SEDIMENTOLOGICAL AND FACIES ARCHITECTURAL CONTROLS ON HYDROCARBON-BEARING INTERVALS IN PARTS OF THE NIGER DELTA, NIGERIA

BY

UBULOM UBULOM UBULOM

(B. Sc. GEOLOGY, M. Sc. PETROLEUM GEOLOGY/EXPLORATION GEOPHYSICS)

BEING A THESIS IN PARTIAL FULFILMENT OF THE

REQUIREMENTS FOR THE AWARD OF DOCTOR OF

PHILOSOPHY (Ph. D.) IN APPLIED GEOLOGY OF THE DEPARTMENT OF GEOLOGY, FACULTY OF SCIENCE

OF THE OBAFEMI AWOLOWO UNIVERSITY,

ILE-IFE, OSUN STATE, NIGERIA

AUGUST, 2012

CERTIFICATION

This is to certify that this work was carried out by Ubulom Ubulom Ubulom (SCP05/06/H/3402) in the Department of Geology, Faculty of Science, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria.

------------------------------------ ----------------------------------

Prof. J. I. Nwachukwu

(Supervisor)

Prof. J. O. Ajayi

(Head of Department)

DEDICATION

This work is dedicated to the Almighty God for His special favour and kindness to me and to my grandmother, late Mrs. Dada Orofori Ijong Ikan who devoted her life to guide my early steps in life and to rear me.

ACKNOWLEDGMENT

I wish to express my profound gratitude to my amiable and indefatigable supervisor, Professor Joseph I. Nwachukwu, whose encouragement, enthusiasm, moral support, corrections and advice helped to create and metamorphose this thesis to its final state. He offered enormous personal sacrifice, time and effort through the lengthy period of research data acquisition to the analysis stage, interpretation and even the final copy.

I sincerely acknowledge the encouragement from lecturers in the Department who were very friendly. Chiefly, thanks to our former HOD, Dr. O. O. Ocan and his successor, Prof. J. O. Ajayi. I am truly grateful to Profs. S. B. Ojo, M. A. Rahaman, B. D. Ako and M. O. Olorunfemi of Geology Department, as well as Drs. Lawrence Fadiya, A. A. Adepelumi, D. E. Falebita, Alao Olatunbosun and Mr. Ehitua Esiegbe, a Ph.D student in the Department for their affability and moral support. Thanks to Dr. J. A. O. Oyekunle of Chemistry Department for assistance during Soxhlet extraction; my friend, late Benjamin Ikpeme Umoh, and Wachua Obedah Hildi, fellow Ph.D students for mutual encouragement. I am grateful to Mr. A. T. Adesiyan of the Geochemistry laboratory for analytical support. Special tributes to my great and beloved late uncles; Chief Nelson Ikan Mbajah, who led me to start school, Elder Stephen Ikan for immense love and financial support of my education and Chief Maxwell N. Ikan Mbajah, the Mgbugbo Akwan VIII for affection and moral support. I fondly appreciate my Aunt, Mrs. Martha Lewis

Adasi and Uncle, Mr. Monday Ijong Ikan. Their collective efforts and sacrifices have yielded positive results.

I am indebted to Chevron Nigeria Limited for providing the data used for this work, including Figure 1 and to the staff of the Department of Petroleum Resources (DPR) who facilitated data acquisition from Chevron. Special thanks to Mr. Kweku Segoa, the Managing Director of EOGAS Petroleum & Geosciences Ltd, for an opportunity to use the company's Landmark Geographix Workstation for my interpretation work. The numerous authors whose works were consulted are gratefully acknowledged. Thanks to Mr. Johnson Salako, the Managing Director and Mr. Toju Jemide, the Executive Director Finance of Goland Petroleum Dev. Company Ltd for moral support.

My family showed huge support, encouragement and love. I am eternally grateful to my beautiful wife and true friend, Peninah; our lovely children, Awajiomin, Mary, Elizabeth, Stephen-Ikan and Oromimaemi who constantly asked; "Daddy, how is your study?" I treasure your patience and understanding. Special tributes to my Step-Mother, Mrs. Bartha Monday. She steadfastly stood by my hardworking and caring father, Mr. Ubulom Ubulom to start my Secondary School training at that very crucial stage. My dear Cousin, Mr. Edwin E. Ubulom ceased not his words of encouragement and ardent interest, thanks. I appreciate my beloved Cousin and his dear wife, Engr. and Mrs. Leopold S. Ikan; together you are a fountain of love and inspiration. To my beloved sister, Mrs. Ugwem Adasi, Brother Edward, Cousin, Pastor Festus Nathaniel, Mrs. Janet Kyrian, Engr. Nwauche Erastus and all other relations not mentioned here, please accept my appreciation. I humbly acknowledge continuous moral support

and prayers from my Church, Methodist Church Nigeria, Okoro Mbokho, where I was first prayed for at the commencement of my educational programme.

A special tribute to my awesome Grandmother, late Mrs. Dada Orofori Ijong Ikan (Nee, Adasingo). You started it all, after your daughter, Mary's early home call, such that I knew her not; you planted the seed of hard-work, self-confidence, integrity and meekness in me; loved and guided me on the path of excellence. Finally, I ascribe all honour, glory and majesty to my Lord God Almighty. Great is your faithfulness. You oh my Lord, have done to me exceedingly great things, beyond every human imagination. All who shall put their faith in you, will not fail, they are beckons of light and of your faithfulness in their generation and the coming ones.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES **273 - 404**

ABSTRACT

This study appraised sedimentological and facies architectural controls on reservoirs of Imaemi Field, offshore Niger Delta. This was with a view to incorporating sedimentological and facies architectural characteristics in exploring reservoirs and identifying transgressive-regressive sequences. It also intended to generate models of spatial variability of lithofacies architecture and petrophysical properties of reservoirs, at sub-interwell scale and related their association to hydrocarbon distribution.

Well logs from 25 wells and core samples from 2 wells within the field were used for petrophysical, grain size, petrographic and heavy mineral analyses. Sequence boundaries were defined by transgressive-regressive technique and stratigraphic sections were built from logs. Quantitative lithofacies data yielded shale, sandy shale, silt, shaly sand, silty sand and sand occurrences used for sequential indicator simulation. Sequential Gaussian simulation was used for petrophysical properties and fluid saturation models.

Eleven sequence boundaries named SB-1 to SB-11 were delineated in the field. Reservoir architectural analysis yielded 24 vertically stacked, youngest to oldest reservoir bodies (A-Sand to Q-Sand) within channel-fill, abandonment phase, delta plain and prodelta depositional settings. Traditional reservoir characterization and geostatistical simulations of lithofacies and petrophysical properties for H, I, J, L, M and N-Sands showed lithofacies spatial distribution, lenticular sand geometries, shale beds continuity, intra-reservoir flow barriers, shale volume (11.00 to 67.00 %), effective porosity (5.00 to 30.00%), permeability (0.02 to 5949.15 mD), pore aperture radii (0.05 to 0.29 μm), effective pore radii (20.57 to 206.57 μm) and hydrocarbon saturation (18 to 82%) distribution. Gas and oil saturation up to 82.00% were associated with cleaner sand intervals, except in M-Sand, where irregularity occurred; while low saturation (32.00%) in shale-rich portions was due to high surface area, low effective porosity, excessive percentage bond water and low pore aperture radii. Pore aperture radii (r) values less than 0.10 μm indicated wet intervals, while 0.10 μm and above depicted hydrocarbon presence. Compartmentalized pools in the reservoirs reflected lithofacies distribution and highlighted hydrocarbon-bypassed prone zones in the six sand bodies studied. Reserve growths potential occurred to the northwest, southwest and southeast of the area.

The study concluded that, the spatial distribution of lithofacies and petrophysical properties were related and influenced hydrocarbon distribution.

CHAPTER ONE: INTRODUCTION

1.0: Preamble

The science of exploration and production of petroleum has advanced steadily, prompting hydrocarbon search in the ultra-deep offshore basins and other hostile environments. Discovered onshore and shallow offshore fields are maturing, while major proportions may not be viable, compelling checks of conventional and emerging field evaluation practices. Earth scientists therefore, are faced with the task of understanding and integrating the length-scale variability of spatial reservoir sedimentological and petrophysical properties in relation to contained fluid, addressed in this study. Imaemi Field was discovered in 1968, offshore western Niger Delta. It has a surface area of 54.81 km^2 (21.16 mi^2) in 9.14 m (29.99 ft) water depth and is here informally named "Imaemi Field" due to proprietary reasons, while the actual location is retained.

It is increasingly obvious that conventional approach alone rarely resolves reservoir lithofacies micro-scale architecture, petrophysical properties and associated fluid spatial distribution. This therefore, necessitated integration of traditional techniques with geostatistical simulations to unveil the spatial and regionalized distribution of geologic properties and fluid, even at sub-interwell scale in the field.

1.1: Statement of Problem

The spatial distribution of indeterminate sedimentological facies and petrophysical properties, such as pore aperture size and permeability, dictate hydrocarbon distribution and recovery in reservoirs. Conventional reservoir characterization methods alone rarely provide field-wide distribution of these properties in undrilled areas. There is, therefore, the need for a simplified, integrated approach that combines conventional and geostatistical estimation methods to address their spatial variability in reservoirs; hence this study.

1.2: Research Objectives:

The specific objectives are to

(a) present an integrated technique that incorporates the significance of sedimentological and facies architectural controls in field management;

(b) elucidate detailed architecture of reservoirs in Imaemi Field; unveil field-scale architectural stacking pattern and distribution of the reservoirs;

(c) quantitatively characterize the distribution of geologic facies and reservoir petrophysical properties for geostatistical modelling at sub-interwell scale;

(d) construct three-dimensional geostatistical models or realizations based on quantitative facies architectural analysis and petrophysical data, depicting heterogeneity at sub-interwell scale; and

(e) use the geologic models to explain the relationship among geologic facies, petrophysical properties and hydrocarbon saturation distribution, relevant for predictive reservoir management in similar geologic setting.

1.3 : Research Justification

The main justifications of this study are that:

1) the indeterminate nature of facies changes, often below well spacing distances are very difficult to represent in the horizontal direction. Geostatistical simulations present a simple approach to capture their variations, even in unsampled locations;
2) it is impracticable to sample every point in a field (even at a meter length scale) to assemble data useful for predictive reservoir management. The use of conventional log-derived data and core information to generate field-wide models through geostatistical simulations, hence, presents scientific basis and promising cost effective alternative for predictive reservoir management;
3) integration of quantitative facies data and petrophysical properties to assess reservoir characteristics and fluid distribution can allow monitoring of reservoir behaviour and comparison with models in other basins;
4) the approach can aid to identify hydrocarbon-bypassed pay intervals in producing fields, proximal to production facilities and could therefore add significantly to production and extension of mature field life; and

5) integration of sedimentological properties, facies arrangement and petrophysical properties would enhance effective reservoir management, increase recoverable reserves and therefore advance effort to meet the rapidly growing global energy needs.

This study developed a technique that would foster the production of geologic models that depict spatial and regionalized distribution of facies, petrophysical properties and fluid necessary for prediction of hydrocarbon occurrence even in undrilled areas.

1.4: Location of Study Area

Imaemi Field is located 8.00 km (4.97 miles) offshore in the western part of the Niger Delta within 9.14 m (29.99 ft) water depth. It is within a mega-structural framework commonly locally referred to geologically as the "Inner Trend", which runs almost parallel to the coastline, along an elongated rollover anticlinal structure (Fig.1.1). The field is situated within the palaeogeographic zone referred to as the Upper Miocene/Pliocene and Pliocene/Pleistocene of the delta formation cycle (Etu-Efeotor, 1997). The Niger Delta has five depobelts in three major environmental settings namely; onshore, continental shelf and deep offshore, determined by major regional faults (Reijers, 1996). The onshore has the Northern depobelt, Greater Ughelli, Central Swamp and Coastal Swamp depobelts. The shallow offshore depobelt however, occurs in the continental shelf and the deep offshore depobelt follows in the deep waters. The Imaemi Field is found in the offshore depobelt, coinciding with the Upper Miocene/Pliocene and Pliocene/Pleistocene delta formation cycle. The three major Niger Delta environmental settings qualify as extensional, transitional and compressional zones (Fig. 1.2) and are characterized by three categories of structural styles, namely; growth faults, diapirs and toe-thrust structures respectively. Imaemi Field is in the continental shelf, shallow offshore depobelt distinguished by growth faults.