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Geomechanical modeling using finite element method for prediction of in-situ stress in Krishna–Godavari basin, India

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ABSTRACT

This study provides quantitative rock mechanical properties and analyses of in-situ stress and pore pressure in several oil/gas fields of East and West Godavari sub-basins. High pore pressure gradients varying from 11.85 to 12.80 MPa/km exist within these oil/gas fields. Vertical stress (S_V) gradients in the range 21.00 to 22.85 MPa/km are seen to exist. Minimum horizontal principal stress (S_h) magnitude is found to vary from 64% to 76% of S_V, while maximum horizontal principal stress (S_H) magnitude is observed to vary from 90% to 92% of S_V within normally pressured to over-pressured sediments. The breakout derived S_H orientation from two well varies from N14°E to N22.5°E in the Krishna–Godavari basin. Rock mechanical properties such as Young's modulus, Poisson's ratio and unconfined compressive strength have been estimated from logs of compressional and shear wave travel time. Two-dimensional (2D) stress modeling using finite element analysis has been carried out for some important oil/gas fields situated within East and West Godavari sub-basins as a part of the current study. Regional S_H orientation has been used for application of stress at the model boundary. Discontinuities in the stress pattern which can be associated with interfaces between weak and competent layers have been commonly observed and especially where silici-clastic and volcanic inter-bedded sequences are encountered. The model predicted stress orientations are verified with the Formation Micro Imager (FMI) log data of wells at the above-mentioned sub-basins.

1. Introduction

Geomechanical studies are of significant interest in the areas of geological sciences and engineering. Accurate modeling of the several geomechanical properties is crucial in order to safely and efficiently drill a well in technically and economically challenging reservoirs [1–3]. Knowledge of the orientation and magnitude of the principal stresses along with pore pressure and fracture pressure is essential for building comprehensive geomechanical models. Directions of principal stress orientation hardly remain stable over lengthy intervals, and can be often seen to be rotated in the presence of faults, salt diapirs, mountains or other complex structures [4–8]. Subsurface sediments respond to applied stresses through deformation, accompanied by changes of rock mechanical properties. Faulting, lithological changes and contrasts in rock mechanical properties within a geological formation can lead to stress perturbations and produce local stresses that can significantly deviate from the regional stress field [9]. A valid and sufficiently accurate geomechanical model of the oil/gas fields would allow us to address the many challenges that characterize basin studies and exploration, exploratory well drilling, appraisal drilling and development drilling that could necessitate drilling of highly deviated wells, which cannot be planned without a geomechanical model of sufficient accuracy in place. Well engineering, assurance of wellbore stability during drilling, efficient well completion and delivery, initial testing and production profiles plans are heavily dependent upon the availability of robust geomechanical models of the sub surface, to start with. Even a reasonably accurate prediction of long-term response of a reservoir to pore pressure depletion would be impossible without valid geomechanical models of the sub surface [10–13]. Geomechanical models of the sub surface do have great relevance and importance in the areas of basin studies and exploration as such models yield valuable insights into oil or gas reservoirs presence in the subsurface and often provide huge synergies when integrated with models.

Geomechanical reservoir models in present study attempt the pre-drilling prediction of the local variations in stress magnitude and orientation. This requires a numerical modeling approach that is capable of incorporating the specific geometry as well as the distribution in space of mechanical properties of the subsurface reservoir [9]. Therefore for the purpose of effective geomechanical

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modeling, we focus on (a) determination of the in-situ stress field, pore pressure gradient and fracture initiation pressure gradient of selected oil/gas fields located in the Krishna–Godavari (K–G) basin, (b) computation of mechanical properties such as Young's modulus, Poisson's ratio and unconfined compressive strength from logs of compressional/shear wave velocities (V_p/V_s), (c) construction of finite element model (FEM) which represents the subsurface geometry and deformation distribution, using the above well point data (d) quantitative assessment of model's (response) sensitivity to variation in material properties and boundary conditions and, finally (e) validation of stress orientation from breakout data of Formation Micro Imager (FMI) logs.

2. Study area

The K–G basin is a passive margin pericratonic basin situated on the Eastern Continental Margin of India (ECMI) and encompasses large areas both on land and offshore including those located in deep waters. The basin itself came into existence following rifting along ECMI craton during early Mesozoic. Both on land part of the basin and its offshore host a large number of structural traps that have been mapped and a large number of them has been established through drilling [14]. The basin was created as a result of tensional basement tectonics and is characterized by ENE-WSW to NE-SW trending horsts and sub-basins/grabens overlying a rifted basement structure. K–G basin is subdivided into three sub-basins namely; Krishna, West Godavari and East Godavari which are separated by Bapatla and Tanuku horsts respectively (Fig. 1) [15,16]. It is characterized by a normal faulting tectonic regime. West Godavari sub-basin is further subdivided into the Gudivada, Bantumilli grabens separated by Kaza–Kaikalur horst. The Mandapeta graben and Kavitam–Draksharama high [14] are situated on either side of Tanuku horst in the East Godavari sub-basin. In addition to the basin margin fault, three more regional faults developed: Matsyapuri–Palakollu fault of Eocene age on land, a Miocene structure building fault in shallow water near to the coastal area and a Pliocene structure building fault in deeper water [17]. The thickness of sediments varies from 3 km (Krishna graben) to over 7 km (Godavari offshore) and commercial hydrocarbon is found in the Permo-Triassic to Pliocene reservoirs. Geological cross-sections such as, AA′ (56 km long) and BB′ (160 km long) (Fig. 2) show the disposition of the sedimentary formations top and basement across N–S and SW-NE directions respectively traversing the K–G basin. Subsidence in the south-Eastern part of the East Godavari sub-basin may contributes to the formation of a steep step-fault zone in early Paleocene Razole Formation (basalt). This fault zone is known as the Matsyapuri–Palakollu fault zone [14]. The AA′ section shows the sediment deposition pattern from onshore to offshore. Razole basalts are deposited at depth in the offshore areas but occur at shallower depth in on land.

The candidate wells chosen for the current study (and named as KM, KA and KR respectively) are located near producing gas fields in the basin. Sedimentary formation penetrated in the Suryaraopeta and Mahadevapatnam fields at the West Godavari sub-basin include Raghavapuram Shale at the base, followed by Tirupati Sandstone, Razole volcanics and Nimakuru Sandstone at the top, ranging in age from Early Cretaceous to Paleocene age [14]. Raghavapuram–Tirupati is the dominant petroleum system in the West Godavarisub-basin [17]. The wells KG, KS and KK are located between the Rangapuram gas field and Ravva oil field at the East Godavari sub-basin and penetrate Vadaparru Shale at bottom followed by Matsyapuri Sandstone and Godavari Clay at top, ranging in age from Eocene to Pleistocene. Gamma ray (GR), resistivity (LLD), density (ρ) and sonic travel time (DT) logs have been used to identify the top of the formations encountered in these wells. Multi well correlation through KG–KS–KK at the East Godavari sub-basin (Fig. 3a) identifies the top of Matsyapuri Sandstone Formation which overlies the Vadaparru Shale and capped by Godavari clay. The Vadaparru–Ravva/Godavari clay system is one of the relatively younger petroleum systems in K–G Basin of Tertiary age which includes a narrow coastal strip of

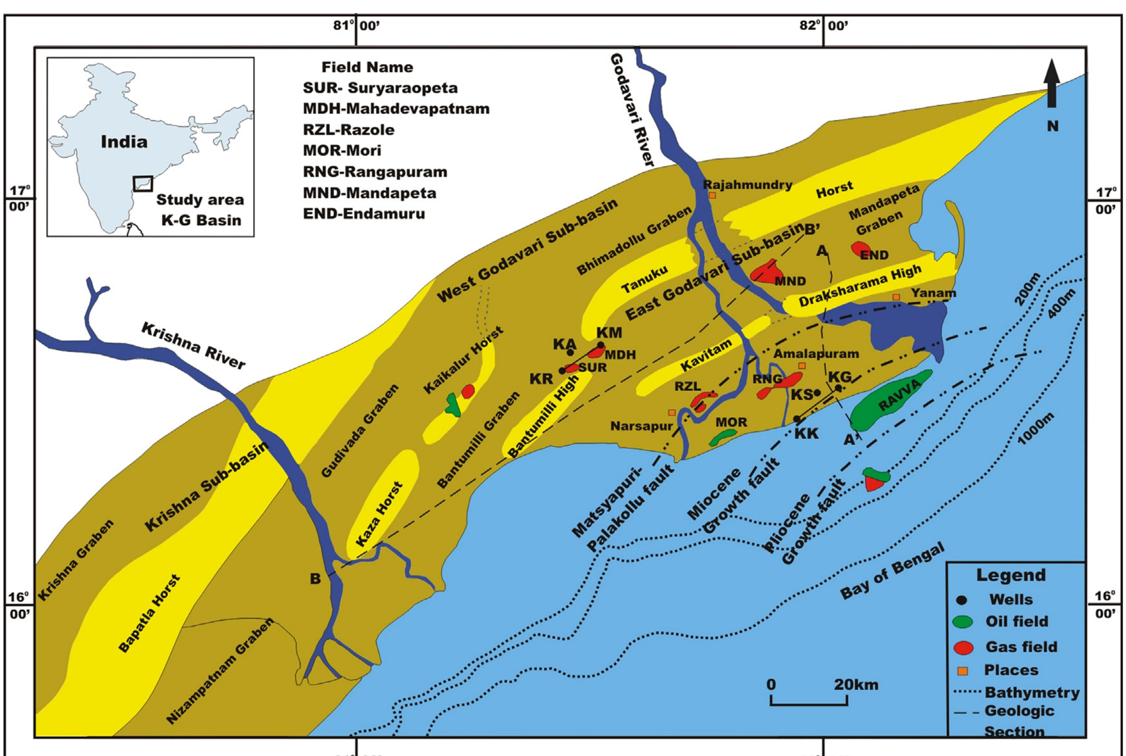

Fig. 1. Illustrates location of six wells including two geological sections AA′ and BB′ in K–G basin [42]. Major oil/gas fields are shown near the six wells [14].