

Time of Flight Survey by Artificially Generated Neutrinos: A Novel Complementary Approach in Remote Sensing Geophysics

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Abstract

In the present article I present a novel complementary geophysics methodology that represents a means for achieving an improved understanding of the Earth's seismic activity. The concept is based on neutrino particle physics whereby neutrinos, artificially generated, are passed through the Earth's lithosphere and core at varying angles to be detected by an array of fixed or mobile neutrino counters. By real-time assessment of time of flight of neutrino particles crustal deformation or strain changes may be made. This is based on the straightforward premise that deformations within the Earth's crust shall alter the lengths of selected neutrino pathway baselines through areas at the junctions of tectonic plates forming active fault regions. The system can be arranged to scan an entire selected fault line at depth in an attempt to detect early on strain variations in the crustal structure that may be a prelude to fault line slippage or shear. The concept is built partly around the notion of dilatancy in crustal structure under stress in fault line regions and can be used to assess the contribution of this factor towards seismology. Physical alterations in rock structure via dilatancy principle would be predicted to adjust the baseline length for neutrinos passing through the crust. Such neutrino baseline determinations are carried out via neutrino sources and detectors placed remotely from the active site(s) of fault movement. Variations in Earth surface topography are not relevant to the approach, thus removing a significant source of error inherent with other methodologies aimed at fault site tracking. These methods are limited to surface analysis with data extrapolation to distortions occurring at some depth, viz: to the region(s) of initiation of seismic activities. Suitable internal and complementary controls are presented for neutrino time of flight, for example via InSar geodetic measurements. Combining the time of flight concept with measurements by other currently used seismological methods may be beneficial in assessing whether a pattern of recognition can be set up to estimate earthquake forerunner activity. Comparison to other currently accepted technologies for crustal strain measurement are made and comparative advantages of the time of flight concept are given. Drawbacks in development of the technique are discussed in the light of the current state of play of neutrino physics and likely error sources. From a remote geophysics aspect, the neutrino time of flight approach in combination with other procedures such as neutrino oscillation tomography may enable an improved understanding of fluid movements and rock rheology as part of the dynamic Earth's structure. Overall, time of flight offers the potential as a useful additional technique to be developed for remote sensing geophysics.

Keywords: Coseismic; Fault zone; Geologic dilatancy; Interseismic period; Lithosphere; MSW effect; Neutrinos; Neutrino oscillation tomography; Neutrino time of flight; Tectonics

Introduction

There can be no doubt that there are few fields of research in applied geophysics requiring more urgent development than seismology. Little introduction is required to emphasize the pressing need for additional complementary technologies to reinforce our ability to predict earthquakes. Regions such as Japan, New Zealand and within the Middle East (Iran) and on the Western fringe of the United States to name but a few are subject to unexpected and devastating seismic events, for example, the 1995 Kobe destructive earthquake of magnitude (M) 7.2. This was considered an example of strike-slip frictional shear brake-down of faultline. The focus of the earthquake was less than 20 km below Awaji-shima, an island in the Inland Sea of Japan not far from the city of Kobe. The earthquake was particularly devastating as it followed a shallow focus. The resulting surface rupture presented with an average horizontal displacement of ~1.5 m on the Nojima fault which runs along the northwest shore of Awaji-shima Island. Destruction in Kobe was widespread. The 2011 seismic event in Van, Eastern Turkey, was also of M 7.2 and followed the Ercis faultline, a known risk area. The destructive capabilities of tsunamis/tidal waves occurring as a secondary feature to sub-ocean earthquakes in particular has all too well been evident in recent times, particularly with the 2011 Tohoku earthquake, ~70 km from Japan's Eastern shore.

These events provide ample evidence that the Earth's crustal

structure is ever changing. An approach is needed that is able to directly, in real time, measure or scan the structure of the Earth's lithosphere in order to assess structural alterations or strain occurring in the subsurface as a result of stress buildup along faultlines. These measurements could then be translated into a comparative correlation with other indirect assessments such as surface strain analyses and seismological wave measurements to estimate whether a pattern can be established that may forecast forerunners to significant seismic activity.

The novel approach I take in this article is to propose the use of the properties of neutrinos to directly probe/scan in real time the internal structure of fault zones by measuring the time of flight between remote sensors and source-neutrino time of flight (NTOF). This method is based on the notion that fault zones contract and dilate and undergo internal shearing and torsion alterations under

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the influence of seismological stress. Small variations in the crustal thickness of the fault zone that occurs as a result may be sensitively and specifically directly imaged in real time by measuring the travel time a controlled and directed neutrino beam takes to traverse the fault area. By building up a pattern of time variations over a scanned region of the crust in the area of the fault a time-based tomographic map may be constructed which outlines the internal time-changing architecture of the zone of interest. Controls taken over a region not involved in the fault zone can serve as a reference. It is estimated that this novel remote sensing approach can complement other currently available more indirect methods employed in seismology. The final outcome of combining these complementary techniques being aimed at providing information that will aid in greater accuracy in earthquake prediction.

This article reviews relevant literature in this field such as the use of neutrino oscillation tomography (NOT) as an essential background to the present proposition. This approach [1,2] can be combined with NTOF for more detailed structural analysis of the Earth's interior in general—not only around fault zones. By employing a scanning 'CT-like' approach as outlined in this review, data analysis may be synthesized via NTOF and NOT that potentially would allow for an improved understanding of rock rheology, dilatancy, fluid flow amongst other features in a direct real time fashion. Overall, this application of technologies using neutrinos can have a significant impact upon our understanding of the Earth's structure overall.

My own background is from medical research and here I present the analogy of the Earth as the 'patient' under study and the approaches being used to 'image' this 'patient' are likened to CT scanning in that structures deep to the surface are being examined. In a similar fashion, the science of Earth related studies can be in a way compared with that of diagnosing a medical patient. The technology I describe in this review relies significantly on the same principles CT scanning employs to delineate structural information within the body. Examining through use of remote radiation source and sensors one may gather important information concerning features laying deep within. Also, in a similar fashion to medicine, complementary approaches can be combined in Earth sciences thus yielding information of importance for geosciences.

Methodology: Background and NTOF Concept Development

For the purpose of this study, the literature is examined in regards the use of neutrinos for determination of seismic activity, indirectly via assaying distances through the Earth's lithosphere. It was considered by the author that a useful relationship could be developed that may be effective as a complementary technology to present day seismological methods. Selected key words used in examining the literature were: neutrino tomography, seismology, earthquake prediction, neutrino time of flight connected via the Boolean operator 'and'. The concept used was to relate two independent literature fields: seismology and neutrino, thereby deriving a novel relationship between the two. This approach of literature based research is oftentimes employed in the medical sciences in order to derive novel and important relations [3]. The process of generating novel concepts via connecting seemingly unrelated scientific facts (or indirect associations) is known as 'literature-based discovery' (LBD). LBD is based on the consideration that two islands of knowledge (concepts) A and C may be related to each other if they share a link to an intermediate concept, B. This approach is generally known as Swanson's 'ABC' model [3].

In this present article, I consider concept A as representing

seismology/seismic activity and concept C as representing neutrino particle physics. Concept B linking these knowledge 'islands' being a physically measurable quantity such as distance (indirectly: fault zone distortion-strain). Therefore neutrinos in the NTOF approach are being used to assay, indirectly as a remote sensor, the distortion/strain deformation in the fault zone.

Neutrino time of flight measurement was initially put forward to assess, in real time, continental drift as an aid to earthquake prediction [4]. It was indicated at the time that this technique had great potential to measure accurately the distances between two points one on either side of a fault line by measurement of time of flight. This concept with use of neutrinos artificially produced to survey for earthquake prediction from tectonic drift was, at the time, a first in its class and provided a stimulus for my development of the present NTOF technology for remote sensing geophysics in seismology.

The technique, as originally stated [4], makes use of a structured beam of high energy accelerator protons such as existed at Fermilab and CERN. At that time, 53.2 MHz radiofrequency accelerating system of the main ring of Fermilab made 400 GeV protons which were produced as described in 'buckets': 1 ns wide with 10×10^{10} protons/bucket and with 18 ns separation between the 'buckets'. After target impingement, pions and kaons are produced. The subsequently produced muon and electron neutrinos are formed as decay products of the secondary particles, viz: kaons and pions. These then traverse with minimal interaction through the Earth to be detected. It was considered that muon neutrinos could be sampled at the receiver with these carrying a significant proportion of the neutrino energy. In terms of detection, a whole target calorimeter detector was one of the types considered. The proposed detector array consisted of a three-dimensional lattice of very fast-reacting photomultipliers located in a subterranean region. The photomultipliers provide a set of measurements of the amplitude and time of arrival of the Cherenkov light events from the muon neutrino interactions. From these data the trajectory and indexed proton reference 'bucket' can be calculated. In-so-far as time synchronization was concerned the use of Cesium atomic clocks were considered for this purpose. In this scheme, the detectors are in fact Cherenkov-based and placed undersea. The precise location of the detector must be known with reference to a fixed bench-mark as a calibration and this may be done with aid of acoustical positioning techniques. The limit of accuracy to which a particle beam line (baseline) measurement could be made was given by [4]:

$$\Delta d = ct_b \sqrt{12n}$$

Assuming uniform distribution of neutrinos within a 'bucket', c = speed of neutrinos—believed then to be speed of light (as it is today); t_b is the time width of the bucket/packet which is taken as 1 ns, n = number of interactions detected. Assuming a 0.5 ns resolution in time of arrival of the pulse and with 10×10^5 interactions then the accuracy in beam line measurement—the length or distance between source and detector—was considered to be ~0.3 mm.

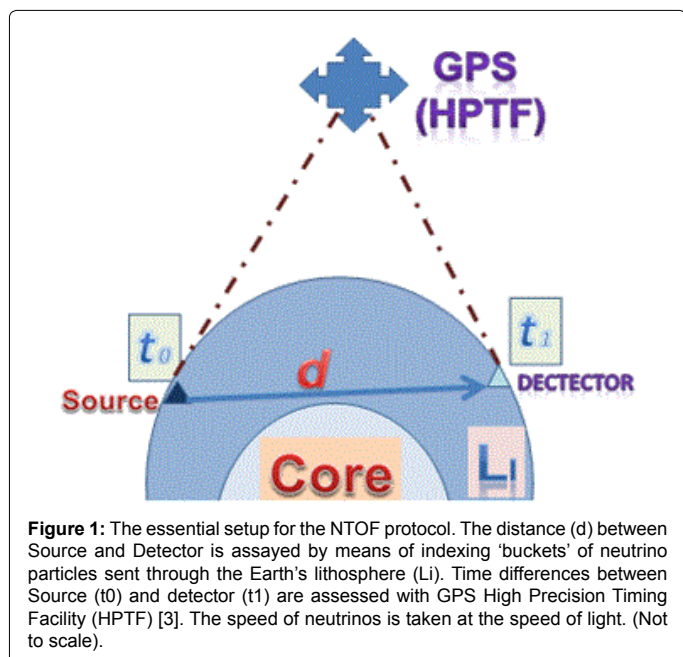
The decay tunnel used to produce the neutrino beam will cause a smear effect in transit time—as kaons and pions will decay at varying lengths along the tunnel—not just in one spot. This smearing can be calculated and corrected. For example, a 14 GeV pion decaying in a 2 km tunnel the smear time difference is 0.3 ns. A correction equation is available [4].

It was stated in the research proposed at that time [4], given the level of technology, that the accuracy of distance measurement would be enough to see the tidal (10s cm/day) and lateral motion of the

Earth (approx 100 cm/day). Additionally, tectonic plate motion of cms/yr could be confirmed if a detector is on one plate and emitter/source placed on another tectonic plate. For example, using the North American plate for Fermilab source emitter and with a detector on either the Caribbean plate or Juan de Fuca plate. It was considered that the benefit of this proposal was to in effect measure relative tectonic plate motion that may relate a pattern effect to earthquake formation. In fact, it has been shown that precursory seismic quiescence occurs not uncommonly prior to earthquakes [5] and may be quite relevant to the scheme proposed [4].

Technical advances clearly have been achieved since then that would appear to rate this approach (NTOF) now relatively practical. OPERA (Oscillation Project with Emulsion-tracking Apparatus), an experiment to test the phenomenon of neutrino oscillations, uses CERN at Gran Sasso (CNGS) as a baseline with a high intensity and high-energy beam of muon neutrinos made at the CERN Super Proton Synchrotron in Geneva directed through the Earth's crust to the Gran Sasso laboratory 733km away in central Italy. It aims to detect tau neutrino appearance from oscillation of muon neutrinos in their ~3 millisecond time of flight. The CERN beam was created artificially by accelerated protons with a graphite target and the resultant particles—pions and kaons—decay to muons and neutrinos with the muon neutrinos passing through the Earth's lithosphere arriving at Gran Sasso. Plastic scintillator counters count the particle interactions in the detector and arriving particles are assessed by magnetic spectrometers for momentum and charge identification in real time. This remains one of the most sophisticated experiments to date that has taken into reality the earlier proposal to examine neutrino time of flight through the Earth [4]. Yet it has not been designed to examine continental drift nor any inherent structural feature of the Earth—rather to examine aspects of neutrino 'physiology'. In the present article I aim to build on that theme to demonstrate the practicality of using NTOF methodology to assess the Earth's structure—with particular reference to seismology.

In principle, I utilize and develop NTOF for accurately and precisely measuring the distance between two points located within the lithosphere via the relation: $d=vt$ (Figure 1). The concept was devised



as based on the OPERA experiment (above) and further stimulated by the work of Bostrom et al. [4]. GPS is used to synchronize the atomic clocks in this scheme and thus for distance determination. More up to date time links have been devised [6]. The high precision timing facility (HPTF) is a GPS-based timing facility with a calibrated time-link to the GPS receiver at the CERN and with continued real-time monitoring of time delay in neutrinos to the receiver underground.

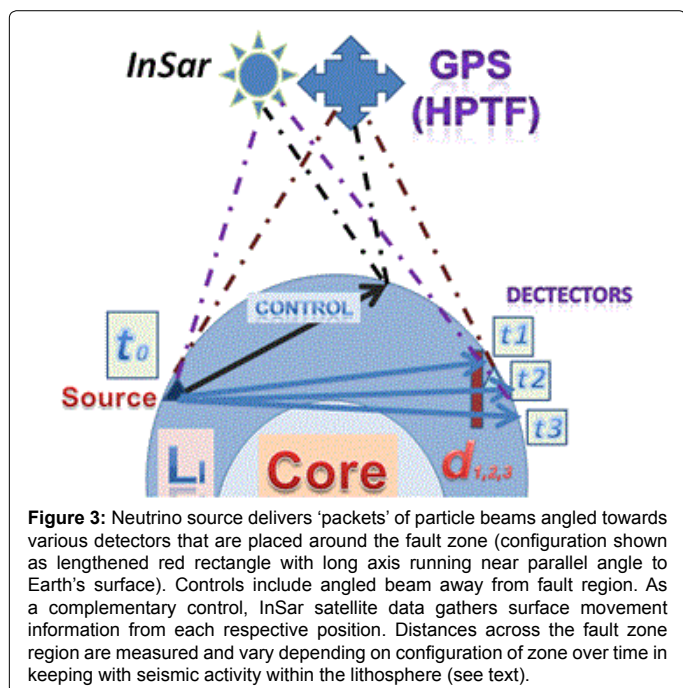
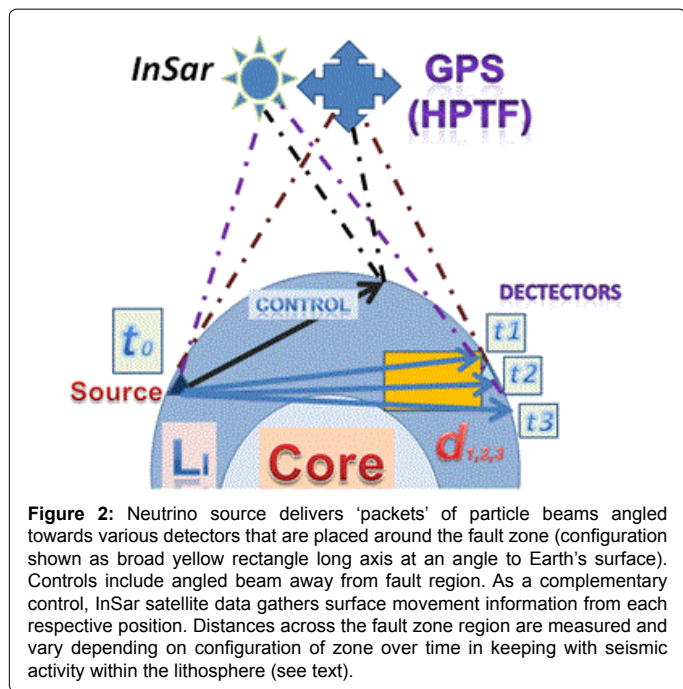
The OPERA neutrinos were produced over a time spectrum initially and to eliminate statistical errors CERN later produced 'bunches' of proton beams resulting in neutrinos. These bunches were produced at 3ns at intervals of 524 ns. Thus every neutrino event may be correlated with a given proton/bunch unambiguously tying a time event of proton and neutrino production with a received neutrino package. After correcting for electronic errors in data analysis it was concluded that neutrinos travel through the Earth unaffected by the material passing through and dedicated to light speed. Error analysis indicated that the determination could be made within 5 ns for the distance observed using bunched proton data. My present scheme follows on from the use of 'bunched' neutrino packets by OPERA and as outlined previously [4].

Independent yet complementary means to monitor distances which produces surface shifting uses the InSar principle (Interferometric synthetic aperture radar) [7]. This approach, used in geodesy and remote sensing, employs synthetic aperture radar (SAR) images to create maps of Earth surface contour. InSar is capable of defining cm-scale alterations in surface configuration due to seismic activity over time, for example with the Bam, Iran earthquake in December 2003 [8]. InSar is used alongside the NTOF protocol in order to cross-compare with an established methodology and relate the NTOF findings to surface shift phenomena in order to determine if clear predictive relation may exist.

Suitable negative controls are designed whereby NTOF data is gathered simultaneously from zones remote from the area of seismic interest (fault zone). InSar data is likewise collected from such areas. NTOF data may be gathered from artificially altering the baseline between source and receiver in order to offer a positive control. Sources of error such as GPS timing and clock and communication lead disturbances and atmospheric and surface subsidence for InSar offer systematic errors that need to be taken into consideration. Means for minimizing such errors and controlling for these are discussed (General Discussion and Conclusion).

My overall proposed methodology for performing NTOF surveying approach is outlined in Figures 2 and 3. In this technique, neutrinos originating artificially from source are directed at differing angles through the Earth. These beams are detected at a number of locations. The 'time of flight' between source and detector determines the length of each selected baseline that in turn is used to generate a remote sensing tomographic map of the fault zone and surrounds in real time. Locations of sources at different sites can generate a baseline time-dependent tomographic mapping that may allow quite specific definition of altered fault zone configurations. Detectors may be located underground to avoid surface interference from diurnal temperature variations and subsidence. Alternatively, the detector may be located above ground or even be satellite-based. In this regard, mobile scanning of a fault zone region could be considered.

Thus, in summary, in terms of localizing a particular shift in distance to either represent a compression or torsion or other dimensional change within the fault zone the NTOF procedure can be seen as



readily applicable. Baselines from varying sources could be made to intersect over the scanned fault leading to a 3-dimensional map of the altered focus within the fault zone—again, very much like the process a CT or MRI uses to localize a region of altered density/pathology within a patient undergoing imaging tests. In this analogy, 'slices' are taken through the fault zone and built-up into a 3-dimensional pattern via computer reconstruction using digital geometry processing, much as a medical CT scanner employs. The baselines can be set up to 'scan' the fault area through a common axis of rotation—again, much as in the same way a CT scanner operates. The analogy with a CT scan is useful in this context as, with the case of medical approaches, deeper

structures can be visualized—so too with analysis of the fault zone, by remote sensing applied geophysics, viz: NTOF. Baselines not passing through altered areas will seek to further define the extent/localize the focus of fault zone distortion. In turn, these gathered data can be thence correlated with other seismic imaging technologies such as seismic wave analysis to cross-compare.

Key to this scheme are suitable controls. Internal controls can be designed to angle the Source beam towards regions of either tectonic plate forming the fault zone but away from the region of direct seismic activity. This would control for inherent tectonic drift unrelated to fault zone activity and also control for Earth-related movement such as tidal influences. Such internal checks would also serve as a positive control to examine the accuracy and precision of the NTOF approach as compared to current gold standard (GS) measurements such as InSar. Comparative sensitivity and specificity in relation to the GS and the development of receiver operating characteristic (ROC), would be of use to determine the inherent utility of the NTOF method for distance analysis in real time. Certainly, appropriate complementary InSar controls are needed to independently account for tectonic drift, Earth movement and surface variations (diurnal and subsidence) that would interfere with the distance measurements. If the Source is on a distant tectonic plate unrelated to those bordering the fault zone in question then these outlined controls are particularly important and need to relate to the relative movement of plates that source and detector are placed on. NTOF data analysis would necessarily have to take into due consideration correction for confounding Earth/tectonic movement variables as these would certainly have a strong bearing on measuring fine distance displacements in real time.

In Figures 2 and 3 the seismic area is depicted as a rectangular box in two varying configurations. It is imagined that the box zone may undergo torsion or compression/elongation. It ought to be pointed out that clearly any scheme such as depicted in these diagrams represents in reality a gross over-simplification. Seismic activity zones are inherently complex structures (The 'anatomy' of a fault line—relevance to seismology). The technology would therefore require modeling multiple overlapping physical seismic zone configurations—therefore taking into consideration the complexity of the fault area. This inherent complexity has been adequately outlined previously for the Longmenshan fault zone [2] (Neutrino applications in Earth science).

Results and Discussion

The 'anatomy' of a fault line—relevance to seismology

In the medical profession the first line of understanding comes from anatomical dissection. In a similar way, the 'anatomy' of a fault zone ought to be first discussed. An excellent review on this subject has been presented earlier [9]. As a feature of the fault zone it can be said that shear pressure localization in narrow zones of the Earth's crust results in fault rocks. The deformation of these fault rocks is oftentimes controlled by fluids (see Section: Dilatancy). It can be said too that fault rocks differ significantly from surrounding host rock. There are dilating and compacting regions within the fault zone. Fault zone permeability is related to stress and strain rates amongst other factors and all of these issues are important in seismogenesis—particularly the features related to fluid pressures and overall permeability. These discussions are not inconsistent with the application of the dilatancy hypothesis (see below).

It is important to note that the seismogenic capability of a fault zone depends very heavily on internal structure. Rupture propagation

Vs. arrest depends on dilational areas and fault bends. Furthermore, frictional properties of faulted rocks determine whether the fault slips unstably or via slow creep mechanisms.

In terms of the evolution of the fault zone, a unifying picture here is difficult as fault zones are heterogeneous with highly complex internal structure. Localized slip areas occur so very focal weaknesses are present which are hard to detect. There is a significant role for host rock weakening and peripheral fracturing (the so-called: damage zone) in fault zone evolution. Dilatant fractures in low-porosity rocks form as an initial fracture event and can place a zone around the rupture. So these dilatant fractures result in weakening of the host rock next to the developing fault and lead to widening of the fault and are just as important as inherent rheological fault rock properties.

Shear fractures can evolve from microcracks perhaps occurring in the dilatant fracture area. Elastic stress fields around the tensile microcracks promote brittle shear fractures. This accounts for anastomosing faulting patterns in the fault zone. So these peripheral fractures are important in the 'anatomy' of the developing fault zone. Dilatant fracturing is also a feature of porous water imbibing limestone's in early faulting.

Fault zone rock rheological changes are very significant in the development of faulted areas. In this respect, high porosity sandstones show deformation band faulting. This relates to fluid migration and resulting displacements are mm to tens of cm. Over time, work hardening of the fault rock occurs with localization of displacement zones or deformation zones. These features tend to typify higher porosity rocks.

Interestingly, in the case of alluvial deposits around seismogenic faults in California, it has been noted that fault damage zone width- or peripheral fracturing zone width- develops early on in fault zone evolution [10]. The active section of the fault zone narrows with further strain displacement. Therefore a time-dependent monitoring of fault zones is important so that narrowing regions are not missed during a later analysis (Discussion). Localization of early deformation into narrow slip zones is also seen from data from fault zone limestone's in the Gulf of Corinth in Greece [11]. It has been shown in a study of the narrow Median Tectonic Line in Japan that there is intense localization of deformation into a narrow central slip zone (mm's to cm's wide) within the fault zone region [12]. This suggests that in order to detect such areas a 'diagnostic approach' of very high sensitivity is needed (Discussion).

In terms of fault zone permeability structure, it ought to be borne in mind that faults are zones of deformation. Faults possess central areas of low permeability and peripheral damaged zones of higher permeability providing a conduit for fluid flow around the fault [13]. In active faults there is a heterogeneous distribution of fracture dilatant fault rocks. Porosity and permeability data from fault gouges is not easily achieved due direct measurement difficulties of these quantities. Nevertheless, there remains a need to measure the porosity-permeability relation under varying rock stresses to improve our understanding of the essential structural design of the fault zone. From what is understood though there are two fault rocks which are present of contrasting poro-mechanical properties-viz: low permeability granular material and higher permeability fracture dilatant material of an elastic-fracture nature [14].

With respect to seismology, the internal architecture of the fault zone is certainly of critical importance. Earthquakes are due to ruptures that nucleate, grow and terminate in a fault zone. Earthquake dynamics

is key here and is associated with elastic strain energy around the fault and release of this in the quake itself. Fault behavior depends on fault friction and shear fracture development. Most faults are seen as having an unknown internal structure and reaction to internal stresses with unknown resultant internal strain variations-the presently proposed scheme aims to help elucidate these unknowns (Discussion & Conclusion). Exhumation of rocks samples in the fault zone shows a level of complex architectures, for example, in strike slip faults. In this way, exhumation of the Punchbowl fault to 5 km depth in the San Andreas system shows 30 km slip on a metre scale wide fault core with a surrounding damage zone of 100s of meters. Most of the deformation is localized in focal parts of up to cm scale slip zones. Clearly sensitivity in detection is needed to localize these areas accurately (Discussion). Although there is no doubt that seismic wave behavior of fault zones yields much useful data for numerical modeling in order to understand heterogeneous internal fault zone structure, it is an aim of the present article to present a more direct approach to this problem via neutrino TOF tomography.

The all important aspect of seismology revolves around rupture nucleation and spread. Nucleation of earthquakes is due to frictional instability along a fault. Key to this is that fault surfaces are irregular and develop stresses within small zones at these so-called asperities. Ruptures nucleate in velocity weakening rocks only although fault zones are composed of heterogeneous areas of velocity hardening and velocity weakening zones. In propagation, sub seismic slip rates mm up to cm/sec are influenced by frictional interfaces between velocity hardening and weakening zones. This is not relevant at seismic slip rates-1 m/sec.

Seismic rupture propagation can be said to depend on material heterogeneities represented as velocity heterogeneities. Gaps between velocity weakening fields have to be not too large otherwise the velocity kick will not propagate through to the next velocity weakening field. So the outlay of the various composite rock structures within the fault zone determines to a large degree how the seismic wave shall propagate through the deforming rock of the zone.

A final key feature is rupture arrest. Kilometer scale dilational/contractional zones may form a reliable barrier to arrest large earthquakes [15,16]. Velocity strengthening materials also may stop a rupture if sufficiently located within the fault zone region. This argues for a relationship existing between dilation/contraction and the nature of the rocks in respect to proportions that are velocity hardening vs weakening. This can have implications with respect to prediction of where a given earthquake may terminate. Certainly, recent data have shown that whether the rupture is by unstable earthquake slip vs slow steady creep is controlled by velocity strengthening vs velocity weakening material distributions.

The NTOF technique explored in the present review may shine light on detailed analysis of such kilometer scale dilational/contractional zones. It ought to be noted that plastic deformation is also a part of rupture arrest [17,18]. This may in turn lend itself to being detected via the technique I propose in the present review.

Finally, in this section, it can be stated that two components are found in fault zone anatomy, a fracture dilatant permeability conducting area and a granular non-conducting barrier area. These concepts are key in understanding fluids dynamics in earthquake slip mechanics. The complexity/heterogeneity of fault zone internal structure makes predicting fluid flow and seismogenic activity very challenging. It has been indicated that linkage of fault zone internal

structure to seismic activity needs ‘a leap of scientific imagination’ [9]. A combination of approaches may assist though as such via seismological field data, direct drilling observations and laboratory measurements of frictional changes and fluids in various fault rocks. It is my intention to show that NTOF can add a further dimension to this process of linkage of fault zone internal structure to seismic activity. This could represent conceivably a tangible step forward in attempts to forecast earthquakes—the ultimate aim.

Dilatancy and relevance to neutrino time of flight

An important aspect to my present proposition with the use of NTOF is the notion that under physical stress, rocks deform or dilate (see above). This notion has been modeled previously [19]. American seismologists have used the dilatancy diffusion model and in this model it is proposed that an earthquake occurs in areas of maximum stress following a period of dilatant crack expansion. Diffusion of water in and out of the dilatant volume being needed to explain recovery of seismic velocity prior to earthquake. Soviet seismologists have argued that growth of rock cracks is also involved but diffusion of water is not required. Here, earthquakes occur during falling stress and velocity recovery is due to crack closure as stress relaxes.

To provide a further background to this concept is the earlier heavily cited defining work of Brace et al. [20]. In this study, volume alterations of granite, a marble, and an aplite were measured during deformation in compression. Stress-volumetric strain behavior is qualitatively similar for these rocks with elastic volume behavior being observed at low compressive stresses. As the compressive stress increased to a third or two thirds of the fracture stress the rocks demonstrate dilatant behavior at a given pressure. This means that the volume increases relative to elastic changes. The actual size of the dilatancy ranges from 0.2 to 2 times the elastic volume change that would have occurred if the rock behavior were simply just elastic. The degree of dilatancy is not found to be greatly affected by pressure. The process is interestingly time dependent—therefore, for granite the stress level at which dilatancy was first seen was higher the greater the actual loading rate. This may have in itself implications with respect to seismogenesis. Dilatancy represents an increase in porosity and leads to open cracks in the granite which form in parallel to the direction of maximum compression in these laboratory analyses. Again, this has implications with respect to earthquake fault zone architecture and seismology (see above and Discussion).

As indicated above with regards the dilatancy model, fluid ingress is a feature according to Western researchers [19]. Testing this effect in a time-dependent deformation-fracture simulation in granite has been performed in work from the 1980s [21]. In this study, specimens of granite are tested while in direct contact with water. It was noted that uniaxial compressive strength and the fracture toughness decrease by about 5% from the levels measured at routine room temperature and humidity. At very rapid loading rates (dynamic loading), the effect of water on strength is small yet in all time-dependent tests for creep strain, static fatigue and slow crack velocity, the effect of water is quite significant—that is, where the load is applied over a period. The creep strain and slow crack velocity increase and the long-term strength decrease when water is present. This suggests that imbibition of water by the rock via a dilatancy diffusion process leads to a rheological plastic alteration or creep. Where the rate of loading is fast it may not allow enough time for the rock to imbibe and become rheologically plastic. At a stress level of 65% fracture limit the steady state creep rate shown by lateral strain increased by 300% when water was present. Again,

these findings are important when it comes to considering earthquake propagation.

Therefore, to all intents and purposes, the dilatancy concept may be certainly considered to ‘hold water’ as one may say.

In regards earthquakes, the dilatancy hypothesis has been presented [22]. In this discussion, it is indicated that a significant proportion of prediction research is in fact centered around the theory of dilatancy. In this informal presentation it is indicated that when a rock is stressed it begins to expand - dilate. This is due to micro-cracks and fractures in the rock opening up and becoming larger and this appears to start when a rock is about half way toward its breaking point. Indirect subterranean seismic measurements are able glean information regarding what is actually occurring. Rocks under stress undergo deformation. In this respect the rock transmits seismic wave energy at changing speed. Indeed other properties such as inherent magnetism and electrical resistivity alter also. Physical dilation of rocks underground when spread over a significant area such as in a fault zone may lead to a general uplifting of ground surface and indirectly alter groundwater pressure and levels [23]. Workings based on aspects of dilatancy have also been applied to volcanology [24].

In earthquakes, the dilatancy hypothesis has significant experimental support and therefore forms an important backdrop for the present proposal. Having said this, recently, an excellent general overview monograph of the whole subject area has indicated that dilatancy is seen as commanding less importance in terms of earthquakes and volcanology at the present time [25]. In my present article I seek to add a further technology, viz: NTOF. There is certainly scope and potential for this novel approach to actually directly assess the degree to which the dilatancy concept applies in seismology and thus to determine its overall cause and effect relevance in the fields of today’s earthquake and volcanic studies (Discussion).

Neutrino ‘Physiology’

Essential to appreciating NTOF relates to understanding aspects of neutrino physics or ‘physiology’. In this section a basic over-view of the ‘physiology’ of the neutrino probe is presented as a prelude to my more detailed presentation of NTOF. The reader is also directed to much more in-depth accounts of the subject area [26]. The neutrino is a weakly interacting elementary subatomic particle with a half-integer spin, chirality and a disputed but small non-zero mass. It is able to pass through ordinary matter to all intents and purposes unaffected. The neutrino (meaning “small neutral one”) is denoted by the Greek letter ν (nu) in the research literature.

Neutrinos do not carry electric charge, which means that they are not affected by the electromagnetic forces that act on charged particles such as electrons and protons. Neutrinos are affected only by the weak sub-atomic force, which comes in a much shorter range than electromagnetism, and neutrinos are therefore able to travel great distances through matter without being significantly affected by it.

Neutrinos are created as a result of radioactive decay or nuclear reactions such as those that take place in the Sun, in nuclear reactors, or when cosmic rays interact with the Earth and its atmosphere. There are three types, or flavors, of neutrinos: electron neutrinos, muon neutrinos and tau neutrinos. Each type also has a corresponding antiparticle, called an antineutrino with an opposing chirality.

Most neutrinos passing through the Earth originate from the Sun. About 65 billion solar neutrinos per second pass through every square

centimeter perpendicular to the direction of the Sun in the region of the Earth.

One issue that has placed neutrinos to the fore of physics is with respect to their connection with the Sun (Neutrinos & Helioseismology). This was termed originally the Solar Neutrino Problem—this issue being that the number of electron neutrinos arriving from the Sun was between one third and one half the number predicted by the Standard Solar Model. This discrepancy remained unresolved for some thirty years until it was found that neutrinos possessed oscillation (changing flavor states) and mass.

It has been noted that flavor oscillations can be modified when neutrinos propagate through matter. This so-called Mikheyev–Smirnov–Wolfenstein effect (MSW effect) is important to appreciate as it is of relevance to the proposed use of neutrinos in geophysics as outlined in my review. A detailed description of the quantum physics behind the MSW effect is beyond the scope of this review nevertheless some outline is warranted. The MSW result is also known as matter induced oscillations. The concept of neutrino oscillations is that a neutrino has a quantum mechanical description (called an Eigenstate) that is actually a mixture of two different flavors or kinds. So, there is always a small probability that a neutrino might spontaneously change (oscillate) from one kind to the other. In a vacuum the probability is too small to reasonably explain the solar neutrino deficit. However, in the presence of high density matter (for example in the solar interior), then the probability of oscillation is strongly enhanced, almost to a certainty. Recent experimental data confirm the MSW model in that as a neutrino traverses through matter, its oscillation length is no longer the same as in vacuum. Electron neutrinos acquire an extra potential due to their interaction with electrons in the matter.

This explanation shows that the neutrino actually makes its change, from one kind to another, well inside the sun, and not while on its journey between the Sun & Earth in a vacuum. Hence the MSW matter interaction effect and neutrino oscillation and the Solar Neutrino Problem are all interconnected and show that neutrinos may possess an intrinsic property of reflecting matter density. This feature can be exploited for Earth-based seismological studies as will be examined in this review. Again, this is a further complementary technology to the proposed NTOF usage that I place forward in this article.

Geoneutrinos

A mention at this stage of geoneutrinos is of relevance to techniques dealing with neutrinos and applied geophysics. Neutrinos are part of the natural background radiation. In particular, the decay chains of ^{238}U and ^{232}Th isotopes include beta decays which emit antineutrinos. These so-called geoneutrinos can yield up quite useful information on the Earth's interior. Geoneutrinos therefore provide information as another type of probe to examine the Earth's substance. They indicate heat flow within the Earth and compositional status [27]. Convective heat flow is in turn related to tectonic movement and so geoneutrinos have a valuable place in seismology as a further complementary technology. In fact, radiogenic heat is a key source of the planets intrinsic internal heat generation and can be detected via geoneutrino analysis [28].

Neutrinos, helioseismology and applied geophysics

Neutrino physics and the study of the Sun has been a close relationship since the description of the Solar Neutrino Problem (see above). No discussion concerning neutrinos would be complete without presenting the Sun and its central place in understanding

and appreciating the place neutrino particle physics plays in applied geophysics as a whole [29]. The solution of the Solar Neutrino Problem demonstrated the oscillation behavior of neutrinos (see above). The importance of the Sun in terms of neutrino observations can be extended to helioseismology [30]. Helioseismology is the study of the propagation of wave oscillations, notably acoustic pressure waves, in the Sun. Despite the name, helioseismology is the study of solar waves and not solar seismic activity which does not exist per se. The name is taken from the use of seismic waves to infer indirectly the structural composition of the interior of the Earth. Helioseismology provides a three-dimensional view of the solar interior, which is important in understanding solar flows, magnetic structures, and their interactions. Time-distance helioseismology, introduced by Duvall et al. [31] uses the travel times of acoustic waves, a traditional terrestrial seismological approach, to the study of solar time-distances. Using this method now one may be able to study key solar phenomena such as subsurface homogeneities near sunspots.

The review by Turck-Chieze and Couvidat [30] suggests that due to the success of Borexino in detecting the solar elemental neutrino signals that this is due justification for the building of a new generation of detectors to measure the entire solar neutrino spectrum.

Real time experiments, Kamiokande, Super Kamiokande, SNO and KAMLAND have contributed significantly in increasing the statistics of solar neutrino detections. The first experiment, Kamiokande and, later, Superkamiokande, detected the neutrino elastic interaction on electrons. The next generation of experiments, Sudbury Neutrino Observatory, Borexino, and Icarus, aim to measure further these elastic interactions.

The first real time experiment was the Kamiokande experiment. Its principle was based on elastic neutrino scattering. The scattered electron is detected through the Cerenkov light emitted and its direction is strongly correlated with the direction of the incoming neutrino. The main background sources do not have any correlation with the Sun's direction and so may be minimized. Nevertheless, it remains a constant experimental challenge to reduce the backgrounds to a very low level—to enhance signal to noise ratio.

Neutrino astronomy has real potential to make a significant contribution to the understanding of the solar interior and structure. This no doubt can be also reflected in neutrinos adding considerably to the understanding of planet Earth—the focus of my research being in terms of seismology.

A key very well cited study with respect to this section on the Sun is by Turck-Chieze and Lopes [32]. This research examines the solar neutrino puzzle and discusses the point of view that neutrinos and helioseismology are two complementary probes of the solar interior. It indicates this feature well before the first direct evidence of solar neutrino oscillation came in 2001 from the Sudbury Neutrino Observatory (SNO) in Canada. In a way, this study points in the direction of the great utility of neutrinos in the analysis of structural objects in the Universe—of which, the Sun and Earth are part thereof.

There is no doubt that the Sun's neutrino spectrum assesses a great deal of information regards the Sun's structure. Real time experiments in Kamiokande, Super Kamiokande and SNO detect helionutrino elastic interaction with electrons as mentioned. The key feature is that neutrinos form a complementary probe to study the Sun and its interior and a fairly coherent picture has emerged from neutrino physics and helioseismology. So one can surely say that the Sun developed neutrino physics and neutrinos developed solar physics! This parallels much as

I shall present here in this article with respect to neutrinos forming a crucial complementary probe to study the interior actions of the Earth—specifically in this article, probing via an artificially generated controlled beam of neutrinos to investigate the terrestrial phenomenon of earthquakes.

Neutrino Applications in Earth Science.

Neutrinos have been already considered for tomographic imaging of the Earth and this has been summarized in an excellent review on the subject [1]. Much like medical tomography (from the Greek: tomos—part or section and graphein—to write) whereby a deep section of the body is examined via a remote sensing imaging technique commonly using xray radiation the Earth too can be potentially scanned for internal lesions (geophysical faults) or ‘pathology’ with the use of neutrinos.

Neutrinos as mentioned are very universal subatomic particles being produced in the Earth’s mantle and crust (geoneutrinos—see above) and also in supernovae, in the Sun and in fission reactors (Neutrino Physiology). Cosmic interactions with the atmosphere and high energy accelerators such as MINOS also produce neutrinos. The article by Winter [1] discusses the use of high energy neutrinos, above TeV and methods using the MSW effect (Neutrino Physiology) to examine lower energy neutrinos in the range of MeV and GeV as geophysical probes.

In the world of the neutrino the probability of oscillation (changing from one neutrino flavour to another) is related to medium density as alluded to above. Logically, the degree of rock porosity along a given baseline averaged over that baseline ought to affect this factor. As porosity relates to rock dilatancy and perhaps other, as yet unknown rheological alterations, a pattern can emerge from the neutrino oscillation that has a significant potential with respect to seismology. This has been proposed very recently [2] and shall be discussed (see below).

Presently, the review by Winter [1] shall be examined to provide a background for appreciation of the strategy of neutrino tomography as a prelude to viewing my currently proposed use of NTOF survey and distance tomographic mapping in seismology. Essentially, neutrino tomography depends on the reaction of the Earth’s matter with neutrinos. The greater the neutrino particle energy the greater the interaction with matter along any given baseline. In this field there are two imaging possibilities—viz: neutrino absorption tomography (NAT) and neutrino oscillation tomography (NOT). These shall be outlined below.

With respect to geophysics, neutrinos are highly useful since: 1—they propagate in straight lines; 2—neutrino absorption is directly proportionately sensitive to matter density, that is, nucleon (proton-neutron) density; 3—neutrino oscillation is sensitive directly to electron density (note in seismic wave geophysics one needs to indirectly reconstruct mathematically matter density from propagation velocity profiles); 4—neutrinos are sensitive to density averaged over the entire baseline whereas other techniques are less sensitive to the innermost parts of earth, for example, seismic shear cannot propagate in the outer liquid core so a proportion of seismic energy and thus information is reflected at the mantle-core boundary.

In neutrino absorption tomography the greater the energy of the neutrino the greater the interaction with matter and so energies over 1 TeV are needed to observe neutrino attenuations to make inferences regarding matter structure. So NAT assesses directly the density of

matter across a given baseline. At this time, the CERN LHC—Large Haldron Collider—may be used to generate neutrinos of sufficient energy. The fixed source can be angulated for whole Earth tomographic exam—much like producing a full body scan of a patient—in this case, the Earth itself. Detectors or ‘neutrino telescopes’ such as IceCube at the South Pole can be used [33]. It was proposed too in the article by Winter [1] that a mobile muon detector in a van would detect variations in flux as related to subsurface density alterations over a scanned area. A main drawback is operating a high energy neutrino beam. Techniques based on high energy neutrino beams have been outlined [34]. In this study, neutrinos produced in a TeV proton synchrotron have been proposed for geological research. Project GENIUS—Geological Exploration by Neutrino-Induced Underground Sound—proposes to look for oil and gas at large distances from the accelerator (remote sensing exploration). It depends on the coherent sound signal produced underground by millions of neutrino interactions along the subterranean neutrino beam baseline. Surface measurements of the acoustic pulse allow for deep probing of crustal structure. Project GEMINI—Geological Exploration with Muons Induced by Neutrino Interactions—is designed to search for deposits of high-Z elements (high atomic number of protons). This depends on neutrino-induced muons measured on the surface produced by the neutrinos in their last final kms voyage to ground level. Project GEOSCAN aims to measure attenuation of the neutrino beam as it scans the whole Earth (see above) to assess the density profile. These techniques have ready application to earthquake analysis via probing the Earth’s interior.

Neutrino oscillation tomography (NOT) relies on the MSW effect (Neutrino Physiology) for assessment of matter interactions. To achieve effective NOT one needs a neutrino source of known flux and flavor composition, a detector with controls composed of known matter structures between source and detector to enable calibration. As oppose to geoneutrinos the interest is not in the source per se but in the intervening matter.

Neutrino oscillation as indicated relies heavily on the MSW effect [35,36]. The MSW effect or coherent forward scattering in matter causes a relative phase shift of the electron flavor as compared to the muon and tau flavors of neutrinos (see above). This phase shifting depends on the electron density of matter the neutrinos pass through. Neutrino energies between 100MeV and 35 GeV are needed to study the Earth’s interior via NOT as produced from a so-called Neutrino factory.

In NOT detector design varies depending on neutrino energy and for lower energy spectrum neutrinos a water Cherenkov detector is appropriate and for medium energy neutrinos liquid scintillators are required and for high energy particles iron calorimeters are necessary. As mentioned above, NOT relies on the electron density of matter the neutrinos pass through. The substance of the Earth contains many electrons but nil muons or tauons—consequently, charged current interactions with host Earth electrons with the electron neutrino flavor via the coherent forward scatter effect leads to a relative phase shift compared to muon and tau neutrino flavors. There is, as discussed in the article by Winter [1], some material composition effect on the electron fraction of the matter, that is, electron ratio to nucleon ratio. This determines the oscillation of the electron neutrinos. Therefore the technique may be somewhat sensitive to Earth composition and this is an important consideration in addition to it being reflective of material baseline density.

In the discussion by Winter [1] an example is presented using naturally occurring solar neutrinos to probe into the Earth’s interior

to look for alterations in density (cavities). In this scheme, the rotating Earth allows for a mobile detector against and fixed source (Sun) sweeping through the Earth much as a tomographic scanner moves and scans around a patient. The negative issue is that solar neutrinos have limited energies to below 20MeV and these are not ideal to allow spying deep into the Earth. Supernova neutrinos have higher energies and may be harnessed to allow this form of analysis.

Artificially generated neutrino beams for NOT allow for greater control over the variables involved. Such sources rely on pion/kaon decays and are termed superbeams [37,38] or depend on muon decays [39]. Alternatively unstable nuclear decay from beta-beams can be used [40]. With artificial neutrino sources certain quantities are under control such as the flux and flavor composition. One issue that remains a problem lies in terms of understanding mixing angles that determine matter effects in flavor oscillatory transitions.

The main consideration in any imaging diagnostic test is sensitivity and specificity of the analysis. As in the medical analogy with the Earth as the patient the proposed test must be of sufficient diagnostic clarity and specificity to render it of use. For example, can one measure accurately the size and density alteration of a zone within the Earth's 'body' via the neutrino tomographic technology presented here? Winter [1] shows that by use of a 500MeV superbeam reasonably accurate positional information can be obtained. The example of a water dense cavity is given with location sensitivity to 100 km length and size specificity of density alteration can be measured to +50 km [41]. As compared to NAT, the NOT approach differs in that it can locate the actual position of the cavity as reconstructed from a single baseline within +100 km.

Another consideration is the resolution of edges and structures and a limitation is that structures smaller than the oscillation phase length in matter cannot be resolved. Nonetheless, neutrino oscillations in matter are very sensitive to average densities and the arrangement of structure on the length scale of the oscillation phase much as any physical waveform analysis in physics performs [42]. It becomes apparent therefore that in the final analysis, NOT is a suitable complementary technique that may need to be worked with other approaches such as the more traditional seismic tomography to assess deep Earth strains and structures. This might be readily compared to the complementary scanning procedures used in medicine such as positron emission tomography (PET) and CT. PET/CT combines the strengths of two well-established imaging modalities, CT for anatomy and PET for function, into a single imaging device.

In terms of geophysical aspects of neutrino tomography it is important to recognize that matter density uncertainties dampen the accurate extraction of oscillation parameter data from the measurements. Nonetheless, having said this, measuring density per se may be achievable and this could of course directly reflect porosity in rocks associated with the phenomenon of dilatancy as a potential precursory event for earthquakes.

In summary, NOT can certainly be regarded as a good complementary technology in the field of seismology. Certain benefits are presented with the use of neutrinos in seismology. These are related to the fact that neutrinos travel in straight lines with nil uncertainty in their path. Neutrino tomography is sensitive to nucleon density (absorption tomography) and to electron density (oscillation tomography). Comparatively, seismic waves have certain drawbacks, viz: their paths are less certain and may be altered/curved. Also, matter density has to be inferred indirectly via a reconstruction process from the propagation velocity profile by the equation of state as alluded

to above. Nevertheless, seismic waveform analysis is a powerful complementary technique to neutrino tomography—just as PET scanning complements medical CT analysis (above).

Overall, neutrino tomography provides a more direct handle as it were on crustal and deeper Earth density profiling. A further advantage is that neutrinos may probe the Earth's core—whereas, seismic waves are reflected off the mantle-core boundary. Neutrinos, as indicated, have the principle advantage of providing a precise measurement along a highly-defined path. No other technique can achieve this. Now this is a key statement as far as this article is concerned as it says that one can target a very specific path with extensive baselines and obtain very detailed information for that particular path—in real time as well potentially. Density is the typically discussed parameter in the neutrino tomographic work to date. In my present article, another parameter that can be established along this detailed and precise baseline path is neutrino time of flight—a measurement of distance in real time. The proposition is that this can be used to yield highly informative complementary information in terms of seismological interest.

Winter [1] points out that there lies ahead certain challenges in the field of neutrino tomography. These refer to the production of high energy sources needed for neutrino absorption tomography and advanced improved statistics measurements for NOT. NOT can provide average density along a path but to achieve the ability to see a full density profile along a given axis or path is not yet a simple process. NOT is sensitive to densities averaged over the actual oscillation length making precision difficult (see above discussion on cavity resolution). Sophisticated detectors and high energy beams are required.

It is interesting nonetheless to ponder on the geophysical application of neutrino tomography. For example, in the article by Winter [1] a scheme is outlined showing three neutrino factories (viz: CERN in Europe, FermiLab in the USA and JHF, the Japan Hadron Facility). These factories could be used to generate beams to traverse the Earth's inner and outer core regions as baselines to assess densities. Proposed locations of the detectors are given which very interestingly show detector sites running through Eastern Turkey and up the Californian coast and Mexico. These are of course key 'hot spots' for earthquake development. Winter [1] concludes that active discussions need to be held between geophysicists and neutrino physicists. This is a central theme of this present review where I outline the utility of harnessing neutrino physics in seismology.

It has been suggested that, as a logical follow on from the above, that neutrino tomography can be looked at as a practical technique for analysis of earthquake prediction [2]. In this article, the possible use for neutrinos in predicting earthquakes is outlined in respect to design and overall practicalities. Neutrinos are seen as the 'probes' emitted from suitably located reactors traversing through regions known to be earthquake prone. The matter effect—MSW effect (see above) is used to provide alterations of neutrino oscillation as detected via NOT in the fault zone. Geometrical and matter density considerations are taken into account in the fault region. A signal of the coming earthquake may be represented by an anomalous accumulation of electrons that reflects a density variation at the fault zone earthquake wavefront. The difference in electron matter—neutrino interactions that result can be approximately 3%-control vs altered density pathway/baseline. As has been mentioned above, oscillation length of high energy neutrinos from 'neutrino factories' may limit this form of analysis to resolve density variations. The authors suggest that in the future given better appreciation of the anatomy of the fault zone and detector advances

that it may be feasible to draw some conclusions from the use of this approach to earthquake prediction.

Certainly, the geological structure within a fault zone is not stable and varies actively. It is hypothesized that drastic variations within the region of such geological structure can induce severe earthquakes. Before an earthquake takes place, the variation in the matter-density or more exactly, the electron density of the fault zone can be outlined as a very significant factor. The relevant effects of these active structural alterations have been categorized into four aspects [2]:

Strain: Strain can change the matter density directly. During the Wenchuan earthquake, the Longmenshan fault zone was notably strained. The Eastern edge of the Qinghai-Xizang Plateau is close to the region where strain intensity changes steeply. The Longmenshan fault zone undergoes intense focal strain change with measurements showing that strain intensity on the west side is four times larger than that on the east side of the fault.

Shear: Shear plays an important role in slippage of the fault. It can either increase or decrease matter density. The maximum shear strain rate of the east of the Longmenshan fault zone is 3 to 10-fold less than on the Western side of this fault. This represents a significant shear strain contrast across a fault and maybe is fairly typical of fault zones overall.

Anomalous electric fields: These have been observed around fault zone regions.

Rock dehydration: It is suggested that under the influence of large amounts of shear and strain rocks undergo a dehydration process which also contributes to the density shift in the fault zone.

Shear and strain and dehydration effects have relevance in the novel NTOF approach that I have adopted in the present review (below).

Application of the NTOF survey approach to remote sensing seismology

Wang et al. [2] have presented an example of fault zone geometry that could be used in modeling neutrino tomography analysis. In this configuration the actual geometry of the fault zone is provided by three parameters, viz: length, depth and width. The authors indicate the example of the Longmenshan fault zone which is formed by a 300 km long and 50 km wide deformation zone. Therefore they use a model in which the fault zone is depicted as being cuboid with length 300 km, width 50 km and depth 10 km, and with its upper edge parallel to the Earth's surface. The cuboidal fault zone is placed within a central portion of the crust layer where earthquake hypocenters have been located. I have done a similar outline in schematic form (Figures 2 and 3) with regard to the NTOF proposition. The utility of the schemes outlined in these figures could be first simulated by computer to determine the preferred locations for detector and source angulations. Ideally, the sensitivity must be high to determine small alterations and the measurements must specifically detect crustal movements to a particular focal area and not surface changes secondary to thermal change, subsidence and/or weather influences. The latter would lead to background interference or 'noise' that, despite controls, may mask important subsurface information being gathered.

Other confounding variables include tidal influence as well as lateral Earth motion (see above). To correct for that, control baselines need to be set up in parallel, in real time, to enable calibration of NTOF distance measurements.

The examples in Figures 2 and 3 show where the baselines are variously angled to the direction of the central fault line/zone being examined. For means of presentation this is simplified to represent a single fault zone (although certainly in reality it is much more complex with branching fault anatomy (The 'anatomy' of a fault line—relevance to seismology). Based on the hypothesis that subterranean movements in terms of dilatancy or fault shear or compression occur in fault zone rocks then theoretically there ought to be a time alteration for NTOF in the path-length of the baselines.

The outlines presented in Figures 2 and 3 may be considered reminiscent of the discussion by Winter [1] where this author shows that varying sources can be used to generate tomographic global mapping data. My own depiction of this scenario would be to employ varying sources to remote scan a given crustal region for seismic activity and hence gain information on the development of geophysical architectural flaws that may relate to forerunners of earthquake activity.

In terms of an example of the NTOF approach a typical working calculation may be outlined as follows. Assume a baseline of 500 km and over the period of a day (24 hr) the corrected variation in the baseline is 1m. Appropriate correction factors are required to allow for natural Earth motions and if detectors are located above ground then correction for surface variations need to be accounted for (see above). Central to this approach is the evidence that neutrinos travel at light speed. The speed of light is taken at 299,792,458 meter/s (with an uncertainty of 4 parts per billion). Now, as stated above, assume over a given time frame (24 hr) the difference in the corrected $t(1)-t(0)$ displacement over the selected baseline is 1m. The relation: $d=vt$, allows one to calculate that the time for the neutrino beam to travel over the 500 km baseline is: 0.0016678204759s. At time (1), 24 hr later, a 1m shift has occurred over the baseline. The time of flight is now 0.0016678171403s which represents 3.34ns time alteration. This time difference is constant for a given distance shift and therefore independent of baseline length. The uncertainty in the speed of light itself is in parts/billion and so this would be below the limit of the difference that would be seen for 1m change and so not a relevant error. Repeating this analysis over varying source to respective detector: D1, D2, D3...Dx baselines sampling over a continuous period of time could build an 'internal view' or 'scan' of strain activity within the Earth's lithosphere which may in turn, relate to seismic forerunner activity.

Clearly, in order to accurately detect in real time small distance disturbances over a zonal region a degree of technical improvement needs to be undertaken to resolve such comparatively small differences. This is based on the recent CERN-Gran Sasso experiments which have an error margin of +10 billionths of a second (10 ns) in the measurement of NTOF: CERN to Gran Sasso. There is no doubt measuring devices and improvements in computing technology will rapidly follow in the wake of the current surge of interest in neutrino physics. Indeed, improved timing mechanisms for such refined NTOF measurements have been developed in the wake of these experiments [6] (Methodology—background and NTOF concept development).

General Discussion and Conclusion

In terms of my own interest, I have been considering methods that may aid earthquake prediction for some time. Recently, it was indicated to me that a number of earthquakes may display precursory phenomena, as detected by current technologies, and indeed the challenge is in recognizing such form of behavior for what it is in advance of the main quake. Indeed, satellite monitoring of electromagnetic precursors to earthquakes and volcanic activity has been considered for a period of

time as evidenced by the DEMETER and Quake Sat missions (Sean Solomon, personal communication, Director, Dept of Terrestrial Magnetism, Carnegie Institution of Washington). Many believe that accurate forecasting of earthquakes is not yet possible and no doubt remains the holy grail in this field for seismology to establish.

There is a great deal of current technology aiming to understand tectonic movements that relate to the inherent build-up of stress and resulting strain that occur along fault zones. These developments may well greatly assist in elucidating improved practical means to aid in short to medium-term earthquake forecasting. For example, Three-dimensional model of Hellenic Arc deformation and origin of the Cretan uplift GPS velocity vectors have been used in recent years to model and monitor, by finite element analysis, the 3-D structure of Nubian plate subduction beneath the Aegean block and its deformational/strain-related consequences [43]. The relatively simple model broadly reproduced observed uplift patterns, earthquake activity, and loci of extension and contraction. Clearly, the NTOF approach could well be a workable complementary approach to this type of analysis in the field such as to tangibly measure foci of contraction and expansion in a given fault area. The question too of monitoring aseismic gaps may be better approached by use of my NTOF survey method as earthquake-producing fault systems like the San Andreas fault in California show structural variation. Earthquakes cluster in space, leaving aseismic gaps between clusters. Whether gaps represent overdue earthquakes or signify a lower risk is a question which oftentimes baffles seismic-hazard forecasters. These results suggest that although gaps may succumb to rupture propagation they are less likely to be sites of nucleation for earthquake development [44].

Intense investigation examining not only historical records but also contemporary GeoNet surveys is underway in order to understand seismic hazards particularly in areas of key activity for example in the Tokyo region- the consequences of a significant earthquake in that region being very severe indeed as has been already pointed out [45].

Similarly, several analytic and modeling approaches to study fault geometry and evolution, including depth-converted, deep-seismic-reflection images, P-wave-velocity field, gravity data, elastic modeling of shoreline uplift from a late Holocene earthquake, and kinematic fault restoration have been achieved for the Seattle fault. This is a large, seismically active, east-west-striking fault zone under Seattle, and is the best-studied fault within the tectonically active Puget Lowland in western Washington State, USA. Nonetheless, its subsurface geometry and evolution are not well defined [46]. As an aside, reflection seismology, alluded to in this investigation, can be considered the seismological counterpart of medical ultrasound- oftentimes used for imaging in patients from heart function studies to obstetrics. Again, I take advantage of viewing the patient in my article as the Earth which indeed is not entirely an unreasonable assumption under the circumstances. Perhaps in reference to Puget Lowland, the NTOF protocol would be able to offer complementary useful seismic forerunner information.

Another seismological event that has attracted a great deal of inspection has been the earthquake in Bam, Iran [8]. It was stated in this study that understanding of the earthquake process needs a careful and detailed insight into the mechanisms tectonic interfacial stresses buildup and then in turn release in fault zones. Satellite radar data was used to generate a displacement field diagram based on vectorial analysis from the EnviSat of the European Space Agency. Detailed examination of surface deformation indicates that in fact the majority of the seismic moment release along the 20 km long strike-slip rupture

occurred at a depth of 4-5 km. Notably, the rupture did not break the surface. The Bam earthquake can be said to represent a case of shallow slip deficit-type seismic activity. In this model, co-seismic slip in the more superficial crust is less than that found at seismogenic depths of 4-10 km. InSar satellite surface displacement data from this example indicated that there was a generalized distribution of superficial crustal strain in the inter-seismic period leading to failure. This was shown diagrammatically where significant pre- and post-seismic deformation through a large area extending from the fault zone could be readily evidenced. Co-seismic displacements occurred maximally relatively close and in a focused area of 3 km wide over the seismic area reaching maxima of approximately 50-60 cm on either side of the fault.

The READI methodology (Real-time Earthquake Analysis for Disaster) is based on a GPS network [47]. Essentially, the location and magnitude of an earthquake event is determined readily and the after-event, such as reactive tidal-wave or tsunami, may be estimated. The determinations are based on real time assessments of GPS data. The technique appears robust to the point of being able to deliver information that informs seismic stress-rupture [48]. This was performed on the Nicoya Peninsula in Costa Rica which in itself is an interesting experimental area to test GPS predictive technologies for seismic activity as the subduction seismic active zone is overlaid by land not ocean. Large scale (>M7) earthquakes occur here every ~50 years and as the last one happened in 1950 another is anticipated soon. GPS and seismic measurements have located a 'locked' portion of the fault which builds up seismic strain to be released. On 5 September 2012 the anticipated Nicoya earthquake occurred within the locked plate region. This study highlights the significance in anticipatory abilities of geodetic measurements in late interseismic period [48]. The study does not predict earthquakes as the timing is still not accurate but we can say where and how large.

These studies point to the fact that currently a number of complementary technologies exist including satellite based InSar and GPS to ground based seismic sensors to provide insight into potential and likely seismic activity.

One approach that is attracting a great deal of attention is termed seismic interferometry. Interferometry is a group of techniques whereby waveforms are superimposed in order to extract information about the waves including source and modifying variables. The instrument used to interfere the waves is called an interferometer. Simply put, by combining waves that are in similar phase a constructive interference pattern arises and the resulting combination of waves that are out of phase will undergo a destructive interference. These patterns of interference can be readily assessed. As a background to this approach, I have had a considerable interest in astronomy for a number of years and have had the privilege of visiting the Narrabri Stellar Interferometer (Sydney University Stellar Interferometer-SUSI) in Western NSW, Australia. In this approach, aperture synthesis is used to in effect combine telescopes separated by thousands of kilometers to form a radiotelescope of resolution to that of a single dish of thousands of kilometers in diameter. Thus, in effect, a virtual array is constructed between the main receivers and makes the independent stations appear to function as one complete receiver. In seismic interferometry, interference patterns between pairs of seismic signals can be used to also generate a virtual field of signals such as to allow mapping of the subsurface- a truly remote sensing achievement for applied geophysics [49]. Limitations exist with respect to this technique in terms of attenuation and geometrical spreading as well as the consistency of noise/seismic sources. Nevertheless, this is a very

active field of interest and no doubt certain hurdles shall be overcome in time. Interestingly, the application of interferometry is already widely accepted in seismology in an indirect sense via the use of InSar–Interferometric Synthetic Aperture Radar (below). This methodology forms an important complement to the use of my proposed NTOF methodology.

The NTOF protocol is a little different and lateral in its methodology. I build my scheme on a previous suggestion for the use of neutrinos to measure continental drift. The more recent propositions for use of neutrino tomography have allowed me to consider and develop this concept further for seismology as a remote sensing application. In the present article neutrinos are considered to be of use for the development of a distance-time based tomographic map or survey of major fault regions of significance. It is of significance that it was reported a re-structuring of the TOF CERN experiment has been achieved in order to check the actual observation related to neutrino speed and resulting flight time [50]. This review points out some interesting principles. The artificially produced neutrinos in the CERN Gran Sasso experiment commence as a beam of protons at CERN. The neutrinos thus generated then beam through the Earth's crust to Italy. CERN fired the protons in a relatively long pulse lasting 10 microseconds. Initially, considerable excitement arose by the fact that the neutrinos appeared to arrive 60 nanoseconds at the Gran Sasso detector sooner than light would have over the same distance. Because the neutrinos were generated over a pulse and not discretely then the time calculation is based on a statistical analysis. It has not been possible by the present methodology to examine the time of flight of a given neutrino. By comparative statistical analysis errors may be introduced into the data. A redesign of the experiment was achieved by sending the protons that generate the neutrinos at the source in short bursts or 'buckets' of 3 ns. A gap of approximately 500ns was devised to separate each burst. In that way, a method to index each bucket or burst of neutrinos from source to detector was directly feasible and cross-match a given source bucket with a detected bucket which allowed for a more direct analysis of NTOF.

This recent experimental set-up is entirely reminiscent of earlier work [4] (Methodology–background and NTOF concept development). In that former proposal it was discussed that Fermilab could make 400GeV protons which would be produced, as described, in 'buckets' 1ns wide with 10×10^{10} protons/bucket separated by 18ns gaps. From the resulting neutrinos produced, trajectory and indexed proton reference bucket can be calculated aiding the accuracy of the NTOF calculation. Notably too, the decay tunnel used to produce the neutrino beam will cause a smear effect in transit time—as kaons and pions will decay at varying lengths along the tunnel—not just in one spot. This smearing can be calculated and corrected for, and, for example, a 14GeV pion decaying in a 2km tunnel the smear time difference is 0.3ns. This correction method was shown by Bostrom et al. [4]. It appears that this earlier work has provided considerable insight into a current day problem. Further to that, it gives an indication as to the overall usefulness of neutrinos in terms of TOF survey possibilities in applied geophysics—a theme that I have developed in my present article.

A focus of my presentation has been from a medical viewpoint portraying the Earth as a 'patient' and the various methods that can be used to probe the interior of this particular 'patient'. 'Illness' has struck and the 'patient' is unstable and a sensitive and specific method is needed to examine the case before further deterioration occurs. In medicine, one often has a gold standard to compare to. Of tentimes

medical tests combine to yield in to complementary information such as CT/PET that display a picture of the patient's internal workings and pathology. In the current scenario, the Earth is being investigated as the 'patient' and combined examinations are suggested via both seismic tomography and InSar as accepted standards comparing to novel NTOF distance-time tomographic analysis. By examining the 'patient' (Earth) via a different modality a new mechanism or relationship may unfold. This is my aim: to develop NTOF as a workable supplementary technology for seismic analysis and forecasting and to probe novel earthquake mechanisms.

Having said the above, a number of hurdles need to be overcome. Firstly, the practicality of multiple neutrino detectors and sources. Technological advances certainly shall be required to enable thorough scans of fault zones as depicted in this review. Satellite-based detection systems are imaginative but again, require considerable technical feats to be overcome. Mobile rapid scans via moveable sources/detectors are not currently practical but may be developed in the future. The measurement of the variations in the baseline shall have to be able to detect small changes over a large baseline for extended periods. In the article by Bostrom et al. [4], it was indicated that theoretically a 0.3 mm resolution could be obtained and 0.5 ns time variation detected. This would not yet be possible with present day techniques. In addition to the matter of accurate time calibration which is needed to within a narrow margin other problems may occur. For example, several movements may be superimposed one on another in a given baseline thence confusing the net observation in terms of distance being surveyed. Perhaps this is readily overcome by obtaining additional information from another baseline at another angle to control for this and monitor confounding movements (Figures 2 and 3).

It has been indicated that fault damage zone width develops early on in the so-called 'evolution' of the fault zone [10]. The active section of the fault zone tending to narrow with further strain displacement. Therefore a real time dependent monitoring of fault zones is needed such that such physically altering regions in the fault zone that may be a prelude to a significant event are not missed. This poses a technical challenge in itself to be able to constantly scan all regions of the fault zone so as not to overlook any one particular focus. A further challenge may be to reduce background interfering noise levels from extraneous neutrino sources—although in itself this may not be an issue when focused detectors are specifically trained on a given source baseline or baselines.

Controlling for extraneous movement is an important feature of the experimental setup. In the schema presented InSaris employed to provide an external calibration and control. It ought to be borne in mind that InSar itself may yield significant errors in its own right. InSar is a radar method often applied as a geodetic approach. It combines radar images by phase interference to generate a topography of surface conformation in time via satellite or aircraft. The sensitivity is high and it can assess cm changes over days to years. So its uses are many from seismological—measuring fault zone creep and strain accumulation—to plate tectonics and volcanology as well as assessing subsidence. An important source of error in the wave phase interferograms is caused by the atmosphere. Variables such as temperature and pressure and water vapour affect this measurement. Ground interference too can be a problem from snow cover or vegetation so forth. Having said this, InSar has proven itself to be a useful tool in seismology. The sensitivity is high as mentioned and studies have used InSar to demonstrate that interseismic slip rates can be determined to cm scale measurements per year [51]. By taking InSar data these investigators concluded that slip

rates occur in the range of 17-32 mm/yr below 5-33 km on the extension of the surface fault on the North Anatolian fault system. In terms of examining active tectonic movements, InSar has been of considerable assistance [52]. The studies here showed that InSar views coseismic displacements and detection of movements at nearby faults triggered by the earthquake. It also measures interseismic crustal deformation and fault creep. Clearly, it is a very sensitive approach and specific upon suitable control for interfering variables such as confounding factors like vegetation and atmospheric interferences. In this way, it can be considered to represent a gold standard for comparison as I have selected in this review.

With respect to the 2003 Bam Iran earthquake, InSar has been instrumental in determining seismic dilatancy [53]. In this investigation it was pointed out that oftentimes earthquakes radiate from slip in localized faults and commonly involve distributed deformation over a broader fault zone—particularly in more superficial crustal layers. Rock strain differences in the coseismic period result from heterogeneity in elastic stress energy preseismically and through variations in actual rock physical properties as well as geometry of the fault zone. Stress alterations in the slip fault zone coseismically result in dilatancy in the faulted area that heals postseismically. This study was the first to observe dilatancy and its recovery via InSar geodetic means. Thus InSar measurements have shown in the Bam event that reversal of coseismic dilatancy occurs postseismically and this healing is notable directly above the region of greatest seismic slip at depth. The dilatancy and follow up healing compaction demonstrates a distribution of shear damage coseismically that redistributes postseismically. These observations are important as they show that InSar is a very capable technique overall and is able to infer dilatancy around the event time. This is a key point as I propose using InSar as a central control (Figures 2 and 3) within the experimental setup for NTOF. As dilatancy effects are to be tested via NTOF then InSar forms an ideal standard for comparison and complementary control technique. It is my proposition in the current article to use NTOF to assess these InSar data as a basis for determining the utility of NTOF in general terms as a robust predictive technology.

Traditionally, techniques such as seismic tomography have been very useful and will continue to provide key information in seismological studies [54]. In terms of geophysical event anticipation, seismic tomography has a clear place [55]. P-wave velocity data show that velocity information may help to define important elements, such as asperities, that control fault rupture, and thus may help to anticipate the location and size of future events. Other approaches such as particle image velocimetry have proven useful particularly with reference to volcanic seismic activity [56]. Importantly, in this investigation, a combination of optical geodetic and seismic observations was employed. So techniques have been found to be complementary in the past in seismology. In my present review, I emphasize the complementary nature of established technologies alongside my novel NTOF method to estimate earthquake precursors and to examine seismic activity.

Having said this, the NTOF protocol as a novel approach in seismology may well aid in understanding a number of geophysical phenomena. These include mining-related seismic activity [57], in addition to improving understanding of the Gutenberg-Richter magnitude-frequency relationship and associated b-value. In the New Zealand Christchurch earthquake it has been proposed that seismic rupturing occurred on previously unrecognized faults that appear to be components of a complex zone [58]. Subsurface information has only been available from seismic studies and it is possible that NTOF

could delineate and expose further unknown regions of faulting that may undergo future seismic instability.

The NTOF protocol has limitations as any other seismic procedure in regards systematic error. As NTOF relies on a GPS calibrated timing mechanism with linked atomic clocks to define accurately times at two independent locations (between source and receiver) then the protocol is limited by the systematic error of GPS. Although timing improvements have been made since the original OPERA experiment for neutrino TOF via high precision timing facility-HPTF (Methodology) this factor remains an important source of error. InSar carries its own source of errors as discussed above. Appreciating such sources of error are key in terms of interpreting results particularly when small alterations in distance are to be assayed over extended periods of time when strain is developing around a fault zone.

As to the practicality of NTOF there are certain comments that ought to be made. The CERN Gran Sasso experimental setup that initiated my thinking along the lines of NTOF has been replicated in the USA with NumI at Fermilab which produces neutrinos as detected by MINOS which consists of two detectors one at 1km and another 735 km away. Therefore the technology is well underway to rapidly develop the NTOF approach. Many countries already are interested in possessing neutrino detectors for example, in India, a neutrino observatory is planned [59]. It is expected to be functional in 2015. This underground laboratory, called the Indian Neutrino Observatory (INO), is being built in the Bodi West Hills Reserved Forest in the state of Tamil Nadu. INO will initially study atmospheric neutrinos. This adds then to the developing chain of neutrino detectors around the world such as the Super-Kamiokande in Japan and the Sudbury Neutrino Observatory in Canada. INO scientists hope the observatory will also be used to detect neutrinos beamed from specialized neutrino factories at CERN or Fermilab. Clearly, these developing sites around the globe are setting up exactly as the NTOF protocol would call for.

Clearly, then the NTOF procedure is not impractical. As has been indicated in this review technical difficulties still lie ahead. The actual ‘anatomy’ of the seismic event zone poses the greatest problem for examining preseismic activity. Only a small region of a given fault zone may be involved in precursory shear seismic initiation and a very specific and sensitive technique or combination of techniques is needed to pick this feature out early for earthquake hazard warning. As has been stated many a time in the medical literature with a patient presenting with a spreading cancer for example, the location of the primary tumor can be extremely difficult to determine at times as it may be very subtle. So too in seismology, where the initiation event is oftentimes not obvious or indeed concealed whereas the after-event is tragically all too evident. Advances in understanding of fault zone seismic pre-activity and further method development for detecting same will necessarily fill this gap.

Conclusion

As stated by Swanson [3]: ‘If two literatures are linked by arguments that they respectively put forward—that is, are ‘logically’ related or connected—one would expect them to cite each other. If they do not, then the logical connections between them would be of great interest, for such connections may be unintended, unnoticed, and unknown—therefore potential sources of new knowledge’ and rather poignantly: ‘The significance of the ‘information explosion’ may lie not in an explosion of quantity per se, but in an incalculably greater combinatorial explosion of unnoticed logical connections. Science responds to growth by increasing specialisation, but tends to

neglect connections'. It is my specific aim in this article to research and bring to light the productive connection between neutrino physics and seismology— a relation needing exploration for its intrinsic value and one that exposes valuable insights aligning with Swanson's ABC model as used in medicine [3]. The rationale in developing NTOF for seismology is based on examining traditional earthquake determination methodologies such as seismic tomography and surface mapping with InSar. As yet, neither one method nor combination of approaches may predict earthquakes—at best, contemporary methods may anticipate magnitude and seismic location [48]. NTOF is proposed for seismology in adding materially to more accurately forecast seismic events. Further, improved remote geophysical sensing approaches are needed particularly for fault zones distant from a land mass. NTOF may assist in this by promoting remote sensing development. In general terms, NTOF carries the benefit of directly examining and pinpointing remote lithosphere pre post and co-seismic events as dimensional changes in a fault zone or developing zone(s). Extensive areas of the Earth's crust may be surveyed in real time continuously to establish a baseline and subsequent patterns of change. Seismic activity as related to such altering dimensional measurements may allow improved predictive algorithms— a 'holygrail' within this field.

In the present article the use of neutrino oscillation tomography (NOT) is outlined as an essential background to the present proposition [1,2]. This approach may be combined with NTOF for detailed structural analysis of the Earth's interior in general—not only around fault zones. By employing a scanning CT-like approach as outlined in this review, data may be obtained via NTOF and NOT that potentially would allow for an improved understanding of rock rheology, dilatancy, and convectonal heat flow amongst other features in real time. Overall, this application of novel technologies using neutrinos can have a significant impact upon our understanding of the Earth's structure.

In respect to the applied geophysics of seismology understanding seismology risk factors can be summarized in the following words:

"There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know" (US Secretary of Defense Donald Rumsfeld, February 12, 2002 DoD briefing).

This describes the situation with regard to earthquake analysis. There are factors that remain as unknown unknowns. The known knowns include aspects of fault zone architecture that have been outlined already in this review. The known unknowns could be for example: unknown faults within the region of established faults as outlined above for the Christchurch event [58]. Most faults are seen as having an unknown internal structure and reaction to internal stresses with unknown resultant internal strain alterations. Unknown unknowns pose as mysterious entities at present that remain to be considered as Earth slowly, but surely, yields its secrets.

In summary, there is much already known and much that seismologists know that is specifically unknown that has important bearing on earthquake events. Pinpointing the unknown unknowns will require a much further in-depth direct analysis of the structural features around faults pre- & post- and co-seismically. In this vein, I portray the presently proposed remote sensing NTOF survey protocol as a potentially practical and complementary approach. In a way, the sayings: 'if only these stones could speak what story they would tell' and 'leave no stone unturned' are apt in that the Earth itself has the answers ready to discover— it is breaking its age-old silence with new

approaches that may yield effective and specific and sensitive means to predict significant seismic events. Development of the NTOF approach into a workable proposition may not be simple but can perhaps be best described by the words of President John F. Kennedy in his Rice University speech in Texas in 1962: 'We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win...'. Doubtlessly, an effective theme as outlined in my present article, is to aim towards improving predictive strategies that ought to greatly alleviate the shocking harm and damage earthquakes can achieve worldwide. Importantly too, application of NTOF in combination with NOT protocols may open new doors in a deeper fundamental understanding of the Earth's internal functioning—a sought-after goal by geophysicists.

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