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Some Insights into Possible CO_2 Sequestration in Subsurface Formations beneath Deccan Volcanic Province of India

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ABSTRACT

The mid-western part of on-land India and adjoining offshore region are covered with a thick pile of 65 Ma old Deccan volcanics, which are known to be the largest flood basaltic eruptions on the earth's surface. Extremely rapid eruption and fast cooling of these lavas have severely affected their physical properties like density, porosity and permeability, which have relevance to geologic sequestration of CO_2. Since this region is now being considered primarily for such an endeavour, the knowledge of the thickness details along with physical properties and structural disposition, besides what lies above and below these volcanics becomes essential. Based on some previous and our present multi parametric geological and petrophysical studies in a 617 m deep Killari bore hole (KLR-1), drilled in the eastern part of the Deccan Volcanic Province (DVP), we infer that these volcanics appear to be composed of thick columns of alternating layers of both massive and vesicular/amygdaloidal type basalt. Vesicular basalt has low density, low velocity and high porosity. In some areas (including offshore), Deccan volcanics are underlain by thick Mesozoic sediments, followed further by either Jurassic volcanics (like Saurashtra region) or high density, high velocity CO_2 rich amphibolite to granulite facies transitional mid-crustal rocks. Based on our findings, we suggest that in comparision to Deccan volcanics, the subsurface thick Mesozoic sediments as well as immediately underlying Mesozoic volcanics, can be seriously considerd as a leading option for geologic CO_2 sequestration. At the same time, since the entire DVP is pervasively fractured, faulted and highly deformed, apart from being seismically active since historical times, CO_2 sequestration in on-land exposed volcanics should be given least priorty.

INTRODUCTION

In the last 300 Ma, there have been several volcanic episodes on the earth's surface like, Columbia River, Ethiopian, Deccan Traps, Serra Geral, Karoo and Siberian basalts . The 65 Ma old Deccan volcanics, which cover almost one-sixth of the Indian landmass and extends for over half a million square kilometres on the onshore and offshore near western margin, is considered the largest among them all. These volcanics are composed of a large number of gentle dipping tholeiitic basat flows, having an estimated thickness of more than 2 km at places, resting directly either over the late Archaean crystalline basement or thick Mesozoic sedimentary cover. The main phase of this historic volcanism had an extremely short duration of only about 10,000 years (Courtillot, 1990).

Currently, this large igneous province (Fig. 1) is viewed as a prominent site for the storage and injection of CO_2 either directly into Deccan volcanics or underlying sediments to reduce greenhouse warming. Present study aims at discussing various possible options including Deccan volcanic formations for CO_2 storage, based on recently acquired geological and geophysical informations.

NEED TO CO_2 CAPTURE AND STORAGE

It is no secret today that as much as 22 billion tons of CO_2 is getting pumped into atmosphere from man- made or anthropogenic sources (Benson and Surles, 2006). It is feared that it may cause considerable stress to the climate and thus to the existence of mankind itself. On world wide scale, CO_2 injection for enhancing oil recovery , has been considered a major option since 1950's (Karmarkar, 2014). However , as a remedial measure to global climate change, CO_2 capture and sequestration (CCS) in deep geological formations, has emerged as an important option over the past two decades (Torp and Gale, 2002; Benson and Cole, 2008). It started in a big way in 1996 with a Sleipner saline aquifer storage project in the North sea (Torp and Gale, 2002), followed by many such projects like In-Salah gas field project in Algeria in 2004 (which stores CO_2 in the flank of a depleting gas field) and Weyburn project in Saskatchewan (Canada), where enhanced oil production and storage of CO_2 in the Weyburn oil field happens simultaneously (Moberg et al., 2002; Riddiford et al., 2002). Currently, some of the large scale CCS operations involve storing of around one million tons a year, and encouragingly, several such projects are planned by many other countries like Algeria, Mexico, Saudi Arabia and United Arab Emirated . To have a significant impact on climate, many billion tons of CO_2 need to be sequestrated annually and that would require selection of proper depository sites.

BASIC REQUIREMENTS FOR SITE SELECTION

Basic requirement for CO_2 sequestration is the site selection and thereafter monitoring. Selecting an appropriate

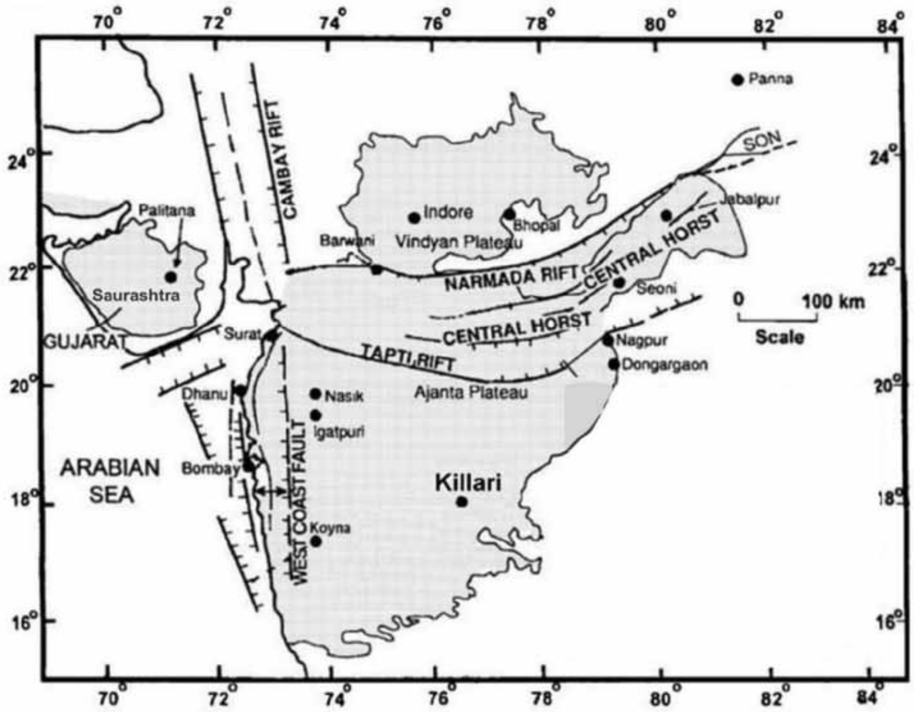

Figure 1. Major geotectonic elements and known extent of on-land Deccan flood basalts in western India.

storage site with minimal leakage risk is not an easy task. Current scenario indicates that there is no serious problem in sequestrating CO_2 directly into (i) thick permeable sediments of depleted oil and gas reservoirs, (ii) brine-filled porous reservoir rocks saturated with brine (or saline formations), and (iii) deep thick coal seams (Benson, 2005; Metz et al., 2006), if they have impermeable and low porous cap rocks (viz., fine grained shale, mudstone or carbonate rocks like limestone and dolomite etc.) above and below the sequestrated layer. Apart from thick sediments, fluid filled deep volcanic sequences are also now being considered a safe option, if its physical properties are favourable, with proper capping of rocks. Such regions preferably need to be devoid of faults and aseismic in nature. Thus, before embarking on CO_2 sequestration in volcanic formations, knowledge of their thickness, physical properties, structural disposition as well as what lies above and below of it, becomes essential.

CONSTRAINTS ON POSSIBLE CO_2 SEQUESTRATION IN DECCAN VOLCANICS

Deccan volcanic magmas (tholeiitic basalts) apparently fractionated in the lower crust, before their fast extrusion on the earth's surface (Pandey and Negi, 1987). They are not derived directly from the mantle and as such, their shallow origin and rapid extrusion as well as cooling, considerably affected their physical properties. Conforming to this, the estimated Mg Ratios for the Mahad - Mahabaleswar section, which is one of the thickest Deccan Trap sequence, were found quite low (0.34 - 0.50). Unusual nature of these basalts has been further confirmed by laboratory measurements on core samples derived from KLR-1 borehole drilled in the epicentral region of 1993 Killari earthquake region (Gupta et al., 2003).

This 617 m deep borehole penetrated 338 m thick Deccan basalts, followed further by 8 m of intratrappean sediments and 270 m of late Archaean crystalline basement (Gupta and Dwivedi, 1996). 53% of the basaltic column above the basement, comprised massive basalts with a high density of 2.90 g/cm^3 (Fig. 2), while the rest 47% of the basaltic column consisted mainly of non-massive vesicular variety, characterized by dry and wet densities of 2.36 g/cm^3 and 2.56 g/cm^3, respectively (Gupta et al., 2003). Non-massive variety is found to contain lots of void spaces with estimated porosity of 20% and more. Average density of Deccan basalt is estimated to be around 2.65 g/cm^3 only. Our own measurements too have indicated a wide range in dry density from 2.24 g/cm^3 to 3.00 g/cm^3 for the Killari borehole basalts, conforming to their both massive and non-massive nature. The average density of these volcanics is lower than the expected density.This is also reflected through much lower P-wave velocities of 4.3 to 5.2 km/s (Kaila et al., 1990; Sain et al., 2002; Sain and Zelt, 2008; Dixit et al., 2000, 2010; Murthy et al., 2010, 2011; Pandey et al., 2011).

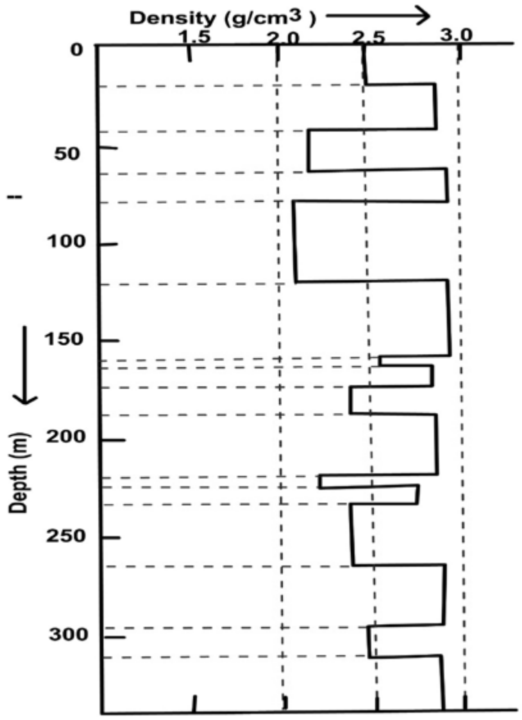

Figure 2. Measured mean density variation in Deccan Trap sequences penetrated by KLR-1 borehole in killari region of Maharashtra (Gupta et al., 2003). Massive and vesicular and/or amygdaloidal basalts are characterised by high and low densities respectively.

The underlying crystalline basement below the Killari earthquake region has been diagnosed as high density (2.82 g/cm^3) , high velocity late Archaean amphibolite to granulite facies transitional mid crustal rocks, containing more than 2 wt% of CO_2 (Pandey et al., 2009, 2014; Tripathi et al., 2012 a, b). Similar grade high velocity basement rocks are expected in other Deccan volcanic covered areas also (Rathore et al., 2000; Krishna, 2006; Pandey, 2009; Rao et al., 2013).

It is indicated from the recent geophysical and deep drilling results that apart from exposed areas, considerable thickness of such volcanics are concealed below thick sedimentary column at several places that would include offshore areas too, for example, Cambay graben, Kachchh-Saurashtra region and adjoining onshore and offshore areas (Biswas, 2005; Sain and Zelt, 2008; Carmichael et al., 2009; Dixit et al., 2010; Pandey et al., 2011; Murty et al., 2011). On-land, low density porous volcanic formations are as thick as 45m, which are bounded on either side by massive non-porous high density basalts (Fig. 2). Similar massive/porous Deccan volcanic formations are also present at subsurface depths below the thick sediments, as they too are characterised by a Vp~ 4.75- 5.2 km/s (Dixit et al., 2010), similar to the on-land exposed volcanics (Vp~ 4.6 - 5.0 km/s; Murty et al., 2010). These subsurface volcanic layers are sometimes quite thick. For example, near Ankleshwar, more than 3 km thick volcanics are expected to be present below ~2 km thick sedimentary column (Dixit et al., 2010). The low density/low velocity, sub surface highly porous non-massive volcanic zones, which are sandwiched between massive (high density and almost zero porosity) volcanic layers on top and bottom, could turn out to be a suitable on-land/offshore site for CO_2 sequestration. It would fulfil major geological criteria, like leakage, impervious cover and large storage capacity. Interestingly such volcanic layers have thick overburden and multiple impervious horizons.

SEQUESTRATION IN MESOZOIC SEDIMENTS

Recent studies (Kaila et al., 1990; Dixit et al., 2000; Sain and Zelt, 2008; Carmichael et al., 2009; Murty et al., 2010, 2011; Pandey et al., 2011; Rajendra Prasad et al., 2010) indicate presence of thick Mesozoic sediments (up to ~ 3km thick) below Deccan volcanic flows. They mainly contain sandstone and claystone rocks (Dixit et al., 2000; Pandey et al. 2011). Fig. 3 illustrates the nature of one such sequence. Deep-seated column of porous sandstone, a few thousand meters below the surface and having suitable cap rocks on top and bottom, may provide an ideal situation for CO_2 injection and storage. The pore spaces in sedimentary columns are usually filled with salt water (saline formations), where oil/gas reservoirs are often located. Importantly, multiple sealing units, like claystones will protect against fluid migration, a pre-requisite condition for CO_2 sequestration.

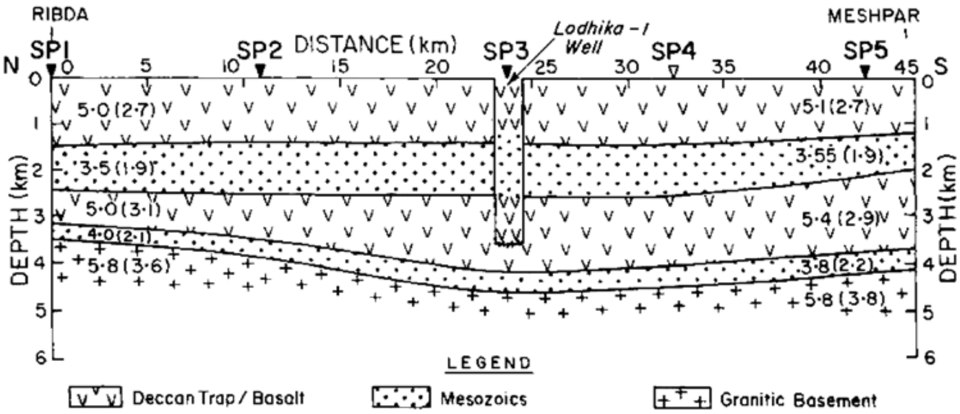

Figure 3. Occurrence of subsurface Mesozoic sediments and older Mesozoic volcanics along the Ribda-Meshpar profile, in the Deccan volcanic region of Saurashtra, Gujarat (after Dixit et al., 2000). P- and S-velocities of each layers, together with the location of the Lodhika-1 borehole, is also shown.

CO_2 SEQUESTRATION IN JURASSIC VOLCANICS - A STILL BETTER OPTION

In certain areas like Saurashtra peninsula, Deccan basalt covered Mesozoic sediments are further underlain by 0.75 to 1.5 km thick older volcanic sequences of early Jurassic age (~184 Ma), having a relatively higher velocity of 5.0 to 5.4km/s (Dixit et al., 2000). They are concealed below a total overburden of about 2 to 3 km (Dixit et al., 2000; Sain et al., 2002) and formed consequent to thermal perturbations caused by initial rifting between Africa and India. These volcanics may prove to be a better option for CO_2 sequestration than Deccan volcanics. Having a thick and multiple impervious overburdens, they would be free from leakage problem and fluid migration. Only disadvantage could be limited pore volume than the Mesozoic sediments. Their porosity, however, would probably be similar to the Deccan volcanics, in view of the velocity estimates (Fig. 3). It will also fulfil the requirement of high in-situ temperature and pressure.

DISCUSSION AND CONCLUSIONS

Different types of subsurface rock formations can be considered as large carbon reservoir. They include coal seams, organic rich shales, hydrocarbons and carbonate-rich rocks. In connection with the enhancement of oil recovery, CO_2 sequestration was initiated as early as 1950's (Khatib et al., 1981; Grigg and Schechter, 1997; Rogers and Grigg, 2001; Karmakar, 2014). However, for a large quantity of geologic sequestration of CO_2, the depleted oil/gas reservoirs may not always be readily available.

It is feared that injection of million tons of super critical liquid CO_2 directly into deep geological formations, may induce earthquakes. In this context, Deccan volcanic region, unlike countries like Norway, where CO_2 injection has been successfully attempted, may not be ideal as it is highly fractured, faulted and seismically unstable (Ravi Shanker, 1995; Agrawal and Pandey, 1999). This region has witnessed mild but significant seismic activity in the past in the form of many damaging earthquakes, like, 1967 Koyna (M 6.3), 1993 Killari (M 6.2), 1997 Jabalpur (M 5.8) and 2001 Bhuj (M 7.7) (Pandey et al. 2009).

Interestingly, there are no such reports of significant increase in induced seismicity with any of the storage sites so far. In any case, it can be managed with suitable monitoring. Taking the above facts and the latest geological and geophysical findings into consideration, we suggest that subsurface rock formations like (i) Deccan volcanics, concealed below thick Tertiary sediment cover, (ii) thick Mesozoic sediments underlying these subsurface volcanics, and (iii) the older Mesozoic volcanics which form the base of Mesozoic sediments (like that found in Saurashtra region, Fig. 3), may form imminently suitable sites for geologic sequestration of CO_2. Out of the three options outlined above, second and third options are preferable. However, earlier detailed factors must be taken into consideration before embarking on such an endeavor.

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