P- and S-wave velocity modeling and inversion using 3-C seismic data in Western Dharwar Craton (WDC) of southern India to image shallow crustal structure with compositional changes and understand its tectonic settings

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Keywords

Dharwar Craton; 3-C Seismic data; Modeling; Ray-trace inversion; $\frac{V_P}{V_S}$; Poisson's ratio; Shear Zones

Summary

We present 2-D shallow P- and S-wave velocity models (V_P and V_S) using ray-trace inversion of first-arrival traveltimes picked for the wide-angle 3-C seismic data acquired along the 200 km long E-W trending profile in the Western Dharwar Craton (WDC) of southern India, which traverses across major shear zones like Chitradurga Shear Zone (CSZ). The 2-D velocity models have been constrained to a maximum depth of 15 km mainly confined to the upper crust of this highly complex and oldest (3.2 – 3.5 Ga) Archean granitic-greenstone belts of India having rich resources of several different types of mineral assemblages like diamond, Cu-Ni and PGE elements as well as dominated by mushrooming of dykes. The velocity model depicts presence of alternate horst and graben structures with high V_P(6.35 km/s), low V_S(3.65 km/s) and relatively high $\frac{V_P}{V_S}$ (1.73) and Poisson's ratio (0.25) computed for the upper crustal rocks near the CSZ and extends towards west with large exposure of lower crustal mafic rocks rich in fluids (due to lowering of V_S) as compared to the rock types towards eastern part of the CSZ. Hence CSZ can be considered as the major boundary dividing Eastern Dharwar Craton (EDC) rich in felsic composition of rocks as compared to the unequivocal presence of mafic rocks in the WDC part of the Dharwar Craton. The 3-C wide-angle seismic data acquired for the first time in an Indian subcontinent provides very good insight of the rock compositions based on the inversion results. The inversion is constrained from RMS residuals (close to the picking uncertainty), traveltime fit of the observed data with respect to the response computed for the model for each layers as well as the normalized χ^2 parameter close to 1.0.

Introduction

Archean rocks are the oldest (3.5 Ga) rock formation exposed on the surface of earth and found in different cratons across the world such as from Greenland, the Canadian Shield (Superior Province), Australia (Yilgarn and Pilbara), South Africa (Kaapvaal Craton) and South India (Dharwar Craton). Archean rocks are either metamorphic or igneous type. During Archean, the volcanic activity was considerably greater than today with numerous hot spots, rift valleys and eruption of lava having komatite, which has high melting point. In addition to its extensive volcanic eruptions, the Archean Earth's subterranean regions were also extremely active with flows of magma producing intrusive igneous rocks that predominate throughout the crystalline cratonic remnants of the Archean crust. The Archean intrusive rocks include granite, diorite, intrusives from ultra-mafic to mafic (high melting temperature to medium melting temperature), anorthosites and Mennonites known as sanukitoids. Archean rocks are often heavily metamorphosed deep-water sediments, such as greywackes, mudstones, volcanic sediments, and banded iron formations.

Archean Cratons across the world have a common feature that is the occurrence of Greenstone-genesis association. Archean cratons are always associated with a shear zones and an intervening fold belt which is composed of metamorphosed, deformed Proterozoic rocks, this shows that Archean craton fold belts have undergone rifting and splitting during Proterozoic period. Dharwar Craton is one of such craton and occupies a major part of southern part of India spreading in Karnataka, Goa, Andhra Pradesh, Telangana, Tamil Nadu and Maharashtra. It is exposed over an area of about 2,50,000 sq. km between latitudes 12º N to 22º N and longitudes 74º E to 80º E (Fig. 1). It forms a contiguous block and is bound on the west by Arabian Sea, in the north by the Narmada and Godavari rifts, in the east and south by Eastern Ghats Mobile belt. It is confined by Neoproterozoic Southern Granulite Belt (SGT) in south (Ramakrishnan, 1993), in north by Deccan trap, in northeast by Karimnagar Granulite Belt (2.6 Ga), which occupies the southern side of Godavari graben and in east by Eastern Ghats of Proterozoic age. Dahrwar Craton (Fig. 1) has many sub-parallel NNW to N-S trending shear zones mostly at eastern boundaries of major schist belts. The Dharwar Craton (DC) is one of the oldest carbonic blocks of the world having Archean gneissic and granite-greenstone terrain, which is divided into two important segments called Mesoarchean Western Dharwar Craton (WDC) and Neoarchean Eastern Dharwar Craton (EDC). Dharwar Craton is dominated by tonalite-trondhjemite-granodiorite (TTG) gneisses. The WDC is composed of volcano-sedimentary greenstone belts deposited during 2.9-2.6 Ga over the TTG (Tonalite Trondhjemite Granodiorite) gneisses as the basement of 3.4-2.9 Ga age. The EDC is dominated by 2.5 Ga granitic plutons, which is intruded through the gneissic basement as narrow elongated greenstone belts (Chadwick et al., 2007). The TTG suit is believed to be formed by hydrous melting of mafic crust and a last stage differentiates of mantle, accounting for crustal growth, horizontally and vertically. Apart from TTG, Dharwar Craton is extensively composed of Greenstone or Schist belts which are voluminous basalts with fine clastics and in certain areas with basalts conglomerate and shallow water clastics (ripple bedded quartizites), limestone and dolomite. Dharwar schist belts, comoposed of greenstone belts and intercalated metasediments, have N-S trend and show gradual increase in metamorphism from north to south. In the Dharwar Craton, the Peninsular Gneisses are found to contain tonalitic gneisses and enclaves of older metavolcanic metasedimentary rocks categorized under name Sargur Group. Thus, it is likely that the peninsular gneiss with its enclaves of older tonalitic gneiss and Sargur Group of rocks served as the basement upon which the Dharwar supracrustals were deposited (Swami Nath and Ramakrishnan, 1981).

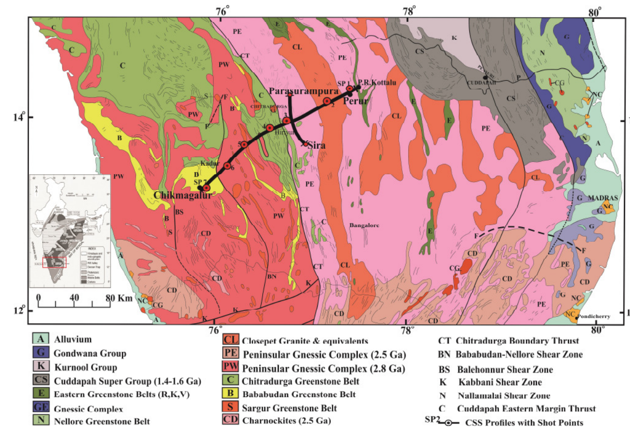

Figure 1: Geological map of the Dharwar Craton with NNE-SSW trending Perur-Chikmagalur deep seismic profile shown for seven 3-C wide-angle shot points (SP1-SP7) acquired in the WDC part of it. The different rock types exposed on the surface are shown in color legends.

The presence of green-schist and amphibolite facies mineral assemblages in the greenstone belt indicates that the region was uplifted and eroded with the exposures of the deeper portion of the crust. The plate tectonic model suggests a Neoarchean convergence of the two cratonic blocks near the Chitradurga Shear Zone (CSZ) comprising the major divide between EDC and WDC, which is addressed by using the 3-C wide-angle seismic data acquired in the Dharwar Craton by the Controlled Source Seismic Group of CSIR-NGRI during 2009-2010.

3-C Wide-angle seismic data

Due to the advancement of technology, it is possible to acquire 3-C wide-angle seismic data, process and interpret for better understand the subsurface complex geology, which in turn help to find many precious economic mineral deposits as well as play very important role in hydrocarbon exploration. Since the demand for better understanding of the subsurface geology for exploration of new mineral deposits is growing day by day and becoming a major challenge for the geoscientists all over the world, hence 3-C seismic data acquisition is becoming very popular as well as cost effective for exploration of minerals, hydrocarbon exploration as well as deep crustal studies to understand the tectonic and geodynamic setup of the Earth. Multi-component seismic data plays an important role in providing more information of the subsurface geology in terms of P- and S-wave velocities ($\boldsymbol{V_P}$ **and** $\boldsymbol{V_S}$), $\frac{V_P}{V_S}$, Poisson's ratio ($\boldsymbol{\sigma}$), Anisotropy, which can be suitably incorporated with the geological model to constrain lithology, mineral compositions, presence of fluid with the crust as well as differentiate the geological terrains based on the different rock types. The main task after 3-C seismic data acquisition is to perform special processing task of 3-C rotation of seismic data from Vertical (Z), Northing (N) and Easting (E) to its corresponding rotated coordinates such as Vertical (Z), Radial (R) and Transverse (T) components for further processing and analysis of 3-C seismic data. Here, we are analyzing 3-C seismic data using both P- and S-waves to understand subsurface geological features based on their velocities. This will help to distinguish different rock types based on the P- and S-wave velocities and develop a geologically plausible velocity model using ray-trace inversion of 3-C seismic data acquired in the WDC part of the Dharwar Craton. Since, rigidity modulus ($\boldsymbol{\mu}$) of liquid is zero and hence S-wave cannot travel through the liquid medium, the S-wave data analysis will provide the presence of fluids within the rocks in the subsurface. This 3-C seismic data analysis also helps find important mineralized zones such as mylonites with fluid inclusion in the rocks. This type of study will also help to find deeper hydrocarbon bearing reservoirs and accelerate the hydrocarbon exploration activities in the world.

To understand the complex geological and tectonic settings of this study region of WDC (Fig. 1), deep seismic data have been acquired by the Controlled Source Seismic Group of CSIR-NGRI in the Dharwar Craton (Rao et al., 2015a, b) along the 200 km long NNE-SSW Perur-Chikmagalur profile (Fig. 1) during 2009-2010. The wide-angle 3-C seismic data has also been acquired along the same profile using standalone Taurus Seismographs to develop a well constrained crustal velocity model. There are total seven wide-angle shots (SP1 to SP7) recorded by 3-C standalone Taurus Seismographs having continuous recording at 4 ms sampling interval using 4.5 Hz 3-C geophones. The data was acquired with 45 standalone seismographs in spread wise having 400 m geophone interval so that each spread covers maximum 18 km and maximum offset of coverage is ~180 km.

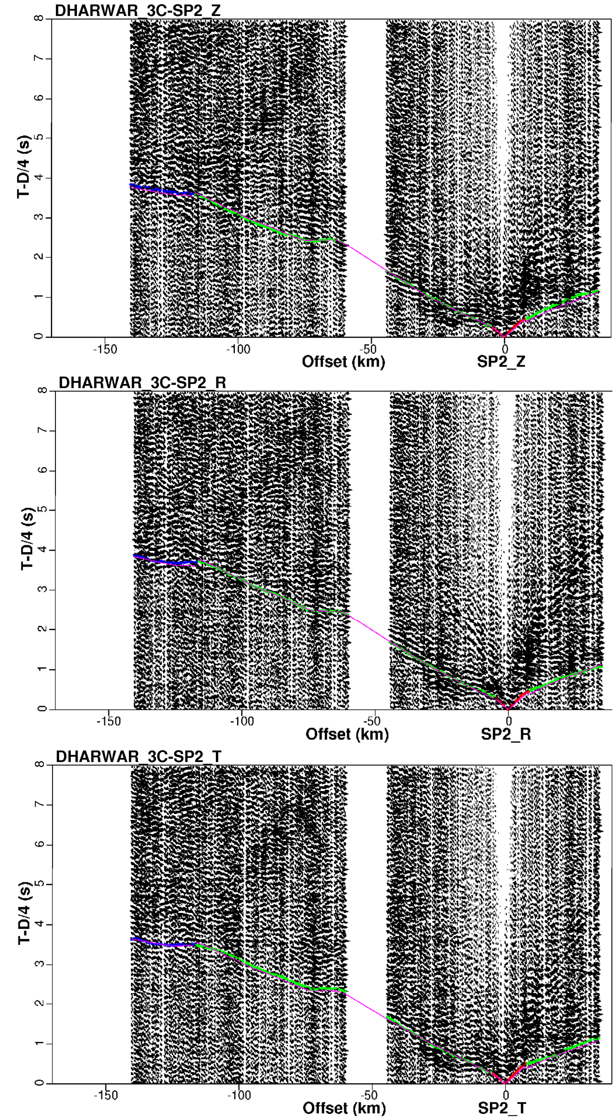

Figure 2: 3-C wide-angle seismic data recorded along the Perur-Chikmagalur deep seismic profile in the WDC of southern India shown for vertical (Z), radial (R) and transverse (T) components of S-waves for SP2. The S-wave first-arrival phases picked for ray-trace inversion are indicated by respective colored dots and modeled response is superimposed on the picks as magenta line. For clarity, the data have been plotted in reduced scale with reduction velocity of 4 km/s.

The seismic data was acquired by using explosives blasted in a pattern of holes and the charge size increases as the spread length increases, which varies from 100 kg to 1850 kg depending upon the distance between the shot point and the corresponding spread of data acquisition. The most important aspect of 3-C seismic data analysis is to provide information of the subsurface geological structures from Vertical (Z), Radial (R) and Transverse (T) components (Fig. 2). This data analysis will provide important information of crustal velocity model along with velocities such as V_P, V_S, $\frac{V_P}{V_S}$, Poisson's ratio (σ), Anisotropy along with thickness of different geological discontinuities.

Methodology

Processing of multi-component seismic data very complex and time consuming as compared to the conventional P-wave seismic data. The basic methodology for 3-C seismic data analysis starts with rotation of each trace of the data acquired by the standalone 3-C Taurus Seismographs and prepare individual shot gathers. Once the shot gathers are prepared, then field geometry was applied using the survey data (co-ordinates, distances, elevation etc.). All these preliminary seismic data processing was performed using the ProMAX commercial seismic data processing software licensed at NGRI. Once the data was conditioned (geometry corrected) then proper gaining and filtering was applied with spherical divergence correction to compensate the loss of energy and decay of amplitude due to propagation of wave with distance. The presence of ground roll and other types of noises were attenuated using spiking deconvolution and F-K filtering. These data are now ready for picking of different phases for modeling and inversion using standard ray-trace inversion of Zelt and Smith (1992). The starting velocity model was used as developed by Rao et al., 2015 (a, b) for both P-wave and S-wave modelling using the 3-C seismic data to derive final $\boldsymbol{V_P}$, $\boldsymbol{V_S}$, $\frac{\boldsymbol{V_P}}{\boldsymbol{V_S}}$, Poisson's ratio (Behera et al., 2006; Prasad et al., 2006). Other statistical estimates like errors in velocity, depth, $\boldsymbol{\chi^2}$, resolution and uncertainty estimates of each velocity and depth nodes of the model are computed, which are a measure of the robustness of the derived model. Since this region has been sheared and large scale presence of crustal intrusives and juxtaposition of two different crustal blocks WDC and EDC with Chitradurga Greenstone Belt/Chitradurga Shear Zone as the main divider, emancipation of crustal fluids to shallow level through the shear zone for the geodynamical evolution of this region. The fluids in the crust and shear zones can be inferred from P-to-S converted wave analysis of the wide-angle 3-C seismic data, which is a very good indicator of its presence as compared to simple P-wave data analysis.

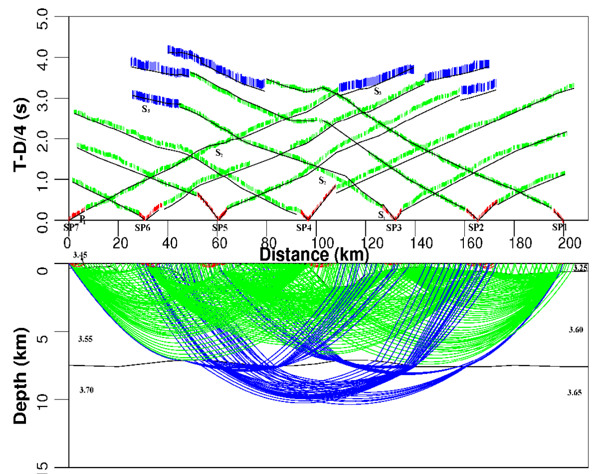

Figure 3: Ray-trace inversion of 3-C S-wave seismic data picked for the Z-component along the 200 km long deep seismic profile in the WDC. The corresponding data fit (black line) as well as the ray paths for the respective phases picked (colored vertical bars) are shown for all the 3-C SP's along the profile. The data have been plotted in reduced scale to avoid aliasing effect with reduction velocity of 4 km/s.

Here, we have obtained the shallow upper crustal velocity model down to 15 km depth along the 200 km long Perur-Chikmagalur profile. For this we have used both P-and S-wave velocity modeling using 2D ray-trace inversion using Rayinvr (Zelt and Smith, 1992). Different S-wave phases were picked manually for all the seven shot points for each component and ray-trace inversion of the picked first-arrival phases made to obtain the $\boldsymbol{V_S}$ velocity model (Fig. 3). Assigning uncertainties to the picked phases are important to avoid under or over fitting the data. Uncertainties are assigned by inspection, taking into account the signal to noise ratio and the frequency content of the data (Behera et al., 2004). The picked phases were modeled to obtain the crustal velocity structure using the travel time inversion method. Inversion is an iterative procedure and involves model parametrization. Model parametrization allows amplitude information to constrain the model features which was not resolved by travel-time data alone (Zelt and Smith, 1992). Similarly the corresponding P-wave velocity model ($\boldsymbol{V_P}$) was also derived along the same profile using first-arrival P-wave phases (Fig. 4).

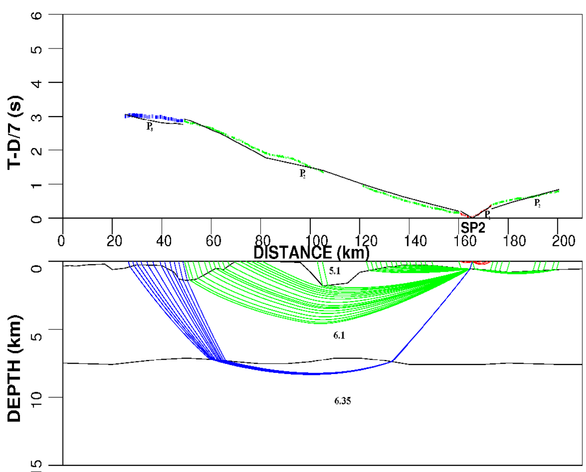

Figure 4: Ray-trace inversion of P-wave seismic data picked along the 200 km long deep seismic profile in the WDC is shown for example shot SP2. The corresponding data fit (black line) as well as the ray paths for the respective phases picked (colored vertical bars) are shown for SP2 along the profile. The data have been plotted in reduced scale to avoid aliasing effect with reduction velocity of 7 km/s.

Results

P-wave velocity only cannot provide much information about the lithology of subsurface rocks, for example sand and shale have overlapping zone of same $\boldsymbol{V_P}$ values (Christensen, 1996). But when both the $\boldsymbol{V_P}$ and $\boldsymbol{V_S}$ are used, the lithology of the rock types are constrained. Also the $\frac{V_P}{V_S}$ is very sensitive towards gas saturation, lithology and porosity and mineralization zones. Here, with the help of ray-trace inversion of both P- and S-waves of the 3-C seismic in the WDC shows that $\boldsymbol{V_P}$ varies from 5.0-6.35 km/s vertically from 0-15 km depth. Similarly the $\boldsymbol{V_S}$ varies from 3.0-3.70 km/s from 0-15 km depth with $\frac{V_P}{V_S}$ varies from 1.48-1.78, Poisson's ratio varies from 0.085-0.27 within this range in the upper crust along this profile with a clear distinction between EDC and WDC with CSZ as the major divide for the juxtaposition of the two cratonic blocks. It is also observed that the $\frac{V_P}{V_S}$ and Poisson's ratio values are large (1.78, 0.27) in the upper crust towards WDC as compared to that (1.69, 0.23) towards EDC. Based on this study and the geological evidences, we infer presence of numerous shear zones as well as mushrooming of mafic dykes in this region (Fig. 5).

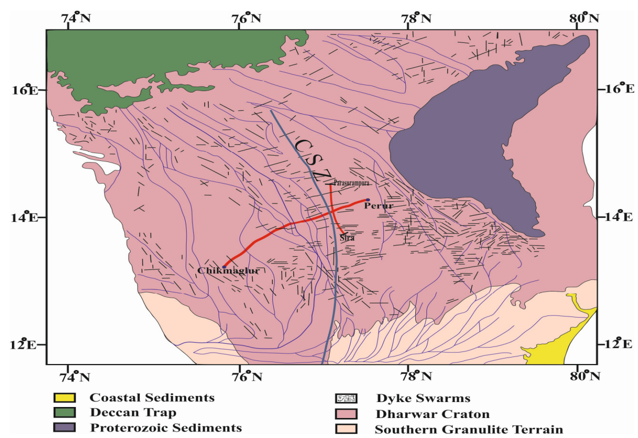

Figure 5: Different dykes prevalent in the Dharwar Craton along with the major shear zone imaged called Chitradurga Shear Zone (CSZ) dividing mainly EDC and WDC.

Conclusions

The rock composition of different rocks in the upper crust (upto 15 km depth) have been obtained for the first time in Dharwar Craton using deep seismic wide-angle 3-C seismic data. The velocity model (both V_P and V_S) provide very good insight about different lithological boundaries controlled by a major shear zone called CSZ, which divides EDC and WDC. The composition of rock types inferred from $\frac{V_P}{V_S}$ and Poisson's ratio indicates EDC has felsic rocks as compared to ubiquitous presence of mafic rocks in the WDC with numerous shear zones as well as dominated by dyke swarms, which may infer to intense igneous activity during Meso-Proterozoic period. The presence of CSZ is well defined with faults near 120 km of the model distance. The basement is also highly undulated at 7 km depth overlying the upper crustal rocks.

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