were deformed by the Cheyenne belt, which is a set of steeply dipping amphibolite-grade shear zone. And to the south of the Cheyenne belt is the Green Mountain formation ca, 1.79 -1.78 Ga (Premo and Van Schemus, 1989).

The FM-LM suture zone is made of different type of metamorphic rock equivalent of sedimentary rocks and volcaniclastic rocks and other type of metamorphic rocks. These were interpreted by the paper as tectonic silver of ophiolite within sedimentary accretionary complex. This however was contrary to that of (Foster *et al.,* 1999) that interpreted as a tectonic boundary on the bases of strong lithology contrasts.

A continuing convergent tectonics was interpreted for FM-LM suture zone on the bases of presence of tectonic generation of the third order. This evidenced from the crisscrossing of axial planes on the folds and foliation experienced during the shearing and this resulted in the conclusion that the suture zone was a multiple shear zone due to discovery of tectonic fabric generations.

The rocks in the south are found to be younger than those of the North of the suture zone. The younger rocks also have higher peak of metamorphic assemblages than those of the north, which have low peak metamorphic. These are the supracrustal granite ca, 1.746-1.735 Ga (Premo and Van Schemus, 1989) rock of the Rawah. The interpretation of the occurrence of the different metamorphic regimes was attributed to the reactivation of the structural boundary based on ca1.680Ma Sphene date in the Soda Creek-Fish Creek shear zone 30 km to the south (Chamberlain, 2002). In the northeast of FM-LM is a shear zone knows as Soda Creek-Fish Creek, which was highly strain and ductile (Snyder, 1980) and the presence of tectonic generations, it was inferred as synkinematic with adjacent ca, 1.42 Ga Mouth Ethel pluton.

Seismic reflection showed that the Archean-Proterozoic boundary connected to group of opposite dipping reflection (Morozova *et al.,* 2002), which corresponds to sharp contrast between highly reflective crust to the north and low reflective crust to the south (Fig. 4). This Archean and the Proterozoic boundary was interpreted as an interwedged feature along conjugated thrust (Fig. 4). To the south, the Proterzoic depicted a south dipping reflection that appeared at the Cheyenne belt and a north dipping reflection as representing underthrusting of ca,2.1Ga Oceanic lithosphere northward beneath the craton margin. This confirmed that the high velocity body is Proterozoic in age and it is due to anisotropic olivine fabric. And the south dipping reflection that reached 22km close to the LM was interpreted as a contrast between adjacent metasedimenatry and metavolcanic assemblages in a wide suture zone that are separate from the Green Mountain Formation

The integration of the geologic and seismic data was used to make tectonic analogue model of Proterozoic crust at the Cheyenne belt and the Farwell Mountain- Lester Mountain. Consequently, the paper suggests that the assembly of the Proterozoic crust at the Cheyenne belt and FM-LM is similar to the collision of the Australian continental crust with the island of Timor. And they deduced from the model the interpretation as showed in Fig. 6. Fig. 6A shows a thinned craton margin due to rifting (post 2.1 Ga rifting) in which the Paleoproterozoic Snowy Pass supregroup was deposited. The south dipping subduction system formed the Green mountain arc at 1.79-177 Ga resulted in the closure of the ocean. Fig 6B depicts the craton margin migrating towards the trench system at 1.77-1.76 Ga and subsequently discontinuation of the south-dipping subduction. Fig. 6C shows the collision of the craton margin with the Green Mountain. At 2.1 Ga the oceanic lithosphere was underthrust northward. By 1.75 Ga the movement of the Cheyenne belt and FM-LM backthrust stopped and the Green Mountain arc crust was wedged into the Archean crust along the conjugate thrusts. This is showed in the regions in seismic reflection section as where there is a sharp reflective contrast which represent the Archean-Proterozoic boundary. Evidence in support of the underthrusedt slab was the presence of the high velocity body interpreted in the seismic section (Fig.3),

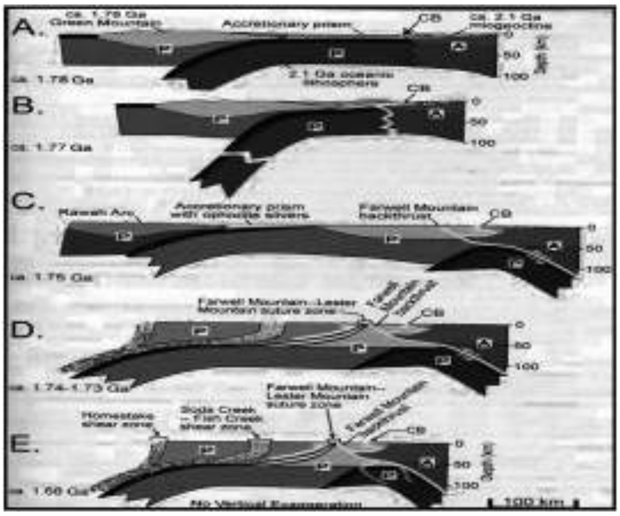

Fig.6: *Analogue model representation of FM-LM su-*

ture zone (Tyson et al., 2002)

depicted was the piece of Proterozoic oceanic crust mantle adjacent to the Archean mantle, and reflected that subduction was not matured as a result of the absence of Proterozoic magmatism above it. D depicts that at 1.76-1.72 Ga Rawah arc collided with the Proterozoic margin at 1.746-1.74 Ga and finally E shows the steeping of the accretionary structure ca, 1.68 Ga as result of continued convergent tectonism.

CONCLUSION

The following conclusions are drawn for the paper.

In spite of the different hypotheses proposed as to the causes of subduction polarity reversal; collision, slab break off and roll-back are the major mechanisms required for subduction polarity reversal to take place.

That the use of integrated geologic data which include structural, metamorphism, P.T data, heavy minerals and sedimentary facies, geochronology and use of seismic and tomography data are important factors needed for the delineation of subduction polarity reversal. Provided such geologic data are coeval with the period of the occurrence of subduction.

That subduction polarity reversal leads to the formation of uplift and deformation of the upper crust and continued collision may also results in strong deformation that may lead to seismicity and Orogeny respectively. And such Orogens that emanates from subduction polarity reversal are characterized by very short-lived duration.

That rocks occurring beneath subduction zone record events activity and the occurrence of high pressure-temperature minerals surrounded /parallel to the occurrence of low pressure-temperature in the upper crust like in obduction and core complexes.

That occurrence of different metamorphic regimes was an indication of subduction polarity reversal.

REFERENCES

Andreasson, P.P., Gee, D.G., Whitehouse, M.J. and Schoberg, H. (2003). Subduction-flip during Lapetus Ocean closure and Baltica-Laurentia collision. *Scandinavian Caledonides:Terra Nova* **15 (6):** 362-369

Carr, S.D., Easton, R.M., Jamieson, R.A. and Culshaw, N.G. (2000). Geologic transect across the Grenville orogen of Ontario and New York. *Canadian Journal of Earth Science* **37:** 193-216

Davidson, A. and Van Breemen, O. (2000). Age and extent of Frontenanc plutonic suite in the central Metasedimentary Belt, Grenville province, southeastern Ontario, Radiogenic Age and isotopic studies; Report 13, Geological Survey of Canada Current Research A2000-f4 7p

Davidson, A. and Van Breemen, O. (2001). Mid-Mesoproterozoic granitoid rocks of the north bay area, Greenville Province, Ontario; Radiogenic Age and isotopic Studies:Report 14; Geological Survey of Canada, Current Research 2001-F8,15p.

Dewey, J.F. (2005). Orogen can be very short;www.Pnas.org/cgl/dol/10.1073/pnas.0505516102

Dewey, J.F. and Bird, J.M. (1970) Mountain belts and new global tectonics. *Journal of geophysical Research* **75:** 2628-2647

Dewey, J.F., Helman, M.I., Turco,E., Hutton, D.H.W and Scott, S.D. (1989). Kinematics of the western Mediterranean. In: Alpine tetronics (Coward, M., Dietrich, D. and Park, R. eds). *Geological Society,* London Special publications, **45:** 265-283

Hamiton, W. (1979). Tectonic of the Indonesian region. *U.S Geological Survey Professional Paper* **1078:**1-308

Henmer, S. and McEeachern, S. (1992). Kinmatic and Rheological Evolution of a crustal-scale ductile thrust zone, central Metasedimentary Belt, Grenville orogen Ontario. *Canadian Journal of Earth Sci-*

ences **29:** 1779-1790

Konstantinovskia, E.A. (2001). Arc-continent collision and subduction reversal in the Cenoozoic elution of the Northwest pacific and example form Kamchatka (N.E Russia). *Tectonophysics* **33 (1-2):** 75-94

McEeachern, S. and Van Breemen, O. (1993). Age of deformation within the central metasedimentary belt boundary thrust zone southwest Grenville orogen; constraints on the collision of the Mid-Proteroxoic Elzervir terrane. *Canadian Journal of the Earth Sciences* **30:** 1155-1165

Mckenzie, D.P. (1969). Arc-continetal collision and subduction polarity reversal. *Geology* **18:**1-32

Morozova, E.A., Wan, X., Chamberlain, K.R., Smithson, S.B. and Karlstrom, K.E. (2002). Interwedging nature of the Proterozoic sature zone from seismic reflector data, *Geophysical Research Letters* (in press)

Sipila, P. (1992). The Caledonia Halti-Ridnitohkka igneous complex in Lapland. Geological Survey Finland, bulletin **362:** 1-362

Rivers, T. and Corrigan, D. (2000). Convergent margin on soutjeastern Laurentia during the Mesoproterozoic; Tectonic Implications. *Canadian Journal Of Earth Sciences* **37:** 359-383

Solomon, M. (1990). Subduction arc reversal and the origin of porphyry copper-gold deposit in island arc. *Geology* **18:** 630-633

Tyson, A.R., Morozova, E.A., Karlstron, K.E., Chamberlain, K.R., Smithson, S.B., Ducker, K.G. and Foster, C.T. (2002). Proterozoic Farewell Mountain-Lester Mountain suture zone, Northern Colorado: Subduction flip and progressive assembly of arcs. *Geology* **30 (10):** 948-846

Wasteneys, H., Mclelland, J. and Lumbers, S. (1999). Precise zircon geochronology in the Adirondack lowlands and implications for revising plate-tectonic models of the central Metasediment of Belt and Adirondack Mountains, Grenville Province Ontario and New york. *Canadian*