DERIVATION OF REFRACTION STATICS SOLUTION FOR 3D SEISMIC DATA IN OML-23 SOKU, NIGER DELTA USING THE DELAY-TIME APPROACH

By

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APPROVAL

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DEDICATION

This PhD Dissertation is dedicated to God Almighty – The Author and Finisher of my Faith, from whom I draw strength daily in the journey of life and HIM who has continued to prove himself as GOD in all my affairs even in the "darkest of days".

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ABSTRACT

OML-23 SOKU is a prospect in the onshore Niger Delta Basin with huge hydrocarbon potential but is plagued with statics problem. This poses a serious challenge for the seismic imaging of the prospect which in turn, would result in erroneous interpretations. To avert these problems, it is imperative for a refraction statics solution to be derived and applied for OML-23, SOKU which has necessitated the study. The aim of the study is to derive a refraction statics solution for 3D seismic data from OML-23, SOKU using the delay time approach. The objectives are to: generate a near-surface model of the prospect in terms of weathering and sub-weathering layer thicknesses and velocities; adapt the near-surface model in deriving a refraction statics solution for the prospect; determine the effectiveness of the statics solution on shot gathers from the prospect; determine the effectiveness of the statics solution on stacked and migrated sections of dataset from the prospect. Seismic noise and amplitude compensation problems which were identified on the seismic dataset were resolved using appropriate processing strategies as their undesirable effects on data quality would hamper the successful actualization of the focal objective for the study. The methodology involved using an integrated (hybrid) approach of inversion of refracted arrivals and up-hole data using special plugins on PROMAX and VISTA software to build a reliable near-surface model of the area. The near-surface model formed the input for deriving the refraction statics solutions for the SOKU dataset. The solutions comprised field statics, refraction statics, 1st and 2nd residual statics which resolved the remnant, uncorrected long and short wavelength statics effect. These solutions were loaded on both software and applied to the dataset using appropriate flow commands to perform the statics correction for the dataset in order to resolve the identified statics problem of the prospect. The result obtained from the near-surface model showed a weathering layer and three consolidated sub-weathering layers. The thicknesses obtained for the weathering, first, second and third consolidated sub-weathering layers ranged from (3 - 18m), (14 – 124m), (62 – 322m) and (248 – 493m) respectively while the velocities ranged from (520m/s), (1614 – 1723m/s), (1708 – 1758m/s) and (1950 – 1976m/s) respectively. At the shot gather processing stage, better alignment of reflection events was achieved; reflection events were exhibiting better continuity and assumed a near-hyperbolic appearance. At the stacking stage, reflectors were properly aligned and continuous with no incidence of mis-ties of reflectors, jittery reflections were moved to their actual position on the common midpoint (CMP) panel. At the migration stage, imaging quality (spatial and temporal resolution) was tremendously enhanced. Reflection continuity across the migrated section was grossly improved and true amplitudes were restored from the post migration results. In conclusion, the derived and applied refraction statics solution had adequately resolved the statics problem of SOKU. This is evident from the enhanced quality of seismic subsurface imaging results achieved. The correct derivation and application of refraction statics for seismic datasets plays a crucial role in enhancing subsurface seismic imaging for accurate geophysical and geological interpretation in the quest to identifying potential and prolific hydrocarbon reservoirs.

CHAPTER ONE
INTRODUCTION

1.1 Background to the Study

The primary objective and ultimategoalin reflection seismicdataprocessingisto obtain as accurately as possible theimageof thesubsurface,whichis very vitalfor accurateinterpretationduringexplorationforhydrocarbon resources andothergeological targets. Thetypical targetofseismicinterpretationisidentification offeatureswhichcouldreveal theoil andgasprospectsoftheregionunder investigation.The commonwaystofindpotential hydrocarbon accumulation istolookforstructural andstratigraphictraps by employing the means of modern sophisticatedimaging and interpretationsoftware tools. Theseimagesare obtainedbyusing a sequenceofprocessingsteps,andthereforetheinterpretationcan onlybe meaningful and reliablewhenallthese processing steps arecorrectandsufficientlyaccurate.

Oneof thekeystepsof seismicdataprocessingisthestaticscorrection.Theterm statics denotesthehighlyvariabletraveltimes ofreflectedwaves (ray path 2)(Figure1.1)

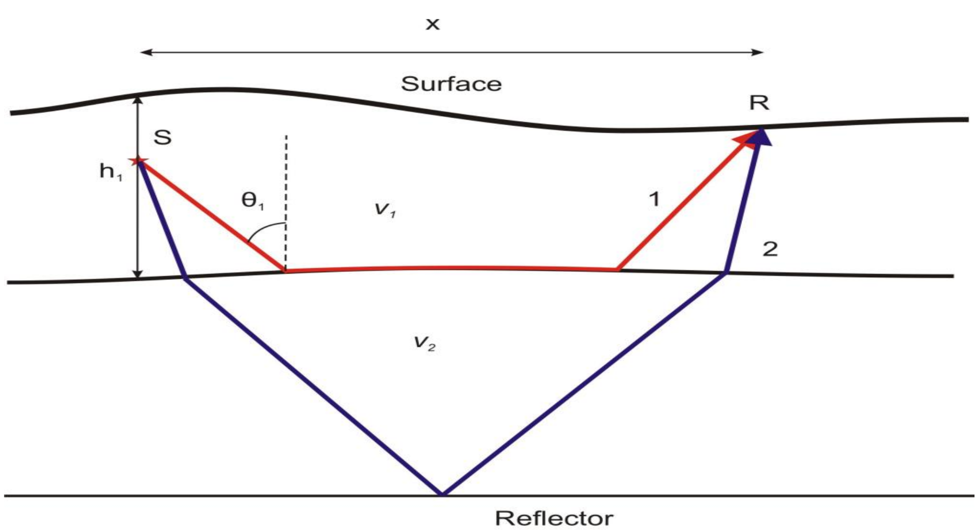


Figure1.1:Schematicsofa2Dreflectionsurveysubsurface.Thesourceis atpositionSandthe receiveris positionedatR. The ray path “1” represents ahead waveandray path “2”is a reflectedwave. (Atul, 2009)

accumulatedduring their propagationwithin theshallow subsurface(Telford *et al.*,1990).Thenear-surfacelayer(weatheredzone)is unconsolidatedandsignificantly morenon-uniformthan thedeeperlayers.Theuneventhicknessof thenear- surfacelayersandlowvelocitiesleadtolarge(often upto~50msormore),strongly variabletimeshiftsofthereflectedwavesrecordedfrom thedeeperlayers(Figure1.1). Because reflectedrays propagatenearlyverticallywithinthelow-velocityweathered zone,suchtimeshiftsarepracticallyindependentofthedepthofreflections,andthey areconsequentlycalledstatics.

Ifnot properly reduced or mitigated,staticshiftsarecapableof completelydisruptingthecoherenceof reflectionsduringcommonmidpointstacking.Spuriousreflection patterns on shot gathers andlossof depth resolution could equally be a consequence of incorrect orinaccuratestatics.Images obtained from such spurious reflection patterns would most certainly lead toerroneousinterpretationswhich is not desirable and money and time would have been wasted.The processforcompensatingstaticsisreferredtoas staticscorrection;thisis oneofthemost criticalandtimeconsumingstepsinreflectiondataprocessingand formsthefulcrum for this dissertation, as a refraction statics solution would be derived and applied to 3D seismic field datasets from OML-23 SOKU, in the Niger Delta Basin, to resolve the statics problem, so that an accurate subsurface image could be obtained for interpretation and exploitation purposes.

1.2 Statement of the Problem

Therecognitionoftheeffectofthenearsurfacelayeranditsvelocity distribution plays a vital role in the estimation of static corrections especially for onshore seismic datasets. The accuracyofstaticcorrections estimationhasessentialeffectsonresultsofmany processingprocedures.Theimportantonesarevelocityanalysis,stacking and migration. The errors instatic correction estimation arethesources ofserious structural andstratigraphicinterpretationerrors.Also,seismicinversion,andAVO proceduresareadverselyaffectedby poorstaticcorrections. Before statics correction can be well derived and implemented to seismic records, it is pertinent to first estimate the model of the near surface in terms of weathering and sub-weathering layer thicknesses and velocities.The weathered layer lies just below the ground surfaceand consists of unconsolidated sediments overlyingthebedrocks.Itvariesinthickness andthe velocity of the weathered layer is generally less than the sub-weathered layers belowit. Itisheterogeneousincompositionwithawiderangeofvelocitiesand largeenergydistributionasaresultoffrictional lossesin unconsolidatedsediment, whichcausesvariabledelayintraveltimesoftheseismicwaves (Cox, 1999).This delayintraveltimes causes or gives rise to inaccurate near-surface velocity estimation which when not properly accounted or corrected for eventually introducesstructural anomalies in deeperseismicreflection eventswhen observedon seismicrecords.

The problem of derivation of a reliable refraction statics solution for 3D onshore seismic data in OML-23, SOKU is thus the focal problem which this dissertation is seeking to address, to mitigate as much as possible, its undesirable effectsfor furtherprocessingof the seismicdataset.Themotivation for this research direction/path was anchored on our resolve to providing a solution to the statics problem of SOKU (OML-23). The research target therefore, is to derive and implement refraction statics for the SOKU 3D seismic datasets and to determine the effectiveness of the derived and implemented refraction statics solution on shot gathers, a stacked and migrated sectionsof the seismic data over the investigated prospect.

1.3 Aim and Objectives of the Study

Theresearch aimistoderivearefraction staticssolution for 3D seismic data in OML-23 (SOKU) Niger Delta using thedelay - time approach.

The objectives of the study are,

i) Generation of a near-surface model of the earth over OML-23 (SOKU) in terms of weathering and sub-weathering layer thicknesses and seismic velocities.

ii) The generated near-surface model of the earth would then be adapted into derivinga refraction statics solution that would be incorporated into the processing workflow for thedataset.

iii) Determining the effectiveness of the derived refraction statics solution on shot gathers from the investigated prospect in Field File Identification (FFID) configuration.

iv) Determining the effectiveness of the derived statics solution on a stacked section of the data over the investigated prospect.

v) Determining the effectiveness of the derived statics solution on a migrated section of the dataset over the investigated prospect.

1.4 Scope of the Study

The scope of the research would entail estimation ofanearsurface velocity and depth model over the prospect using the Delay-Time approach. Distortions due to near-surface velocity variations would be removed after identifying the Low Velocity Layer (LVL) from the estimated near surface model. Subsequently, a reliable refraction statics solution(statics correction) for OML-23 (SOKU) would be derived and applied to the seismic field datasets from the estimated near-surface model. The effectiveness or success of the derived and appliedrefraction statics solution would thereafter be determined on shot gathers, a stacked section and finally, a migrated section of the dataset.

1.5 Limitation of the Study

A minor limitation for the present study is the unavailability of a special tool called “Tomostatics” which is a recent tomographic or imaging modeling tool that could have been deployed to image the near-surface. The “Tomostatics” application is not running on the current software tools (Vista™ , 2012 edition and Promax™) being deployed for the study. Efforts to get the “Tomostatics” application have been unsuccessful in the past several months, which is the reason a hybrid approach, of combining refraction arrival inversionand uphole survey measurements,(with the aid of special processing plugins)is deployed in the near-surface imaging for the present study.

1.6Significance of the Study

Errors in static correction induce errors in procedures such as velocity analysis, stacking and migration. Inaccuracy in these procedures will result in spurious structural and stratigraphic anomalies which are not true representation of the subsurface and eventually leads to misinterpretation of potential geologic and geophysical targets.

The research therefore is very important and would benefit the following;

A) Industry based 2D/3D seismic data processors:

The refraction statics solution to be derived and implemented on the 3D seismic datasets for the present study would grossly enhance the accuracy and reliability of the following key seismic processing procedures;

i) Velocity analysis
ii) Inversion
iii) AVO applications
iv) Stacking
v) Migration

B) The Academic/Research communities:

The academic/research community would be presented with processing strategies and steps which would be documented as journal papers to demonstrate how the methods adopted were applied in solving the processing challenge at hand. They in turn could adopt these documented processing strategies to solve future related seismic processing challenges.

1.7Location, Geometry and Geologic settings of the Study Area

The prospect (OML-23, SOKU) lies withinthe onshore part of the Niger-Delta Basin, Nigeria(Figure1.2).The prospect is situated in the south-eastern part of the onshore Niger Delta and is a few kilometers away from Port Harcourt in Rivers State of Nigeria. The prospect covers areas and towns in parts of present day Rivers and Bayelsa States of Nigeria.The landsurfacewithintheprospect areaischaracterizedbylow-lyingplainstypicalofthemodern NigerDelta.Theseplainshaveswampsthatarecommonlyfloodedduringthepeak ofrainyseason.The prospect area is also characterized by sediments which are predominantly aerated, unconsolidated and undulating sands with variable thicknesses. The geographical grids of the prospect is 5°11'- 5°40'N and 6°42' - 7°11'E. The area slopesimperceptiblyinthesoutherndirectiontowards theAtlantic Oceanandisdrainedby a network ofriversandtheiradjoiningcreeks.

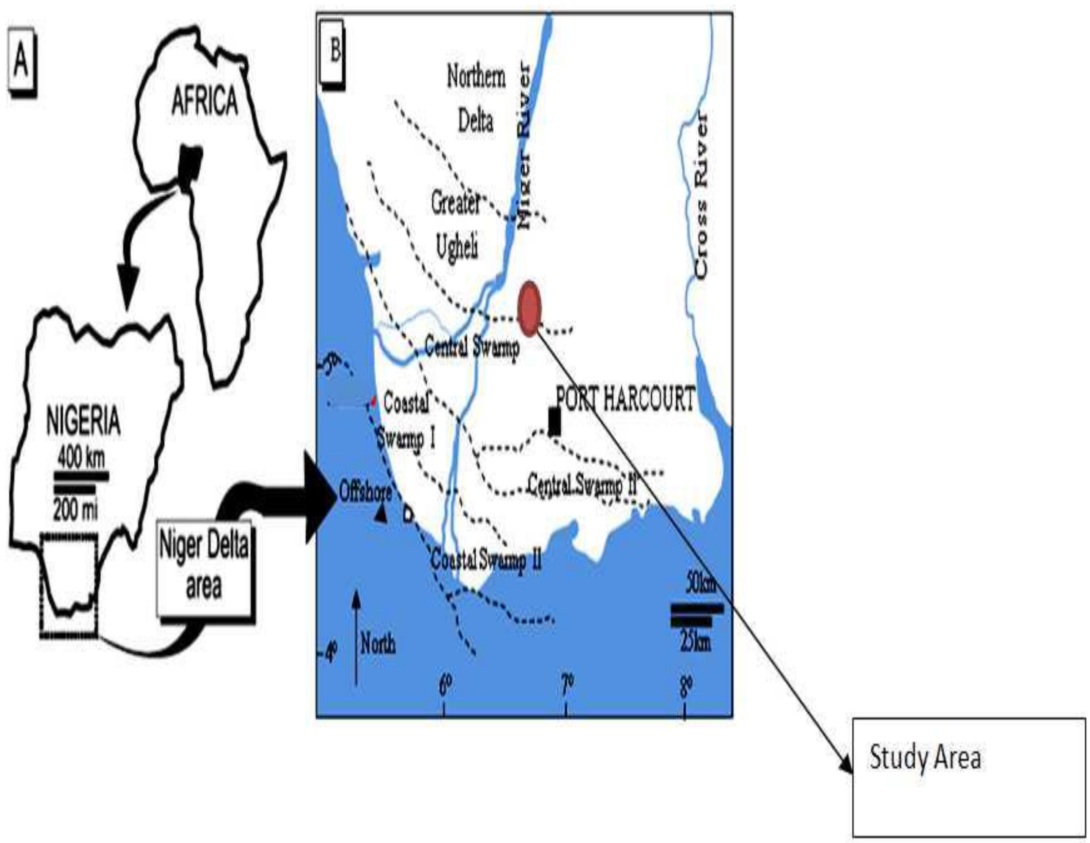


Figure 1.2: Map of the Niger Deltashowing location of the study area

The prospect covers an extensive area of over 151.3 square km., the geometry of the prospect is as shown in Figure 1.3 with its boundaries clearly defined in terms of their respective coordinates.

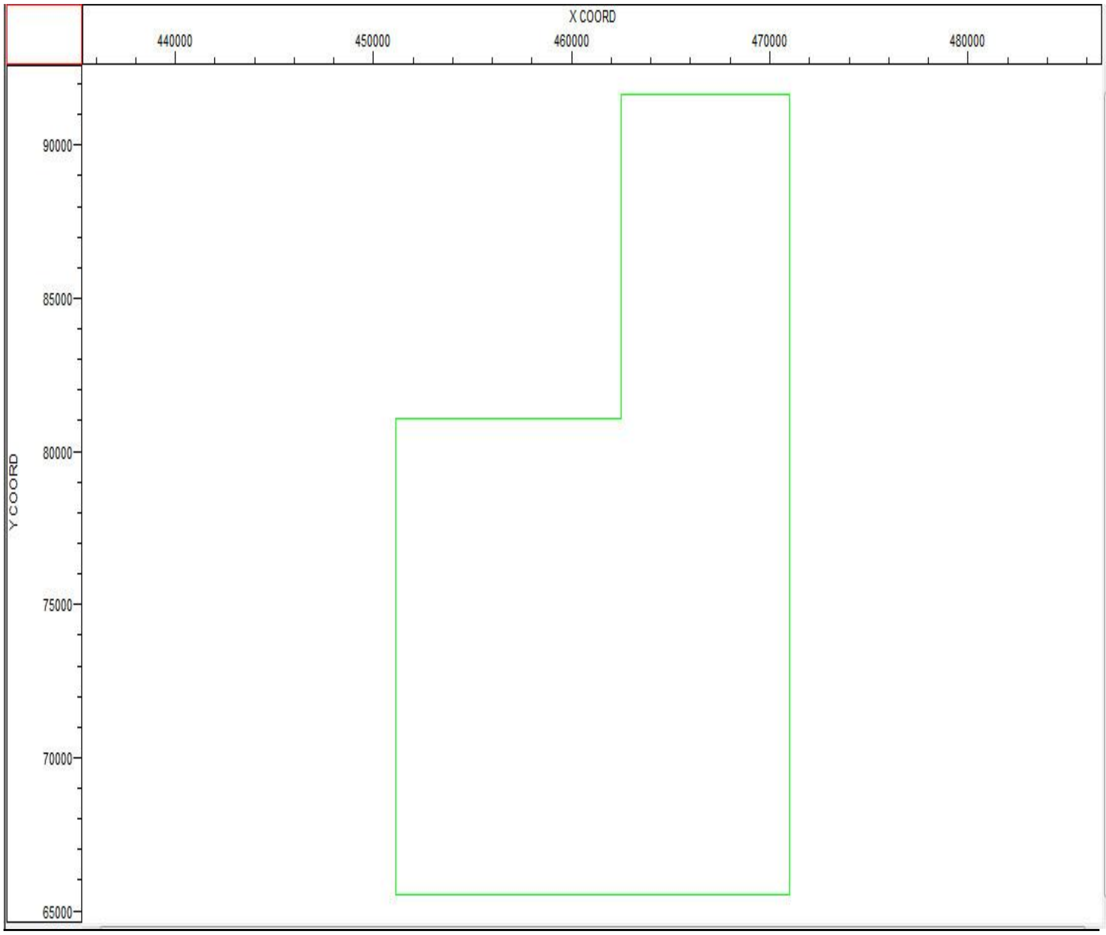


Figure 1.3: Geometry of the prospect field showing its boundaries and coordinates.

The vegetation around the prospect is mainly mangrove which posed a serious challenge of easy access for the seismic crew during the acquisition program. The 3D seismic acquisition for the prospect was executed in three (3) phases. Each acquisition phase covered approximately 13 swaths. The entire acquisition was prosecuted with well over 27,500 shots using a Sercel 428 recording instrument. The shooting geometry was a symmetric split spread configuration with an offset range from 25-6500m. Prior to the 3D seismic data acquisition program, a total of about 50 uphole location points were established for uphole shooting across the entire prospect. The prospect (OML-23, SOKU) is currently being evaluated for its hydrocarbon potential.

CHAPTERTWO

LITERATUREREVIEW

2.1Previous works on Refraction Methods, Near-surface Imaging and Refraction Statics

Therefraction method was thefirstseismic technique to beused inpetroleum exploration,andinthe1920's,itachievedspectacularsuccessinIranandthe Gulf CoastoftheUSA.The1950'srepresentasignificantperiodin thedevelopmentof refractiontechniques.Almostallofthemajorissueshadbeen identifiedandmany advances had been achieved. Theyinclude themappingofirregular refractors, complexwave-speedfunctionsinthelayersabovethe targetrefractor,undetected layers,wave-speedreversals,anisotropy,andrefractionmigration (Feroci *et al.*, 2000 and Stark, 2008).In thelastfifty years, mostresearchhas focusedonthevariousmethods forinverting travel-time data to map targets in the near surface region for geotechnical, groundwaterandenvironmentalapplications,andfor staticscorrectionsfor seismic reflectionsurveys (Stone, 1995).

Refractiondatacanbeacquiredeitherbyaseparaterefractionsurveyinthefield,orbyusingthefirstarrivalsrecordedaspartofaseismicreflectionsurvey.The latterapproachisnowmoreappropriatethanitwasafewyearsagobecausethe groupinterval,andhencearraylengths,are much smaller,therebyminimizingthe attenuationoftherefracted arrival.Toobtaingoodestimatesofrefractionarrivaltimes,thesourceandreceivershouldbeasbroadbandaspossible with minimal filtering applied tothedatarecording(Hagedoorn,1959).Duringseismicreflection acquisition, thearrivaltimes ofrefracted waves,often referredtoasthe'firstbreaks',are alsorecordedandusuallyusedtocalculatenear surfacevelocitystructureforstaticscorrection.Someadvantagesof usingseismic reflectionrecordsforan analysisofrefractiondataareasfollows:

i)Therearenо additional acquisition costs.

ii)Alargeamountofredundancy for acquisition crew or field personnel is achievable.

iii)Thesourceandreceiverlocationsarethoseusedin thereflectionsurvey.

iv)Refractorscanusuallybemapped wellbelowtheweathered layerand ona continuousbasis.

Severalauthors have described and documented proceduresfor calculatingnearsurface layer characteristics andstaticscorrectionfromhighresolutionseismicsurveys.Some of their findings are hereby presented;

ChunandJacewitz(1981)discussedthe contentof the firstarrivalsandpresenteda surfaceconsistentsolutionofrefractionstaticsbytheformationof timesurfaces. They also indicated that largeerrordistributions oftenremained aftersolutions havebeenobtained.Steeples *etal.*,(1990) described pitfalls and key point in calculating staticscorrectionforshallowseismic reflectionsurveys.BrouwerandHelbig(1998)developed ‘raytracingstaticscorrection’methodthat givesbetterresultsforshallowstructuresinhighresolutionseismicsurveys.

Pugin and Pullan(2000)presented anewtechnique ‘firstarrivalalignments static correction’which they applied on shallowhighresolution reflection data. This techniquecalculatesandtakescareofshort,mediumandlongwavelengthstatics. It is an iterative process inwhichthevelocity modelofthenear surfaceisknownandsomekindofcomparisonofraytracedresultsanda known modeliscarriedouttogetthefinalstaticscorrection.

Lawton (1989) useddifferences in first-arrival travel-times between adjacentrecordsinmultifoldreflectionsurveystocomputethedepthandvelocitystructure ofnear-surfacelayers.Thetravel-timedifferencesasa functionofsource-receiver offsetprovideadirectindicationofthenumberofrefractors present,witheach refractorbeingdefinedbyanoffsetrangewitha constanttimedifference.Foreach refractor,thetime-differencevalueatacommonreceiverfromtwoshotpointsis used topartition theintercept timeinto thedelaytimeateachshot-point.This procedureisrepeateduntilthedelaytimesatallshotpointsandforallrefractors havebeencomputed.Refractordepthsandvelocitiesareevaluatedfromthissuite ofdelaytimes.

ZanziandCarlini (1991)proposedanewmethodforrefractionstaticsreducingthe computationaltimewithoutreducingaccuracy. Thefirstarrivals,common-offsetorganized,formedthe dataspace.The methodinvolvedFouriertransformation of any common-offsetdatavectorwithrespecttothecommonmid-point.Asa result,the dataaredecomposedin a numberofsubspaces,associatedwiththewave-numbers, whichcanbeindependentlyinvertedtoobtainanywavelengthofthe near-surface model.

Docherty (1992) investigatedthe feasibility of computing theweathering model fromtravel-timesofrefractedfirstarrivals.Theproblemwasformulatedintermsof the difference in arrival time ofadjacent receivers, resulting inamuchsparser matrix for inversion. Lateral variations inboth the weathering thickness and velocitywere sought.Inmostcases,itwasnecessarytoincludeasmall number of constraintstoobtainthetrueweatheringmodel.Anyroughnessinthesolutionthat wasnotrequiredtofitthedatawasmosteffectivelyremovedusinga seconddifference smoothing technique. Two layers makeupthemode:alaterallyinhomogeneous weathering layer and a uniform high speed refractor. The weathering layersweredivided into cellsofconstantvelocity.Eachcellwasboundedbytheobservation surfaceandbelowbytherefractor.Boundariesbetweenadjacentcellswerevertical. In thestudya constantrefractorvelocitywasassumed.

Bohm*etal.*, (2006)usedajointinversionofbothfirstandrefracted arrivals in order toobtain a well-resolved velocity field for the computation of staticscorrection.Aftertheanalysisofthedivingwaves,theyinvertedthetravel-timesassociatedwiththerefractedeventsbyusingthevelocitymodelobtainedfromthe divingwaves as theinitialmodel. Also afterinverting thetworefracted arrivals separatelytheyusedtheresultingoutputvelocityfieldasanewinitialmodelfor jointly inverting again the direct arrivals and the travel-times with thefirstand secondrefractedwaves,in ordertoobtaina moreaccuratevelocityfieldindepth.

Zhu *et al*., (1992) demonstrated that turning ray tomography could image near-surface velocities more accurately than refraction statics methods. In their study, the medium to be imaged was discretized into grids of small rectangular cells, each of which contains a single velocity. Sources and receivers were both located on the surface. The updated velocities were slightly smoothened (damped) after every iteration. This was an approach they termed the Constrained Damped Simultaneous Iterative Reconstruction Technique (CDSIRT). Their study confirmed that tomostatics is noticeably closer to the true statics where velocity inversions are significant. Generally, long spatial wavelength statics appeared to be estimated better using tomostatics, although a tomostatics bias exists with increasing depth due to damping and smoothing in the tomography algorithm. The output image of their linear inversion was remarkably robust to a wide range of reasonable initial models.

Stefani (1995) used turning ray tomography for estimating near-surface velocity structure in areas where conventional refraction statics techniques failed because of poor data or lack of smooth refractor/velocity structure. The method comprised nonlinear iterations of forward ray tracing through triangular cells linear in slowness squared, coupled with the LSQR linear inversion algorithm.

Rajasekaran and McMechan (1996) performed the tomography on prestack time picks using the Simultaneous Iterative Reconstruction Technique (SIRT) algorithm with modifications to include reflected as well as turned rays. Travel times of head waves were well approximated by rays turned in a small velocity gradient below a high contrast reflector, and so were included automatically as a special case of turned rays. The reflections, which correspond to predominantly near vertical propagation, define horizontal changes in the model, but not the vertical changes. Conversely, the turned transmissions were better able to define the vertical changes. Increasing the effective aperture by combining reflection and transmission data and performing tomography on this composite data set produced a better image of the 2D velocity distribution.

Opara *et al.*, (2017, 2018) implemented first and refracted arrival inversion to build a near-surface model and compute a preliminary (partial) statics correction for 3D seismic field datasets from an onshore Niger Delta prospect field.

Lanz *et al*., (1998) investigated the applicability of surface based 2D refraction tomography (turning ray tomography) for delineating the geometry of a landfill. The depth of the near-surface model did not exceed 100m. The velocity in the layers encountered rapidly increased from 1000m/s to 1500m/s. geophone and source spacing were set to 2 and 8m respectively. Sampling interval of 0, 25m was used. The result achieved from the study demonstrated that the tomographic refraction scheme may be an efficient means of studying the very shallow subsurface but complementary geological and other geophysical data are required to make interpretation more reliable.

Zhang and Toksoz (1998) presented a nonlinear refraction travel time tomography method that consisted of a new version of the shortest path ray – tracing approach, a regularized nonlinear inversion method that inverts "travel time curves" rather than travel times alone, and Monte Carlo method for nonlinear uncertainty analysis of the final solution. Seismic ray paths were defined by calculating the shortest travel time paths through a network consisting of nodes and representing the earth. They solved an inverse problem that explicitly minimizes data misfit as well as model roughness.

Ditmar *et al*., (1999) developed an algorithm for tomographic inversion of travel times of reflected and refracted seismic waves. In the case of a very inexact initial model, a layer by layer inversion strategy was recommended as a first inversion step. They assumed that the model consisted of several layers separated by interfaces represented by a set of points connected by straight segments. Velocity distribution in each layer was described by means of its own velocity grid, the layer being completed inside the grid. The velocity values were specified at grid-nodes and bilinear interpolations were used in between nodes.

Bridle and Aramco (2009)analyzed theapplications ofrefractionstatics andTomostatics on testlines.Forlongerdeeperanomalieswithirregularray-paths,refractionstatics and Tomostatics wereexpected to providemajorimprovements;however,only marginalimprovements wereobserved. Inthetestlineconsidered therefraction staticsprovidedthebestsectionvisuallyintermsofsignal strength,sharpnessand continuity,witha structurethatseemsgeologicallyreasonable.

Kolawole *et al.*, (2012)analyzed arefraction seismic surveyintheNigerDelta Basinwherea3–layerearth model wasanalyzed.Thecorrelationandinterpretationof the observedlithologicalsuccessionswithvelocitiesanddepthsofboundariesacross thetworefractionpointswith3-layermodelssuggestanirregularityalongthetrue baseoftheweatheringlayer,probablycausedbyfaulting.Thetruedepthsofbase of weathering layer, as wellas velocities of weathering layerand consolidated layersforthetworefractionpointswith3-layermodelswerecalculated.

Ajani*etal.*, (2013)used thelowvelocity layer(LVL)methodtodeterminethe depthoftheweatheredlayerandvelocitiesofnear-surfacelayersovertheOmerelu Area inRiverState,Nigeria.Inthetestconducted,thedepthofweatheredlayerin the studyareavariesbetween12m-13m.Thevelocitiesof theweatheredlayerandthe consolidated layervariedbetween500m/s–550m/sand1790m/s–1875m/s respectively.

Zhu*et al.*, (2014) applied severaldifferent approaches to obtainingstaticssolutions for theprocessingofdeepreflectionseismic datain the SouthChina province. Each approach they applied yielded an output which they comparedinordertofind the most appropriate statics solution. They observed that statics solutions based on tomographicprincipleor combiningthelow-frequency componentsoffieldstatics withthehigh-frequencyonesofrefractionstatics couldprovidereasonable staticssolutionsfordeep reflectionseismicdatain the province which is characterized by a veryruggedsurfacetopography. They equally observed that thetwostaticssolutionscouldcorrectthestaticsanomaliesofbothlongspatialwavelengthsand shortones.The surface-consistentresidualstaticcorrectionsservedas an extra quality control measure to compensate or tackle the remaining statics effects prevalent on the data after the implementation of thefirststaticssolutions.Their conclusion was that staticssolutionsbasedon tomographicprinciplescould providepropersolutionsforthe statics problem in their terrain that was marked by very uneven and rugged topography. Their opinion was that combiningthe low-frequencycomponentsoffield staticssolutions with the high-frequencyones ofrefraction statics solutions could equallyprovidereasonablesolutionsforthe deep reflection seismicdata in the province. Theirsurface-consistentresidualstaticcorrectionswerealso good compensationsto theproceduresofthe firststaticssolutionsintheir investigationandleftthedeep reflectionseismicdatafreeof staticsanomalies. They final conclusion was that proper staticssolutioncanimprovebothqualitiesandresolutions ofseismicsections.

Staticsproblems arebigchallengesfor theprocessingofdeepreflectionseismicdata and itisvery importanttoaccuratelycalculatethestaticsat the timeofprocessingofland seismicdata.Thissubsequently improvesthe quality of other processing stageswhichinturn impactspositively on the overall integrity, quality andresolutionofthe imagedsection.This process which seems straightforward is quite delicate and could be made more complicated ifthesurveyareais overlain byirregular topography such as sand dunes of varyingheights which introduces a low velocity layer (LVL) challenge into the mix.Toadequately removetheeffect of rapidvelocitychangesinthenearsurfacespecially that of the LVL or weathering layer,correct estimation ofstaticsduetothe presenceofweatheringzones,(sanddunesinthisinstance) becomes very imperative. Roy *et al.*, (2008 and 2010) whileprocessing3Dvibroseisdataacquiredinthe sanddunareaofWesternRajasthan, India,observed thatgatherswerenotalignedproperlyevenafterapplicationoffield statics.Thefieldstaticscalculation was basedonshallowrefraction data.Thestackedoutputof the gathers gaverise to“patchyreflections”inthezonesofinterestaswellasatshallowerанddeeperlevel.Toovercomethisprocessing problem,firstbreakrefractionpickingon3Dvibroseisdatawas utilizedtoestimatethe near–surfacemodel.First breakswere pickedswathwiseonthe 3Ddataandthe near-surfacemodelcomputedtocalculatestatics.Thismethodhas a minor limitation owing from the factthatdifferentstaticsvalueswereobservedforcommonshots/receiversinadjoiningswaths over the entire survey area.They now proposed amethodofemployingentire3Ddatavolumeasasingleinputtobuildnear-surfacemodel.The new resulting stackoutputsshowedremarkableimprovementsas those patchy reflections were reduced and subsequentprocessingstageswere enhanced.

Correctingnear-surfacevelocityand elevation variations withstaticsisanessentialstage in the implementation of staticscorrection which is a very keystep in the processingofland seismic data. The correct implementation of statics correction improvesthe qualitiesofsubsequentprocessingstepsand are key determinants tothe qualityandresolutionofthe finalimagedsection (Li*etal.*,2011; Deere,2009;LaakandZaghloul,2009;Li*etal.*,2009a;Raef, 2009;Stein*etal.*,2009;Han*etal*.,2008;VossenandTrampert, 2007; Yan*et al*.,2006;Criss andCunningham, 2001).Static correctionsas defined by(Cox,1999;Sheriff, 1991) arecorrectionsapplied to seismicdata to compensate for the effectsof variationsin elevation,weatheringthickness,weatheringvelocity,orreference toadatum.Theobjectivetherefore, isto determine the reflection arrivaltimeswhich wouldhavebeen observedifall measurements hadbeenmadeon a(usually)flat plane withno weatheringor low-velocitymaterialpresent.Henceitleadsto theconceptof surface-consistentcorrections, whicharedependentonthelocationof the source(or receiver)but areindependentofthesourceto receiveroffsetor timeofthe recorded data(Deere,2009;Cox,1999).

There aremanyissueswhichareassociatedwiththenear surface andrelatedwiththevariationofvelocity andthickness inthenear-surface layers.Fieldstaticscancompensate thedata for the common datum problem which have been carefully investigated and documented by (Luo*etal*.,2010;Li*etal*., 2009b andHuang*etal*.,2008).Therearelotsofstaticscorrection methodsbased on the seismicrefractionprinciple,whichcanbe usedto resolvevelocitiesof shallowlayers usingheadwaves, suchasslope (orintercept) method(Knox,1967),delaytime method(as demonstrated by Coppens,1985), reciprocalmethod(Palmer,1980), leastsquaremethod(Chang*etal.*,2002;SimmonsandBackus, 1992) andturn-raysmethod (Henley,2009; Criss and Cunningham,2001).Tomographicstaticcorrection methodshave been investigated and applied bymanyresearchers(Liu*etal*.,2010;Li*etal*., 2009b;Yordkayhun*etal*.,2009;Zhu*etal*.,2008;Taner*etal*., 1998)to obtain staticcorrections usingthetomographicvelocitymodelsbasedonthefirst-arrivalinformation.

Thesestaticsmethodsrequire a largenumberofraysgoingthroughthemodelareasevenly withdifferent ray angles.Ray tomographymethodshavebeen usedtobuildnear-surfacevelocitymodels using first-arrival informationandtoestimatethestaticscorrection(Zhang*etal*., 2009;Ke *etal*., 2007).Manyresidualstatics correction methods havebeendevelopedinorderto compensateforthetimedelays in thepastfewdecades,suchas the travel timeinversion basedmethod (Hatherly*etal*., 1994),stack-powermaximizationmethod (Ronenand Claerbout,1985),non-stationaryresidualstaticsmethod(Henley, 2012)andsparsitymaximization method(Gholami,2013).

Inreality,manyfactors pose serious limitations to the correct and appropriate implementation of static corrections thereby making staticscorrection a difficult processing step tohandle. These factors include ruggedsurfaceacquisition topography, non-planar refractors, near-surface low-velocity layers,lateral variant velocitiesofweathering layersand variations of undergroundwater tables (Li *et al.*, 2009b; Wang, 1999).Errorsin static correctionslead to thelossofseismic resolutions,both temporaland spatial, and these poses serious difficulties andconfusions duringtheinterpretationsof such seismicsections.

Near-surface seismicimagingtechniqueshavebeen widely demonstratedandusedinanincreasingnumberof applications (Steeples and Miller,1990;Buker*etal.*,1998; Juhlin*etal*.,2002).Oneofthe difficult challenges inreflection seismicprocessing isthatpoorimagesaregenerally obtained intheupperpartofthesectionsduetoshot- associatednoise,surfacewavesanddirectarrivals that obscurethereflectedenergy(Miller*etal.*,1998).Inmostsituations or instances,theshallowest reflections are removedprior to normal moveout (NMO) corrections and stacking. The resultant effect being thatdetails fromtheupperpartofthesection is lost.Inaddition,heterogeneities or the non-uniform geologic conditions inthenear-surfaceleadtostaticscorrectionproblems.Therefore,a joint interpretation of refraction and reflection seismic data from the near-surfacecan have manybenefits. Several approaches, some simple while others very sophisticated and complex have been deployed in interpretation of refraction seismic data andtomographicinversionschemesonhowtobetter imagethe near-surfacehavebeen extensivelydiscussedin the diverse literatures(HampsonandRussell,1984;LinesandTreitel, 1984;Marsden,1993;Macrides andDennis,1994;BelferandLanda,1996;Lanz*etal.*,1998;Taner*etal.*,1998;Marti*etal.*,2002 and Bergman*etal.*,2004).

Yordkayhun*et al.*, (2007), in a bid to understand the near-surface structure over a CO_2SINK (carbondioxidestorageandmonitoring) project in the Ketzin area in Germany used firstarrivaltravel timestoimagethenear-surfacestructureandtoprovideanimprovedvelocityfunctionfor the interpretation of seismic reflectiondata.Inordertoobtainadditionalstructuralinformationandtoimprovethevelocityfunction estimates, travel time inversion based on the generalizedlinearinversion(GLI)method proposed by Hampson and Russell (1984),basedoniterativeleast-squaresinversion (Lines and Treitel, 1984; Menke, 1984)was adapted by them in building thevelocity–depthmodel of the near-surface.The successfully obtained the velocity-depthprofilesof the upper most 400m over the investigated area which was basically overlain by sedimentarysequences.Thesedimentaryrockswerecharacterizedbyagradualincrease inthe velocityfieldwithdepthwithoutstrongcontrastsand nearly insignificantlateralvelocityvariations.Firstarrivalsrepresentrefracted energythathas propagated alongthefastestpathinthesub-surface beforearrivingatthesurface.Processing andinterpretationtechniques thatinvolveanalysisofthesetravel-timesarewellknownandanumberofpopularmethods areinuse. Recentadvancesininversionofseismic refractiondatahavemadeitpossibletoimageheterogeneous media, as well as solving statics correction problems(Olsen,1989; Boschetti*et al*., 1996; Bergman *etal*., 2004).

There are different approaches in the application of refraction statics corrections for 3D seismic data processing such as the generalized linear inversion (GLI-3D) approach by Hampson and Russell (1984). In this method, an initial subsurface model is input by the user, consisting simply of a number of flat, constant velocity layers. The model is then iteratively updated, by using a generalized linear inversion (GLI) algorithm, in such a way as to reduce the difference between the observed breaks and those calculated from the model. The advantage of the GLI algorithm is full redundancy of observed breaks reducing the sensitivity of the solution to picking errors and the final model of the subsurface is nearly close to the input geological model. The drawback of the

GLI is that the reliability of the inversion schemes depends primarily on the sophistication of the modeling programme and the constraints imposed upon the possible solutions. This limitation is now remedied by a method which is a spin-off of the reciprocal method by Hawkins (1961). This method is called the delay time analysis (Gardner, 1967) which was initially tested and applied by (Barry, 1967) and has been recently fully developed by Lawton (1989). In the delay time analysis or approach, the underlying principle involves using differences in first arrival travel times between adjacent records in reflection surveys to compute the depth and velocity structure of the near-surface layers. The travel time differences as a function of source – receiver offset provide a direct indication of the number of refractors present, with each refractor being defined by an offset range with a constant time difference. For each refractor, the time difference value at a common receiver from two shot points is used to partition the intercept time into the delay time at each shot point.

This procedure is repeated until the delay times at all shot points and for all refractors have been computed. Refractor depths and velocities are evaluated from the suite of delay times. A surface – consistent statics correction to a selected datum level is then calculated at each surface station, using a replacement velocity equal to that of the deepest refractor.Staticscorrectionisoneofthemostimportantstepsinonshoreseismicdataprocessingandisgenerally calculatedwiththicknessandvelocityparametersofanear-surfaceweatheringlayer.Themethodsthat invertthenearsurfacestructuresusingthefirstbreak-timeofseismicdataincluderefractionand tomographicmethods.

Theadvantageoftherefractionmethodisthatitcanobtainarelativeaccuratedelay time,butitreliesonothernear-surfaceinvestigationstoobtainthevelocityoftheweatheringlayer.The advantageofusingthetomographymethodisthatitiscapableofobtainingtheweatheringlayervelocity, althoughitstillreliesontheothernear-surfaceinvestigationstodeterminethethicknessoftheweathering layer.

Atpresent, thestatics correction methodscommonlyusedincludestherefractionstatics correctionandthetomographic inversionstaticscorrection. Another advantageoftherefractionstaticscorrectionmethodover the tomographic method isits capability to obtain good quality andhighfrequencystaticsbyinvertingthegivensurface velocity. Bycontrast, thesurfacestructure modelcannotbeinverted unlessitreliesonothernear-surfaceinvestigationmeanstodeterminethe velocityofthe weatheringlayer asthe restriction.Dueto under-sampling ofnear-surfacedataorthedifferencebetweentheinvestigatedbedsofinterest,itis likelythatsomeerrorinthesurfacevelocitywilloccur(Cox,2004).Theincorrectsurfacevelocity mayleadtoanincorrectreflectordepth,andresultinalongwavelengthstaticsresidue(Lin*etal.*,2006).Th erefore,understandinghowtodeterminearationalsurfacevelocityisakeywaytoimprove theeffectoftherefractionstaticscorrection.Thetomographicmethodextractsthedistributions of velocityandreflectioncoefficientsusingthecomprehensiveobservationresultsfromalargeamount ofshotpointsandgeophone points.Itcantypicallyobtainarelatively accuratevelocitytrend;hence, itslongwavelengthstaticscorrectioncomponent isgood,whileitshigh-frequency componentis generallypoor. Meanwhile,differencesinselectingthetopinterfaceofahighvelocity layer mayalso leadtosomedifferences instatics.Hence,thesetwostaticmethodscomplement eachother,andthey arebothcommonlyappliedtogetherwhendealingwithstaticscorrectioncomputation forcomplex areas.Ingeneral,therearetwowaystocombine thetomographicandrefractionmethods;

i)Perform the tomographic inversion using the model obtained through the inversion of thereflection computation astheinitialmodel,whichachievesthesurfacestructuremodeof thetomographic inversionfeatures.

ii) Calculatethe refractionand the tomographicstatics respectively,using a specified separationradiustoseparatethelong-wavelength componentofthetomographicstatics correctionandtheshort-wavelengthcomponentoftherefractionstaticscorrection,and integrating themtogetherasafinalstaticscorrection.

Thelattermethodhasworkedinsomeareas,butthereare severalfactorsthatleadtouncertainties.Thefirstoneistheinaccuracyoftheweatheringlayer velocityfortherefractionstaticscorrection,whichhadimpactedboththelong-wavelength andthe short-wavelength statics.Theuncertainbottomboundaryofthetomographicinversionmodelmay influencethelong-wavelengthcomponent; Inaddition,thedifferentseparation radiusmayalsodiffer inthefinalstatics. (Kong *et al.*, 2013)proposedamethod toextractthesurface velocityfrom the tomographic inversionmodel,suchthatthesurfacevelocitycanbeusedintherefractioninversion. They wereable to achieve a stableanduniquesolution.Theirapproachcombinedboththetomographic inversionandtherefractionstatic correction in what they termed “Jointinversionoftomographyandrefraction”.

Tomographic statics arecommonlyused during theprocessingofseismicdata, especiallyinthe areaswithrapid lateral velocityvariations(Hao*etal*.,2011;Luo*etal*.,2010; Han*et al*.,2008;Wang,2005;Yang *et al*.,2005). Tomographyis defined by (Sheriff,1991)as amethod forfinding the velocityand reflectivitydistributionfromamultitudeofobservationsusingcombinationsofsourceandreceiverlocations. Thetomographicinversionapproaches usethefirstarrivalinformationof the recorded wave-front to inversethevelocitydistribution of the near-surfacewithouttheassumptionoflayerstructureinorder toproduceanear-surfacevelocitymodelwhichbestfits the observedminimumarrivaltimes.Spaceisdividedintocells andthedata areexpressedas line integrals alongraypaths through the cells. Adjustment and updating of the near-surface velocitymodel is done iterativelyuntil the differences between arrivaltimesofmodelandthoseoftheobserved datareachacceptablelevelsorareunchanged betweeniterations(Becerra*et al*.,2009;Henley,2009;Li*etal*.,2009b;VossenandTrampert,2007;Chang *etal*.,2002).Tomographicmethodsincludethe AlgebraicReconstruction Technique-ART(Henley,2009),the SimultaneousReconstruction Technique -SIRT (Aster *etal*.,2005; Emily and Bradford, 2002) andthe Gauss-Seidel Method(Taner *et al*., 1998).

Thestaticssolutionsbasedon tomographyprincipleneed a largenumberofdifferentraypathstogo througheachof the cellswith awide-anglecoverageandconstrainsofindirect regularization during the inversion are mitigated. The methods provide propercorrectionsforlong andmiddlespatialwavelength componentsof statics correction insituations where the field is characterized by ruggedsurfacetopographyand rapidlychangingvelocitiesinthe near-surface layers. However,there arestillsomeshortcomings of statics correction based on tomographic techniques and the uncertainties in tomographicvelocitymodelshavealsobeen investigated using a 2Dseismicline acquired inColombiathrough a varietyof numericaltechniques(Becerra*et al*.,2009).

Refractionmethodsallowone to derive estimatesofthe thicknessesand velocitiesofthenear-surfacelayersbyanalyzingthefirst-breaksoftheseismicrecords(Luo*et al*.,2010;Wu *etal*.,2009;Duan,2006;Lin *etal*.,2006;Pan*etal*.,2003). Accordingto the Huygens' Principle,everypointonan advancingwave-frontcouldberegardedasthesourceof asecondarywaveand thatalaterwave-frontistheenvelopetangent to allthesecondarywaves(Cox,1999).The importantconceptin seismicrefractionisthatwhenaseismicraycrossesaboundary between twoformationsofdifferentvelocities, thentherayis bent according toSnell'slaw whichdefinesthatthesineof refracted angleisequaltotheratioof thevelocitiesof thetwo formations.Therefore, thestatics correctionbased onrefraction surveyacquires theinformationof thefirst-arrivaltimeof the wave-field from refractor and the refractor velocity. Hence, therearetwo basicconditionsforrefractionsurvey,thatis,a relative stablerefractioninterfacebetween the twoformations andtheacknowledgednear-surfacevelocitydistribution(Bridle andAramco,2009;Liu,1998).Applying thestatics correctionbasedonrefractionsurvey can ensurestructural integrityin theprocessedsection.Refractionstaticsareeffectivefor correctinglongspatialwavelength anomaliesandcompensatingfortheweatheringlayers.Actually, refractionstaticsarealso effectiveagainstshortspatialwavelengthanomalies(Liu,1998).

The weathered zone due to its variable and non-uniform composition induces irregulartimeshifts (statics) for both reflected and refracted waves; statics correction therefore is a procedure that seeks to compensate for these irregular time shifts. Several types ofstatics have been differentiated(Telford*etal.*,1990).Thestaticsduetothedifferencesinsurfaceelevationswhich affectboth sourcesandreceiversare regarded as elevationstatics. Thesestaticscanbecorrectedrelatively easilyiftheelevationsand thenear-surfaceseismicvelocities are known.Sources typicallyhaveadditionalnegativestaticsduetotheir beingburiedatvariable depthbelowthe surface;suchstaticscanbe compensatedby usingthe“uphole”timesmeasuredbythewavepropagationfrom thesourcestothe nearestreceivers.Additional staticshiftsarealsoassociated withvelocityvariations withintheweatheredzoneitself,suchas causedbylayeringorvariations ofits depth.By theirrelationtothesource orreceiverposition,staticsarealsosubdividedtosourceand receiverstatics,andthe“total”staticsofaseismictraceisthesumofallthreestaticsat thecorrespondingsourceandatreceiverlocations.Finally,statics arecalled“surface-consistent”iftheyareonlyrelatedtothesurfacelocationsofthesourceandreceivers andnottotheirindividualproperties.

All ofthestaticsabovecanbeincorporatedintheconceptof“refractionstatics” (Yilmaz,2001).Refraction staticsrepresentagroup ofmethodsbased on constructinga realisticmodelof theshallowsubsurfacebyinvertingtherefracted arrivals (ray path 1) (Figure2.1).Thismodelshouldincorporatethecompletetopography,depths ofburiedsources,aswellas thevariationsinthestructureoftheweatheredzone.Thisis themostcompleteandadvancedapproachtodeveloping refraction staticssolution,anditis the approach employed inthepresent dissertation. Refraction statics calculations arebasedontheuseofrefractedheadwaves tomodel

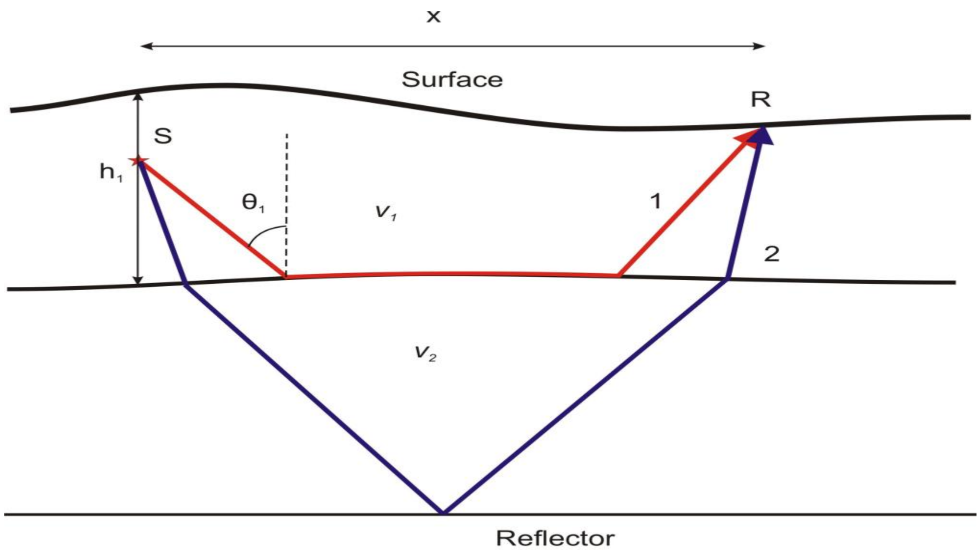


Figure2.1:Schematicsofa2Dreflectionsurveysubsurface.Thesourceis atpositionSandthe receiveris positionedatR. The ray path “1” represents ahead waveandray path “2”is a reflectedwave. (Atul, 2009)

thefirst-arrival travel times.Several refractionstaticsmethodsareinbroaduse today;thesemethodstakethefirst-arrival timesasinputandusedifferentkindsof travel-timemodelingtoderiveestimates ofthedepths and/orsubsurfacevelocities.Most ofthesetraveltimemodelsarebasedonthefollowingdependence equationofAtul (2009), of thehead-wave traveltimeonthesource-receiverdistancexinahorizontalone-layercase (Figure2.1):

$$t(x) = \frac{2h_1}{v_1} cos\theta_1 + px \qquad (2.1)$$

where,h_1 isthethicknessofthelayer 1 in (Figure2.1)v_1 –itsvelocity,v_2 isthevelocityof bottomlayer, and p ($\sin\theta_1/v_1 = 1/v_2$) is therayparameter.

Thisequationrelatesthe observedproperty (time)to thephysicalproperties(depthandvelocity)ofthelayers beneaththesourcereceiverlocations.Byanalyzingthedependenceof $t$on$x$,model parametersv_1,andh_1

inthisequationcanbeestimated.Inpractice,spatially-variable layervelocities andthicknesses areused,andmultiplelayersmaybeneededforaccurate modeling ofthe subsurfacestructure(Figure2.1). Thesedifferences in the models determinethedifferences betweenthevariousmethods.

In ordertoderivestaticsfrom alayeredmodel,consideranearly-vertically propagating rayshownin Figure 2.2.Asshown,formodelingandinversion,itis convenienttousemodelswithmultipleconstant-velocitylayers.Forasinglesuchlayer, ifthedatumislocatedwithinthe“base”layerbeneathit(Figure2.2),

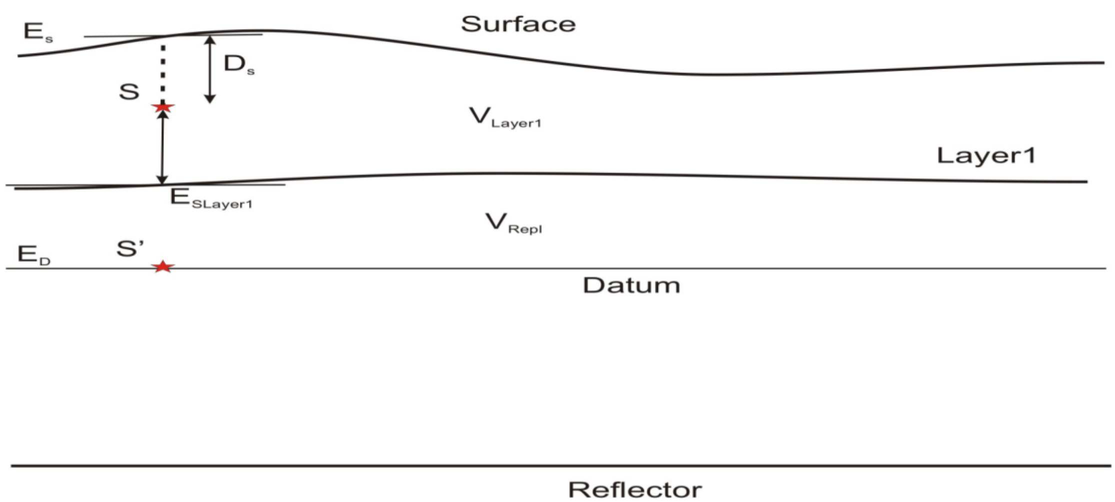


Figure 2.2:Schematics forcalculatingsource staticsfora single-layerweathered zone.E_S, E_D,$E_{SLayer1}$ aretheelevationsat respectivepositions.V_{Layer1} isthe velocityof layer1.(Atul, 2009)

Thetotalsource static is calculated using the equation by Atul as:

$$t_s = \frac{E_s - D_s - E_{sLayer\ 1}}{V_{Layer\ -1}} + \frac{E_{sLayer\ 1} - E_D}{V_{Replacement}} \quad (2.2)$$

where$E_S$is theelevationatthesurfacedirectlyabovethesourcelocation, D_S isthesourcedepth,$E_{Slayer1}$ istheelevationatthebaseoflayerdirectlybelowthe sourcelocation,$E_D$is theelevationofthedatum,and$V_{\mathrm{Replacement}}$is the replacementvelocity. Subtraction ofthisstaticvaluefrom traveltimeswouldeffectivelymovethesource (pointS)tothedatum (pointS';Figure2.2).Thestaticatthereceiverlocationcanbe calculatedinthesameway(withoutthe$D_S$term),andthetotal tracestaticwouldbethe sum ofthesourceandreceiverstatics.Thisdecomposition ofthetotal refractionstatics could aswell be naturallyextendedtoamulti-layercase.

From the foregoing, we could summarize that the application of refractedarrivalstoimagingnearsurfaceheterogeneitiesandtoestimate staticscorrectionis and would remain asubjectofmanyresearch investigations.A new integrated (hybrid) approach to near-surface imaging is implemented for the present study that incorporatesthe fusion of both refracted arrival inversion and uphole survey measurements. This approach would yield a more robust and reliable near surface model which would in turn make the refraction statics solution to be derived and applied to the seismic datasets more ideal.From this literature survey, a complete refraction statics solution for processing onshore seismic datasets within the Niger Delta Basin has not been derived with its efficiency demonstrated on shot gathers, stacked or migrated sections. This is now the focus of the present dissertation as the complete refraction statics solution to be derived and applied would be the first documented for 3D seismic reflection data acquired within the onshore Niger Delta Basin,Nigeria using the proposed near-surface modeling approach.

2.2Introduction to the Seismic Methods

Seismic waves are elastic waves generated bysuddenrelease ofenergyinthe groundorin thewater.Theseseismicwavesarefurtherclassifiedas;

1)Bodywaves,which areoftwotypes;

a)Compressional(P)wavesand

b)Shear(S)waves.

2) Surfacewaves,whichareoftwotypes;

a)Lovewavesand

b)Rayleighwaves.

Surfacewavestravelalongthesurfaceof theearth andare responsible for lossesanddamagesduring earthquakes whereas Bodywaves as the name suggest are the waves that traverse through the subsurface and are critical for imaging the earth subsurface (Pritchett, 1990).Thesewavesare classified based ontheirparticlemotion.ParticlemotionsofP-wavesareinthe directionof wavepropagationwhereastheparticlemotionsof S-wavesare perpendiculartothedirectionofwavepropagation. It is pertinent to note that P-wavestravelfasterthanS-waves.Theparticlemotion of surface waves ismorecomplex.Atthe surface,the particle motion inaRayleigh waveis ellipticaland retrograde to thedirection ofwave propagation and in Love waves;particle motion is horizontal with no vertical motion. A more detailed discussionof these waves and the different terminologiesassociated with explorationseismology could be found in Sheriff(2002).

P-waveseismologyismainlyusedinexplorationwork.P-wavesaretheonly modes that areemployedtoprovideinformationaboutthesubsurfaceinthe current study.With the advancement ofseismic instruments and energy sources S-wave seismologyisalsoincreasingly usedinexplorationwork.P-waveexplorationseismicmethodsfurtherfallintotwobroadcategoriesof;

i)Reflectionseismology;and

ii)Refractionseismology.

Theformeressentiallyreliesonthedetectionofechoesfrom thecontactsbetween differingtypesofrockintheearthwiththefinalgoalofimagingthe subsurface structure (Evans, 1997). Makinga reflectionprofileimagerequiresthata seriesofcorrectionsbe appliedtothedatain ordertoincreasethesignaltonoiseratio.The latter, refraction method does not provide an image but does attempt to describethegeologyin termsoftheseismicwavespeedsandthicknessesoflayers. Thebasicinputtothismethodisthetraveltimesofthe firstarrivingseismicwaves fromthesource.Three P-wavesareofinterestinrefractionseismology(Figure2.3).

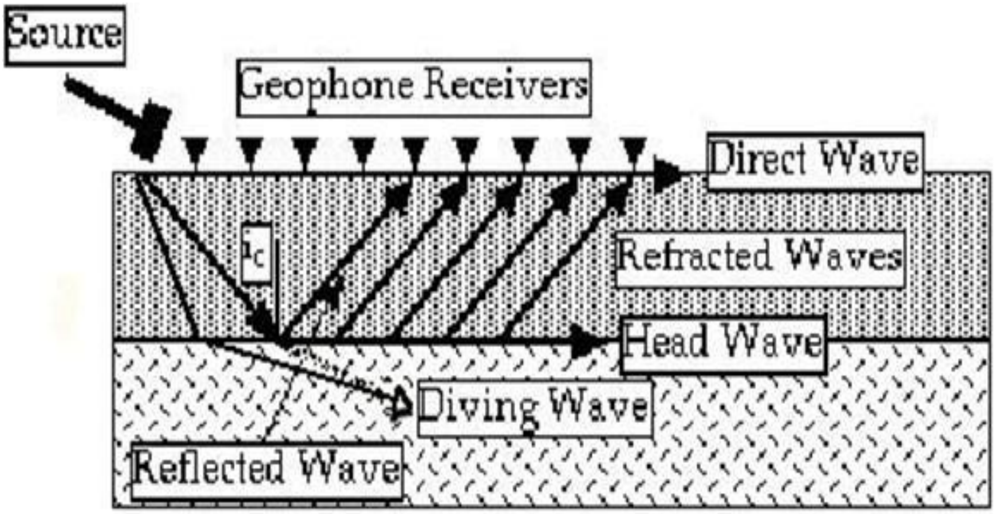


Figure2.3:Sketchillustration showingthereflected,refracted,head,anddirect waves (Source:GlobalGeophysics,UCL,2009).

These three P-waveswhich areofinterestinrefractionseismology are;

1. Direct waves
2. Head waves
3. Refracted waves

The direct wave propagates along the upper surface layer (layer1)boundary.Iftheincidentwavehits at thecriticalangle,thecriticallyrefracted headwavetravelsalongthelayer1 - layer2interface. Refractedwavespropagatefromtheinterfaceastheheadwaveprogresses,with exitanglesequaltothecriticalangle.Seismicwave created by an explosivesourceemanateoutward from theshotpoint in a3D sense.Huygen'sprincipleiscommonlyusedtoexplaintheresponseof thewave.Everypoint onanexpanding wavefrontcanbe consideredasthesourcepointofasecondary wavefront. Theenvelopeofthesecondary wavefrontsproducestheprimarywavefrontsafterasmall timeincrement.Thetrajectories of a point moving outward are known in optics as a ray, and hence in seismic exploration are referred toas aray path.

Brief explanations of the characteristics of some key seismic events are presented below;

2.2.1Reflections: Thephenomenoninwhichtheenergyorwavefromaseismicsource hasbeenreturnedfromaninterfacehavingacousticimpedancecontrast(reflector)orseries ofcontrastswithintheeartharecalledreflection.Thisphenomenonispictoriallyrepresented in Figure 2.4.

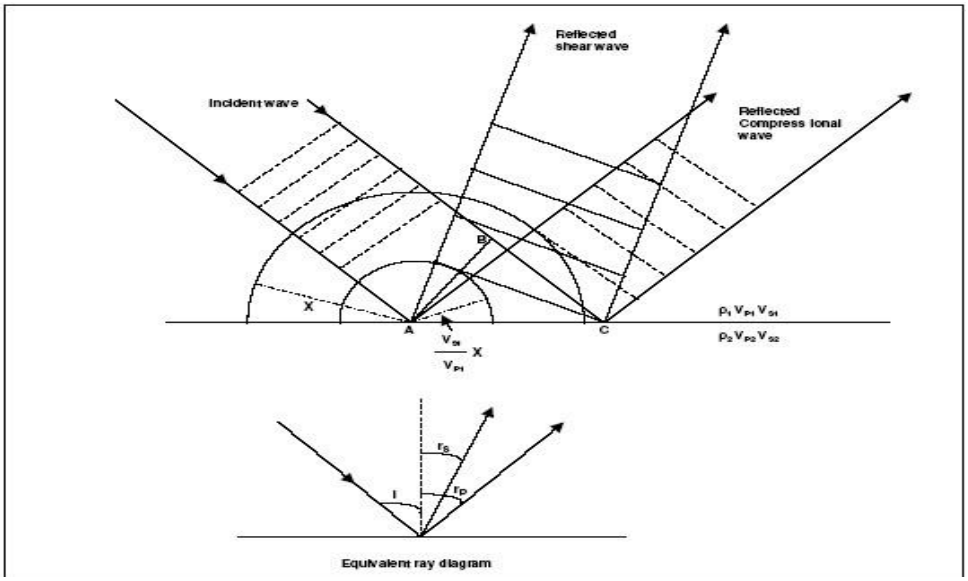


Figure 2.4: Reflection of a plane compressional wave at an interface (Kumar, 2005)

The amplitude andpolarityof reflectionsdependontheacousticpropertiesof the materialonbothsidesof the discontinuity.Acousticimpedanceis theproductof density and velocity.Therelationshipamongincidentamplitude A_i, reflectedamplitudeA_r, and reflectioncoefficientR_C, is given by the expression of Sheriff and Geldart, (1999):

$$A_r = R_C \times A_i \quad (2.3)$$

where,

$$R_C = \frac{(\rho_2 V_2 - \rho_1 V_1)}{(\rho_2 V_2 + \rho_1 V_1)} \quad (2.4)$$

Wherevelocity isconstant,adensity contrastwillcauseareflectionandviceversa.Inother words, anyabrupt change in acousticimpedancecausesareflectionto occur.Energynotreflectedistransmitted.WithalargeR_C,lesstransmissionoccursand hencesignal-to-noiseratioreducesbelow such aninterface (Kumar, 2005).

2.2.2CriticalReflection: When an impinging wave arrives at such an angle of incidencethatenergy travelshorizontally alongtheinterfaceatthevelocity ofthesecond medium,thencriticalreflectionoccurs.Theincidentanglei$_C$,atwhichcriticalreflectionoccurs can befound using Snell'sLaw.

$$\text{Sin } i_c = \left(\frac{V_1}{V_2}\right) \text{ Sin } 90° = \left(\frac{V_1}{V_2}\right) \quad (2.5)$$

2.2.3Refractions: Thechangeindirectionofaseismicray uponpassingintoamedium withadifferentvelocityiscalledrefraction.Snell'slawdescribeshowwavesrefract.It statesthatthesineoftheincidentangleofaray,(sini),dividedbytheinitialmedium velocityV_1 equalsthesineoftherefractedangleofaray(sinr),dividedbythelowermediumvelocityV_2, thatis:

$$\text{Sin } \left(\frac{i}{V_1}\right) = \text{Sin } \left(\frac{r}{V_2}\right) \quad (2.6)$$

Whenawaveencountersanabruptchangein elasticproperties,partof the energyisreflected, andpartis transmittedorrefracted (Figure 2.5)withachangein thedirectionofpropagation occurringat the interface.

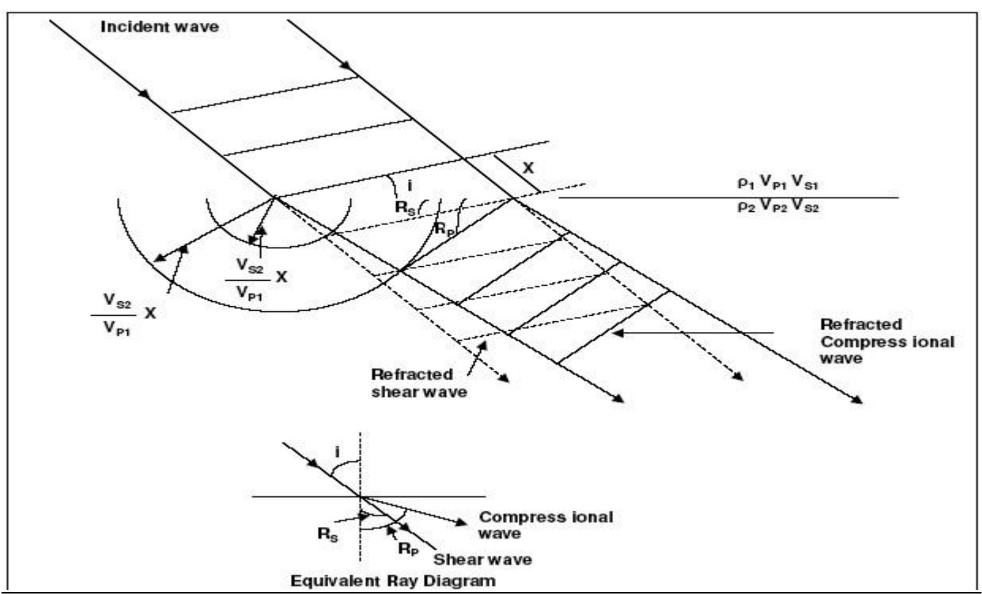


Figure 2.5: Refraction of plane compressional wave across interface (Kumar, 2005)

2.2.4Diffractions: Diffractions (Figure 2.6)occur atsharpdiscontinuities,suchas atthe edgeof abed,fault,orgeologicpillow.Whenthewavefrontarrives attheedge,aportionof theenergy travelsthroughintothehighervelocityregion,butmuchofitisreflected.The reflectedwavefrontarrives atthereceivers andgetsalignedalong thetrajectory of aparabolaon theseismicrecord.

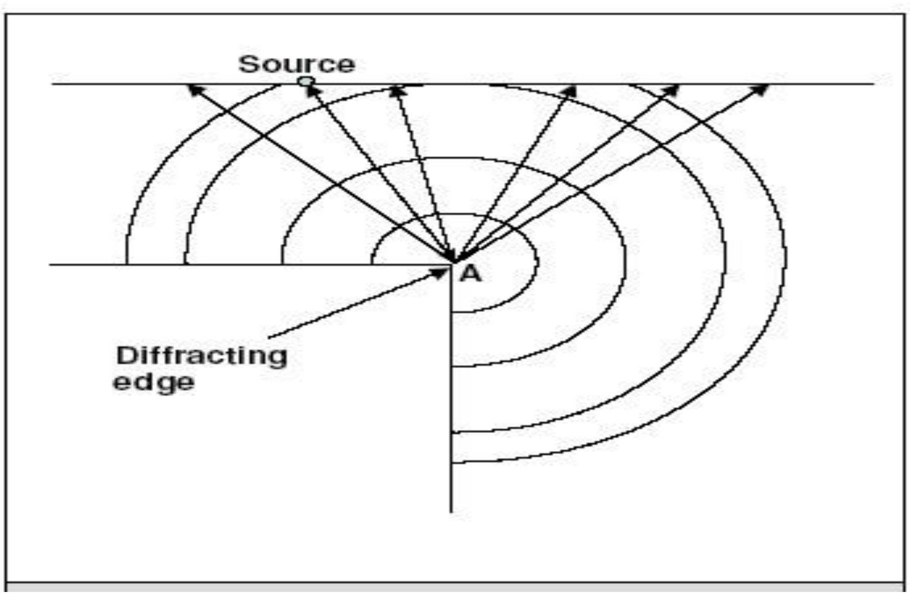


Figure 2.6: Diffraction from the edge. The source of a diffracted radiation has been set into oscillation by waves generated on the surface. Radial lines with arrows are ray paths; circular arcs are wave fronts (Dobrin and Savit,1988).

Inconventionalin-linerecording,diffractionsmay arrivefromoutoftheplaneofthe seismicline/profile. Suchdiffractionsare consideredasnoise andreducethesignal-to-noise ratio.However,in3Drecording,inwhichspecializeddataprocessing techniques areused (i.e., the3D seismicmigration), thediffractions areconsidered as usefulscattered energy becausethedata-processingroutinestransferthediffractedenergy backtothepointfrom whichisgenerated,thereby enhancing thesubsurfaceimage.Hencein3Dsurveys,out-of-the planediffractionsevents are consideredpartofthesignal (Yilmaz, 1987).

2.2.5Multiples: Seismicenergiesthathavebeen reflectedmore than once arecalled multiples.Virtuallyallseismicenergycontains some forms of multiples. They could be grouped into long-path and short-path multiples. Theimportantdistinction between long-path and short-path multiples is thata long-path multiple arrives as adistinct event whereasashort-path multiple arrives soon after theprimaryand changesthewaveshape.

2.2.6Seismic Noise: Thereliability ofseismicmappingisstronglydependentonthequalityoftherecords/data.Theterm“signal”is often used to denoteanyeventontheseismicrecordfromwhichwe wish to obtain information from whereas everything else istermed “noise”, including coherent events that interfere withtheobservation andmeasurementofsignals (Gadallah and Fisher, 2005).Thesignal-to-noiseratio(SNR)istheratioofthesignalenergy inaspecifiedportion oftherecordtothetotalnoiseenergy inthesameportion.Poorrecordsresultwheneverthe signal-to-noiseratio is small. Seismicnoise maybe either

a) Coherentor

b) Incoherent

Coherent noise includessurfacewaves,reflectionsorreflectedrefractionsfrom near-surfacestructuressuchas faultplanesorburiedstream channels, refractionscarriedby high-velocity stringers,noisecausedbyvehiculartrafficorfarmtractors,multiplesandso forth.Alltheprecedingexceptmultiplestravelessentially horizontallyandallexcept vehicularnoisearerepeatableonsuccessiveshots (Sadi, 1980).Coherentnoiseissometimessubdividedinto:

i) Energythat travelsessentiallyhorizontallyand

ii) Energythatreachesthespread moreorlessvertically

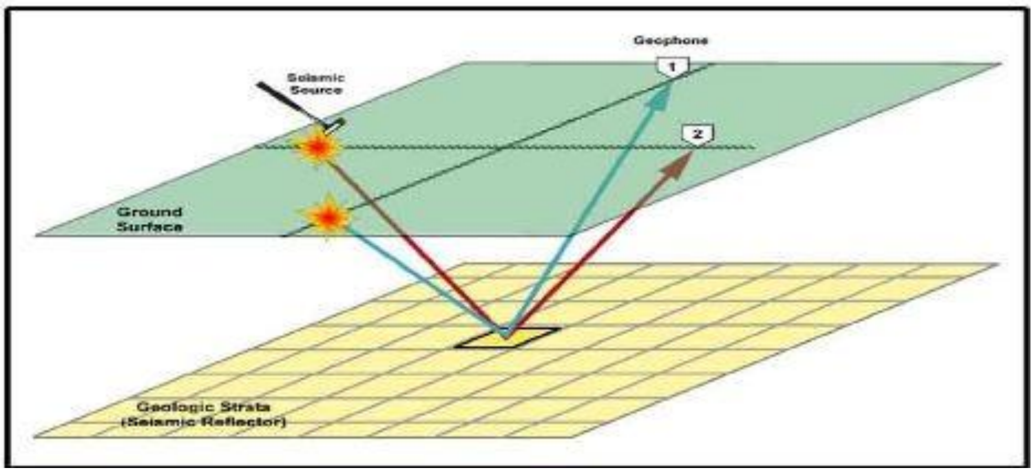
Incoherent noise on the other hand is oftenreferredtoasrandomnoise(spatiallyrandom),which impliesnotonlynon-predictabilitybut also, that they possesscertain statisticalproperties.

Incoherentnoise isduetoscattering fromnear-surfaceirregularities and inhomogeneitysuchasboulders andsmall-scalefaulting.Nonrepeatablerandomnoisemaybedue towindshaking ageophoneorcausing therootsof trees tomove,whichgeneratesseismic waves,stonesejectedby theshotandfallingbackontheearthnearageophone,oceanwaves beatingon aseashore, distantearthquakes, apersonwalkingnearageophone,and so on(Kearey and Brooks, 1991).

2.3 Overview of 2D/3D Reflection Seismic Data Acquisition

Inseismic reflection, differentseismic acquisitiongeometriescanbeadaptedbut the basic concept remains the same for all. Essentially, in 2D active source seismology, theacquisitiongeometryconsists ofalineofreceivers (Figure2.7) alongwhichtheseismicsourceisactivated. Thereceiverswillinmostcases,at leastforlandsurveys,be geophoneswhichprovidea voltageproportionaltothe amplitude oftheparticlevelocityofthegroundmotionasthewavepasses (Knodel *et al*., 2007).3D reflection techniques in which a 3D volume (x,y,z) of crust is sampled and monitoredusinga planar,ratherthana lineararrayofshotsandreceivers.In practice, this isaccomplished by layingoutthousands ofgeophones along parallellinesofreceivergroupsandthenshootingintotheentirearray(receivers) fromeachshotpointalonga seriesoforthogonal shotlines (Sheriff and Geldart, 1999).

On land, 3D data are normally collected using the crossed spread array and thereforesamplesavolumeofthesubsurfaceratherthananareacontained ina verticalplane.Thepositions ofalltheshots(source)anddetectors(geophones) mustbeaccuratelysurveyedsothateventuallycorrectionsaremadeforelevation and weathering variations (Cox, 1999). Although complicated by the factthat atypical3D survey(Figure2.7)containsordersofmagnitude(enormousdata)to beprocessed,the actual processing steps are fairly similar to those for 2D surveys. The end result, however,isadatacubethatcanbeslicedtoproducesynthetic2D profilesinany arbitrarydirection through the data, horizontal slices at arbitrary depths (time slices),horizon slices showingreflectivity variations in map-plan for picked markerhorizons,and3Dtomographicimagesthat canbeviewedfrom any perspective.Intheparlanceofsuchexploration,the'offset'referstothedistance of agivenreceiver fromtheseismic sourcealongthesurface oftheearth. In seismicreflection,seismicenergyisreflectedbacktothesurfacefromunderlying layer ofhigherdensityand velocity. Whereas inseismic refraction thewaveis refractedbacktothesurfaceandrecorded (Stone, 1995).



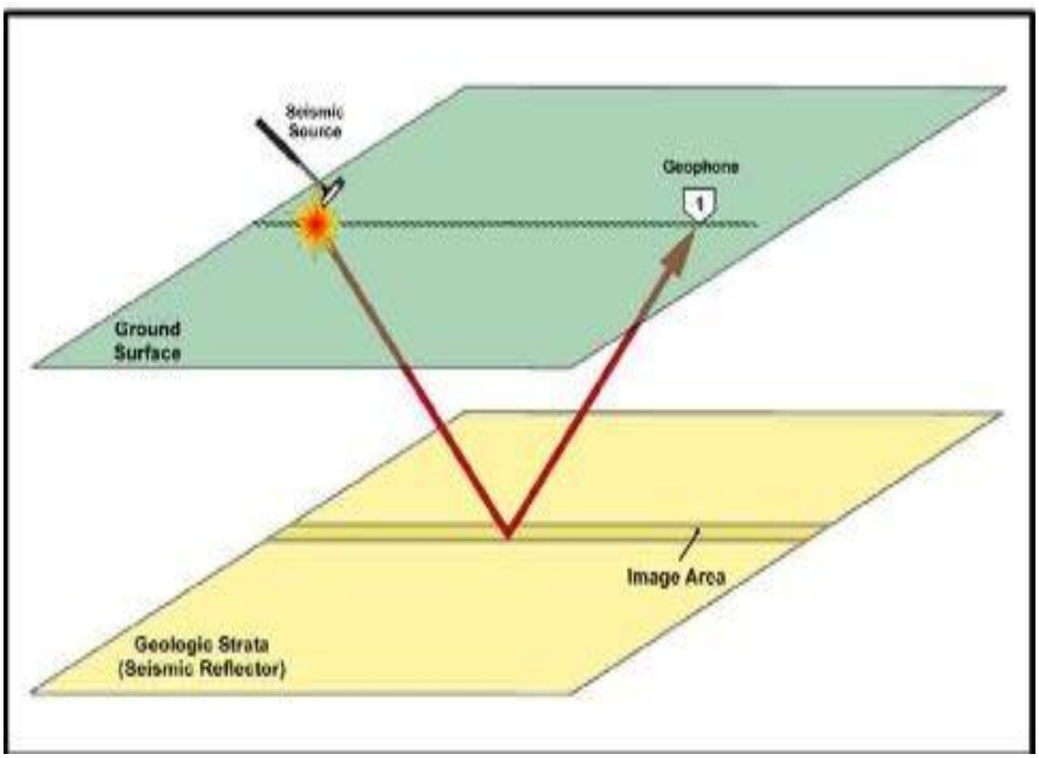


Figure2.7:Schematicdiagramofa 3D(top)and2D(bottom)survey.

For a typical seismic reflection acquisition, refractions are also unavoidably recorded(Figure2.8).

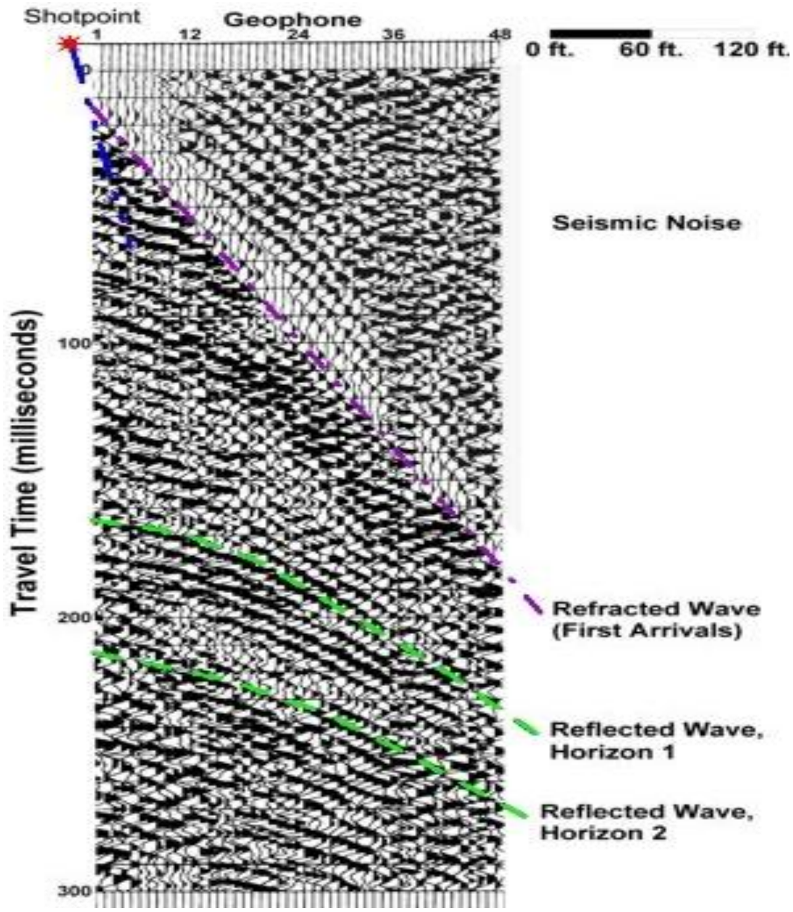


Figure2.8:Arefractedwaveasitappearson a rawseismicshot record(Enviroscan,2009).

Hence,therefractionanalysisisessentiallycomesforfreein the acquisition ofhighresolution seismicprofiling, although theirutilitycanbe diminishedbytheuseof geophonegroupswhichaveragetheresponsesometimes overmanytens ofmeters. Energysources forgenerating seismic wavesareof different types andmostcommonlyusedlandenergysourcesaredynamiteand seismicvibrators.Theformergivesasharpandhighenergypulsebutfora variety ofreasonsincludingcost,environmentalimpact,andsafetyit isoften avoided.The dataset for the present studywas acquired from a 3-D seismic reflection survey using dynamitesources.As seismic waves travel from thesource to the receiver their travel time is recorded. Thedistance betweenthesourceand thereceiver isknownandthis traveltimeis used to calculate velocity ofthesubsurfacematerial.Theseismic velocity is animportantphysicalpropertythatcanrevealagreatdealaboutthe compressibilityoftherockanditsfluidcontent(Figure2.9).

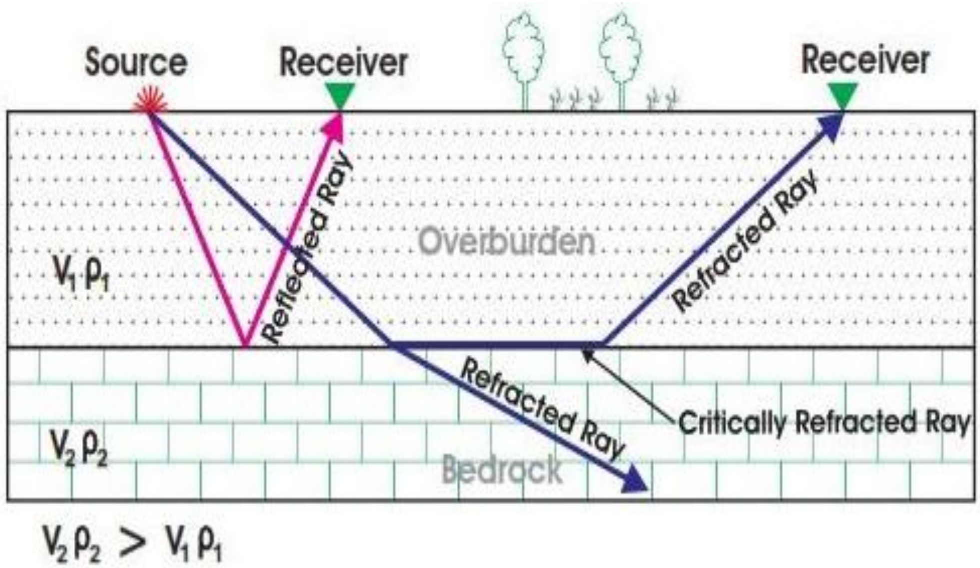


Figure2.9:Sketchshowingseismicreflectedandrefractedwavewithsimpletwo layercase.Velocity(V_1)anddensity(ρ)offirstlayer(Overburden)is lowerthanthevelocity(V_2)anddensity(ρ_2)ofsecondlayer(Bedrock) (Ahmad,2006)

The seismic reflection method is mainly used to produce imagesof the subsurfacestructure.Seismicrefractionanalysis,areusedtoobtainthe subsurface velocityinformation.Together,thesemethodsprovide meaningful complementaryinformation and are usefulforgeologicalinterpretation (Sjogren*et al.*, 1979 and El-Behairy*et al.*, 1997).

2.4 Overview of 2D/3D Seismic Data Processing

Theseismic exploration method hasgreatlyimproved over time in both the areasofdata acquisition and processing. Digitalrecordingalong with theCMPmultifoldcoveragewasintroducedduringtheearly 60’s.Dataacquiredfromthe field are usually preparedforprocessing by thefieldparty or acquisition team themselves andthensenttothe data processing centre.Processing isrequiredbecausethedata collectedfromthefield isnotatrue representationofthesubsurfaceandhencenothingofimportancecanbeinferredfromit.

Withtheadventofhighendcomputing systemsmodernday processing hasbecomealot easierthanitreally usedtobe.Turnaroundtimeshavethereforecomedownwithlotof processingtakingplacein-field or onboard (Beckett *et al*., 1995).

Field records which are obtained after 2D/3D seismic data acquisition is usually a superposition or combination of the following;

2.4.1) Reflections,
2.4.2) Coherent noise, and
2.4.3) Randomambientnoise.

2.4.1 Reflections: Reflections are recognized bytheir hyperbolictravel times. Ifthe reflectioninterfaceishorizontally flat,thereflectionhyperbolaissymmetricwithrespectto zerooffset.Ontheotherhandifitisdippinginterface,thenthereflectionhyperbolais skewed in theup dip direction.

2.4.2 Coherentnoise: Coherentnoise could further be subdivided into several categories.

i) Groundrollisrecognizedbyitslowfrequency,strongamplitudeandlow groupvelocity. Itistheverticalcomponentof dispersivesurfacewavesi.e. Raleighwaves.Typicallywetry toeliminategroundrollinthefielditself by array formingofreceivers.

ii) Guidedwavesarepersistent,especiallyinshallowmarinerecordsinareas withhard waterbottom. Guidedwavesalsoarefoundinthelandrecords. Thesewavesarelargely attenuatedby CMPstacking (Yilmaz, 1987).Becauseoftheir prominently linearmove-out, inprinciplethey alsocanbesuppressedby dip filtering techniques.Onesuchfiltering technique isbasedon2DFourier transformation oftheshotrecord.

iii) Sidescatterednoisecommonlyoccursatthewaterbottom,wherethereisno flat, smooth topography.

iv) Cablenoiseisanotherformofcoherentnoisewhichislinearandlowin amplitude andfrequency.It appearson shotrecordsaslate arrivals.

v) Anotherformofcoherentnoiseistheairwavewhichhasavelocityof300 m/s.Itcanbe aseriousproblemwhenshooting withsurfacecharges.Notch mutingistheonly wayof removingthem.Powerlinesalsogiverisetonoisy tracesin theformofa mono frequency wave of about(50 or 60 Hz).

vi) Multiplesareanothertypeofcoherentnoise.Theyaresecondaryreflections havinginter- orintra-bedray paths.They propagatebothinsubandsuper- criticalregions.

vii) Powerlinesalsocausenoisytracesintheformofamono-frequencywave.A mono- frequencywaymaybe50or60Hz,dependingonwherethefield survey was conducted.Notchfiltersare oftenusedinthefieldtosuppress such energy.

2.4.3 Randomnoise: Randomnoisecould result fromvarioussources during seismic acquisition, such as poorplantingofgeophones, wind effects,transient movementsin and around thevicinity where a survey is being carried out,wavemotion inthewater(for marine surveys)andpossibly from faulty recording instruments – what is termed electricalnoise.

Oneimportant and very crucialaspectof seismic dataprocessing istouncovergenuinereflections by suppressing allunwanted energies(noiseof varioustypes) so that meaningful interpretations can be made. Theobjectiveof seismicdata processing is therefore toconverttheinformationrecordedinthefieldtoaformthatcanbeusedfor geological interpretation.Through processingwe are enhancingthesignal tonoise ratio,removing theseismicimpulsefromthetrace(inversefiltering)andrepositioning the reflectorstoitstruelocation(NMO,DMOandmigration),thereby makingita true representation of the actual subsurface structure (Yilmaz, 2001).

Seismicdataprocessingiscomposedofbasically fivetypesofcorrectionsand adjustments:

a)Time,
b)Amplitude,
c)Frequency-phase content,
d)Datacompressing(stacking), and
e)Datapositioning(migration)

Theseadjustmentsincrease thesignal-to-noiseratio, correctthe data forvarious physicalprocessesthatobscurethedesired(geologic)informationof theseismicdata,and reduce thevolumeofdatathatthegeophysicist mustanalyze.Thegeologicinformation desiredfromseismicdata is theshapeandrelativeposition ofthegeologicfeaturesofinterest.

a) Timeadjustments:Timeadjustmentsfall into two categories:

i) Static and
ii) Dynamic

Statictime corrections areafunction of both time andoffsetandconvert thetimesof thereflectionsintocoincidencewiththosethatwouldhavebeenrecordedatzero offset,that is,to whatwouldhavebeenrecorded if source andreceiverwere locatedatthe samepoint (Cox, 1999).

b) Amplitudeadjustments:Amplitudeadjustmentscorrecttheamplitudedecay withtimeduetosphericaldivergenceandenergydissipationintheearth.Therearetwo broad typesofamplitudegain programs:

i) Structuralamplitudegainingor automaticgain control(AGC), and
ii) Relative trueamplitudegain correction

Thefirstscalesamplitudestoanearly alike amplitude andisgenerally chosenforstructuralmapping purposes. The second attempts to keep the relative amplitude information so that the amplitudeanomaliesassociatedwithfacieschanges,porosity variations,andgaseous hydrocarbonsarepreserved.

c) Frequency-phase content: The frequency-phase content of the data is manipulated toenhance signal and attenuate noise. Appropriate band-pass filters (one-channelfiltering)canbeselectedby referencetofrequencyscansofthedatawhichaidin determining thefrequency contentof thesignals.De-convolutionis theinversefiltering techniqueusedtocompressanoscillatory (long)sourcewaveform,oftenseeninmarinedata, into asnearaspike(unit-impulsefunction) aspossible.Ghosts,seafloormultiples, andnear-surfacereverberationscanoftenbeattenuatedthroughde-convolutionapproaches.Many de-convolutiontechniquesusetheautocorrelationof thetracetodesignaninverseoperatorthat removesundesirable, predictable energy.

d) Data compressing (Stacking): Thedatacompressiontechniquegenerallyused is thecommonmidpoint (CMP)stack.Itsums alloffsetsof aCMPgatherintoonetrace. 48-foldto96-foldstacksarecommonly used today.Conventional2Dseismicdatainitiallyexistina3Dspace:thethreeaxesaretime,offsetandacoordinatexalong thelineof survey.3Ddataconsistinitially ofa4Ddataset;thecoordinatesbeingtime,offsetandtwo horizontalspatialcoordinates, x and y, which liesonthemidpoint axis.

e) Data Positioning (Migration): Thedatapositioningadjustmentisalso known as migration. Migrationbasically seeks to moveenergyfromitsCMPpositiontoitsproperspatiallocation.Inthepresenceof dip,theCMP locationisnotthe truesubsurface locationof thereflection.Migration collapses diffractions tofoci, increases thevisualspatialresolution,andcorrects amplitudes forgeometricfocusing effects andspatialsmearing.Migrationtechniqueshavebeen developed for applicationto pre-stack datasets, post-stack datasets, or acombination ofboth (Yilmaz, 2001).

The overall objectives for seismic data processing could therefore be summarized as;

i) To enhance thesignal to noiseratio (S/N).

ii) To produceseismiccrosssection representativeof geology.

iii) To meettheexploration objectivesofthe client.

2.5 Overview of Routine 2D/3D Seismic Data Processing Sequences

Since the introductionof digitalrecording,aroutinesequence inseismicdataprocessing has evolved. Therearethreeprimarystepsin processingseismicdata

i)De-convolution,

ii)Stacking, and

iii)Migration,

Figure 2.10 is a schematic showing the dimension and order ofapplication of these processing sequences. The block representsthe seismicdatavolumein processingcoordinates–midpoint, offset and time.

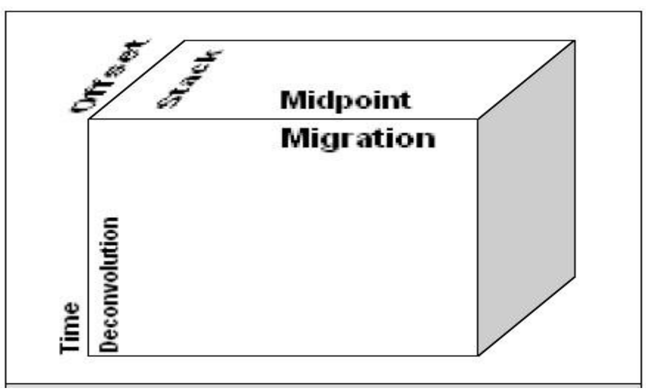


Figure 2.10: Seismic data volume represented in processing coordinates – midpoint – offset – time. Deconvolution acts on the data along the time axis and increases temporal resolution. Stacking compresses the data volume in the offset direction and yields the plane of stacked section (the frontal face of the block). Migration then moves the dipping events to their true subsurface positions and collapses all diffractions, and thus increases lateral resolution(Kumar, 2005).

Allotherprocessingtechniquesmay beconsideredsecondary inthatthey helpimprovethe effectivenessoftheprimaryprocesses.Thesecondary processingstepsincludecorrections (statics,geometric,NMO,DMO,velocity analysis,filteringetc.).Many ofthesecondary processesaredesigned to makedatacompatiblewiththeassumptionsof thethreeprimary processes.Deconvolutionassumesastationary,vertically incident,minimum-phase,source waveletandwhitereflectivity seriesthatisfreeofnoise.Stacking assumes hyperbolicmove-outwhilemigration is basedonazero-offset(primariesonly)wavefieldassumption. Conventionalprocessingofreflectionseismicdatayieldsanearthimagerepresentedby a seismicsectionusually displayedintime.Aconventionalprocessingflow (Yilmaz, 2001) is presented below highlighting relevant procedures that are carried out in the cause of seismic data processing.

1. Pre-Processing
   a.Demultiplexing
   b.Reformatting
   c.Resampling
   c.Editing
   d.GeometryMerging(Labeling)
   e.Static Corrections
   f.True Amplitude Recovery
      i.SphericalDivergenceCorrection
      ii.Absorption/AttenuationCorrection
   g.Muting
2. Time Invariant Filtering
3. CMP Sorting
4. Deconvolution
5. Velocity Analysis
6. Residual Static Corrections
7. Velocity Analysis
8. NMO Corrections

9. DMO Correction
10. Inverse NMO Correction
11.Velocity Analysis
12.NMOCorrection,Muting and Stacking
13.Deconvolution
14.Time VariantSpectral Whitening
15.Time Variant Filtering
16.Migration
17. GainApplication

2.6StaticsCorrection

Statics correction which mostoften is shortenedto as statics generally refers to “correctionsappliedtoseismicdatatocompensatefortheeffectsofvariationsin elevation, weatheringthickness, weathering velocity, or reference toadatum” (Sheriff, 1991). Staticsare timeshiftsappliedto seismicdata to compensatefor:

i)Variationsinelevationsonland,
ii)Variationsin sourceand receiver depths(marinegun/cable,land source),
iii)Tidal effects(in marine and transitional zones seismic data acquisition and processing),
iv)Variationsin velocity/thicknessofnear surfacelayers,
v)Change in datareferencetimes.

Theobjectiveis todeterminethereflection arrival times whichwouldhavebeenobserved if allmeasurementshadbeenmadeona(usually)flatplanewithnoweathering orlow-velocity materialpresent. Thesecorrections arebasedonupholedata,refractionfirst-breaks, and/or eventshooting.Uphole-basedstaticsinvolvethedirectmeasurementofverticaltravel-timesfroma buried source.Thisisusuallythebeststatics correction method wherefeasible.First-breakbasedstaticsarethemostcommonmethodofmakingfield(orfirst estimate) statics corrections (Hatherly *et al*., 1994). The approach adopted for the present study was an integrated approach of iteratively fusing both methods, that is,refraction arrival inversion with uphole measurements to build a better, robust and more reliable refraction statics solution for data acquired from OML-23, SOKU that is currently being processed.

Theterm‘statics’isused todenoteconstanttimeshiftofwholedatatraces,asopposedto variabletimeshiftsasappliedbyNMOcorrections whicharedynamic (Hampson and Russell, 1984).Theelevationneeded forshot/receivertimecorrectionisobtainedfromlabelingrecords.Thevelocity neededfor calculating the timeshiftisobtainedfromshotupholetimes. The elevationcorrections(also calleddatumcorrection)may beusedtobringalltimesinaseismicrecordtoafixedlevelin the subsurfacewhich now becomes thefinalprocessingdatum (FPD). The FPDcouldbeany arbitrary level (depending on theclientrequirement or the choice of the processor)or mean sealevel.Staticscorrections in a nutshell is simply atimeshiftgiventothetracesinordertocompensatefor effects ofthe lateral variations in elevation, weathering layer thickness, and velocity;Sheriff’(2002)EncyclopedicDictionaryofExplorationGeophysics. Duringseismic wavepropagation fromtheseismic sourceto thereceivers the wavesmustpassthroughlowvelocitynearsurfacematerials.Seismicwavestravel slowerinthelowvelocity materialandtheirtraveltimesareincreased.Because the velocities of the near surface materials can besubstantially lowerthanthe underlyingbedrock,thetimeofareflectionfromdepthwillalsovaryduetothese lateralvariationsintraveltimes.Correctstaticscorrectionisakeyfactorinshallow seismic dataprocessing. If not properly tackled, staticshiftsarecapableofcompletely disrupting the coherence ofreflections during common midpoint stacking. Spurious reflection patterns and loss of depthresolution can also arise from incorrectorinaccuratestatics (Cox, 1999).

Withinthegeneralirregulartimeshiftsrelatedtotheweatheredzone,severaltypes ofstaticsaredifferentiated(Telford*etal.*,1976).Thestaticsduetothedifferences insurfaceelevations whichaffectbothsourcesandreceivers,calledelevation statics.Bytheirrelationtothesourceorreceiverposition,staticsarealsosubdividedto sourceandreceiverstatics,andthe“total”staticsofa seismictraceisthesumofallthreestaticsatthecorrespondingsourceandatreceiverlocations.Finally,statics arecalled “surface consistent” iftheyareonlyrelatedtothesurfacelocationsof thesourceandreceiversandnottotheirindividualproperties.Allofthestaticsabovecanbeincorporatedintheconceptof “refractionstatics” (Yilmaz,2001).Refractionstatics calculations arebasedontheuseofrefracted head waves to model the first-arrival traveltimes. Several refraction-statics methodsarein use,suchasthePlus-Minusmethod,GeneralizedReciprocal method, andtheGeneralized LinearInverse method.Thesemethods takethefirst-arrival timesasinputandusedifferentkindsoftravel-timemodelingtoderiveestimates ofthedepthsand/orsubsurfacevelocities (Russell, 1990).Data-smoothingstaticsmethodsassumethatpatternsofirregularitythatmostevents havein commonresultfromnear-surfacevariations andhencestaticscorrectiontrace shiftsshouldbesuchastominimizesuch irregularities.Mostautomaticstatics determination programs employstatisticalmethodsto achieve theminimization.

Onewaytothinkabouttheseshiftsisifoneweretoessentiallystripoffthetop partsoftheearthmakingthesurfaceoftheearthnow on bedrockandwithno topography. This‘new’surfaceoftheearthiscalledthedatumelevationtowhich all oftheseismictracesarecorrected.Thenstaticscorrectionisappliedanddatais shiftedto that referencedatum.Figure2.11schematicallyshowsthe staticscorrection procedure.After calculating weathering layer thickness and velocity, staticscorrection i.e., time shiftsto source and receiver, is calculated. Staticscorrection is appliedby moving‘source’tothedatum(source)aswellasreceivertothedatum(receiver).

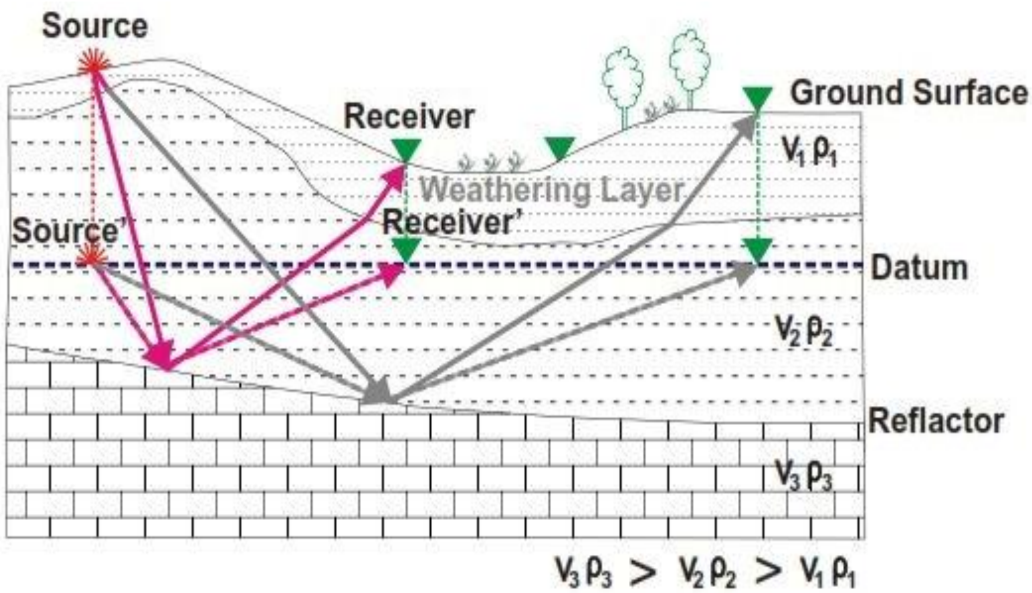


Figure2.11:Sketchshowingstaticscorrectionprocedure.Staticscorrectionisappliedbymoving‘source’ tothedatum(source)as wellasreceivertothedatum(receiver).(Ahmad,2006)

The major focus for the present study is to derive a comprehensive and complete statics solution which would consist of field or datum statics, refraction statics and residual (1^{st} and 2^{nd}) statics for addressing the already identified statics problem of OML-23 SOKU. The impact of the derived and implemented or applied statics would subsequently be determined on several shot gathers from the field in Field File Identification (FFID) configuration and on stacked and migrated sections of the dataset from the prospect.

An attempt is made in this section to describe the underlying principles and give background theories of the approaches we intend using in obtaining the complete set of statics solutions to be derived and implemented for the SOKU seismic datasets to tackle its statics problem.

2.6.1 Field Statics

The concept of field statics which is also referred to as datum statics or at times – elevation statics involves the computation and removal of the effect of different source and receiver elevations by introducing a new horizontal plane (reference datum) below the low velocity layer, in order to place or simulate all sources and receivers on this reference plane (Figure 2.12) which is usually in most cases below the elevation of the lowest source or receiver.

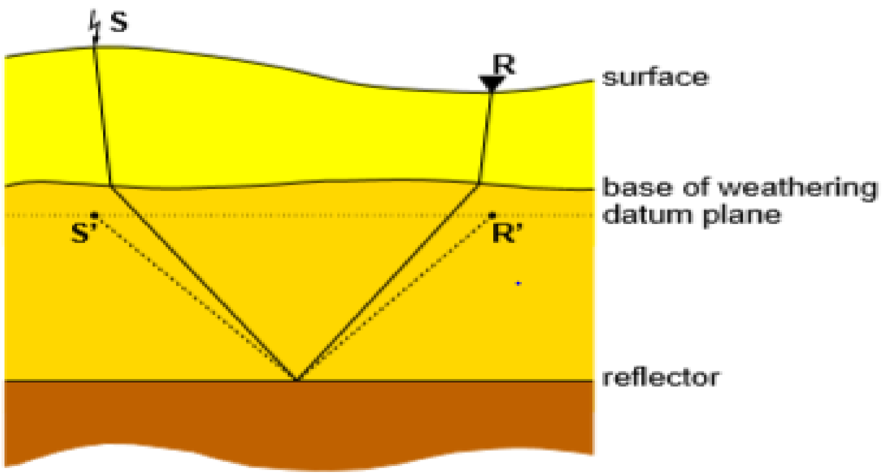


Figure 2.12:Schematic of a pseudo - source and receiver location (S' and R') on a reference datum from the actual source (S) and receiver (R) positions on the earth's surface in the build up to field statics.

A replacement velocity ($\boldsymbol{V_r}$) for the materials between the datum and the source or receiver is needed. This parameter is either assumed from prior knowledge of replacement velocity within an area or by its estimation using either uphole times or direct arrival information.

The field (datum or elevation) statics $\boldsymbol{t_D}$ is given by the expression;

$$t_D = \frac{[(E_S - Z_S - E_D) + (E_R - Z_R - E_D)]}{V_r} \qquad (2.7)$$

For the scenario depicted or described by Figure 2.13

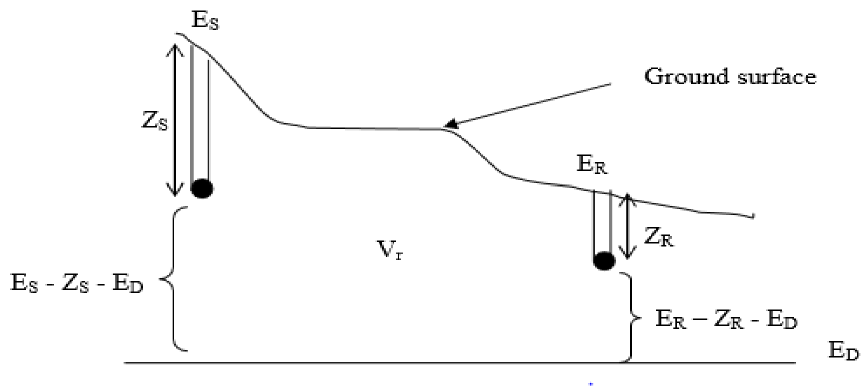


Figure 2.13:Schematic illustration of the procedure for the computation of field statics.

Where;

E_S: Ground elevation at the shot location

Z_S: Depth of shot

E_R: Ground elevation at receiver location

Z_R: Depth of receiver

E_D: Datum elevation

V_r: Replacement velocity

When $\boldsymbol{t_D}$is computed, it is then subtracted from the two –way travel time of the trace belonging to that particular source – receiver pair for the implementation of the field statics. The procedure described above, gives a basic view of what field statics entails. However, it is insightful to state that the procedure could in some instances be some-what more complex than as described above. Field statics have been successfully implemented to seismic datasets (Huang *et al*., 2008; Li *et al*., 2009; Luo *et al*., 2010 and Ponnam *et al*., 2013).

2.6.2 Refraction Statics

Static anomalies whose spatial wave-lengths are longer than a spread-length are not uncommon and if not corrected could produce false structures in seismic sections (Marsden, 1993). Applying refraction statics are an effective means for correcting for these long spatial wavelength anomalies and they could also correct for shorter spatial wavelength anomalies (Liu, 1998). The wavelength of statics being describe here refers to the width of the lateral (velocity or thickness) change in the weathering layer relative to the spread length (maximum offset). Refraction statics is also a means by which the seismic data is compensated for the effect of the low velocity layer (or weathering layer) (Zhu*et al*., 2014).

For the later objective to be achieved, a model of the weathering layer characteristics (thickness and velocity) must be estimated before refraction statics calculation can be performed. A couple of methods have evolved for the computation of refraction statics, ranging from the pioneering approaches of the Plus Minus method (Hagedoorn, 1959) to the Slope/Intercept method (Knox, 1967), both based on the delay – time approximation of refracted travel times to solve for the statics (Yilmaz, 2001). More recent approaches includes the Generalized Reciprocal methods (Palmer, 1981), the Generalized Linear Inversion – GLI (Hampson and Russell, 1984), the Delay Time method which has now been fully developed by Lawton (1989, 1990) based on Gardner's idea. The Delay Time approach has successfully been adapted in recent times to perform refraction statics (Baker, 1999; Butler, 2005; Duan, 2006; Bridle and Aramco, 2009 and Opara *et al.*, 2018). This approach was adopted in the build up to the refraction statics component of the overall statics solution being sought for the currently investigated prospect.

2.6.3 Residual Statics (1^{st} and 2^{nd})

The derivation and application of field statics (also called datum or elevation statics) and the subsequent application of refraction statics does not completely resolve statics anomalies from seismic data (Marsden, 1993; Jing, 2003 and Yin *et al.*, 2014). These remnant or residual static anomalies are due to discrepancies in the low velocity layer. No matter how well the approaches deployed to derive velocity and thicknesses of the near-surface may be, it is still very key to state that such models in actual sense is some-what a simplification of the actual geology because the earth structure is complex and is nearly impossible to model accurately. The discrepancies between the derived model and the actual earth model results in errors in the statics correction estimation. The residual statics anomalies are tackled by the implementation of residual statics (1^{st} and 2^{nd}) corrections. The residual statics corrections are time shifts applied to traces in order to compensate for time delays and the statics model as a function of time and space (Sheriff, 1991; Li *et al.*, 2011 and Henley, 2012).

The residual statics corrections are actually a subset of the statics correction (Cox, 1999). A combination of field statics, refraction statics and residual statics corrections forms ideally a comprehensive and complete statics solution to adequately address the statics problem of seismic field dataset. Residual statics programs are anchored on either linear-surface consistent methods or non-linear surface consistent methods (Russell, 1990). The former method is more widely in use and was the approach used in the study. This approach assumes that the static shifts are time delays that onlydepend on the source and receiver locations on the surface, not on raypaths in thesubsurface.This assumption is valid only if all raypaths, regardless of source-receiver offset, arevertical in the near surface.The surface-consistent assumption is generally good because the weathered layerusually has a low velocity and refraction towards the normal at its base tends to makeraypaths vertical.

The total residual time shift, t_{ijk}, could be expressed as:

$$t_{ijk} = r_i + s_j + G_k + M_k x_{ij}^2, \qquad (2.8)$$

where,

r_i: is the residual static time shift associated with the i^{th} receiver,

s_j: is the residual static time shift associated with the j^{th} source,

G_k: is the difference in two-way traveltime at a reference CMP and the traveltime atthe k^{th} CMP, and

$M_k x_{ij}^2$: is the residual moveout that accounts for the imperfect NMO correction.
G_k is a structural term, while M_k is a hyperbolic term.

The ultimate objective of the residual statics correction procedure is to determine the unknown variables (r_i, s_j, G_k, and M_k) from the known variables (t_{ijk} and x_{ij}).Usually, there are more equations than unknowns; hence, a least-squaresapproach to minimize the error energy is adopted;

$$E = \sum_{ijk} [(r_i + s_j + G_k + M_k x_{ij}^2) - t_{ijk}]^2 \qquad (2.9)$$

Residual statics correction in standard processing practice, involves three progressive phases as detailed in Figure 2.14:

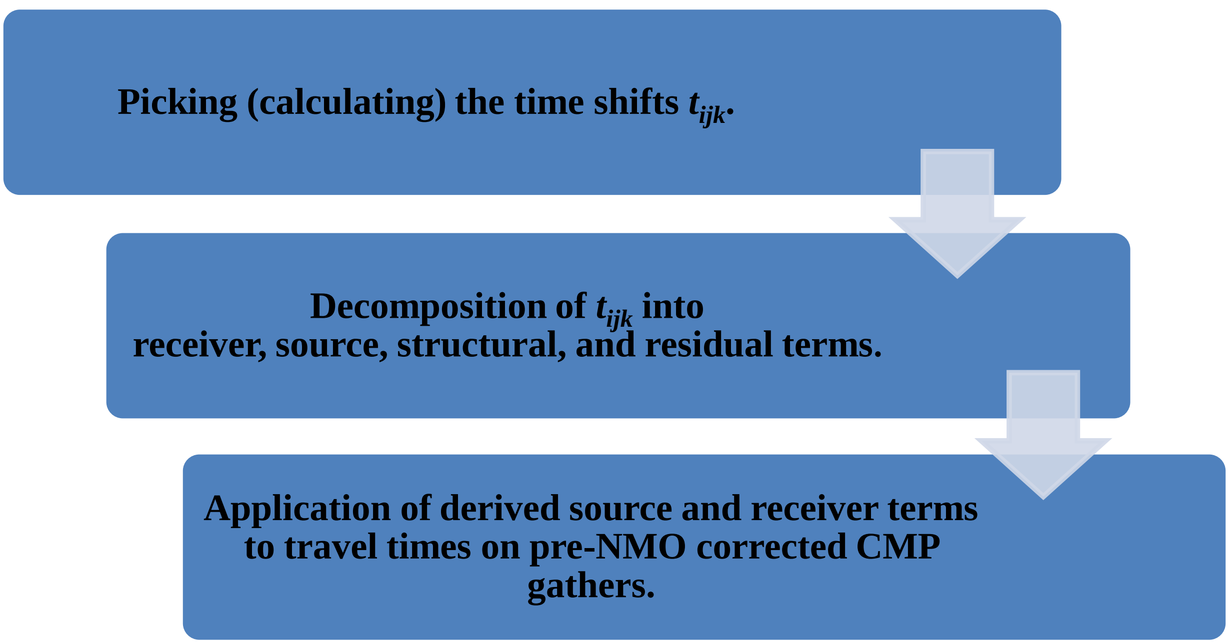


Figure 2.14: Processing sequences entailed in the implementation of the residual statics correction.

2.7 WeatheringLayer

In many land data acquisition areas, the ground is covered with a relatively thin layer of low seismic velocity materials. Geophysicists call this layer the weathering layer. The seismic weatheringlayerisanear-surfacelowvelocitylayerinwhich theportionofairfilledporespaceofrocksisusuallymorethanofwaterfilled (Cox, 1999). The 'geological'weathering layer is the result of rockdecomposition.Ingeneral,thethicknessoftheseismicweatheringlayerisbetween afewcentimeters and50metersormore,butthethickness ofthislayercanbe extremely irregular. Also, thevelocity canvaryrapidlyinthelateralandvertical direction.Inmostcases,theseismicweatheringlayeristhickerthan thegeological one. Thebaseoftheseismic weathering layeris defined as thedepthwherea changetoasignificanthighervelocityoccursorwherethevelocitystabilizes. It coincides sometimes withthewatertableand/orwiththebaseofthegeological weatheringlayer.Theterm low velocitylayer(LVL)isoftenusedfortheseismic weatheringlayer.Thetypicalvelocityfortheweatheringlayerisbetween500m/s and800m/scomparedtosub-weatheringvelocitiesof1500m/sandup.

These weathered layers are mostly related to aerated materials above the water table or to geologically recent unconsolidated sediments on a substratum of harder consolidated rocks. This seismic layer, despite the geophysicist’s terminology, appears to have very little to do with the geologic weathered layer. However, variations in the physical properties of this upperlayercancauseadramaticdeteriorationinthequality oflandseismicdataif they are not acknowledged asa problemandappropriatemeasures or actions taken duringdataacquisition andprocessing to mitigate this effect.This degradation of the quality of land seismic data by these variations is illustrated in Figure2.15 (a) and (b) (Wiggins *et al*., 1976 and Marsden, 1993).

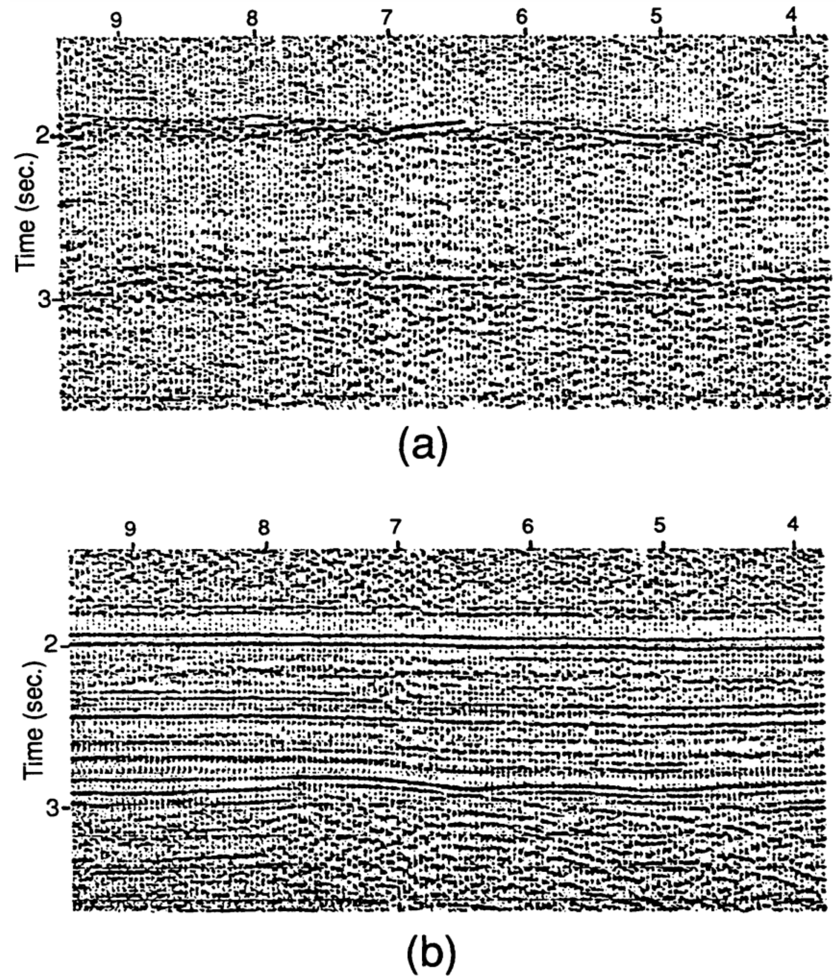


Figure 2.15 (a)Partofaseismiclineprocessedwithoutstatic corrections. (b)Samedataprocessed withstaticscorrection. It is observed that theresolution andcontinuity ofeventsare improvedin(b) than in (a) (Wiggins*etal*.,1976 and Marsden, 1993).

Usually, the thickness of such a seismic weathering layer is determined by refraction seismic or Uphole-surveys. If an Uphole survey is used, the information is obtainedonly atdiscretepointsalongtheseismicline.Theweatheredlayerhasthe sameeffectasalow-passfilter,asitshowsahighrateof energyabsorptionwhich mostlyaffects highfrequencies. Duetoitslooseandhighlyvariablestructure,it maynotjust delaytheseismicenergy,butalsoscatterit.In mostpetroleum explorationsurveysonland,wheretargetsmaylieata coupleofkilometersdepth, the uppermost few hundred meters are dealt with in statics while any deeper structuresareregardedasvelocityanomaliesandtreatedduringvelocityanalysis.

Problems caused by the near-surface low-velocity layer have been known for over half a century. Some of the earliest research papers in geophysical prospecting were concerned with attempts to determine their thickness and velocity, or compensate those early seismic records for the time delays caused by the low-velocity layer. In pre-digital days, field statics and refraction statics were thought to be the complete staticssolution; then, in the wave of the success of residual statics programs (first developed in the 1970s), it was felt that statistical methods alone were the answer. However, the consensus today within the exploration industry is that each method has its own place in adding to the complete statics solution (Marsden, 1993).Despite the many technologies that deal with differentaspects of the near surface, problems or issues related with these technologies still abound as of today.Two of the most difficult, and most often cited, problems are:

i)Need for more accurate near-surface velocity models

ii) Need for models of the near surface to allow adequate acquisition design

The need for higher resolution data is increasing remarkably in recent times and this makes it imperative for better statics correctionsamongotherthings. Staticscorrectionsisperhaps the mostimportant step in theprocessingof landdatafortheir correct and successful implementationleadsto improvedqualityin subsequent processingsteps,whichinturn,impacts positively on the overallintegrity,quality, andresolutionof theimagedsection.Errorsin thestaticscorrectionleadtoalossofseismicresolution,bothtemporal and spatial, and a less-than-optimum interpretation of the seismicdataset.Also,ifstaticscorrections arenotproperly derived,thena myriad ofproblemscouldbesetthe interpreter,suchas,lineswithvariabledatum,seismicevents which mis-tie atintersections, falsestructural anomalies remaininginthedata,falseeventsbeingcreatedoutofnoise, andeventuallythe dataqualityin most instances would notbe optimized (Marsden,1993).

Therefore,a goodstaticssolution isdesirable fortworeasons: toobtain thecorrectstructuralinterpretation andtoobtainahigh-resolutionsectionwhichcanbeusedforstratigraphic interpretation.It shouldbenotedthateitherofthesecriteriacanbe met without satisfying the other by application of one or anotherof thedifferentstaticstechnologiesthatareavailable; however,itismostdesirabletosatisfyboth criteria (Marsden, 1993a, 1993b and 1993c).

2.8 Near-surface Conditions and Near-surface Velocities

In many exploration terrains, the surfaceiscoveredwitha relativelythinanduniformlow-velocitylayer,butfrequentlyweknowthatthisis not always thecase. Someofthenear-surfaceconditionswhicharefrequentlyencountered areall illustratedinFigure2.16.Theyinclude,butarenotlimited to, elevation changes, sand dunesand othereolian deposits, buriedriver channels,buriedglacialscours,permafrost,evaporites,variablewater table, leachedzones,volcanics,peat deposits,andcoalseams.

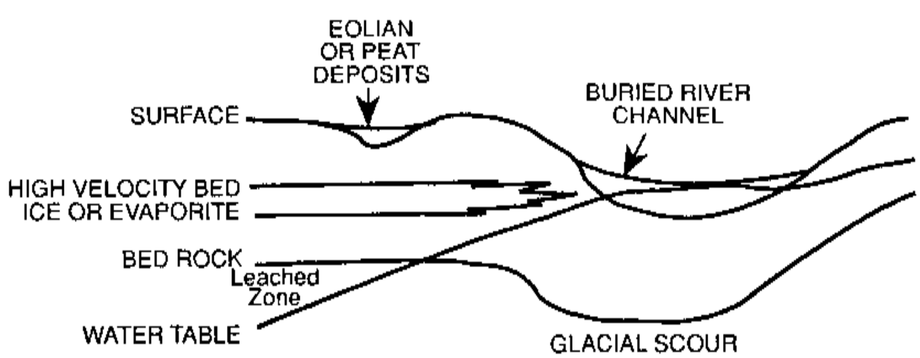


Figure2.16:Someofthefrequently encountered near-surfaceconditions, whichifnotadequately modeled,result inerrors inthecomputed statics corrections and adegradedseismicimage (Marsden, 1993).

Thesimplifiednear-surface earth modelshowninFigure 2.17(Marsden, 1993), illustratestheimpact ofthenear-surfaceproblem.Thedepthmodelhasa variable overburden thickness due to elevation changes and other effects and its interval velocity is assumed constant. The attitudeof theseismicreflectionsclearlydoesnotrepresentthe structuralattitudeof thereflectorsin thedepthmodel.Similar effectscouldbeproduced byholdingtheoverburden thicknessconstantandvaryingits intervalvelocity.Wherethe overburdenisthicker(oroflowerintervalvelocity),a seismic wavelet takes longer to travel through the layer and converselywhereit isthinner(orofhigherintervalvelocity),a seismicwaveletrequireslesstimetotraversethelayer.

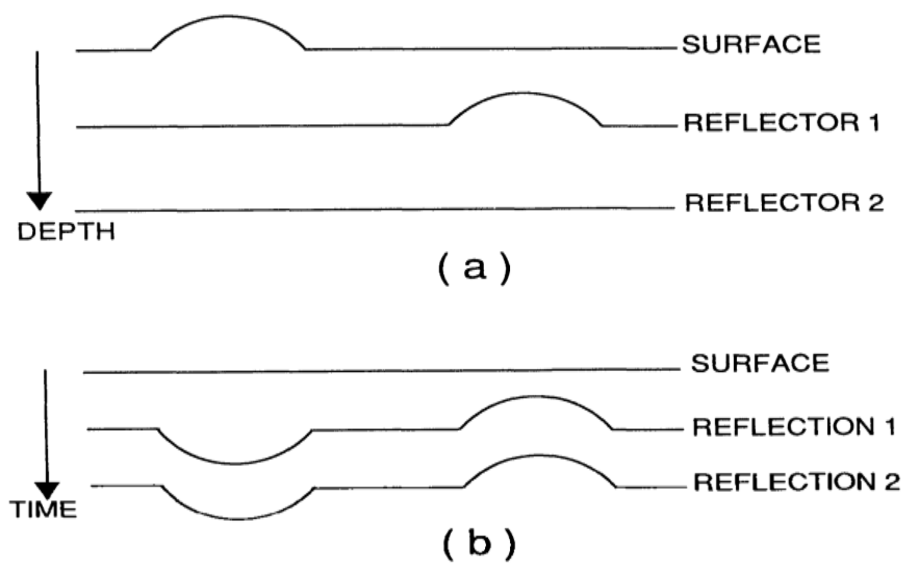


Figure 2.17:(a)Adepthmodel.(b)Themodel's seismictime response,illustratingthefundamental issuesofthestatics problem.Changesintheelevationandthickness ofthe near-surface low-velocity layerproduce timestructures onreflections fromflatreflectors. Lateral variations in the interval velocity of the near surface havesimilar effects (Marsden, 1993).

Seismicrecordinginvolvesa sourceandreceiver,usually many receivers, separated by some offset distance. The ray pathforasinglereflectiononaseismicrecordingisshown in Figure 2.18.

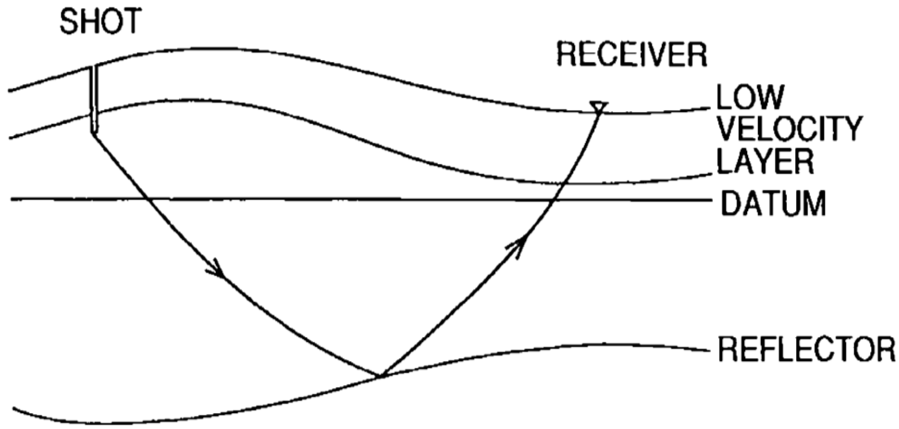


Figure 2.18: Near-surface model with a seismic ray path shown between source and receiver

From Figure 2.17and Figure 2.18, it can easily be seenthat the travel timeofa waveletalongtheray pathisinfluencedbythe surface elevations of the geophone and shot point, by the velocity andthickness ofthenear-surface layers above the datum, by the depth and dip ofthe reflector itself, the distanceseparatingthesourceandreceiver,andlastlybythe averagevelocitybetweenthedatumandthereflector. Duringprocessing, eachoftheaboveeffectsusuallyundergoesoneortwocorrectionsatatime,untiltheseismicdata providea qualityimageofthesubsurface.Withconventional multifolddata,anumberoftracesareaddedtogetherinsuch awaythatthesumming, orstacking, enhances primaryreflectionsat theexpenseofnoiseorunwantedsignal.Corrections applied totheseismic traces sothatthedatacanbe properlystackedareof twotypes,staticanddynamic.Staticscorrections involve aconstant time shift tothedatatraces whereasdynamiccorrectionsinvolvetime variableshifts. Corrections madetoeachseismictraceforelevationeffects (elevationstatics)and near-surfacelow-velocityeffects(weatheringstatics)byconceptually moving theshots(shotstatics) and receivers (the receiver statics) to a common reference surface (thedatum plane) aregreatly simplified if itisassumedthatenergytravelsverticallyin theintervalabovethe datumplane (Marsden, 1993).

Computation of datum staticscorrectionrequires a near-surface model that includes the thicknesses and velocities of the layers present. Near-surface velocities as wellas thosebelowtheweathered layerareneeded.Therangeof velocitiesthisencompassesislarge,fromabout100to7000m/s.Thevelocityof theweatheredlayerisgenerallylessthanthe sub-weatheredlayersbelow it.Ricker,(1977),suggestedanevenlowervelocityintheLowVelocityLayer,notingthatit maydrop toaslowas30m/s. Several researchers havepublishedinformationon velocities of rocks, most of them,indicatingaconsiderablerangeofvelocitiesassociatedwiththenearsurface and weathering layer. Press,(1986),producedacompilation(frommanysources)of compressional and shear wave velocity ranges for commonrocks.The velocity rangesarelistedinTable2.1forseveraligneous,sedimentary,andmetamorphic rocks.

Table2.1:Seismicvelocitiesin Igneous,Sedimentary,andMetamorphicrocks (Cox,1999).

Material	VelocityV_P (km/s)	VelocityV_S(km/s)
Anhydrite	4.1–5.0	2.67–2.99
Basalt	5.06–6.4	2.72–3.21
Chalk	2.1–4.2	
Dolomite	3.5–6.9	
Gneiss	3.5–7.5	
Granite	4.8–6.0	2.87–3.23
Gypsum	2.0–3.5	
Limestone	1.7–7.0	
Marble	3.75–6.94	2.02–3.86
Salt	4.4–6.5	
Sandstone	1.4–4.3	
Sandstone–shale	2.1–4.5	
Shaleandslate	2.3–4.7	

Velocityisavectorandnotascalarquantity,andtherefore its direction should be strictlyspecified wheneveravelocityvalueisgiven (Cordier, 1985).Aswithanyphysical parameter (velocity in this instance), anisotropy exists within the subsurface. Anisotropy in its most basic definition is simply when a value (like velocity) varies with the direction in which it is measured.Elevationstaticscorrectionarecomputedwithavertical velocitywhich, aside from in a few complex or highly folded areas, willbe approximately perpendiculartothebeddingplanes.Undermostgeologic conditions,thisisthe velocitythatisestimated byanUpholesurvey.Incontrast,therefractionstatics methodwhichisoftenusedtoobtaininformationaboutthenearsurface,estimates thevelocityparalleltothebeddingplane.Thecompressionalvelocityparallelto thebeddingplaneistypically10–15%fasterthanthevelocityperpendiculartoit (Sheriff, 2002). Insome circumstances, however,itis possible forthevelocity perpendiculartothebeddingplanetobegreaterthanthatparalleltoit(Postma, 1955).Thus,ifonlytherefractionvelocityisavailable,a suitablefactormustbe applied toconvertthevaluetoanequivalentverticalvelocityforanysubsequent computations of datum staticscorrection. This ratio can be estimated from velocities computedfromrefraction and upholesurveys forspecific formations withinanarea.

Seismic P-orS-waves propagate according to thewaveequation, whichisa partialdifferentialequation.Byintegratingitwecanpredictthewave-fieldatany point and time fromtheinitialsolution, providing themediumis isotropic and homogeneous. ThevelocitywithwhichP-waves(longitudinal)propagatethrough theground,V_p,isassociatedwiththedensityandelasticityoftherocksconcernedas presented by Telford*et al.*, (1976).

$$\nu_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad (2.10)$$

Where $\mu(\rho)$ is known as the shearmodulusand $\lambda(\rho)$ is theelasticmodulus.

2.9 Uphole Surveys

The uphole survey is a viable means of determining the thickness of the near-surface layers and the time for seismic energy to travel through these layers, and hence their velocities (Cox, 1999). The information obtained from uphole surveys provide complementary details that aids in the interpretation of conventional seismic refraction/reflection data. The uphole survey locations serve as control points and when tied to seismic data extends the well location (uphole survey point) information away from the hole or to interpolate between two or more holes across the seismic volume.

Sheriff (1991) defined an uphole survey as; "successive sources at varying depths in a borehole in order to determine the velocities of the near-surface formations, the weathering thickness, and (sometimes) the variations of record quality with source depth". In continuation, he stated further that "sometimes a string of geophones is placed in a hole of the order of 200ft (approximately 60m) deep to measure the vertical travel times from a nearby shallow source".

Uphole surveys are not used universally, and their expensive cost of deployment is a critical factor that limits its wide range of application. Uphole survey information (models) were iteratively integrated with refraction arrival inversion models to build a more robust and reliable near-surface model in a hybrid approach in this dissertation. Two common techniques or configurations exist for data acquisition during uphole surveys, they are;

i) Source in borehole and receivers at the surface

ii) Receivers in borehole and source at the surface

Both configurations are illustrated in Figures 2.19 and 2.20 respectively.

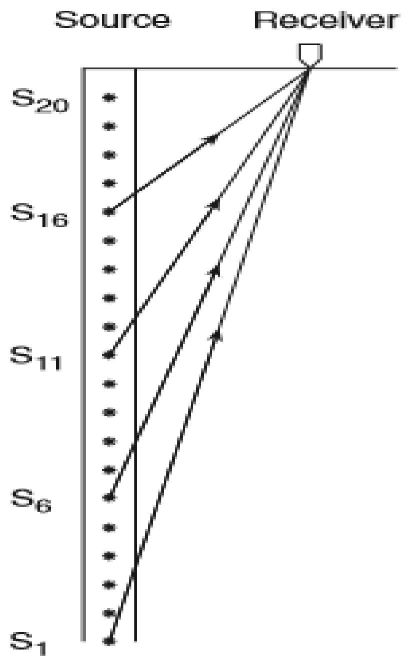


Figure 2.19: Uphole survey configuration for Sources in borehole, Receiver at the surface.
(After Cox, 1999)

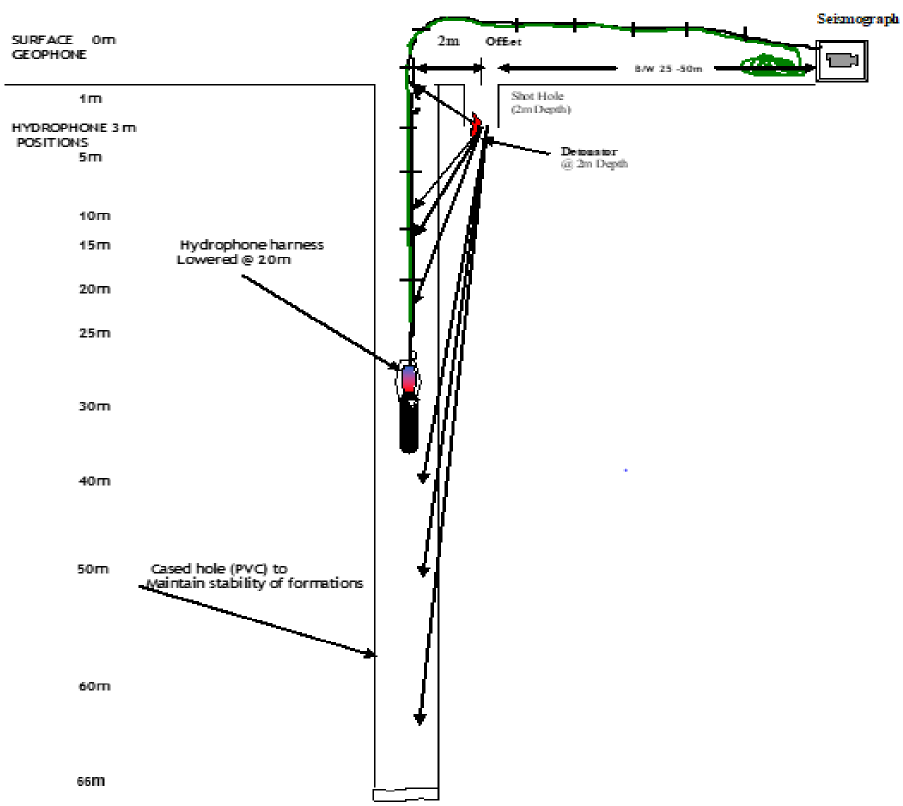


Figure 2.20: Uphole survey configuration for Receivers in borehole, Source at the surface.
(Source: CNPC/BGP Technical Report, 2014)

Regardless of the method or configuration adopted to acquire the data, with either sources (uphole recording) or receivers (downhole recording) in the borehole, the basic procedure is the same. Once the uphole data is acquired, the interpretation essentially entails;

i) Picking the first arrivals from each depth level
ii) Applying any necessary corrections to these times
iii) Plotting the data and estimating the velocities and thicknesses of the various layers identified.

In so doing, a near-surface model would have been obtained. Details on the underlying principles, methods of implementation of uphole surveys, data collection, reduction/conversion and correction as well as interpretational approaches to uphole survey models can be found in Franklin (1981), Wong *et al*. (1987), Hunter and Burns (1990), Whiteley *et al*. (1990a and 1990b) and Cox (1999).

2.10 Replacement Velocity

Datumstaticscorrectionrequirethattheweatheredlayerberemovedandthe times adjusted fromthebaseoftheweathered layerupto,ordownto,thereference datum. Thevelocity used forthiscorrectionisnormallycalledthereplacement velocity,orsometimes thedatumvelocity,elevation velocity,orsub-weathering velocity.If the reference datum is below the baseof theweathered layer, the replacement velocity is normally computed from the velocity profile atthis depth, thatis,thevelocitywithinthesub-weatheredlayer.Ifdatumisabovethe baseoftheweatheredlayer,materialwithavelocityclosetothatatthebaseof the weathered layer isusedto infill the layer. The replacement velocity may be constant foralineor,moretypically, maychangeslowlyalongtheline.Where majorlateralchangesingeology,andhencevelocityoccuratorjustbelowthe base of the weathered layer, thereplacement velocity profile generally reflects thesechanges.Thenecessaryvelocityinformationmaynotbeavailableatthetime thatthedatumstaticscorrections a r e computedduetoinsufficientarealinformation. BeckandSteinberg(1986)however,havesuggestedthatthereplacementvelocity canbecomputedlaterintheprocessingsequence.Thisapproachrequiresallinitial processestobereferencedtothefloatingdatumplane,usinga provisional replacementvelocitytoderivethedatumstaticscorrections.Thefinal replacement velocityisthengeneratedfromallavailableinformation,suchasvelocityanalyses andboreholedata,andusedtoconvertthedatafromthefloatingdatumtothefinal datum. The replacement velocity is used to correct times of almostvertical raypaths (the datum staticscorrection definition assumes verticalray paths). The value used for the replacement velocity is also likely to be used in the interpretation of velocity analyses and as part ofthevelocity–depth modelfor subsequenttimeto-depthconversion,or otherprocessessuchasdepthmigration.A factorthatshouldbenotedis thatanerrorinthereplacementvelocity(for computingtheelevationcorrection)leadstoincorrectstaticscorrections.

2.11 Refraction Seismic in relation to the Near Surface

A seismic ray which crosses a boundary betweentwo formations ofdifferent velocitiesisrefractedaccordingtoSnell'slaw(Figure2.21).Thislawstatesthatthe ratioofthesineoftheincidentangle$\Theta_1$andrefractedangle$\Theta_2$isequaltotheratio ofthevelocitiesofthetwoformations$v_1$andv_2:

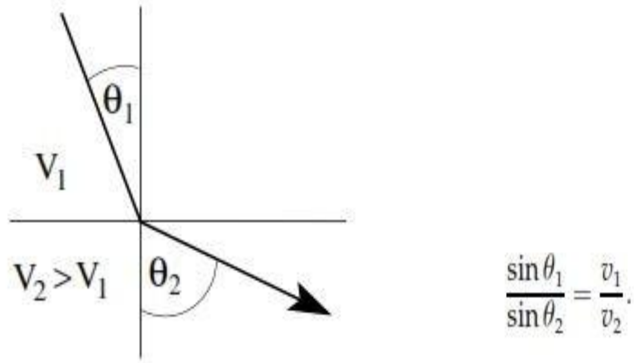


Figure2.21: Aseismicraywhichcrossesa boundary.Theratiobetweenthesineof theincidentangle$\Theta_1$andrefractedangle$\Theta_2$isequaltotheratioofthe velocitiesofthetwoformationsV_1andV_2(Snell'slaw).

Aslongasthevelocityincreases withdepth,therayisrefracted awayfromthe normal.

Forthesocalledcriticalangle,$\Theta_1=\Theta_c$,andtherefractedangle$\Theta_2=90°$.

Thecriticalangle$\Theta_c$followsfromfirst principle (Dobrin and Savit, 1988), as

$$\text{Sin } \theta_C = \frac{v_1}{v_2} \quad (2.11)$$

Ifawave-frontreaches theinterfaceunderthecriticalangle,itpropagates along theboundarywiththevelocityofthelowermedium.Ateverypointof the ray-path alongtheboundary,thereexistsarayfrom theboundarytothesurface.Theangle betweenallthisraysandthenormaltotheboundaryistheincidentangleΘ_c.

Themostconvenient wayto represent refraction datais toplotthefirst-arrival time,***t***vs.thesource-receiverdistance,***x***(Figure2.22a).Inthefollowing,the time-distance relations for the case of two layers with velocities $V_1$and V_2separatedby a horizontaldiscontinuityatdepthZ_0isderived from basic trigonometric identities and the fact that velocity is simply distance divided by time. ThetotaltimealongtherefractionpathABCDin Figure2.22(b)is

$$t_x = t_{AB} + t_{BC} + t_{CD} = 2t_{AB} + t_{BC}$$

$$= 2\frac{Z_0}{v_1 Cos\ \theta_C} + \frac{x - 2Z_0 \tan\ \theta_C}{v_2}$$

$$= 2\frac{Z_0}{v_1 \text{Cos}\ \theta_C} - \frac{2Z_0 \text{Sin}\ \theta_C}{v_2 \text{Cos}\ \theta_C} + \frac{x}{v_2} \quad (2.12)$$

If it is required to express t_x in termsofvelocitiesonly, then (2.12) can be re-expressed as,

$$t_x = \frac{x}{v_2} + \frac{2Z_0\sqrt{v_2^2 - v_1^2}}{v_1 v_2} \quad (2.13)$$

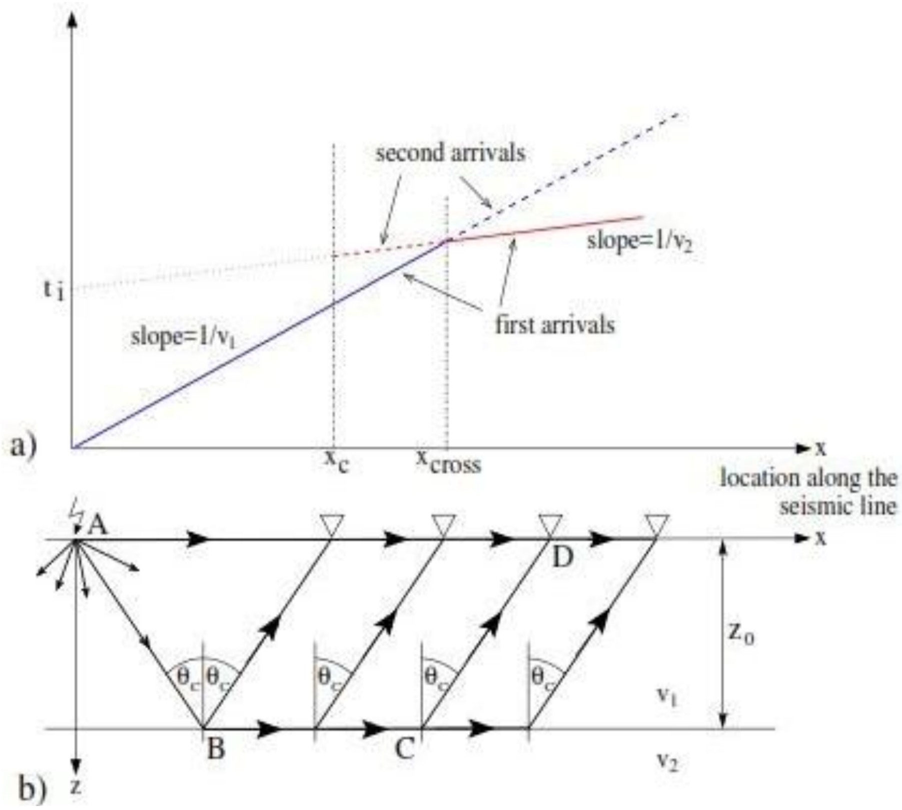


Figure2.22(a)Travel-time curvesoftherefractedandthedirectwave. (b)Refractedanddirectraysinthecorrespondingmodelwithtwolayersseparated byahorizontalinterface (Kearey and Brooks, 1991).

Ona$t_X$versus$x$plot,equation (2.13) is

thatofastraightlinewhichhasaslopeof1/V_2andwhichintersectsthe$t_X$axis(x=0)attheso-

calledintercepttime.

$$t_i = \frac{2Z_0\sqrt{v_2^2 - v_1^2}}{v_1 v_2} \quad (2.14)$$

Thedirectarrivalissimplygivenbyastraightlinewithaslopeof1/V_1 that,ina$t_X$versus*xplot*,intersectsthe$t_X$axis(x=0)at$t$=0.In thetime-distanceplot,thetravel-timecurvesofthedirectandrefractedwaveintersectseachotheratthe crossover distance

$$x_{cross} = 2Z_0\sqrt{\frac{v_2+v_1}{v_2-v_1}} \quad (2.15)$$

ThedepthZ$_0$oftheinterfacecanbecalculatedbymeansofequation(2.14).Intermsof$t_i$andthevelocitiesV_1andV$_2$,equation(2.14)canbesolvedforZ_0toobtain

$$Z_0 = \frac{t_i}{2}\frac{v_1 v_2}{\sqrt{v_2^2 - v_1^2}} \quad (2.16)$$

It can be seen fromFigure2.22thatthefirstrefractedrayintersectsthesurfaceatthecriticaldistancex_c.Thiscorrespondsto thesource-receiveroffsetwherethelength oftherayalongtherefractoriszero,i.e.,thecaseofcriticalreflection.The critical distancecanas well beexpressedas

$$x_c = \frac{2Z_0 v_1}{\sqrt{v_2^2 - v_1^2}} \quad (2.17)$$

Thetheoryexplainedabovehasillustratedthebasicideabehindrefractionseismicforplanarreflectors,only .Adetailed descriptionofa3-layer,dippinglayer,and multi-layer casescouldbefoundinCox(1999).

2.12 Refraction-based methods and existing approaches to obtain a Near-surface Model

Refractionbased methods that can be used to obtain a near-surface model are group into;

i) Intercept-timemethods,

ii) Reciprocal/Delay-timemethods,and

iii) Raytracing/Tomographic methods.

Each technique hasitsadvantages overthe otherandcanbeusedin different geologicalsituations.Thechoiceofthetypeofinterpretationtechniqueisafunction of the complexityof the subsurface geology.

Theintercept-timemethod isthesimplestmethodof seismicrefraction interpretation.Thismethodassumesflatlayersanddoes notincorporate geological dip.Inthismethodslope and intercepttime are usedtocalculate velocityanddepth ofrefractors. However therecan beproblemswithsuchasimplemethodasit does notreadilyaccountfor lateral variations.To understand how refraction techniques acquire information for the near- surface model,it is best to look at a hypotheticaltime-distancecurve(Figure2.23).

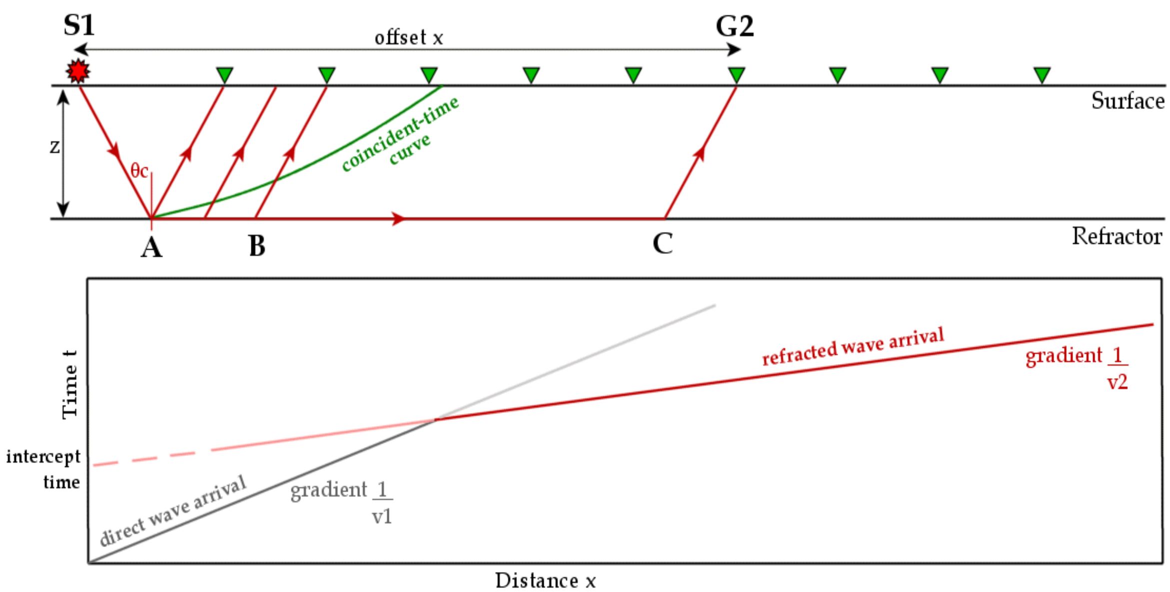


Figure 2.23:Time-distance plot for horizontal two-layer case, showing first arrivals from direct and refractedwaveandextrapolationtoread offtheintercept time (Alten, 2009)

This scenariorepresents aplane,horizontal interfaces of constant velocity, representing a 1D case where only one shot would be necessary to obtain all the information, as there are no dipping surfaces. Above the time-distance curve in Figure 2.23, there is a simplified modelofthespreadlayout.Itshowsthattheboundarybetweenthetwoparallellayers is at depth z and the emergent point of the first refracted wave on the interface is at point A. It can equally be seen that in close proximity to theshot point, the first arrival is the directwaveandit isapparent that the slopeofthetime-distancecurveinthisareaisa directmeasureofthevelocityinthefirstlayerv_1.Therefractedraysmaybevisiblein the form of second arrivals. Rays emergent at point B arrive simultaneously with the directarrivals,sothetwotravel-timecurvesintersect(at thecrossoverdistance which isthe offset at the surface, not along the refractor). At distances beyond B, refracted arrivals reachthereceiversaheadofthedirectwaveandproduceaslopewithgradient $\frac{1}{v_2}$onthe time-distance plot. Toshowthatthevelocityofthesecond layercanbedirectlydeducedfromthese recordings, the following equations are set up (Alten, 2009):

Ifthetimetakentotravel horizontally fromS_1toG_2viaAandCis

$$t = \frac{S_1A}{V_1} + \frac{AC}{V_2} + \frac{CG_2}{V_1} \qquad (2.18)$$

and weknowthelineS$_1$Ahitstheinterfaceatthecriticalangle $\theta_C$atdepthz,wecanrewrite theequation(2.18) as

$$t = \frac{z}{V_1 cos\theta_c} + \frac{x-2z\ tan\theta_c}{V_2} + \frac{z}{V_1 cos\theta_c} \qquad (2.19)$$

UsingSnell'slaw,thisisequivalent to

$$t = \frac{x}{V_2} + \frac{2z\cos\theta_c}{V_1} \qquad (2.20)$$

Equation (2.20) has the form of a straight line equation with $\frac{1}{V_2}$being the gradient. In orderto be abletosolvethisequationwiththreeunknowns(z, V_1, V_2),wedetermineV_1 fromthe slope of the directarrival, V_2 from the slope of the refracted arrival and z is worked out by assuming the offset x to be zero and reading the intercept time off the extrapolated time-distanceplottoobtainavaluefortheterm$\frac{2z\cos\theta_c}{V_1}$,inwhichtherefractordepthis now the only unknown.Thecrucialpointworthy of notehereisthatthismethodislimitedto asimplecaseof parallel bedding planes. Thevelocity is presumed to be constant within the two media and the structures are horizontal. None of these conditions is usually fulfilled in reality and hence is a serious limitation to this refraction interpretation method. A scenario of multi-layeredgeologies andthepossibilityofdippingrefractors,as well as a gradual velocity increase with depth is the ideal situation encountered in the subsurface. Figure 2.23shows that a correct determinationofnear-surfaceinformationrequires, arecordingoftheheadwaveoverany receiver, so that a precise gradient can be read off the time-distance plot. Shorteningthedistanceoverwhichtheslopeis measuredislikelytoresult inerrorsofjudgment onthepart of the interpreter,givinginappropriateresultsfor V_1, V_2andz. This problem becomes even more recognizable in multi-layer cases (Figure 2.24), wherethenumberofrefractorsthatcanbemappedisdependent onstructuralfactorsandspread layouts; this is still a case of a 1D situation with no dips.

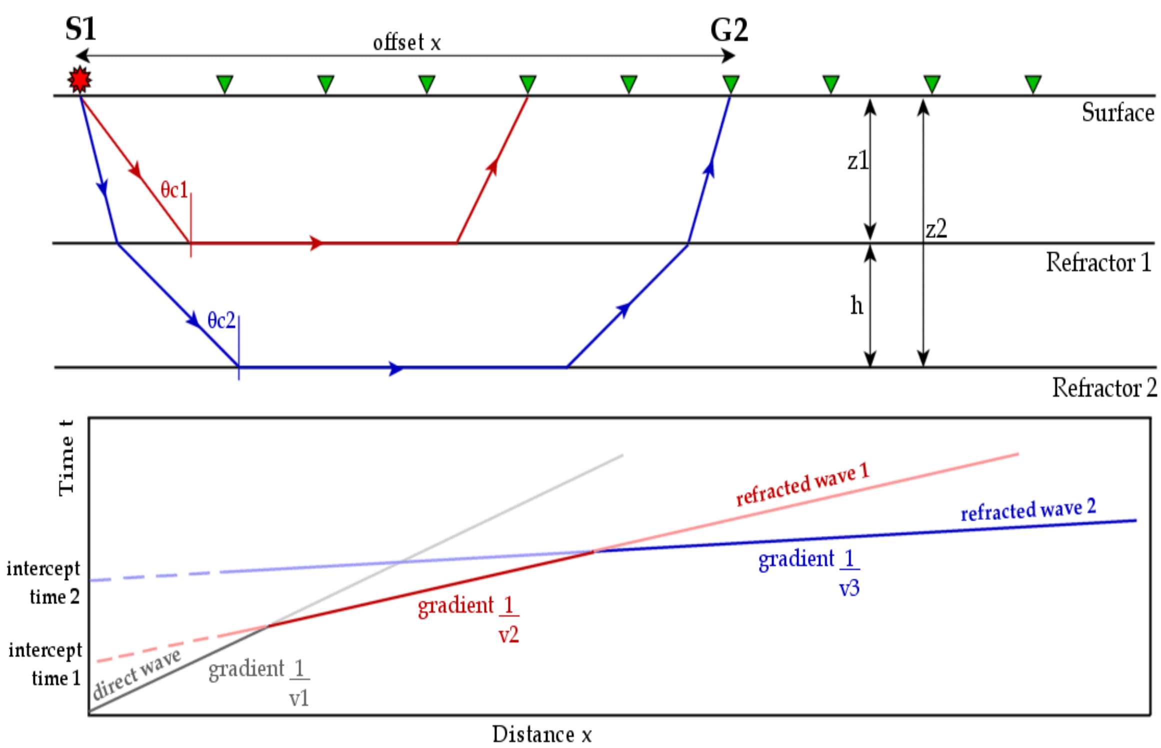


Figure 2.24:Time-distanceplotforhorizontalthree-layercase,wheretwobendsinthefirst arrivalcurve at the crossoverdistancesmarkincreasesinvelocity (Alten, 2009)

Figure 2.24 shows the time-distance curve of first arrivalsin a three-layer case. The equationsforthetwotoplayersarethesameasinasimpletwo-layercase,andthe thirdlayercanbecomputedbyapplyingthesameconceptbut withafewmodifications. The slope of the thirdrefractor is equivalent to$\frac{1}{V_3}$, on the assumption of a parallel horizontallayering scenario.Inordertocalculatethedepthofthislayer(z_2),thesame theory above applies, working with the depth of the refractor relative to the layerabove (h) and using its intercept time (intercept time 2). Whereas the depth of the shallow refractor is equal to its thickness, the depth of the deeper refractor is the sum of its thickness and the depth of the layer above.

Theoretically, this method could be extended indefinitely to any number of layers,buildingupa system of equations tosatisfyevenmorerefractors.Practical limitations,however,suchastheneedforverylongoffsetstorecordfirstarrivalsfrom deep refractors and the problem of differentiating clearly between the layers, particularly if the velocity changes are small, reduce the standard model to a maximum of2to3layers.Thegeologyofthesurveyareagreatlyaffectstheresolutionofthe model.Thebendinthetravel-timecurves marktheonsetofanewlayerandindicates where the crossover distance along the surface is found, that is, where the refracted wave overtakes the direct wave, or in multi-layer cases, where the waves from a deeper refractor overtake those from the shallower refractor. A reasonably strong velocity contrast between two layers manifests itself asa clear bend and hence an easier velocity determination. Too strong velocity contrasts between thin layers, however, might result in hidden layers, as they are not obviously separate refractors on the time-distance plots andleadtoerroneousdepth estimations.Layersof verysmallthicknesscomparedtothe surrounding ones might only appear as a second arrival and not as a first, which makes them impractical for refraction analysis. Another situation which can give riseto hidden layers is velocity inversions(Cox, 1999). This, common in permafrost regions, causes seismic waves to be refracted towards the normal when they hit the interface between the fast layer andthe underlying slower layer. Incident waves will not strike the lower layer at thecriticalangleinordertoproducetherefractedwavethatrunsalongtheinterface and eventually produces the measurable head wave.This shows that the concept of refraction surveys to provide near-surfaceinformation is only valid if thevelocity increaseswith depth. Thisistrue even when dealing with non-horizontal layering situations, leading to 2D/3D scenarios, that is, where one shot does not suffice to acquire subsurface information. Dipping refractors, be it just one or multiple dippinginterfaces, can beresolved adequately as long as reciprocal shotsareemployed.Reciprocalshotsrequire shot-receiverlocationstobe interchangeable to give a forward and reverse shot for the same underground profile. That way, an up-dip and down-dip velocity, along with an up-dip and down-dip thickness could be determined, from which the true values can be deduced. The reciprocity of this method refers to the travel-time of the wave, which should be the same if the shot and the receiver station are reversed.

If the stratigraphy consists of very thin layers, the resolution (governed by the geophonespacingoftherefractionprofile)mightnotbesufficienttodistinguishthem asindividuallayersand,instead,thecurvedtravel-timeplotsappeartogiveavelocity gradient.However, ifthesubsurfacebedsaredipping, as is usually the case, the effective and frequently usedmethodsarethe reciprocalanddelay timemethods.Theterm ‘reciprocaltime’isthetraveltimealongtherefractorfrom oneendshotofthereceiverfor‘forwardprofile’ andviceversaforthe‘reverse profile.Inthismethodbothforwardandreversespreaddatashouldberecorded.This typeofacquisitiongeometryistypicalforseismicrefractionsurveys.Butinthecase of seismicreflection surveyswhererefractionsarealsorecorded,thisforwardand reverseshotscheme mightnotexist.Butanalgorithmdesignedtosolvethesekinds ofcasescansortdataandcreatepseudoforwardandreverseshotschemes.Forward andreverseshotsareusually requiredtocalculatesubsurfacedipoftherefractors. Theoretically,bothforwardandreversetimesshouldbeequalifreciprocity exists. Bothtimesarenotequal becauseof dippingbed,undulating layers,andchange in refractor velocity. Inthissituation, the commonrefractioninterpretationmethodsare the Plus-Minusmethod (Hagedoorn,1959),the ABC method(Edge andLaby,1931), theGardnermethod (Gardner,1967), which has evolved over time and has now been fully developed by Lawton (1990) as the Delay-Time methodand theGeneralized ReciprocalMethod (GRM) (Palmer,1981).

In‘Ray tracing’methods,seismicraypathsaretracedthroughtheinputgeological-velocitymodel;thetheoretical traveltimesare calculatedandmatchedagainstthe actualfirst breaks.Inversioniscarriedout tocalculate thetraveltimedifferences betweenactualandtheoreticalfirstbreaksandtheinputmodelisupdatedwithtravel timeresidualsforthe nextiteration. Iterationscontinue untila predetermined stoppingcriterion ismatched.Inthismethod twodifferentinversion approaches exist,

i) Alayer basedinversion,and

ii) Afullcell/blockbasedtomographic inversion.

Amonglayerbasedinversionmethods, theGeneralizedLinearInversion(GLI) methodiscommon (HampsonandRussell, 1984). Inthismethodthe near surface geologicalmodelisproposedandraysaretracedthroughthismodel.Inthe fulltomographicinversionapproach,thevelocitiesareallowedtovaryinboththe horizontaland verticaldirections.Thesubsurface geologicalmodelisdividedinto blocks/cellsof equalslownesswhichare invertedfor suchasinthe GLI method.Inthe areasof severevelocityvariationsthismethodgivesacceptable results.

There are other methods of interpretingdataacquired from refraction surveys; many arebased onsimilarprinciplestotheonesalready mentioned, whileotherstake awhollydifferent approach, such as wave front methods. The Plus-Minusmethod proposed by Hagedoorn (1959), is worthy of mention here,it requires a reversed refractionprofilewithreceiversatcommonsurfacelocationsforaforward andreverse shot.Theso-calledplustime– thesumofthetwotraveltimesfromthesourcestothe commonsurfacelocation,minusthereciprocaltimebetweenthetwosources– gives informationaboutthetraveltimefromthesurfacetotherefractor andisthusameasure of the delay time. The minus time leads to a straight line equation with a gradient corresponding to the refractor velocity.

AgeneralizationofthisapproachisPalmer's idea ofthegeneralizedreciprocal method(GRM),whichcanbeappliedtoa common surface, as well as common subsurfacelocations.Likewise,itreliesonreciprocaltimesonareversedrefractionprofile,but whilethePlus-Minusapproachworksonparallelhorizontallayering,the GRM is insensitive to dips up to 20^{o}and can handle velocity gradients. The drawback of Plus-Minus andGRMapproachesisthattheyarelimitedtoin-lineapplications,or2D layouts,whilethe Delay-Timemethod(Lawton, 1990) canbeextendedtoa3Dconfiguration which is more desirable.These techniques are exhaustivelydiscussed in Cox, 1999. Forrefractionarrivalsrecorded aspartofareflectionsurvey,the most widely used and accepted interpretation methodsare theDelay-Time approachor tomographic technique. The Delay-Time approach is the method used in interpreting the refraction data which was used to build a near-surface model for an appropriate refraction statics solution to be derived for the seismic dataset from the investigated prospect (OML-23, SOKU), to resolve its statics problem. This choice was guided by the flexibility of the method to be adaptable for a multi-layer, dipping case as is the case in the Niger Delta Basin where the prospect is situated.

2.13 The Refraction Delay-Time Approach

Therefraction delay-timemethodor approach is arecentrefractionstatics correction techniquethatusesthetravel-timesofcriticallyrefractedseismicenergytocompute thedepthandvelocity structureofnear-surfacelayers.It was actually developed and applied by Lawton, (1990) based on Gardner's delay – time analysis (Gardner, 1967). Itassumesthenear-surface structureissimpleandlayerbased.Itneitherhassevereto pography variationsnor hasrapidlateralvelocity variationinlayersbeneaththenear-surfaceweathering layer.Itresolvesintermediateandlong-wavelengthweatheringstaticsanomaliesthat may notbehandledbyresidualstaticscorrections.

The delay time method is basically a continuation ofthe two-layer intercept method. Equation (2.20) for the travel-time t at any offset x was said to be $t = \frac{x}{V_2} + \frac{2z \cos \theta_c}{V_1}$, this can berewritten as an expression of the intercept timet_0 (wherex=0)togivethe depthzas$z = \frac{t_0}{2}\frac{V_1}{cos\theta_c}$, rewritingthisexpression of z togetrid ofθ_c term, we get,

$$z = \frac{t_0}{2}\frac{V_1 V_2}{\sqrt{(V_2^2 - V_1^2)}} \quad (2.21)$$

Thedelay-timeconceptnowsplitsthisintercepttime $t_0$intoashotandreceivercomponentandposits that,ifthetruerefractorvelocityisknown,theintercepttimeat offsetxcorrespondstothetimedifferencebetweentheactualarrivaltimeandthetimetravelled along the interface vertically below shot and receiver,

$$t_0 = t - \frac{x}{v_{refractor}} \qquad (2.22)$$

The raypaths in Figure 2.25, show which travel paths and travel timesthis concept correspondsto.Thedelay-timeasdefinedbyGardner(1967), iscomposedofthe receiverdelaytime $t_{R/delay}$ atoneendoftheprofileandthesourcedelaytime $t_{S/delay}$ at theother,sothatinthespecialcaseofhorizontalparallellayers,thesetwodelaytimes areequal.Ifthisisthecase,eachdelaytimeishalftheintercepttimeandEquation(2.20) canbere-expressedas

$$z_R = t_{R/delay} \frac{V_1 V_2}{\sqrt{(V_2^2 - V_1^1)}} \quad (2.23)$$

or $z_s = t_{S/delay} \frac{V_1 V_2}{\sqrt{(V_2^2 - V_1^2)}}$, (2.24)

givingtherefractor depths at receiver and shot stations, respectively.

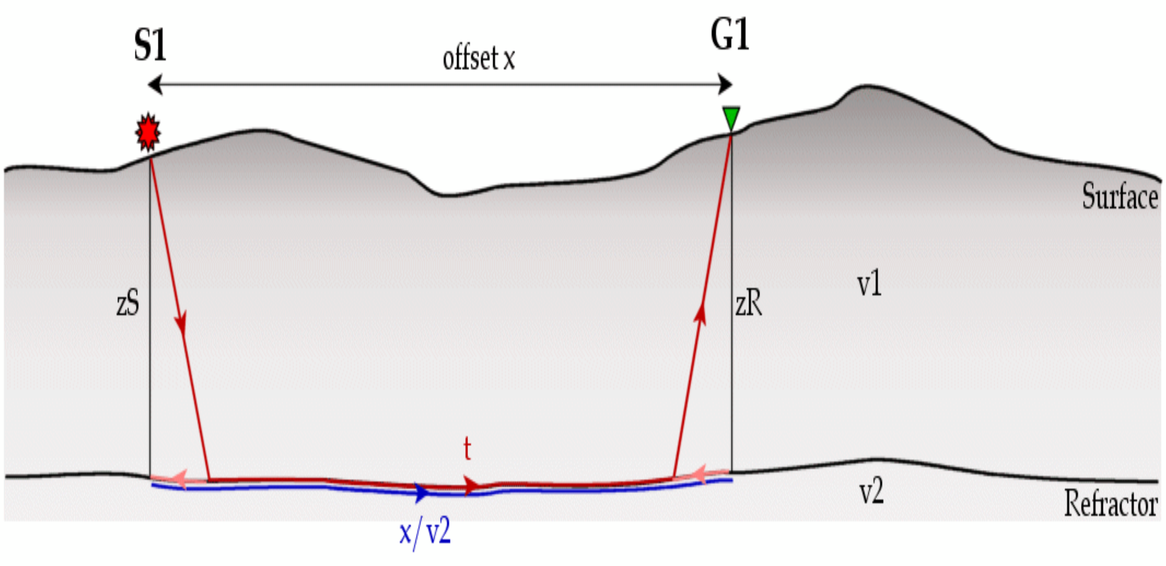


Figure 2.25:Blueray pathcorrespondstodistancebetweenverticaldownwardprojectionsofS_1andG_1, wavestakingtime $\frac{x}{V_2}$;redray pathcorrespondstoactualtraveltimet;delaytimeisthedifference

betweenthetwoandcanbe decomposedtogive depths $z_S$and $z_R$ateitherend ofthe profile (Alten, 2009).

Furtheruseofthedelay-timeconceptissometimesmadedirectlyindatum statics,wherethedelaytimesaretakentobeweatheringcorrectionswhenthelayering is sufficiently flat or only has limited dip, and the critical angle is small enough to assume the incident rays to be close to vertical. Theoverallworkflowtoderivethe correctionstaticsisasfollows:first,thefirst-arrivalenergy(firstbreak)needstobe picked.Normally,only thefirst2to3layersarepicked.The picked first breaks are then examinedforcorrectnessbyperforminggeometryquality control QCandrepositioning them if and where necessary adjustments are required. Furthermore,avelocitymodelisderived,andfinally thestatics is calculated after definingintermediatedatumandfinal datum.Themethodused to interpret the refraction data usedfor the current study (the Delay-time approach), as previously stated wasfirst fully developedby Lawton(1989) based on Gardner' idea, it has evolved (Lawton, 1990) and has been revised in recent times (Baker, 1999; Butler, 2005; Duan, 2006 and Bridle and Aramco, 2009). This methodcanindirectlyestimateintercepttimeandbedrockvelocity usingthefirst breaks.Itusesthemultiplicity offirst-breakdataavailable inmulti-foldreflection surveystodeterminethe numberofrefractors presentandtocalculate statistically robustdelayedtimesandrefractorvelocities.Itmitigatestheambiguity inthe interpretationoftraveltime-distancegraphscausedbythepresenceoftopographyor structure onthe refractor.Figure2.26isatwo-layer modelwithonelayeroverhalfaspace.

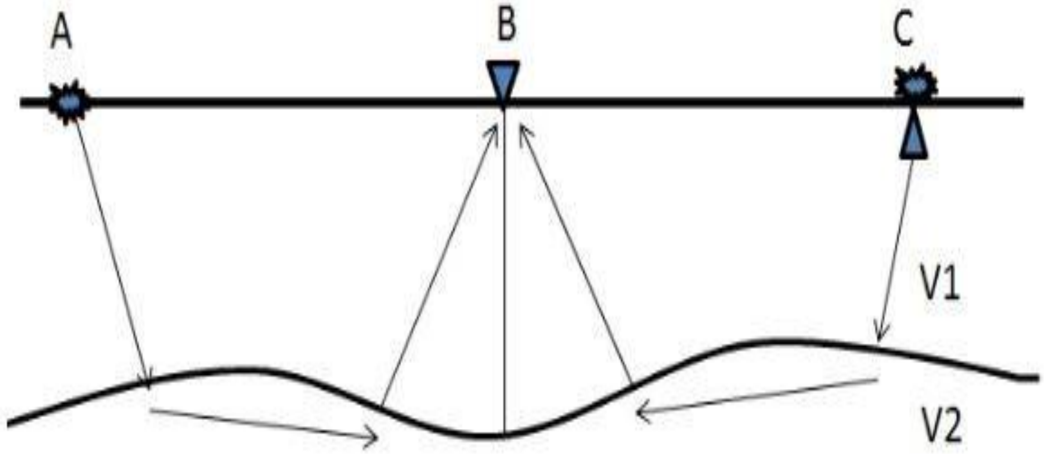


Figure2.26:Twolayer refractiondelay-timemodel(Cox, 1999)

Thefirstlayercouldbeconsideredas the weathering layerwithanundulating base.It showsthree raypathsassociatedwithshot-receiverpairsAB,BC,andAC. Assumingthatthe delay timesforashotpointandreceiveratacommonlocationareequal;the following equationscould easily be derived (Cox, 1999 after Lawton, 1989) asfollows:

$$T_{AB} = T_A + \frac{AB}{V_2} + T_B (2.25)$$

$$T_{BC} = T_C + \frac{BC}{V_2} + T_B \ (2.26)$$

$$T_{AC} = T_A + \frac{AC}{V_2} + T_C \ (2.27)$$

$$T_{AC} - T_{BC} = T_A - T_B + \frac{AB}{V_2} (2.28)$$

$$T_{AB} - (T_{AC} - T_{BC}) = 2T_B \ (2.29)$$

$$T_B = \frac{1}{2} \ (T_{AB} + T_{BC} - T_{AC}) (2.30)$$

$$T_A = \frac{z_A \cos\theta}{V_1}$$

$$T_B = \frac{z_B \cos\theta}{V_1}$$

$$T_C = \frac{z_C \cos\theta}{V_1} \quad (2.31)$$

$$\theta_1 = \arcsin\frac{V_1}{V_2} \quad (2.32)$$

T_{AB},T_{AC}andT_{BC}representfirst-arrivaltraveltimesfrom source toreceiver.T_A,T_B, $T_C$aredelayedtraveltimeforA, B, andCrespectively. Ө isincidentangle. Z_A, Z_B, and$Z_C$arethedepthfromshot/receivertotherefractor,andvelocitiesinthetwo layersare V_1andV_2. Delay timesfordeeperrefractorscanbecomputedinanidenticalmannerby using furtheroffsetfrom theshotpoints.Inthegeneralcaseforrefractorn,thedelayed time (Cox, 1999) isexpressedas

$$T_{ABn} = T_{An} + \frac{AB}{V_{n+1}} + T_{Bn} \quad (2.33)$$

$$T_{An} = \sum_{i=1}^{n} \frac{Z_{Ai} \cos\theta_i}{V_1} \quad (2.34)$$

$$\theta_i = \arcsin\frac{V_i}{V_{i+1}} \quad (2.35)$$

Thisapproachcanbe used to interpret refraction data from subsurface situations where there is a highvertical-velocity contrastandthis is crucial in deriving a correct refraction statics solutioninsuch situations.

2.14Overview of the Geology of the Niger Delta Basin

The Niger Delta Basin is a large arcuate Tertiary prograding sedimentary complex deposited under transitional marine, deltaic and continental environments since Paleocene in the north to Recent in the south.It occupies an area lying betweenlongitude4°E-9°Eandlatitude4°N-6°N.Itisboundedinthe east by theCalabarFlank and Abakaliki Trough,in the west by the Benin Flank, inthenorthbytheAnambraBasinandin thesouthby the Atlantic Ocean. Bothmarine and mixed continental depositional environment characterize the Niger Delta Basin of Nigeria(Uko *et al.*,1992). The Niger Delta covers an area of about 75,000 square km(28,957 mi^2) in southern Nigeria.Figure 2.27 shows the Niger Delta Area in southern Nigeria.

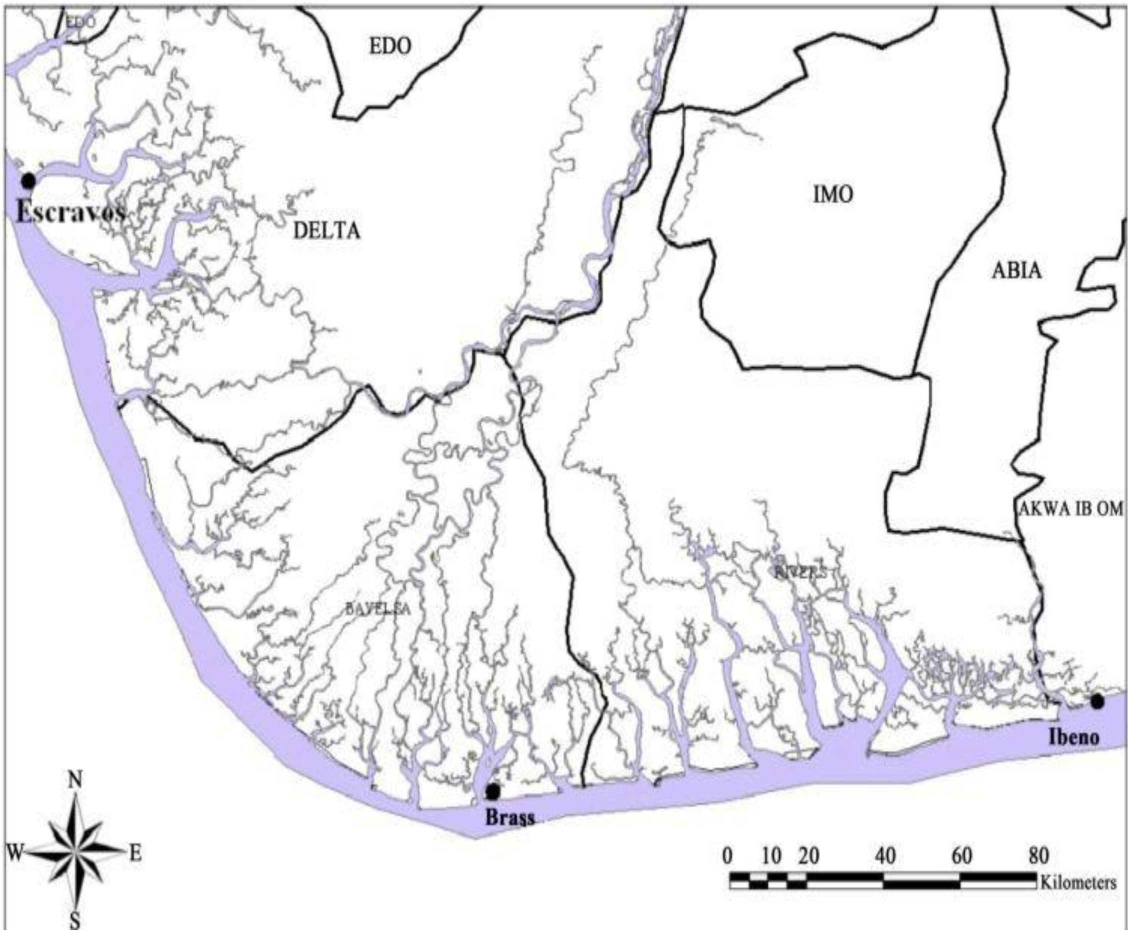


Figure2.27:TheNiger-Delta Area in southern Nigeria(ShortandStauble,1967).

Fromthe Eocenetothe present,the Deltahasprogradedsouthwestward,forming depobelts (Figure 2.28)thatrepresentthemostactiveportion oftheDelta(DoustandOmatsola, 1990).Thesedepobeltsformoneofthelargestregressivedeltasintheworldwith anareaofsome300,000km^2(Kulke,1995),asedimentvolumeof500,000$km^3$and asedimentthicknessofover10kmin thebasindepo-center(Hospers,1965).

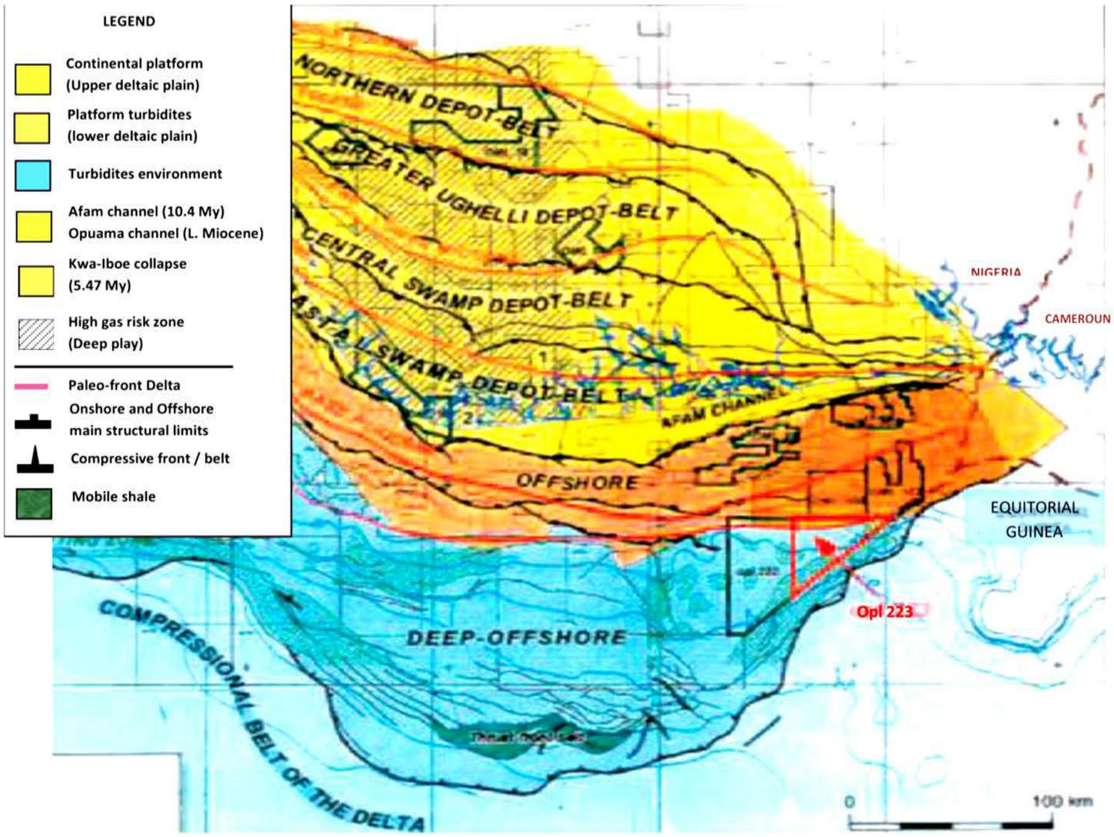


Figure 2.28:Map of Niger Delta showing the depobelts (Short and Stauble, 1967)

The Niger Delta Basin consists of three main tertiary stratigraphic units overlain by Quaternary deposits(Shortand Stauble, 1967)(Table 2.2).Thesethree subsurface stratigraphic units are the Benin, Agbadaand Akata formations.

Table2.2:GeologicunitsoftheNigerDelta(ShortandStauble,1967)

Geologic Unit	Lithology	Age
Alluvium (general)	Gravel, sand, clay, silt	Quaternary
Freshwater backswamp and meander belt	Sand, clay, some silt and gravel	
Mangrove and salt water/backswamps	Medium-fine sand, clay and some silt	
Sombreiro-warri deltaic plain	Sand, clay and some silt	
Benin formation (coastal plain sand)	Coarse to medium sand with subordinate silt and clay lenses	Miocene
Agbada formation	Mixture of sand, clay and silt	Eocene
Akata formation	Clay	Paleocene

The baseisthe Akata Formationcomprisingmainlyof marineshaleand sandbeds. Its composition consists of primarilydark-greysandy,silty-shalewithplantremainstowardsthetop of the Formation.It is over 1200m thick andthoughttobethemainhydrocarbonkitchenoftheNigerDelta Basin (Kulke, 1995). TheoverlyingAgbadaFormationisasequenceofalternating sandstonesandshales.Itconsists ofanupperpredominantlysandysectionwithminorshaleintercalationsandalower shaleunitwhichisthickerthantheuppersandysection.The thickness is over 3000m.TheBeninFormationismadeupofpredominantlymassive,highlyporous freshwater-bearing sandstone, with local inter-bed of shales. Quaternarydepositsmadeupoftopsoil,redlaterite,clay,finesand,medium sandand coarsesand constitute alluviumoftheBeninFormation.Thethickness isvariablebutexceeds 1800m.

TheNigerDeltaisoneofthemosthydrocarbon-richregionsin the world. Exploration and exploitation ofhydrocarbons havebeengoingoninthe regionsince1956,whenoilwasdiscovered at Oloibiri in present day Bayelsa State, Nigeria.Itisanexcellentpetroleumprovince,rankedbytheU.S.GeologicalSurvey World EnergyAssessmentasthetwelfthrichestinpetroleumresources,with2.2 %ofthe world’sdiscoveredoiland1.4%oftheworld’sdiscoveredgas(Klett*etal.*,1997). By virtue ofthesizeand volumeofpetroleumaccumulation inthe NigerDeltabasin,variousexplorationstrategieshavebeen devisedtorecoverthe enormousoilandgasdeposits locked therein. The delta formed at the site of a rift triple junction related to the opening of the southern Atlantic from the Late Jurassic to the Cretaceous. The Delta proper began progading in the Eocene, accumulating sediments that now are over 10 km thick. The Niger Delta Petroleum Province contains only one identified petroleum system, namely the Tertiary Niger Delta (Akata –Agbada) Petroleum System (Klett *et* *al.*, 1997).The western boundary is the Benin Flank - a west-north trending hinge line at the margin of the West Africa basement Massif. The northeastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High and further east-south by the Calabar Flank.The litho-stratigraphic cross section of the Niger Delta Basin is shown (Figure 2.29)with the three distinct – Benin, Agbada and the Akata Formations.

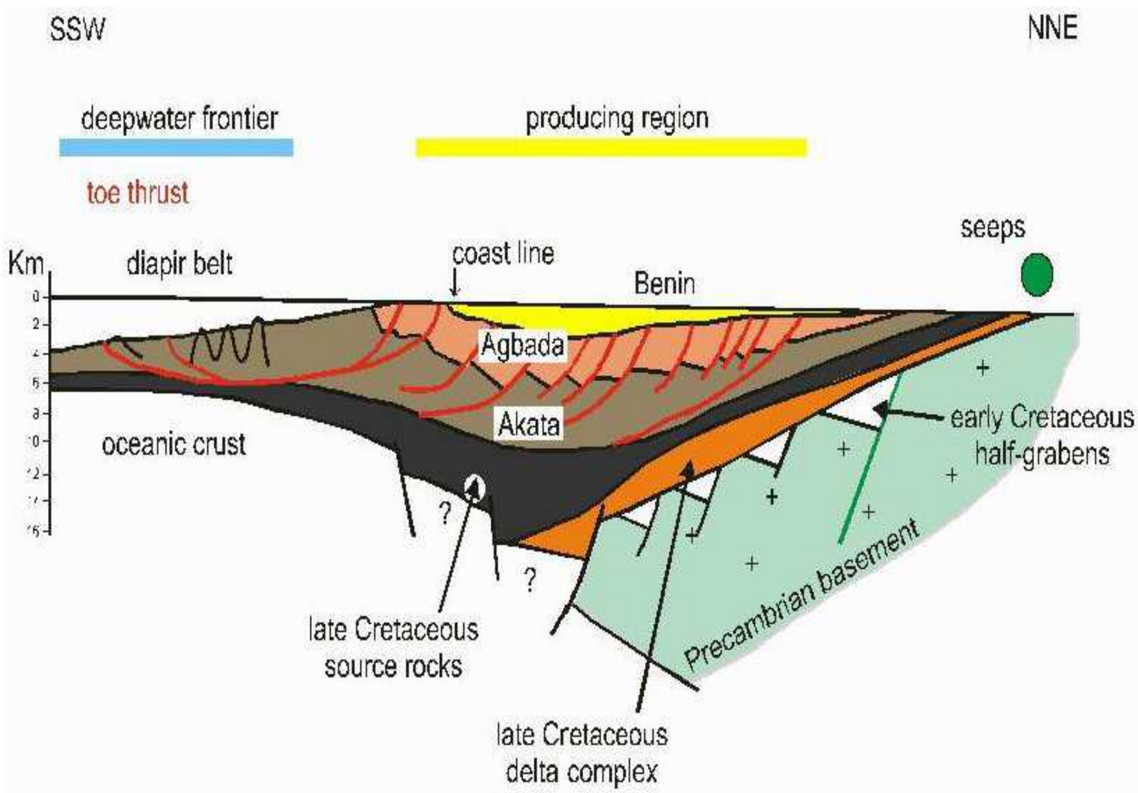


Figure 2.29:The Niger Delta litho-stratigraphic cross section showing the Benin, Agbada and Akata Formations (Allen, 1965)

The Niger Delta Basin is characterized by some fault configurations (structures), those identified include shale diapirs, roll-over anticlines, collapsed growth fault crests, and steeply dipping, closely spaced flank faults. Some of these identified fault configurations are shown in Figure 2.30. These faults mostly offset different parts of the Agbada Formation and flatten into detachment planes near the top of the Akata Formation (Merki, 1970).

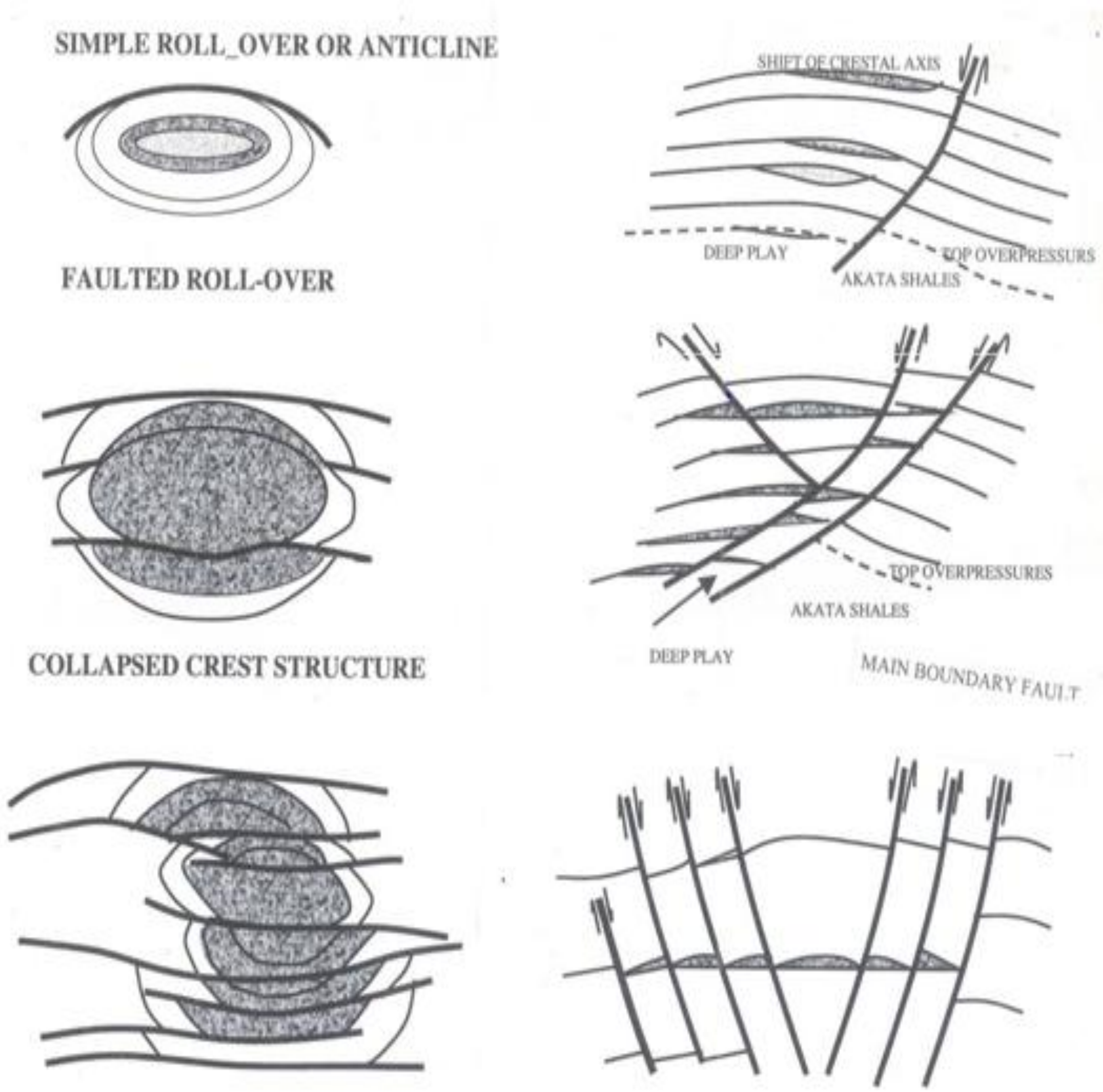


Figure 2.30: Conventional trapping configurations in the Niger Delta Basin (Merki, 1970).

Petroleum resources in the Niger Delta is produced from sandstone and unconsolidated sand reservoirs predominantly in the Agbada Formation. The major migration paths of hydrocarbon from the source rocksto these reservoirs are through the planes of growth faults (Merki, 1970). This is based on the assumption that permeability suitable for migration to take place is due to the presence of sand streak in the fault planes.Another possible migration path for the hydrocarbon could be from the over pressured shale sections.The characteristics of the reservoirs of the Agbada Formation are controlled by depositional environments and the depthsof burial.

Known reservoir rocks are Eocene to Pliocene in age, and are often stacked, ranging in thicknesses from as little as 15m to as large as 45m. The primary source rock is the upper Akata Formation, the marine-shale facies of the delta, which possibly emanated from inter-bedded marine shale of the lowermost Agbada Formation. Oil is produced from sandstone facies within the Agbada Formation, however, turbidite sand in the upper Akata Formation is a potential target in deep water offshore and possibly beneath currently producing intervals in the onshore parts of the Basin.Most known traps in the Niger Delta Basin are structural although stratigraphic traps are not uncommon. The structural traps developed during synsedimentary deformation of the Agbada paralic sequence. A variety of structural trapping elements exists; including those associated with simple rollover structures, structures with multiple growth faults, structures with antithetic faults, and collapsed crest structures. The primary seal rock in the Niger Delta is the inter-bedded shale within the Agbada Formation. The shale provides three types of seals; clay smears along faults, inter-bedded sealing units against which reservoir sands are juxtaposed due to faulting and vertical seals (Merki, 1970).

Intensive exploration efforts over the last 35 years in and around the Niger Delta Basin has led to a succession of significant discoveries, notably are the Bonga, Agbami/Ekoli and Akpo discoveries in Nigeria. However, the full potential of the continental slope and the rise seaward of the shelf break is only recently becoming the focus of attention, with a number of exploration programs having resulted in major successes in recent years. Extensive regional 2D and 3D multi-client seismic data acquisition programsexecuted by a number of companies have provided high quality regional datasets that has enabled the unprecedented discoveries made lately in locating potential and prolific hydrocarbon fields.

CHAPTERTHREE

MATERIALS AND METHODS

3.1Materials (Data) and Software Tools Deployed

Thematerials and processing facilitiesdeployedfor the present study include;

i) Unprocessed seismicdatain SEG-D format from prospect OML-23, SOKU in the onshore Niger Delta Basin (over 28GB size on hard disk).

ii) Theaccompanying Geometry/SPS (Source – Receiver) relation information files for the prospect OML-23, SOKU. (Selected SPS files from the prospect are shown in the appendix.)

iii) Uphole data/information acquired from the prospect OML-23, SOKU

iv) State of the Art High-end PC workstation with substantial Hard disk and Random Access Memory (RAM) size.

v) VISTA^{TM}interactive 2D/3D seismic data processing software for preliminary in-house seismic data processing.

vi) PROMAX^{TM}interactive 2D/3D seismic data processing software for the advanced seismic dataprocessing stages.

vii) MESA Expert Version 10.04 which was used to load the coordinates of the study area. It was equally used to load and display the SPS files.

viii) Global Mapper 15 ^{TM}, which aided in viewing the geographical settings and terrain of the study area in terms of seismic objects (SO) and non-seismic objects (NSO).

ix) Processing support/facilities of the Geophysics Research Laboratory at the University of Port Harcourt and the Data Processing Centre of Excellence of Bureau for Geophysical Prospecting/China National Petroleum Corporation (BGP/CNPC) at Eleme, Port Harcourt.

3.2Methodology

The methodology adoptedat the different stages of the study, from the estimation of the near-surfacevelocity and thickness model over the investigated prospect from pre-stackseismicdata, up to the refraction statics solution derivation stages for OML-23 SOKU, as well as the advanced processing stages where the success of the derived refraction statics solution was determined on shot gathers, and the data quality of both stacked and migrated sections of the datasets, is outlined in this section.

The starting point inderiving refractionstatics solution entails preliminary pre-processing of the acquired data like loading the field geometry parameters, extensive quality control, removal of auxiliary channels and bad traces and possibly carrying out minor noise reduction processes to the data to increase the signal to noise ratio (SNR). Oncegeometryisloaded,theseismicdataaresortedwith sourcenumbersasthe primarykeys, and line numbersand offsetsas thesecondarykeys to enable for efficienttravel-timepicking.Thenextstepis topickthefirstbreaksinthis sorted order. Due to the large amplitudes of the first breaks, they areeasily recognized from the shot displays.However,noisy portions of the datamaybemoredifficultor ambiguous topick because the noise imprints could smear the visibility of the first breaks.Generally, theseismic dataprocessorselects theamplitudepeaks, troughs, orzerocrossingsfortravel-timepicking,and triesmaintainingitsconsistency throughouttheentiredataset.In order tokeeppickingconsistent,switchingtoothersortorders(e.g.,by commonreceiversor midpoints,CMP)couldbeuseful.

Theentire processing methodologydeployed issummarized with these threekey stages:

i.) The datapreparationand pre-processingstagewhichinvolved3DbinningandFold calculation,generatingthe Linear move-out (LMO) plot,pickingfirst breaks and performing qualitycontrol (QC) of the picked first breaks.

ii.)Thesecondstageinvolvedgeneratinga geometry database ofcontrol pointsforthe seismicdata from the prospect – OML-23, SOKU,andbuildinganear-surfacevelocity and thicknessmodelfromthedata using the proposed hybrid near-surface imaging approach.

Then the derivation of the refraction staticssolution whichwillthen beappliedto theseismic dataset, followed by the comparison of theresults between thestatics-correctedand uncorrectedoutput for shot gathers in Field File Identification (FFID) configuration.

iii).The third and final stage is the advanced stage, where the data processing was extended to stacking and migration and the effectiveness of thederived refraction statics solution was equally determined for both the stacked and migrated outputs of the SOKU dataset.

3.2.1Field Data Characteristics

This section describes the testing of parameters used during the acquisition of the dataset and the pre-processing steps taken in achieving the objectives of this study.Thedata acquired from the prospect OML-23 SOKU,hadseveralreceiverandsourcelines as expected.A very significant portion of the data (about 13 swaths) was used out of the full spread of over 30 swaths which were acquired in three (3) acquisition phases. Processing the entire dataset would have been near impossible because superior processing hardware such as PROLIAN Server PC parallel processing workstations and their likes are extremely expensive to acquire and deploy. The portion of the dataset used had the following field characteristics; thereceiver lineswere six(6)in numberandwere trendingintheNorth-Southdirection. Theyinclude In-lines48,62,76,90,104,118.Thecross-lines orsourcelineswhich weretrendinginthe East-Westdirectionincludedcross-lines608,624,640,656,672,688. Severalshot positionswerealsooffsettoeithertheleftorrightofthecross-linetoavoidobstacles whichcould notberemovedfromthesurveyedarea.Theinlineandcross-linerangeof thesource andreceiver linesusedforthisstudy isshown in Figure3.1.

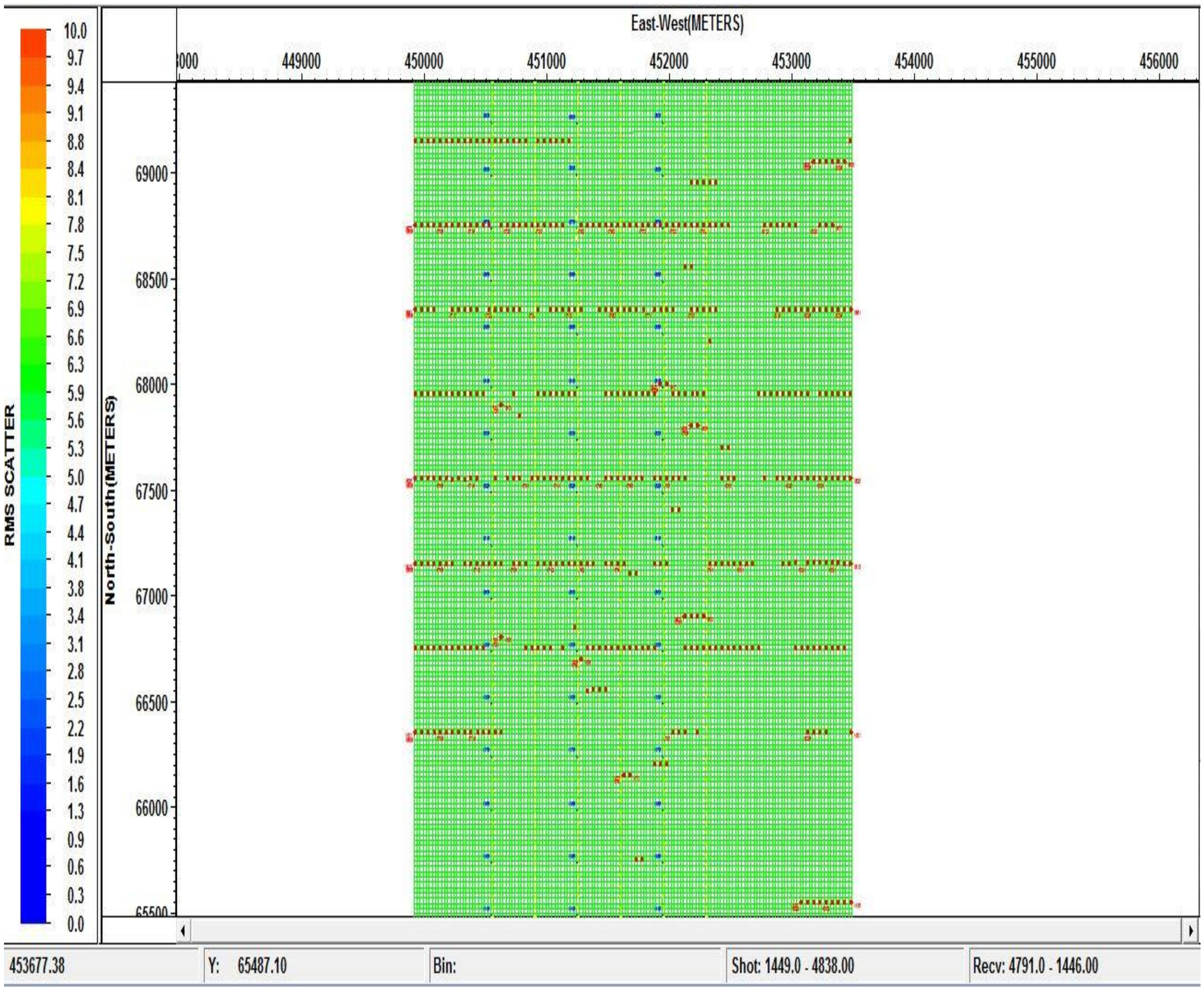


Figure3.1:Inline andcross-lineconfiguration over the surveyedarea.

3.2.2Data Acquisition Parameters

The seismic data used for the study was acquired from OML-23, SOKU. The acquisition was done in 3 acquisition phases with well over 27441 shots. The 3D shooting geometry was symmetric split spread.The 3D acquisition was done by IDSL (BGP/CNPC) using Sercel 428 recording instruments with nominal fold coverage of 56. The 3D seismic acquisition parameters are shown in Table 3.1.

Table 3.1:Data acquisition parameters for the 3D seismic survey in OML-23, SOKU

DESCRIPTION	DETAILS
GENERAL	
Recording format	SEG-D
SEISMIC SOURCE	
Energy source	Dynamite(2kg)
Shot Per Salvo	32
Depth	40m
Shot interval	50m
RECORDING SYSTEM	
Instrument:	SERCEL 428XL
Sample Interval:	2ms
Station Unit Type:	FDUI
Low cut filter:	3 Hz/6 dB
High cut filter:	200 Hz
Recording length	8sec
RECEIVER	
Channel per Patch:	1792
Number of Group:	18
Receiver Point Spacing:	50m
Receiver Line Spacing:	400m
Geophone Type	SM4
Processing Data Format	SEG-D DEMUX (IEEE Flt point)
Polarity	SEG
OTHERS	
Measurement System	Meters
Fold coverage	56
Offset Range	25-6000m
Re-sampling rate	4msec
Bin size	25 by 25m
Shot line interval	400m
Receiver line interval	400m
Hole type	Single deep hole

3.3 Identified Processing Problems

The major task of this research is to derive statics solution that would be used in processing 3D seismic data acquired from OML-23, SOKU. Hence the derivation and implementation of statics correction on the seismic datasets is the principal processing challenge the current study seeks to address. However, other minor challenges which could smear and (or) impede the success of the correct implementation of the statics solution to be derived and applied are amplitude compensation and noise challenges. These two challenges were equally resolved before initiating the process of determining the effectiveness and success of the derived statics solution on the shot gathers the stacked and then the migrated sections of the datasets.

3.4Methods deployed to addressthe identified processing problems

The major processing challenges of the OML-23, SOKU seismic datasets are;

i)Statics Correction Problem.

ii) Amplitude Compensation Problem.

iii) Noise Removal Problem.

These problems were resolved using the processing strategies described in sections 3.4.1, 3.4.2 and 3.4.3.

3.4.1Method of solution to the Statics Correction Problem.

The solution to the statics correction problem was solved using the delay time approach on both VISTA^{TM} and PROMAX^{TM}processing platforms. Fourkey progressive stages were involved in the actual derivation and implementation of the statics correction and these stages are;

i)Field Statics (Datum or Elevation) Correction

ii)3D Refraction Statics Correction (Delay time Model)

iii) 1st Residual Statics Correction (Max. Power) iv)2nd Residual Statics Correction (Max. Power)

Before and after figures would be presented in the subsequent sections to demonstrate the effectiveness and success of the derived and applied refraction staticssolution on the datasets.

3.4.2 Method of solution to Amplitude Compensation Problem.

For real seismic data, the amplitude of a reflection is influenced by several factors, including source and receiver, wave front divergence, stratum absorption, formation structure, reflectors, and interference waves. All of these factors make reflections vary in waveform and energy at different reflection positions (shallow, middle, and deep) as well as among different traces and shots. These differences result in obvious effects on the precision of deconvolution, normal move out, statics corrections, and velocity analysis. Consequently, it is very important to perform the amplitude compensation before stacking to compensate for lost amplitude due to the aforementioned factors. The amplitude compensation problem was solved by applying the following procedures.

i)True Amplitude Compensation (TAC)

ii) Surface Consistent Amplitude Compensation (SCAC)

iii)Q Compensation(Q.C)

iv)Residual Amplitude Compensation (RAC)

3.4.3 Method of solution to Noise Problems.

We faced a couple of processing dilemma in selecting appropriate parameters to either mute or attenuate the diversity of noises present on the acquired data from the current prospect. However, best considerations based on already established processing algorithms and previous processing experiences were used as the basis for selecting band pass and other filter types that were used in tackling the diversity of noise problems identified on the datasets. The processing steps taken to solve the diversity of noise problems that pervaded the SOKU dataset include;

i) Design of Low Cut Filters.

ii) Ground Roll Wave Attenuation.

iii) Coherent Noise Attenuation.

iv) Wild Amplitude Attenuation.

v) Residual Noise Attenuation.

vi) 4D Random Noise Attenuation (RNA)

3.5 Processing steps and sequences adopted

The necessary and relevant processing steps and sequences adopted to enable realizing the processing objectives are itemized below:

1. Field Data Loading/Format Conversion (4ms) and Data Display
2. Geometry Definition/Merging/Binning/LMO
3. First Break Picking/First Break Quality Control Model
4. Analysis of First Breaks and Refraction Statics Calculations/Applications
5. PSTM Bad Shot/Trace Editing
6. Amplitude Recovery
7. Deconvolution (Pre-stack Noise removal)
8. Surface Consistent Amplitude Compensation
9. Q. Compensation (Phase only, optional)
10. Deconvolution (SCDC)
11. 1^{st} Velocity Analysis
12. Residual Noise Attenuation

13. Residual Amplitude Scaling

14. 2nd Velocity Analysis (1km grid)

15. 1st Residual Statics

16. 3rd Velocity Analysis (1km grid)

17. 2nd Residual Statics

18. 4D RNA Applications

19. *Tau-P* Deconvolution

20. CDP to G Depth

21. F-X (Explicit) PSTM Velocity

22. 3D Volume F-X (Explicit) Migration

23. Migrated Stack Generation

24. Post Stack FXY

25. Zero Phase Conversion

26. Final Display (Filter/Scaling)

3.5.1 Field Data Loading / Format Conversionand Data Display

Field seismic data recorded on 3592 cartridge tape in SEG-D format was received, then loaded and converted to Geo-East Internal Format (on Promax™) and SEG-Y (on Vista™). The field seismic data was resampled from 2ms to 4ms after it was loaded. The acquired 3D seismic data from the prospect field were loaded using appropriate flow commands (Disk Data Input) on Promax™. In executing the Disk Data Input flow, all the header details like trace numbers, channel numbers, Field File Identification (FFID) were taken into account. After the loading procedure, the raw shots acquired from the prospect were displayed and inspected. Figure 3.2 shows a display of the raw shots from in-line 79 in FFID and channel number order.

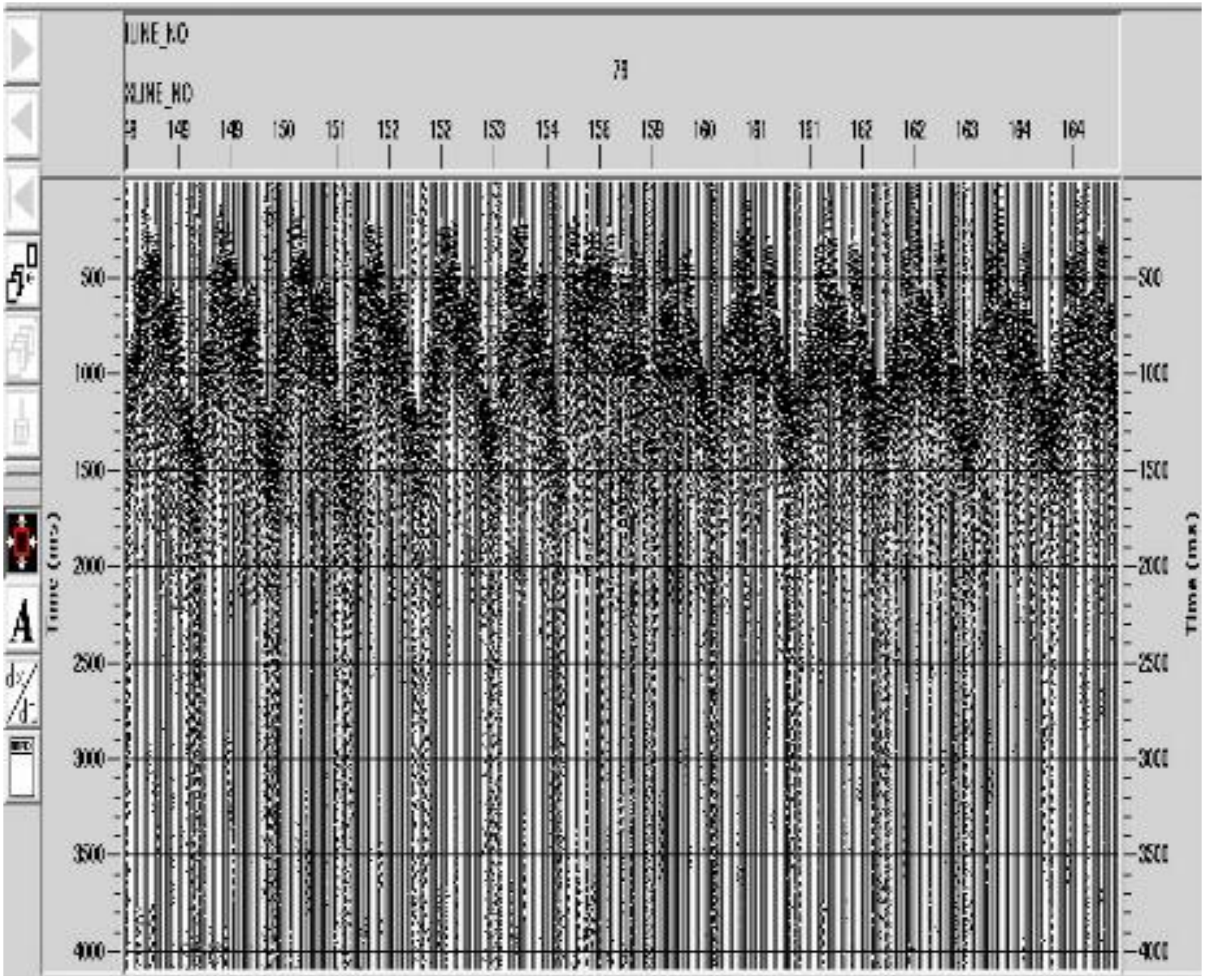


Figure 3.2: Display of raw shots from In-line 79 in FFID and channel number order

3.5.2 Geometry Definition/Merging/Binning/LMO

Graphical Geometry Quality Control (QC) is a special way to quickly find errors in the assignment of geometry. The process applies linear move-out to shots and slices multiple shots together in a vertical fashion based on receiver surface station.The geometry file for the prospect was equally loaded. All details that relates to receiver files, source files and relation files were all entered into a special spread sheet to load the geometry. Thereafter, QC was performed (Figure 3.3) for the loaded geometry to identify and correct possible errors associated with wrong loading of geometry. The QC check showed that geometry was properly loaded as evident from the control line (the green lines).

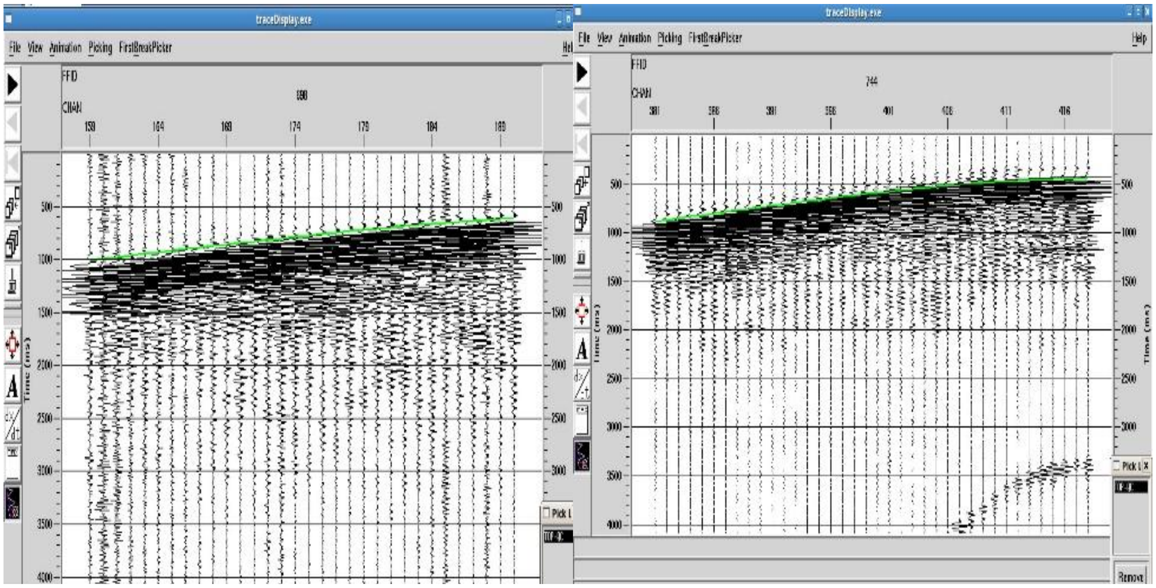


Figure 3.3: Quality Control (QC check) performed on loaded geometry from the field.

The merging of the loaded 3D seismic data file (raw shots) and the loaded geometry (source-receiver- relation, SPS files) was subsequently performed. Linear Moveout (LMO) and LMO QC were equally performed (Figure 3.4) and preliminary frequency spectral analysis of the data to ascertain the frequency and power/energy content of the data (Figure 3.5).

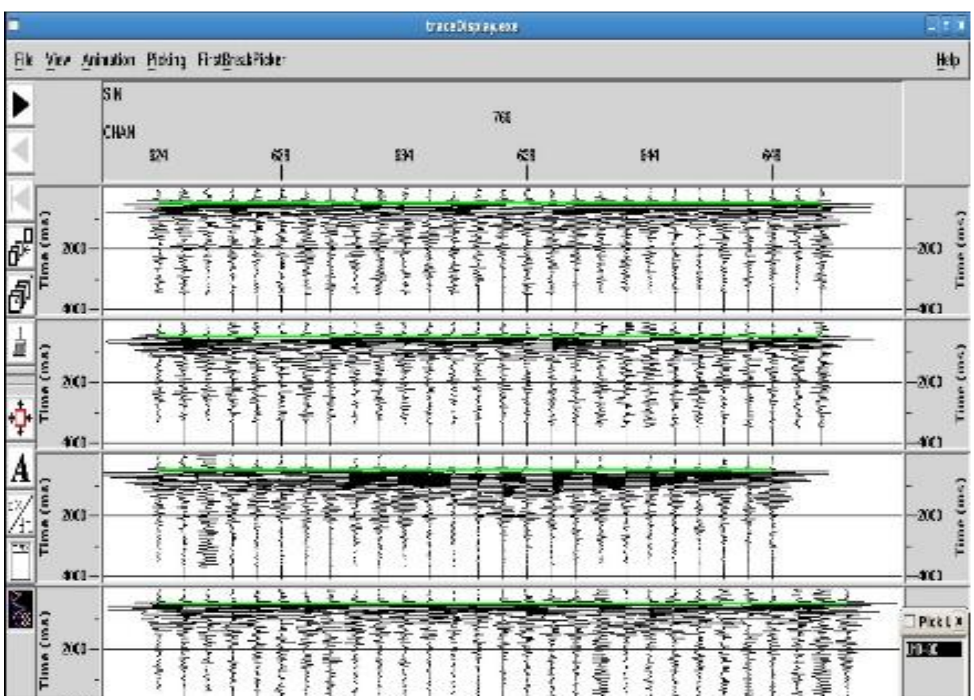


Figure 3.4:Linear Move out (LMO) – QC check performed was satisfactory

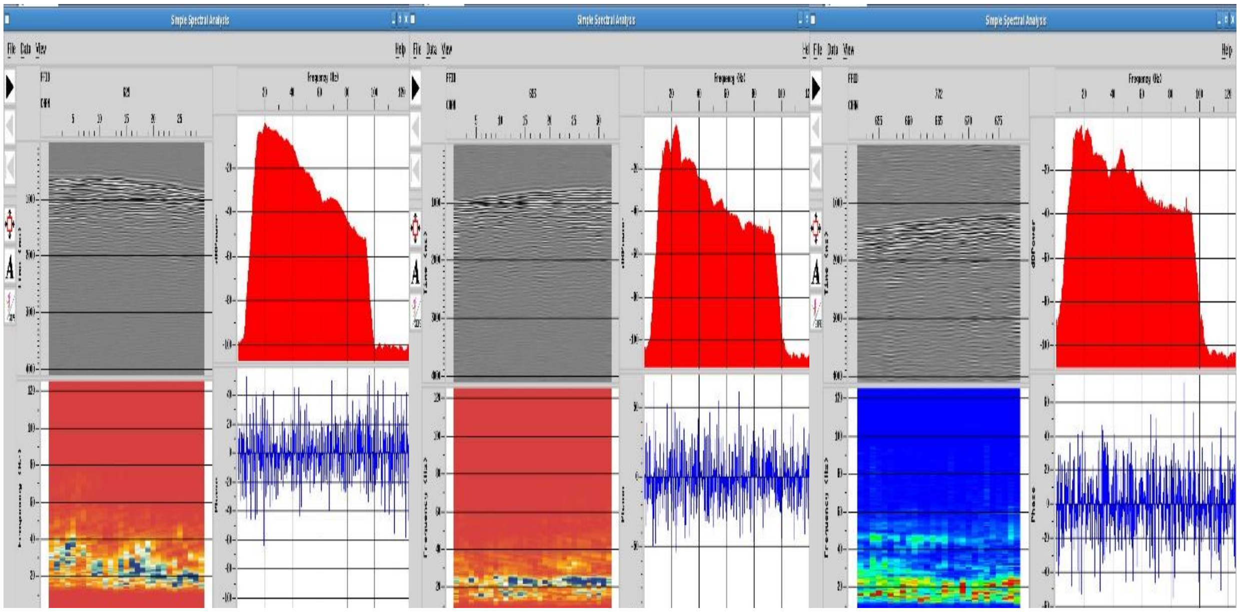


Figure 3.5: Frequency spectral analysis performed for different sections of the data showing the appreciable amount of energy embedded in the acquired data.

3.5.3 First break Picking / First break Quality Control Model

In seismic data processing, first break picking is the task of determining as accurately as possible, the onset of the first signal arrivals from a given set of seismic traces (Sabbione and Velis, 2010). Generally, these arrivals are associated with the energy of refracted waves at the base of the weathering layer or in other instances, the direct wave that travels directly from the source to the receiver. The correct determination of the onset of first arrivals (first break times) is the required and key input parameter for the inversion procedure to image or model the near-surface. The travel time of an arrival could be determined by identifying the point on the trace, when the effects of the seismic wave first appear, this procedure is called picking and the end result is known as a pick, and a wiggle trace is usually the best form of display to work with. Recognizing the onset of an arrival involves identifying a change or break as it were, in the character or appearance of the trace from its pre-arrival state, in terms of amplitude, and/or frequency, and/or phase (Lankston, 1990). The picking of the first breaks was done using an automatic routine after defining appropriate time gates (time gate functions) (Figure 3.6).

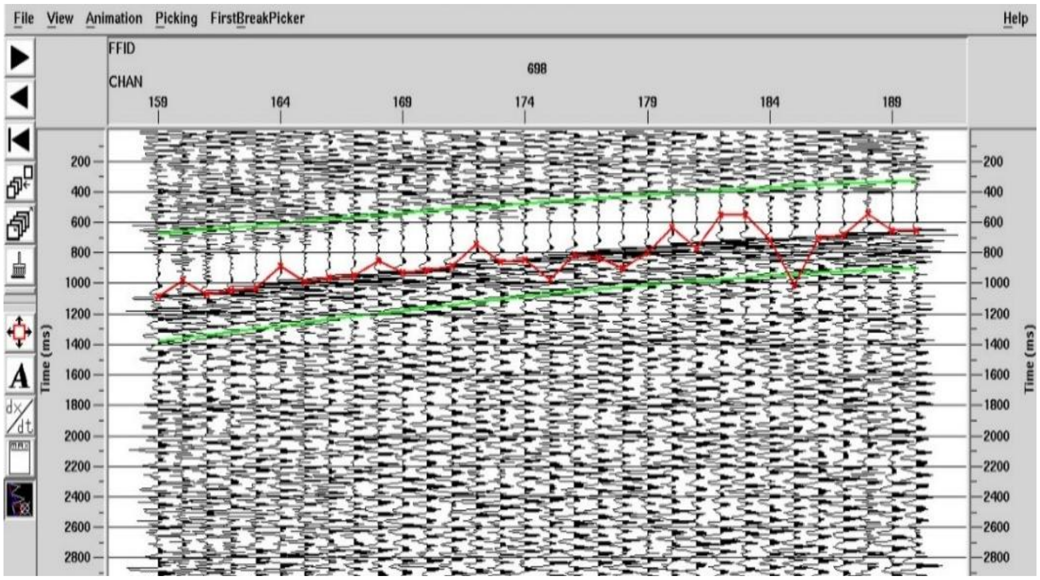


Figure 3.6: The automatic first break picker routine display for Channel 698. The red points are the point of picks by the routine whereas the green border lines represent the time gates defined.

The picks were later on manually edited with utmost care since time shifts due to travel time errors would ultimately lead to non-reliable models of the sub-surface (Bais *et al*., 2003). Figure 3.7 is the edited first break pick for the channel 698 within the defined time gates.

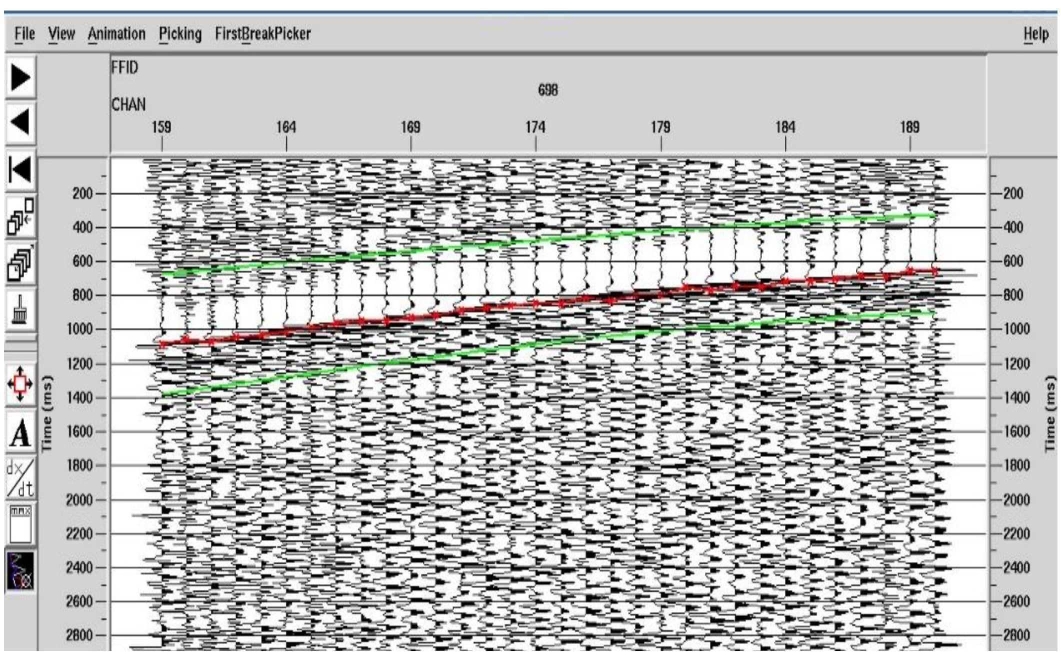


Figure 3.7: The edited automatic first break picker routine display for Channel 698. The red points are the point of picks, which have now been properly aligned to the onset of the first break for all the traces within this channel. The green border lines represent the time gates defined.

Standard quality control (QC) checks were performed for the picks over the prospect (Figure 3.8), showing that the travel times were sufficiently accurate and could be inverted appropriately to yield a reliable and close to accurate near-surface model, which is one of the key objective for the present study.

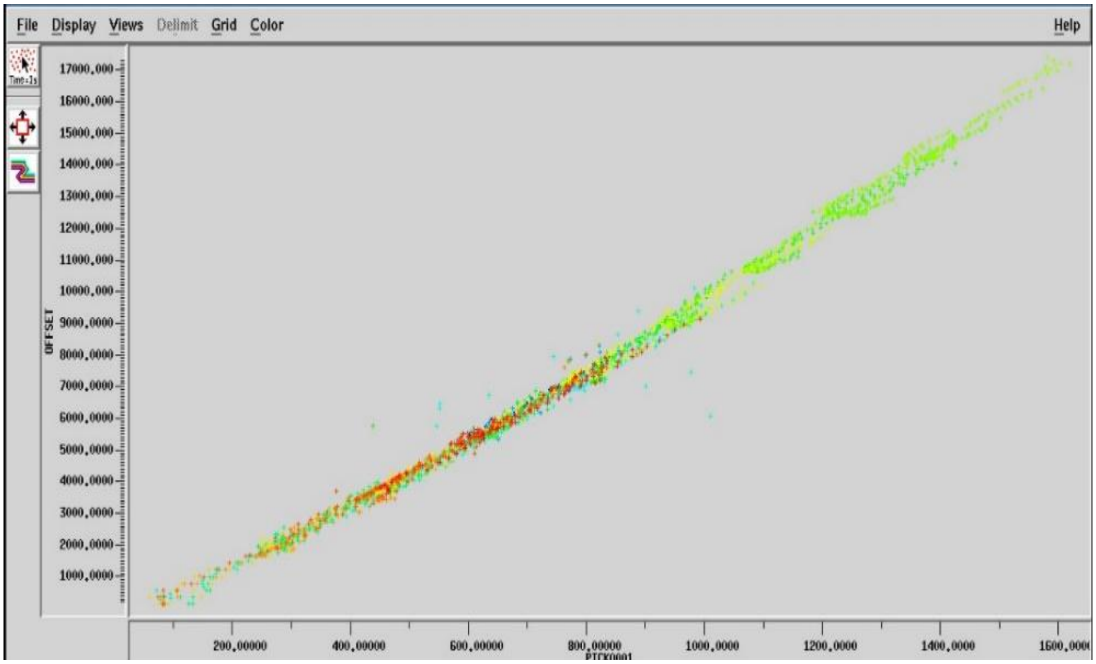


Figure 3.8: The first break pick QC model for the prospect. The near linear cluster of the picked points is a positive indicator that picks were accurately done and could be used as input parameter for a reliable inversion to model the near-surface.

First-break picks associated with the refracted arrival times were used in an inversion scheme to study the near-surface low-velocity zone and in subsequent determination of the statics corrections. Static correction is a correction applied to geophysical (seismic) data, to compensate for the effect of near-surface irregularities, differences in the elevation of shots and geophones, or any application to correct the positions of source and receivers. First breaks were initially picked automatically and then manually edited. The refraction arrival (first break) inversion was integrated with uphole measurements using special processing plugins (add-ons) to build a more reliable near-surface model which eventually would result to an accurate derivation of the refraction statics solution.

3.5.4 Refraction Statics Calculation/Application

Differences in first-arrival travel times between adjacent records in multifold reflection surveys can be used to compute the depth and velocity structure of near-surface layers. The procedure uses the redundancy of first-break data in multifold surveys to enable a statistically reliable refraction analysis to be undertaken for either end-on or split-spread recording geometries. The travel time differences as a function of source-receiver offset provides a direct indication of the number of refractors present, with each refractor being defined by an offset range with a constant time difference. These parameters were crucial tothe proper estimation of the refraction statics correction.

3.5.5 Bad Shot Trace Edit

Every shot was checked and bad traces were edited and (or) muted off with the aid of Promax™ and Vista™ processing routines/modules.

3.5.6 Amplitude Recovery

The raw shot records showed how the amplitude (energy content) level of the raw data decayed rapidly with depth due to transmission losses and wave front divergence. To correct this, standard amplitude compensation routines were applied in order to optimize the processing objectives of the study and obtain the best results.

3.5.7 Pre-Stack Noise Removal

Based on the spectral analysis, the dominant frequency range and velocity of linear noise was identified. Based on the frequency and velocity differences, the linear noises were effectively attenuated. The noise classes that were attenuated from the datasets included coherent noise (predominantly ground rolls), wild noise with some patches of random noise imprints. This was performed to boost the signal to noise ratio (SNR). To achieve the noise attenuation objective, the seismic data was transformed from time-space domain to frequency-space domain; the linear noises were then separated and effectively suppressed, while frequency component outside thedefined range remained unaffected. After the noises were attenuated, we again transformed back the datasets to the conventional time – space domain and an appreciable noise attenuation result was achieved.

3.5.8 Surface Consistent Amplitude Compensation (SCAC)

SCAC is a pre-stack amplitude compensation module which removes the trace energy differences resulting from the source and/or receiver conditions. It first performs the geometric divergence and absorbing coefficients compensation and then the surface consistent amplitude equalization. The pre-stack single trace equalization is the only process or means by which relative amplitude preservation can be achieved. The geometric divergence and absorbing terms could not be accurately (100%) compensated due to inexact absorbing coefficients and velocity functions.

3.5.9 Q Compensation

Phase-Amplitude Q Compensation applies accurate, but slow, temporally and spatially variant Q compensation to seismic data. This compensation may be optionally limited to phase-only or amplitude-only corrections.No migration of the data is performed at this stage. This moduleemploys modifications of the well-known F-K phase-shift and Stolt migration algorithms.

3.5.10 Surface Consistent Deconvolution

Deconvolution is a very important processing stage in seismic data processing. It is applied to attenuate (or remove) multiples and their attendant ringing effects on seismic data, compress wavelet and improve the vertical resolution of the obtained imaging output. In order to achieve optimum results, different deconvolution parameters were tested. The deconvolution gaps of

4ms, 8ms, 12ms, 16ms, 20ms, and 24ms were tested and eventually the 12ms gap was chosen as it gave the best vertical resolution. We equally tested operator lengths of 160ms, 200ms, 240ms, 280ms, and 320ms but also settled for 240ms. Additional white noise (0.01%) was also tested. Predictive deconvolution tests were also run but surface consistent deconvolution was implemented.

3.5.11 Horizon Consistent 1km by 1km Velocity Analysis

Stacking velocities were picked from velocity analysis run on selected in-lines across the investigated prospect. The lines were selected to form a 1km x 1km grid of velocities. The velocities were generally well behaved and had a consistent trend. When all the velocities were picked, a variety of quality control procedures were performed on the data. NMO (Normal Move out) was performed on the gathers for each of the lines using the picked velocities to check the resulting ‘flatness”. Stacking panels were displayed to adjust the velocity slightly. Itwas ensured that all the gathers were monitored and checked properly for enhanced imaging at their appropriate positions.

3.5.12 Residual Noise Attenuation

This module helped to remove residual dominant noise imprints on the datasets (both coherent and incoherent) remaining after the initial noise attenuation routine on the data. Frequency content of the data was carefully taken into account while applying this module to preserve the primary reflections.

3.5.13 Residual Amplitude Scaling

Residual amplitude scaling is a step in seismic data processing to compensate for amplitude attenuation, spherical divergence and other associated effects by adjusting the amplitude of the data. The end goal of this routine is to get the data to a state where the reflection amplitudes relate directly to the change in rock properties giving rise to them. Two processes were involved here; Residual amplitude analysis, which used statistical methods to establish compensation functions in a large spatial range of offset and common midpoint (CMP), and then the Residual amplitude compensation, which applies the compensation function established from the residual amplitude analysis to the datasets.

3.5.14 2nd Velocity Analysis 1km x 1km Interval

Guided by the first velocity analysis, the second velocity analysis was performed. Stacking velocities were picked from velocity analysis run on selected inlines across the investigated prospect. The lines were selected to form a 1km x 1km grid of velocities. The velocities were generally well behaved and had a consistent trend. When all the velocities were picked, a variety of quality control procedures were again performed on the data. NMO was applied to gathers for each of the lines using the picked velocities to check the resulting ‘flatness”. Stacking panels were displayed to adjust the velocity slightly.

3.5.15 Residual Statics

Although datum statics corrections were applied to remove travel-time effects of elevation changes along the seismic line, it was still necessary to remove residual near-surface travel-time delays that are the result of varying velocity and/or varying depth of the weathering layer. Promax™ offered several residual statics applications and all were surface consistent solutions.

3.5.16 4D Random Noise Attenuation (RNA) Applications

This module on Promax™ performed 3D Pre-stack Random Noise Attenuation based on F-XYZ domain predictive noise removal in 3D frequency domain; it used the least square theory of multi-channel complex number to calculate a 3D predictive operator, and then, uses the calculated operator to perform predictive filtering on the 3D seismic data volume so as to attenuate the random noise. Random Noise Attenuation operates and deals with noise in four domains, that is CMP, Offset, Trace and finally in the Time domain. The aim is to produce high resolution datasets and remove unwanted noise on the data as much as possible, to boost the signal to noise ratio (SNR).

3.5.17 Tau-P Deconvolution

Tau-P domain based deconvolution was carried out on the dataset. It was observed that Tau-P deconvolution with an operator length of 320ms and gap of 28ms produced the optimal result. The purpose for using this processing module on Promax^{TM}, was for the purpose of multiples suppression and to remove unwanted noise from meaningful reflection signals, to produce an unambiguous processed output that is most desirable for an accurate and reliable interpretation of the subsurface structures.

3.5.18 Pre-Stack Time Migration.

The CMP gathers for pre-stack migration required that the gathersbe devoid of statics problems, have high signal-noise ratios (SNR) with good energy balance. After pre-stack signal processing, the CMP gathers were ready for pre-stack migration. For reflection imaging of different dip with different stacking velocity, pre-stack time migration became an ideal method to be implemented. At present, pre-stack time migration is rapidly developing and fast becoming the choice technology for seismic migration imaging. It plays important roles in imaging fine structural features which could be associated with traps in the search for potential hydrocarbon (oil and gas) reservoirs. The advantages of pre-stack time migration include;

i) The migration algorithm makes use of the root-mean square (RMS) velocity. This RMS velocity field is relatively easy to adjust.

ii) Pre-stack time migration is the good imaging tool for inhomogeneous media, such as the currently investigated prospect OML-23, SOKU and it is about the most accurate imaging technique fortime domain migration.

The processing sequences entailed in executing pre-stack time migration routines involve the following;

i) Generating an RMS velocity field using stacking velocity and then creating an RMS velocity volume.

ii) Pre-stack time migration using RMS velocity volume by ray-tracing method on the target lines.

iii) Analysing the updated velocity on the pre-stack time migrated gathers of target lines and then updating the velocity field.

iv) Re-generating the velocity volume using updated RMS velocity field.

v) Re-running Pre-stack Time Migration (PSTM) on target lines with new velocity volume;

vi) Repeating steps (i) – (iii) until events in CRP gathers are flattened.

vii) Running PSTM on the whole 3D dataset and outputting all CRP gathers.

viii) Final Mute and stack

3.5.18.1 Migration Velocity Field establishment and Optimization in Pre-stack Time Migration

The migration velocity field determines the diffraction path during the execution of the migration routine and ultimately determines the correctness and accuracy of subsurface imaging. Therefore, the correct basis for executing an optimal pre-stack time migration processing, is anchored on the establishment of an accurate migration velocity field. The migration velocity field optimization sequences involve;

i) Stacking velocity being converted to RMS velocity.

ii) Performing Pre-Stack Time Migration to output CRP gathers.

iii) Running updated velocity analysis with CRP gathers.

iv) Creating a new RMS velocity field and performing the next iteration of Pre-stack Time Migration.

v) Repeating steps (ii) –(iv) to obtain an accurate RMS field for Pre-stack Time Migration.

Migration velocities were picked and updated on selected target lines. The lines were selected to form a 500m x 500m grid of velocities.

3.5.19 PSTM Velocity Analysis

Residual velocity analysis, including second-order and fourth-order based approaches were implemented. This was to correct for residual move-out at large offsets, by estimating weak anisotropy to enable exploitation of the data at very large offsets, than is ordinarily feasible with second-order techniques.

3.5.20 3D F-X (Explicit) PSTM

Promax™ possesses an amplitude-preserving F-X (Explicit) Pre-stack Time Migration (PSTM) routine that is ideal for imaging complex geologic conditions or velocity fields, and does not require employing pre-stack depth migration to meet imaging goals. This module is not limited to the straight ray approximation as is the case for most other PSTM processing tools that use the two-term double square root equation. The applied migration routine accounted for higher order terms in the travel time versus offset and NMO expansion by explicit ray tracing.The routine could alsohave been used to iteratively build the 3D RMS velocity field through target outputs in the form of in-lines, cross-lines, common receiver point (CRP) gathers and full 3D volumes.

3.5.21 Migrated Stack Generation

This processing modulebasically involved the generation of the final migrated stack.

3.5.22 Post Stack FXY Deconvolution

To further enhance the data quality F-XY Deconvolution was applied to the migrated gathers. The Mixing parameters for the F-XY Deconvolution with their time ranges (Table 3.2) was carefully tested and optimized. The Mixing parameter and the time ranges for which they were applied on the migrated gathers and with their associated mix percentages are shown below;

Table 3.2: Table of Mixing Parameters and Time ranges for F-XY Deconvolution

Parameter	Time (ms)	Mix (%)
Mixing	500	70
	900	75
	2400	80
	3000	70
	5200	80
	6000	90

3.5.23 Zero Phasing Conversion

The data for interpretation should be zero phase. In theory, zero phase data would normally have a higher resolution. After analysis and tests, the data was converted to zero phase with the aid of the zero phasing filter factor extracted from the dataset. This stepwas to transform the minimum phase wavelet of the seismic data into a zero phase wavelet that has the same amplitude spectrum.

3.5.24 Final Display Filter Scaling

A time variant scaling function was tested and applied to the seismic data to ensure that the amplitude of the data becomes reasonably balanced. To further suppress traces of undesirable noise and to increase the SNR, a Time Variant Filter (TVF) was tested using Band Pass Filtering.After test evaluations, the following TVF parameters (Table 3.3) were applied to the dataset.

Table 3.3: Table of Time Variant Filter Parameters applied during Time Variant Scaling

Application Time (ms)	Band Filter (Hz)
0 – 1200	8 – 15 – 45-60

1500 – 2700	**7 – 12 – 40-60**
3000 – 6000	**6 – 10 – 24-30**

3.5.25 Spectral Whitening

Spectral whitening which is also known as (broadening or balancing) is used to improve the resolution and appearance of seismic data and is a quick means of attempting to correct for possible frequency attenuations.This routine was carefully and thoroughly implemented on the dataset, to recover attenuated frequencies.

3.5.26 SEG-Y Out

This process offers the means of displaying or outputting a SEG-Y disk image file.

3.6Data Preparation and Pre-processing (First Processing Stage)

In thisfirstprocessing stage of the research,the data wasbinnedusingthegeometry/SPSfiles, beforepickingtheLinearMoveOut(LMO)velocity,thenpickingthefirstbreaks andfinally,performingqualitycontrolanalysisonthe picked first breaks.

3.6.13DSeismic DataBinning

Theprocessofbinning3D seismicdataissimplifiedifonetransformsfrom the survey'sspatialcoordinatestoabinningcoordinatesystem.Foruniformrectangular bins,thistransformalongwithanintegertruncation whichisallthatisrequiredtoassign binsforasurvey(Mark,1994).Whenamulti-fold3Dseismicsurveyisacquired, a majorstepinitsprocessingistheassignmentofeachseismictracetoan arealbin. Binsrepresentlocalareasontheearth'ssurfacewhichare used tocollecttracesfor stacking, processingoranalysis.Duetothe twodimensional nature of3-D seismic survey geometries,locationsofinterestgenerally donotfallona setofsurface points, buttendto scatter throughoutthesurveyarea.Binningistheactof asserting thatagroupoftracescontainsacommongeometricalproperty,usuallythatofbeing closetothesamecommon mid-point (CMP)shotorreceiverposition.Abinningsystemisdefinedbythe boundariesofauniform rectangulargrid.Alltraceswhosesurfacelocationsfall withinthe samecell ofthisgridwill sharethesamebin.EachBinnedGrid hadan approximate dimension of25m×25mwith a lock spacing configuration (Figure 3.9a). The Binninginformationwas subsequentlysavedto the file headers and used to generate the Binning grid (Figure 3.9b), when appropriate processing flows were executed on Vista™ and Promax™platforms.

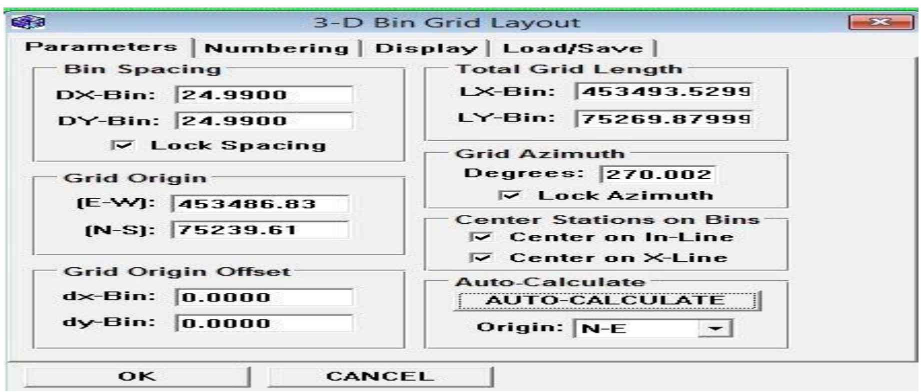


Figure3.9a:Binninggridparameters

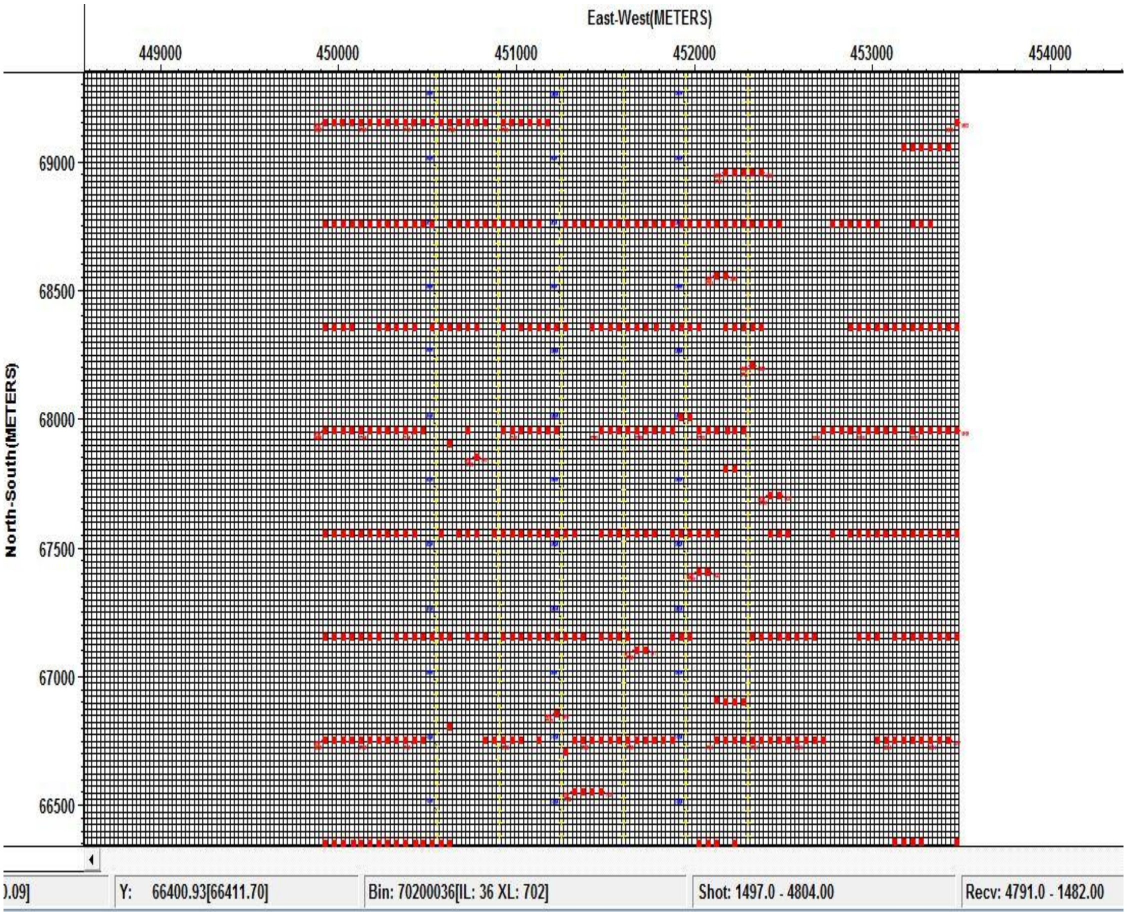


Figure3.9b:Binninggrid(black)definedbysource lines(red) andreceiver lines(blue)

3.6.2 Fold Calculation and Analysis

Inadditiontobinningthedata,thefoldassociatedwithaparticular3Dstackingbin wasequally computed.The foldwhich is also called multiplicity issimply, thenumberoftimesthatthesamemidpointis sampledby differentshotsanddifferentreceivers.It is ameasureoftheredundancy of commonmidpointseismicdata and is equivalent tothenumberofoffsetreceiversthatrecord agivendatapointorinagivenbinthat areaddedduringstackingtoproduceasingle trace.Typicalvalues offoldformodernseismicdatarangefrom 60to240for2D seismicdata,and10to120for 3D seismicdata.Forthe SOKU dataset,afoldvalue of 42wasobtained which is within the recommended range for standard 3D seismic data processing.

Itwasobservedthatthefoldgraduallyincreasedfromaminimum(at the edge of the Bin)toa maximum(at the centreof the Bin), which is the most desirable pattern or trend (Figure 3.10).

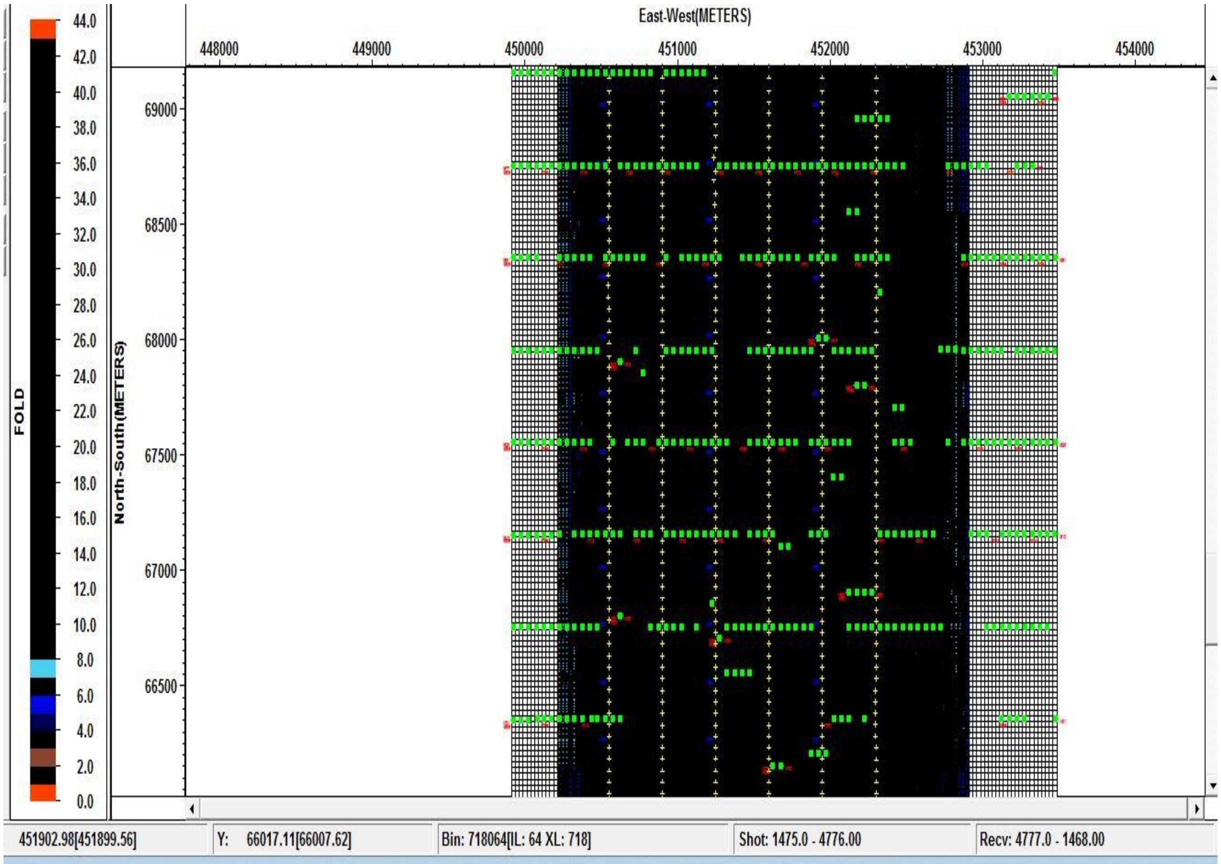


Figure3.10:The foldcomputedfor the OML-23 SOKU datasethad a foldvalue of42.

3.6.3 Linear Move out (LMO)

One common error mostlyencounteredin the pre-processing stages isthat of wrongidentification of shot point location.Itcouldalso bepossible thatthe wrongreceiversare active (picked).Theother possibleerrorcould bewrongly identifiedlocationsof thereceivers.TheLinearMove out (LMO) is a vital tool to identify these errors in the geometry.LMOcomparesarrival timesrecordedfor thegivensource-receiver geometry tothosecalculatedassumingaconstantvelocity surface.Pre-processing qualitycontrolshouldincludethese geometrychecks;thesewere performed in the current study (After Burger*etal*.,1998)with the sole aim of enhancingseismicdataqualityinthe pre-processing stages.Beckett*etal*.,(1995)pointed outtheuseofLMO toidentify geometryerrorsat the pre-processingstages toreduce the overall seismic data processing turnaroundtime.The generally adoptedmethodisto applyLMOandcheckforthedeparturesfrom theLMO.Thesedeparturessignify theerror inthelocationof thereceiversorshotpoint.Inthisstage,theLMOpick iconwasusedtopicktheLMO velocityfrom asingleshot,afterwhichitwassaved tothefile header,andusedasinput torunanLMO processingflow ontheentire seismic dataset (Figures 3.11a and 3.11b) using appropriate LMO functions (Figure 3.12).

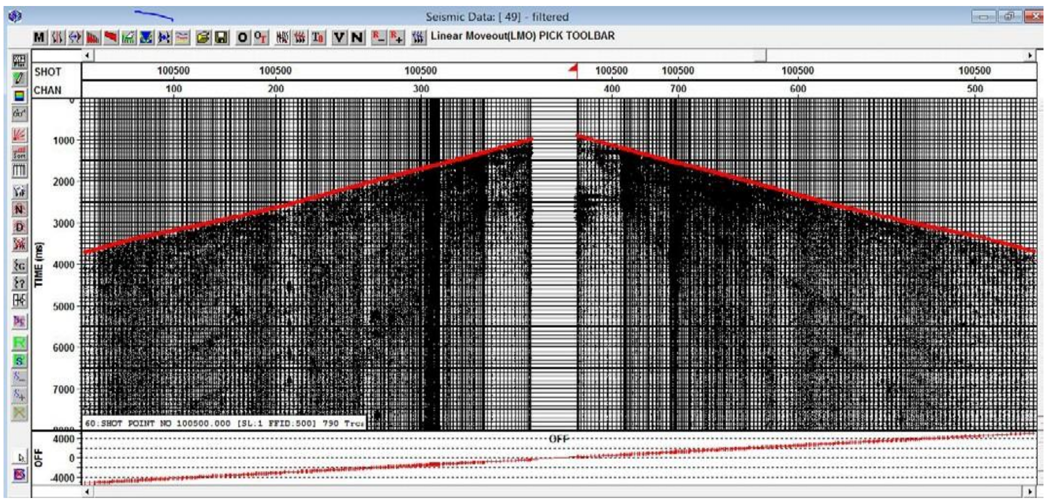


Figure3.11a:LMOvelocity(RedLines) aspickedonthedata set

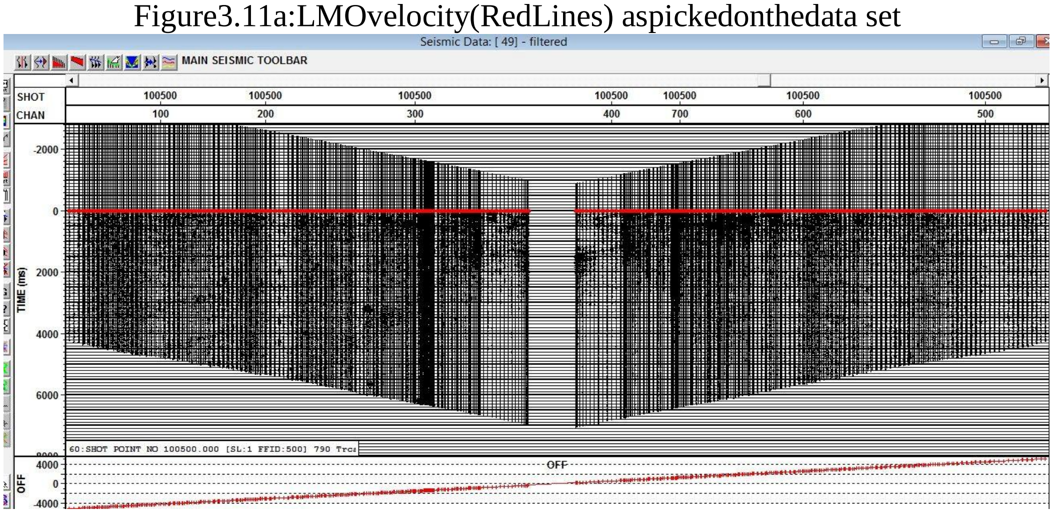


Figure3.11b:FlattenedLMO(velocityinred). The firstbreaksareparallelto theLMO.

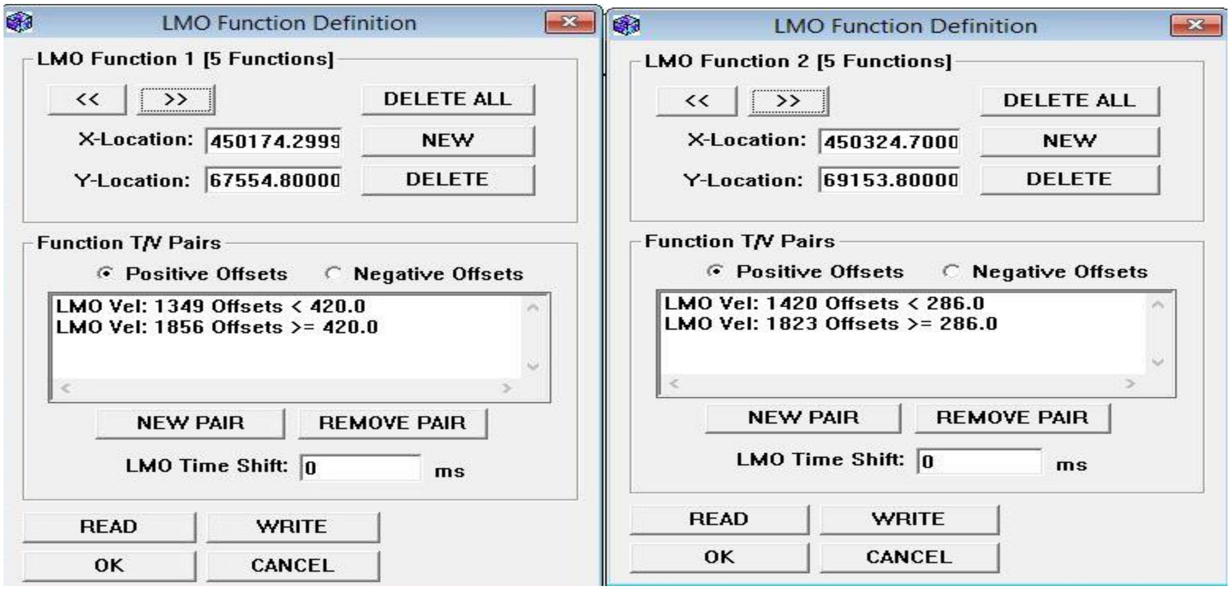


Figure3.12:LMOvelocityfunctionspickedfromthe shotrecord.

3.6.4 First-BreakPicking and Analysis

In seismicdata processing,first-breakpicking isthe act of accurately determining,givenasetof seismictraces, theonsetsofthefirstsignalarrivals.In general,thesearrivalsareassociatedwiththeenergy ofrefractedwavesatthebase oftheweatheringlayerortothedirectwavethattravelsdirectly fromthesourceto thereceiver.Theaccuratedeterminationofthefirst arrivalsonset(first-breaktimes) isa crucial requirement forcalculatingstaticscorrection, which is afundamentaland vital stagein the seismic data processing workflow.Clearly,theeffectiveness ofrefraction-based methods ofstatics correctiondependsonthe picking-processreliability (Yilmaz,2001).Naturally theirarrivaltimeincreaseswithincreasingoffset.Theonshore SOKU datasetwasacquired using dynamitesources, such impulsivesources tendtoyieldfairlyclearsignals.Usingthefirst-breakpickingmodule oftheprocessing software,thefirst-breakpickingwasin the firstinstant performed manuallyforafew shotsandthensubsequently,usingtheautomaticpickerflow command withtheLMOfunction (Figure 3.13)topick theentire portion of the datasetfor first-breaks andthe resultswere corrected interactivelyviavisualinspection.

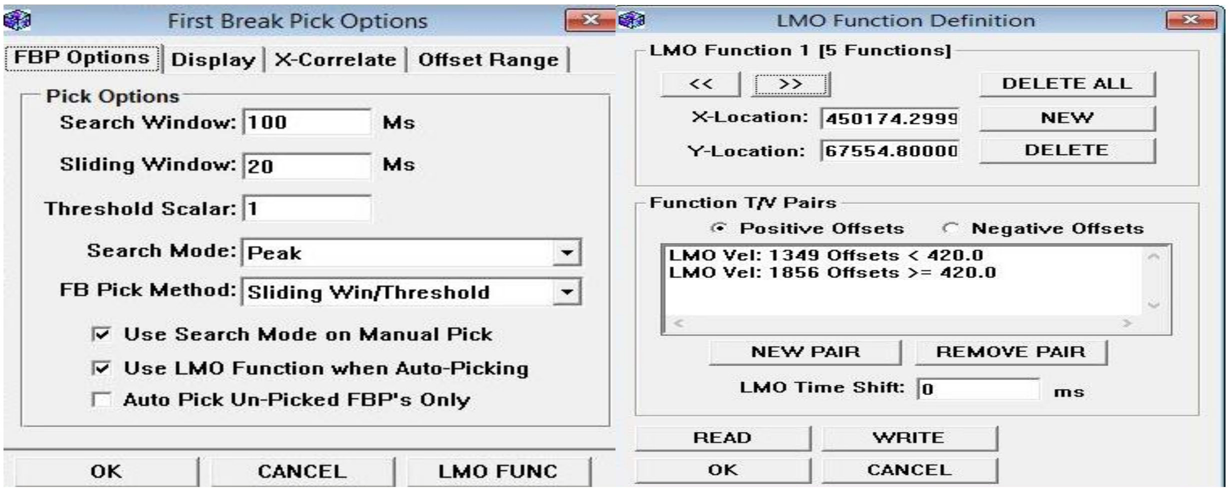


Figure3.13:Parameterization ofthe Firstbreakpickingmodule

The first-breaksofthe shotrecordsover the prospect was properly picked andwith minimal errors. Theseerrorsareassumednot tobe presentwhen picksarescattered throughoutthedata (Figure 3.14a) andare notcongestedor clustered inaparticular area.Congestion of first-breaks in a particular region in the first-break quality control X-T plot is an indication of poorly picked first-breaks. Ingeneral,themaximumstandarddeviationshouldbelessthan20,andtheaverage oftheerrorsforallshotsshouldbearound10.However,inpractice,errorsareoften causedby geometryor pickingerror.Inthiscase,theutility indicatesthedeviation errorrangeforallthefirst-breaksandhowthey aredistributed (Figure 3.14a and 3.14b). Thefirst-break pick (FBP)standarddeviationcolorcodessignifydifferenterrors anddistributionsin the pickedgeometryline,varyingfroma range of 0(inblue)to 14(inorange).Shotswithlargerreciprocalerrors are distinct andthis offers a seismic data processor anopportunitytorefinethefirstbreakpicksshotbyshot at areas where the errors are observed.Figure 3.15 shows the picked first-breaks display on the seismic dataset.

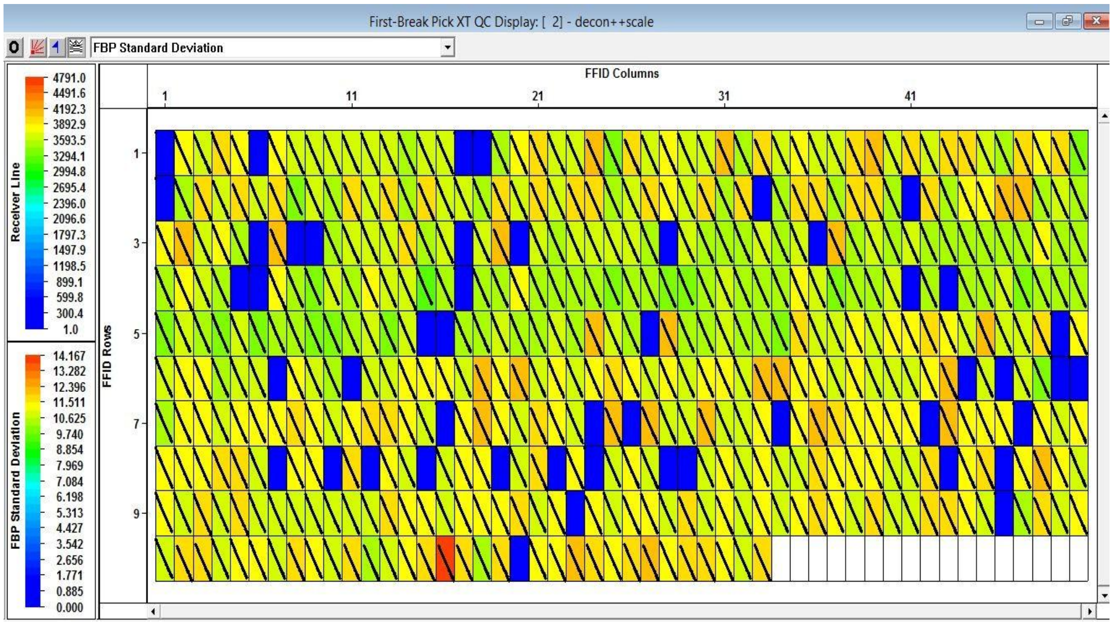


Figure3.14a:First-breaksQualityControlX-TPlot

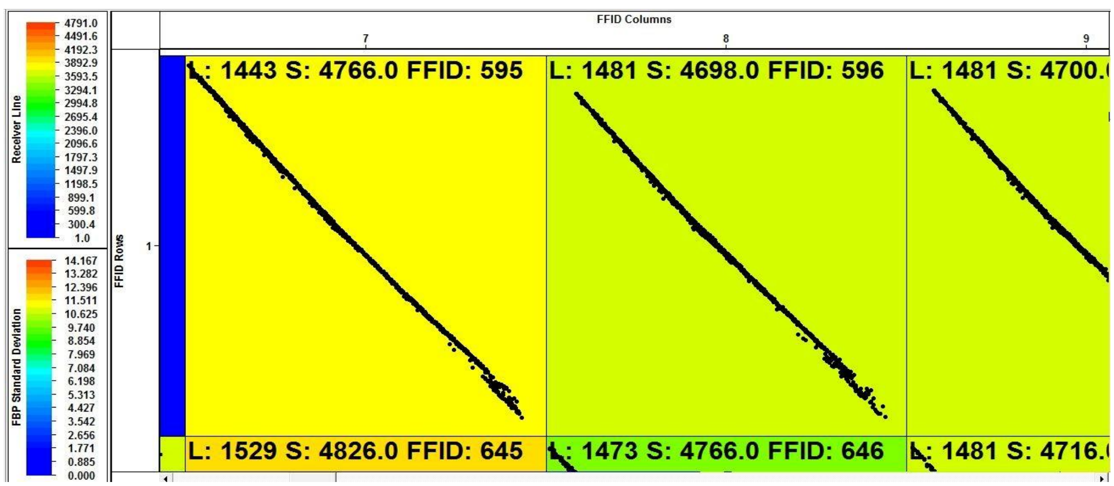


Figure3.14b:First-breaksQualityControlX-TPlot.

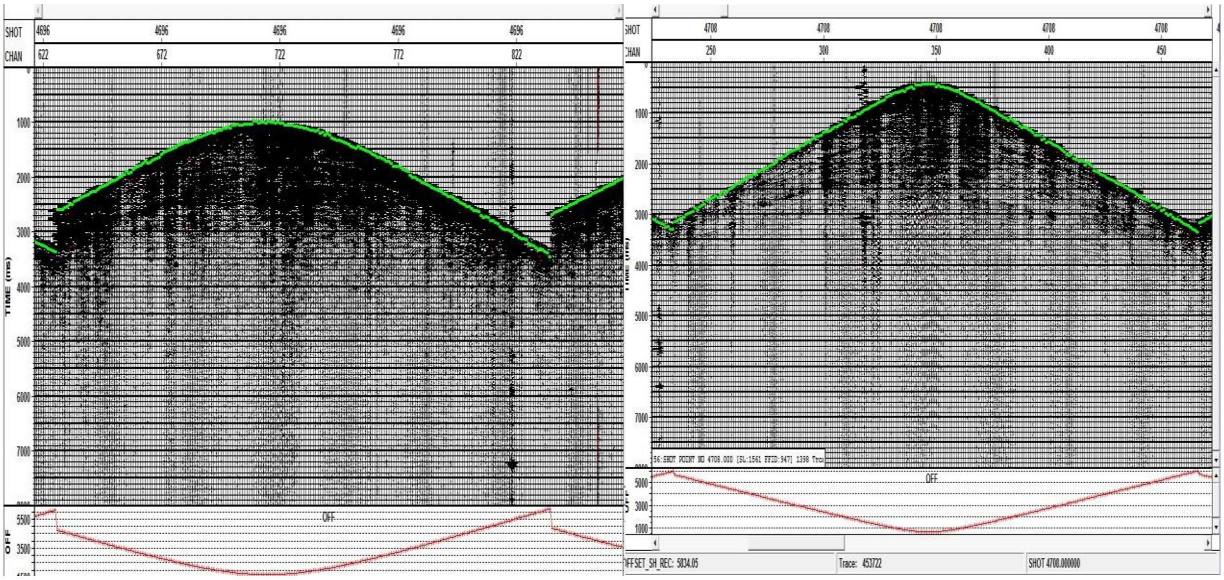


Figure3.15:First breakpicksdisplay onthe pre-stackseismic dataset for OML-23 SOKU.

3.7Refraction Data Processing (Second Processing Stage)

The refractionmethodiswidely usedindeterminingthethicknessesandvelocitiesof the near-surface layers.Itrequiresanaccurate pickingfor thefirst arrivaltimes.The Elevation/Refractionstaticsprogram analysestherelationshipbetweentheseismic dataandfirst-break pickswhichhave beensaved tothefile headers.Itusesthis relationshiptoestimateavelocityanddepthmodelatalllocationwithinthesurvey area. The generalrefractionstaticsprocedureconsistsoffirstly, pickingacontrol point(eithersourceorreceiverpoint)acrossthesurvey area,andvisually checking thecorrespondingpicksforanyform ofscatteringanddeviationsfrom thegather, afterwhich,thevelocity ofthelayersarepickedalongthefirstbreakswithinthe offsetwindow.Secondly,controlpointswere automatically generated alloverthe survey area, basedontheinitialmanually pickedcontrolpoints.Havingfoundthe resultsdesirable,weproceeded togeneratethevariousvelocity anddepth profilesforthe various layers within the investigated prospect with the aid of the processing tool.The3Drefractionstaticsparameters(Figures 3.16a and 3.16b) fora3-layersub-weathering case was applied,usinga weatheringlayervelocity of 520m/s obtained from theup-holesurveymeasurement for SOKU.Arefractorreplacement velocity of1750m/swasused. The desirable range of replacement velocities foronshore NigerDelta Basin datasets is within 1700- 1850m/s.Adatumelevationof0m,a modeltimerangeof350ms(value wasselectedbasedonthe widthof first-breaks),anda minimumandmaximumoffset of20mand6800mrespectively were used to derive the elevation andrefractionstatics.Theshortestoffsets(<50m)wereexcludedfrom thecalculationbecausetheyare most likely emanating from directarrivalsinsteadofrefractions.Similarly, thelongestoffsets(>6800m)were alsoexcluded becausethe signaltonoise ratiotendsto decreasewithincreasing offsetsandatsome pointmightnotbe highenoughtoensure accuratepicks.

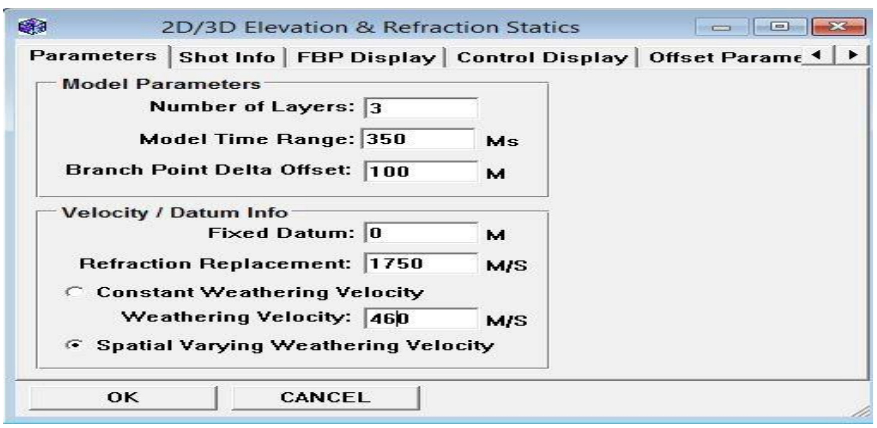


Figure3.16a:3-Delevation/refractionstaticsvelocityparameters

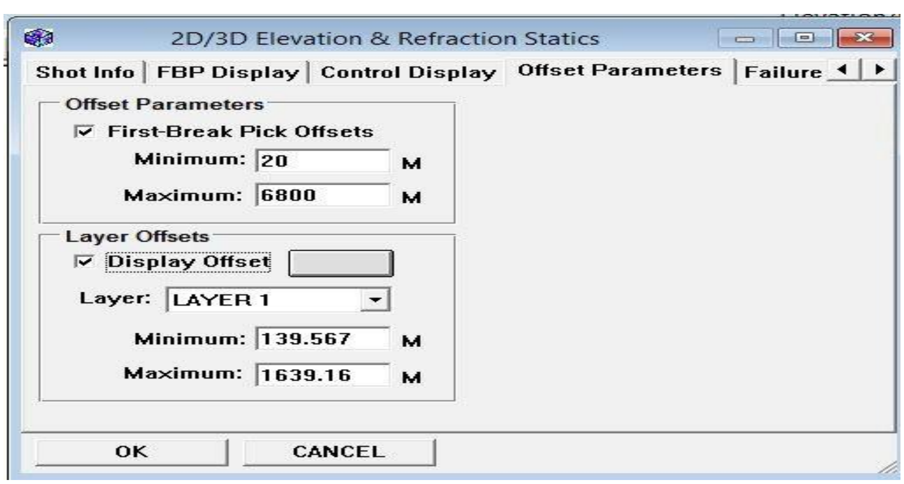


Figure3.16b:3-Delevation/refractionstatics offsetandlayer parameter

3.7.1Control Points and Model Building

Inthisprocedure,onefirstdefinesaseriesofcontrolpointsinthegeometrywindow.

Eachcontrolpointistypically acollectionofmany shots(10to20)- orgroupsof receivers.Thecontrolpointsarespreadaroundthesurvey area andattempts were made togeta reasonably accuratelongwavelengthpictureofthenear surface layers.An incrementinthenumberofshotsinsidethecirclewillhaveasmoothingeffectonthe solution, oncethecircle hasbeendrawn;anOffset-Time(X-T)plotof thefirst breaksforthe shots inside thecircleshould beseenonthe rightpanel (Figure 3.17).If theresult is as desired and reasonably smooth, the layervelocitiesforthecontrolpoint alongthemarked firstbreaksis then picked (Figure 3.18).

The numberoflayersdependsonthe number ofthe differentslopesthatcanbe observedinthefirstbreaks. Theradiusfor automatically generatingthecontrolpointscouldbeadjusted (Figure 3.19) to any desired length.A100mradius was chosen takingintocognizance of thecomputingpoweroftheprocessing hardware deployed for the present study.Thewidthofthebluecorridor

(modeltimerange)andthegapbetweenlayers(branchpointdeltaoffset)couldbe modifiedinthe parametertabas well (Figure 3.19). Subsequently, morecontrolpoints were createdautomatically on the binnedgrid defined for the entire surveyed area of prospect SOKUand a total of over 1250control points were created automaticallyinthegeometrywindow(Figure3.17).

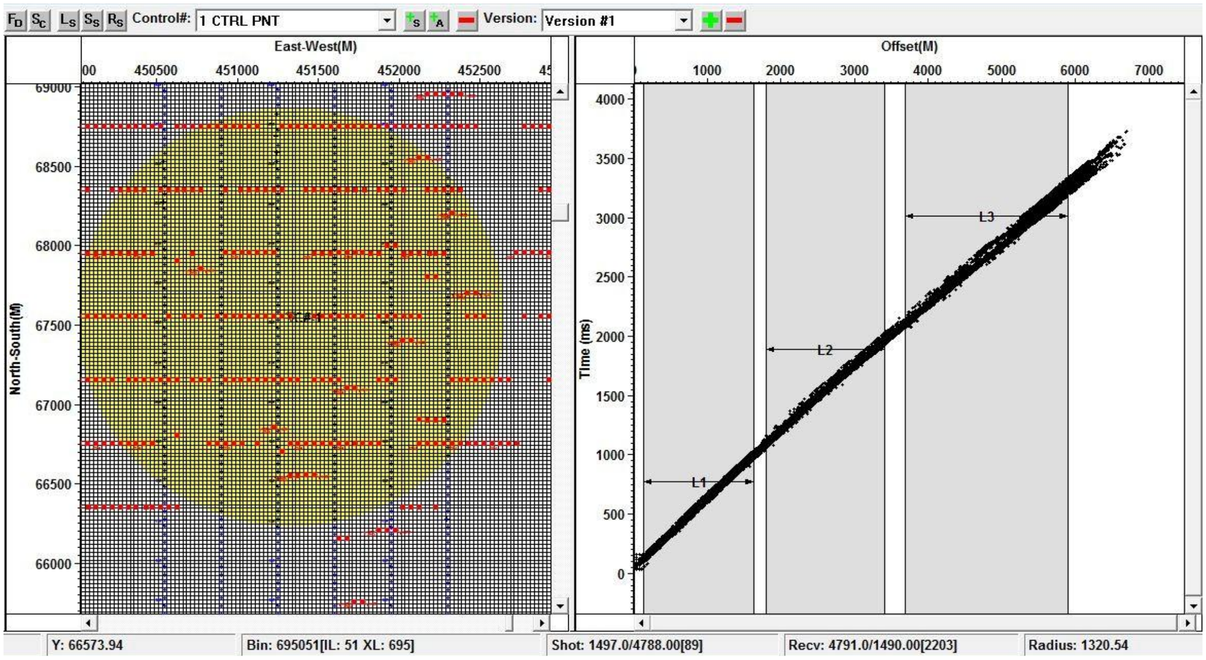


Figure3.17:Pickedcontrolpointsingeometrywindow(left) andthe corresponding first-breakpicksinoffsetwindow(right)

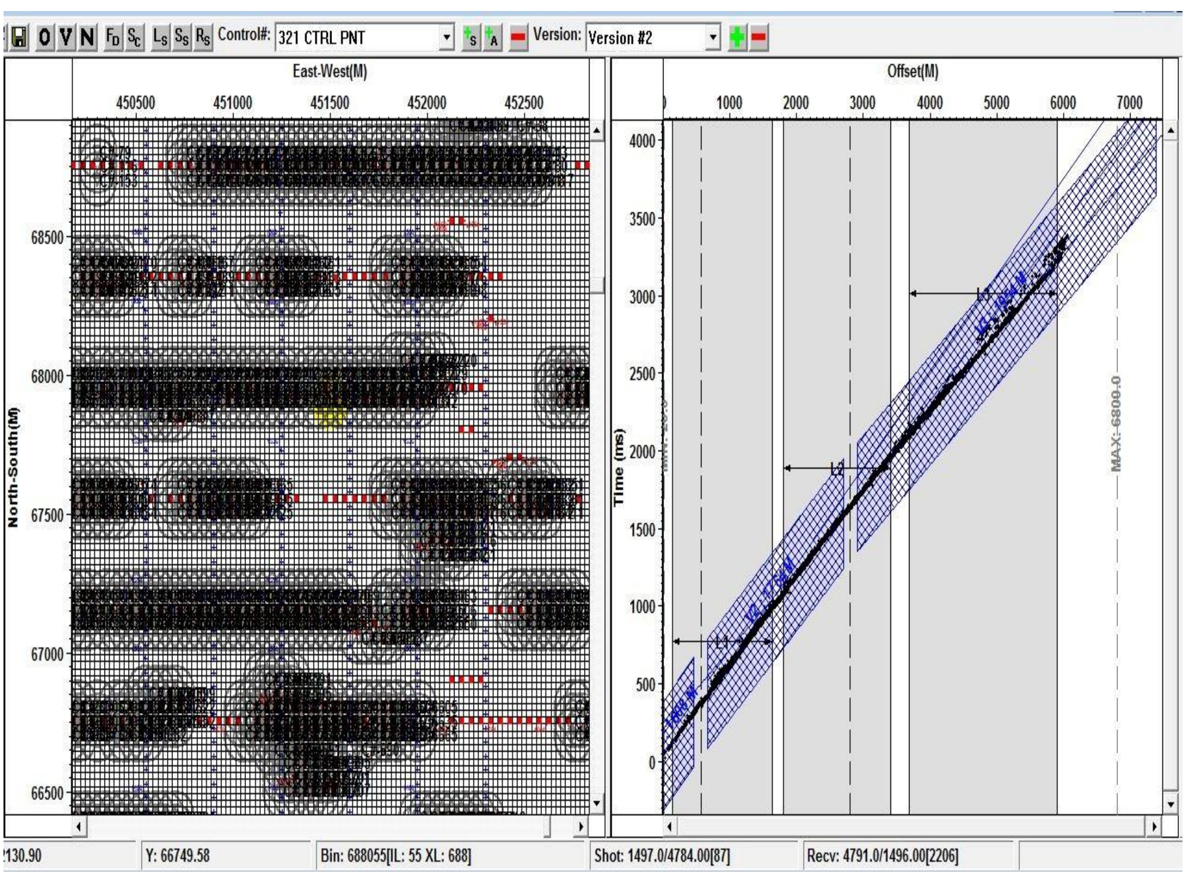


Figure3.18:Pickedvelocitiesfor layers 1,2,and 3(righthand)and interpolated controlpoints for thesurvey(left hand).

Figure3.19:Parameter forinterpolatingAutomatic "fill-in" controlpoints

3.7.2VelocitySmoothening

Inordertomitigate the edge-effectartifactsresulting inexcessive perturbations along theeasternand southern edges of the models,thevelocity model was smoothened.To achieve this, thenear-surface velocity profilewasadjustedsothatitformspartofa consistent near-surfacemodel.Asmoothradiusvalueof100m wasequally appliedtothe three consolidatedor sub-weathering layers(Figure 3.20).

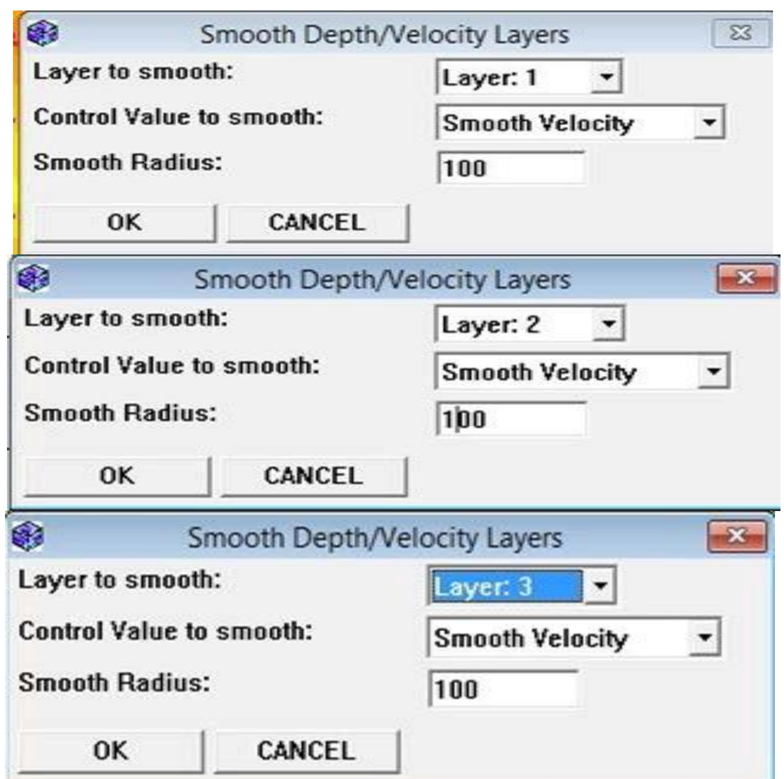


Figure3.20:Parametersusedtoproduce asmoothenednear-surface model.

3.7.3 The Hybrid Near-surface Modeling Approach

The up-hole model of the near-surface, in terms of weathering and sub-weathering properties (thicknesses and seismic velocities), was obtained from the up-hole survey data acquired from the prospect using the UDISYS interpretation tool and guided by the surface (shot point) and shot offset corrections. The refracted arrivals harvested from the 3D seismic reflection survey were equally interpreted using inverse methods. The input parameters to the inversion were the travel times of selected arrivals and the locations of the detectors and the sources. In most of the commonly used refraction data interpretation methods, it is pertinent to group arrivals that have followed equivalent paths through the subsurface;this could be established through their ray-path trajectories. When this was achieved, the methods for inverting the travel time data became straightforward.If the grouping of arrivals was however inaccurate, the inversion will not produce the optimal result or model which best describes or approximates the actual local geology. Adequate care was taken to ensure that the grouping of arrivals was accurately done. Eventually, the two near-surface models were then passed through a special in-house algorithm (program) to adaptively merge both models into an integrated (hybrid) model which is more robust, reliable and a better approximation of the near-surface geology of the prospect. The algorithm leverages on the advantages of both models to build an optimal model.

3.7.4Refraction Statics Computation

Refractionmethodsprovides a vital meanstoderive estimatesof the thicknessesandvelocitiesof the near surface layersby analyzingthefirst-breaksofthe seismicrecords(Luo*et al*., 2010;Wu*etal*., 2009;Duan, 2006;Lin*etal*., 2006;Pan*etal*.,2003).Staticscorrectionbasedonrefractionsurveyrequirestheinformationof thefirst-arrivaltimeofwavefieldfromrefractorandtherefractorvelocity (Cox, 1999).Hence,thereare two basicconditionsrequired forimplementing statics correction from refractionsurveys, these conditions include;arelative stablerefraction interfacebetween the twoformations(that is the boundary between the weathered zone and the first sub-weathering layer) andthe acknowledged near-surfacevelocity distribution(modified after Bridle andAramco,2009;Liu, 1998).Applyingtherefraction staticscorrectionbasedonrefractionsurvey enhances the structural integrityintheprocessedsection;this is a focal and major objective of this dissertation.Refractionstaticscan be effectiveforcorrectinglong spatialwavelengthanomaliesandcompensatingfor theweathering layers,andare alsoeffective againstshortspatialwavelengthanomalies(Liu, 1998).

Forthe present study, a comprehensive statics solutionwasderivedusing the processing software, this solutions comprise of;field (elevation or datum) statics,longwave andshortwave refractionstatics, then 1st and 2nd residual statics. These statics solutions were adapted to a processing workflow which was eventually applied to the 3D SOKU seismic dataset.The longwavestaticswascalculatedfromthederived model whereas the shortwavestaticswascalculatedusingsurface-consistentresidualtimes.Theideaisthatifthedefinedmodelisnotvery accurate or exact,thentheshortwavestaticshelpsto compensate for theerror inherent in the former.Finally, 1st and 2nd residual statics correction routines were equally applied to the SOKU dataset to ensure all unresolved statics effects on the data (after the initial application of the field statics and refraction statics) were corrected. Processing flows on Promax was used to achieve this latter objective. It is incisive to note that slight discrepancies exist in statics correction terminologies on both VISTA^{TM} and PROMAX^{TM} processing platforms, but the idea behind the concept of statics correction on both platforms is essentially the same.

The final derived comprehensive statics solution on the VISTA^{TM} platform was a summation of the elevation statics, long wave statics, short wave statics and the residual (1st and 2nd) statics and is expressed by the relation;

Final Statics Solution=Elevation Statics+Longwave Statics+Short waveStatics + Residual (1st and 2nd) Statics

The equivalent expression forthe final comprehensive statics solution on the PROMAX^{TM}processing platform is simply a summation of the field statics, refraction statics and the residual (1st and 2nd) statics and is expressed as;

Final Statics Solution=Field Statics+Refraction Statics+Residual (1st and 2nd) Statics

3.7.4.1Field (Elevation or Datum) Statics

Thefield (elevationor datum) statics computedwaswithreferencetoafixeddatum.Fieldstaticsinvolve thecomputationandremoval of theeffect ofdifferentsourceand receiveelevations. Thisinvolvesbringing thesourceandreceiver toacommon datum.Forthis to be achieved,areplacementvelocity is usually required.Thereplacementvelocityiseither assumedfrompriorknowledgeof replacement velocity within the areaorit canbeestimatedfromup-holetimesordirectarrivals from an up-hole survey. For our study,we used a replacement velocity value of 1750m/s which was computed from an up-hole acquisition survey that was carried out in the prospect prior to the full execution of the 3D seismic acquisition program.

3.7.4.2 Long wave Statics

Long wave statics primarily involvesresolvinganear-surfacevelocitymodel.Thiskindofstaticsare computed byleastsquare fitting of the first breaks of theshotsinside a circle called the ControlPoint(inthe VISTA^{TM} software parlance).Thevelocity ofthelayersisestimatedfrom theslopeofthe breaksandthelayerthicknessesfrom theinterceptswiththetimeaxis.Longwave staticscorrectsforrelativelylargenear-surface structuraleffectsand this improvesthedisplay of reflection events which ultimately enhancesthe imaging qualityof the subsurface.

3.7.4.3 Short wave Statics

Errorsmadeby thefieldstaticscorrectionaremainly duetothe inaccuraciesinthenear-surfacemodel, which in most instances is a simplificationof the actual geology.Thisadditionalprocessingstepisnecessary tocompensatefor theseerrors. Thisprocessingstepalsoservesas a means toeliminatesmallvariationsofreflectiontraveltimes causedby rapidchangesinelevation,thebaseofweatheringlayer,andweathering velocity.Thisstaticsarea surface consistent solution.Atheoreticalfirst break is computedforeachtracebasedonthevelocitymodelbuiltduringthelongwaverefractionstaticscomputation. The differencebetweenthetheoreticalandtheactual first breakisthen usedtocompute a surface consistentshotandreceiver set of statics basedonrefractions.Shortwaverefraction staticscorrectsforsmallnear-surfacestructuraleffectsand also improvesthequality ofsubsurface image.

3.7.4.4 1st and 2nd Residual Statics

Toachieve surfaceconsistency,1st and 2ndresidual staticscorrection procedures were performed on the seismic data being processed. This provided an additional and more reliable timeshiftforeverysource or receiver location.Residualstaticscorrectionisusually appliedafterdatumcorrectionbutitisalso possibletodoresidualstaticscorrectionwithoutany precedingdatum staticscorrection but this is not an ideal processing practice.Bothlong andshortwavelengthstaticscorrection together with the elevation statics corrections,eachplay their special rolesin the refraction statics solution mix to achieve surface consistency.The parameters for the residual statics correction were defined according to the range of values of the data (Figure 3.21) to apply residual statics correction to the pre-stack traces. Thehigherthenumberofiterations,thelargerthecomputingtimerequiredby the two deployed processing software (Vista™ and Promax™).Both processing software useaGauss-Siedelapproachtosolveforresidualstatics,andneeds aminimumof three iterationsfor convergence. A total of at least five (5) iterations were implemented. The valueswere subsequentlysavedtotheseismic data header file.

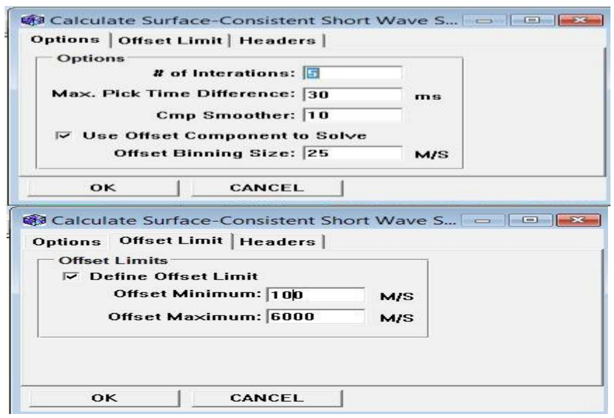


Figure3.21:Residual staticscorrection parameters

3.8 The Refraction staticsprocessing flow

Aftersavingtherefractionstaticstotheheaders,aprocessingflowwasusedtoapply thederived statics solutiononthedata.Thestaticsapplied included the elevation staticsfromthesurface tothe fixed datum,long-waveandshort-wave statics and finally the 1st and 2nd residual statics.The firstApplyStatics(StatShft) icon(Figure 3.22), applied the elevationstaticswhile the second icon appliedthelongwaverefraction statics,while thethirdicon appliedthe shortwave refractionstaticstothe seismic data. The residual statics routines were executed with a separate flow command on Promax™.

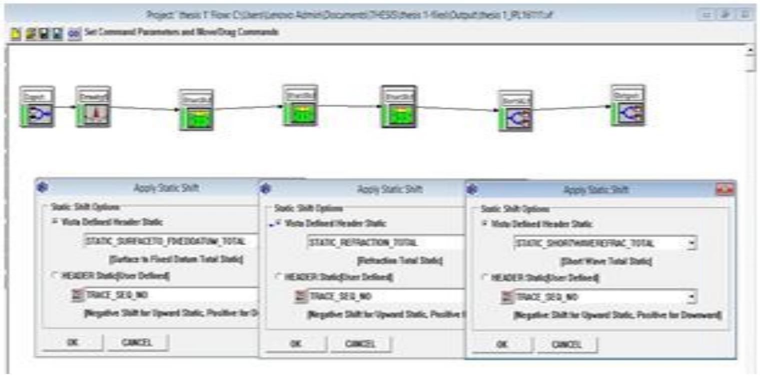


Figure3.22:The final refraction staticsexecution flow

3.9 Final Processing Stage

This stage in the processing sequence basically involved velocity analysis, stacking and migration of the 3D seismic dataset from the prospect - SOKU, in a bid to determine the impact and effectiveness of the derived and applied refraction statics solutionat these final processing stages.

3.9.1 Velocity Analysis

Velocity analysis is an interactive tool used to interpret stacking or Normal Move out (NMO) velocities on 2D and 3D pre-stack seismic data. Velocityanalysisisusuallydoneoncommonmidpoint (CMP)gatherswhere thehyperbolicalignmentisoftenreasonable.Theprocedure basically involvescomparingaseriesofstackedtraces in which a range of velocities were applied in NMO. Velocity analysis can be carried out through either the method of Velocity Spectrum Analysis (***VSA***) (which provides an interactive means to pick the velocity which is correct for applying NMO corrections) or Multi Velocity Function Stacks (***MVFS***) (which displays a series of side by side stacked traces for a set of common depth points (CDP).Thesetraces arecorrected forNMOwithaseriesofdifferentvelocities.Thevelocities canbeaseriesof timevariant velocity functions.In standard processing practice,***MVFS***areusedgenerally tofine tunethevelocity field picked using***VSA***.

3.9.2 Stacking of the Dataset

Stackingis a data compression procedure which primarily is aimed at summing up ofall thetraces which haveacommon reflectionpoint. The common midpoint (CMP) stacking approach was adopted in the study. The CMP stacking equally increased the SNRassignalsgotenhanced at the expense of some category of noise. A brute stack was first generated by stacking the gathers before any form of deconvolution and detailed velocity analysis to havearoughideaaboutthedifferenthorizons or reflecting interfaces andprevailing noises inherent in the data. Thisstack became the reference stack which was compared with the stack generated after the implementation of the full processing workflow with the complete refraction statics solution derived and applied.

3.9.3 Migration of the Dataset

Migrationisan important and crucialprocedure that attemptstocorrectthedirectionsof geological structures inherent in the seismic section. Migration redistributes energy in the seismic section to enhance the imaging of thetruesubsurface geologicalstructures. It is carried out torearrangeseismic datain a way thatreflectioneventsare displayedattheirtruesubsurfacepositions.Itcollapses diffractionbacktotheirpointoforigin.Itimproves temporal and lateral resolutions, thereby providing amoreaccuratetime or depth section. A time migration algorithm (an Explicit Finite Difference 3D Time Method, FX (Explicit) type) was performed for the SOKU dataset.

These conclusions were arrived upon after implementing all the processing routines;

i) Different processing parameters were tested in order to achieve optimal results. The processingoutputs improved step by step (progressively) as the parameters were iterated.

ii) The PSTM processing results was better than onboard processing result as is usually expected.

iii) The target zones of most inlines were of clear(spatial and temporal) resolution.

iv) The final processed output provided a remarkably good and clear subsurface seismic image forareliable geophysical and geological interpretation of structures which could house potentialhydrocarbon (oil and gas) traps.

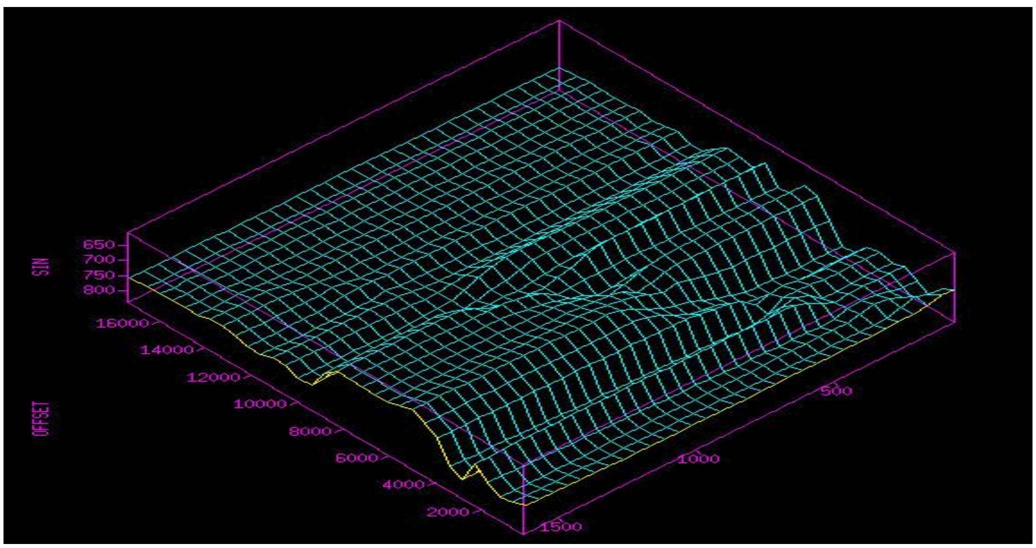
CHAPTERFOUR

RESULTSANDDISCUSSION

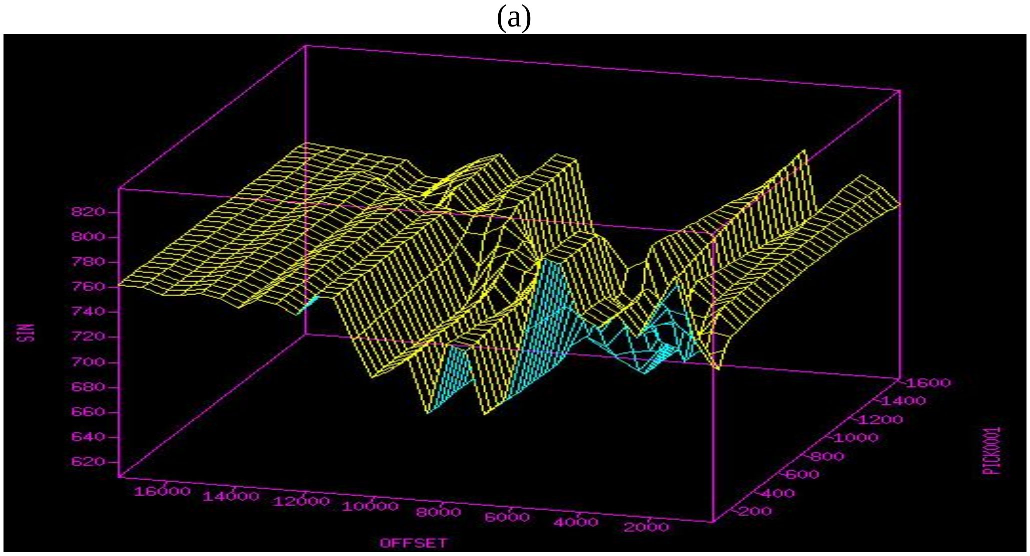
The results are sequentially arranged in the order in which they were obtained. Presented first are the results obtained after modeling the near-surface (velocity and depth models) over the investigated prospect (OML-23 SOKU), from extracted parameters obtained from some preliminary pre-processing stages, inversion of the refraction arrivals,up-hole measurements and header file details. Subsequently the derived refraction statics solution, which was based on the modeled near-surface, would be shown. Quantitative field (source and receiver) statics results would be shown and eventually the derived refraction statics solution would then be applied to the SOKU dataset and its effectiveness would be determined on seismic shot gathers, on a stacked seismic section and finally on a migrated seismic section. The ultimate objective is to show how the derived refraction statics solution has solved the statics problem of SOKU and has enhanced the subsurface seismic imaging of the prospect.

4.1 Near-Surface Model (Velocity and Depth/Thickness of Near-Surface Layers)

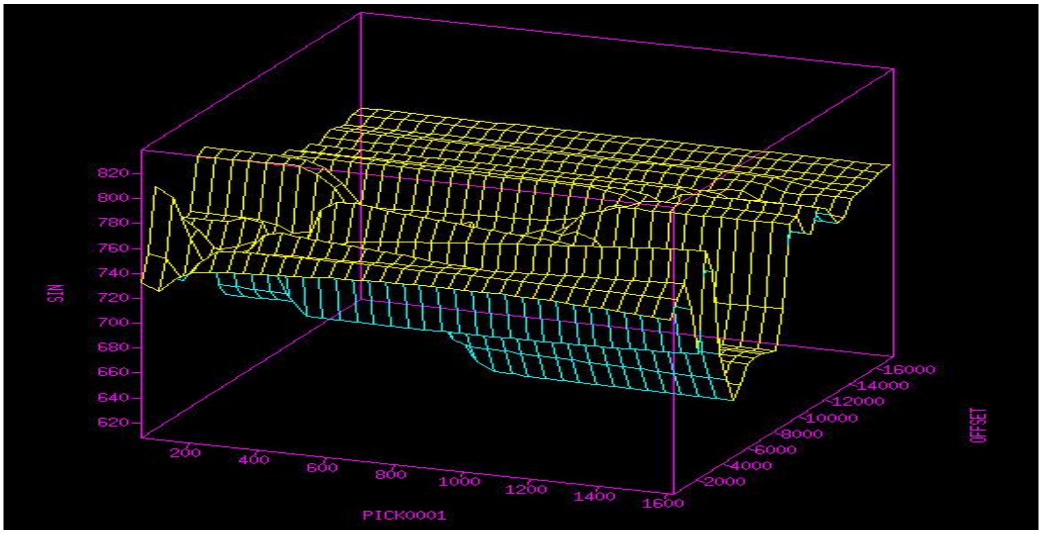
The topography of the SOKU area was mapped to justify (in the first instance) the critical need for deriving a refraction statics solution for the seismic dataset from this prospect. Figure4.1 (a), (b) and (c) are Plots of Offset (source – receiver distance) versus Source Index Number (SIN)over the study area to show the topography. Three different views are shown from different orientations and they clearly reveal a rugged and undulating terrain with non-uniform topography which requires that a reliable refraction statics solution be derived and applied on the dataset to address this uneven topography problem which would certainly induce non-uniform arrival times from the reflectors at different receiver locations.



(a)



(b)



(c)

Figure 4.1: Offset Versus Source Index Number (SIN) Plot Showing Topography

Similarly, Figures 4.2 and 4.3 shows elevation (topography) in In-line and X-line directions respectively over a section of the prospect, and still, clearly reveals the un-even and non-uniform nature of the SOKU area. This further justifies the need for a comprehensive refraction statics solution to be derived and applied to the dataset.

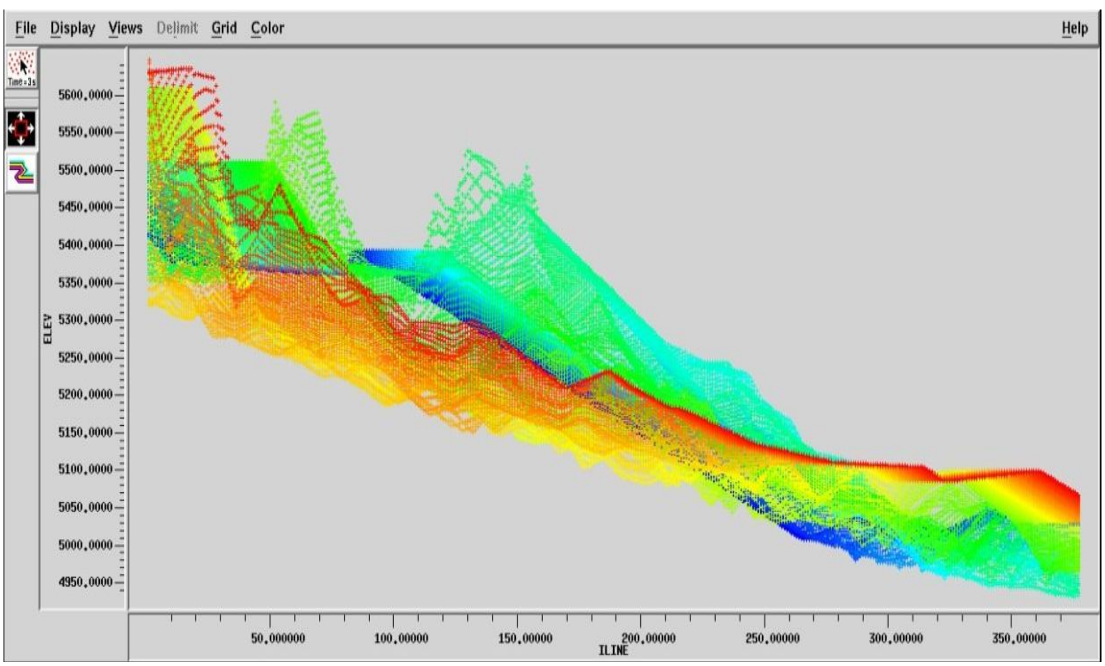


Figure 4.2: A Plot showing the elevation view over the survey area in the in-line direction

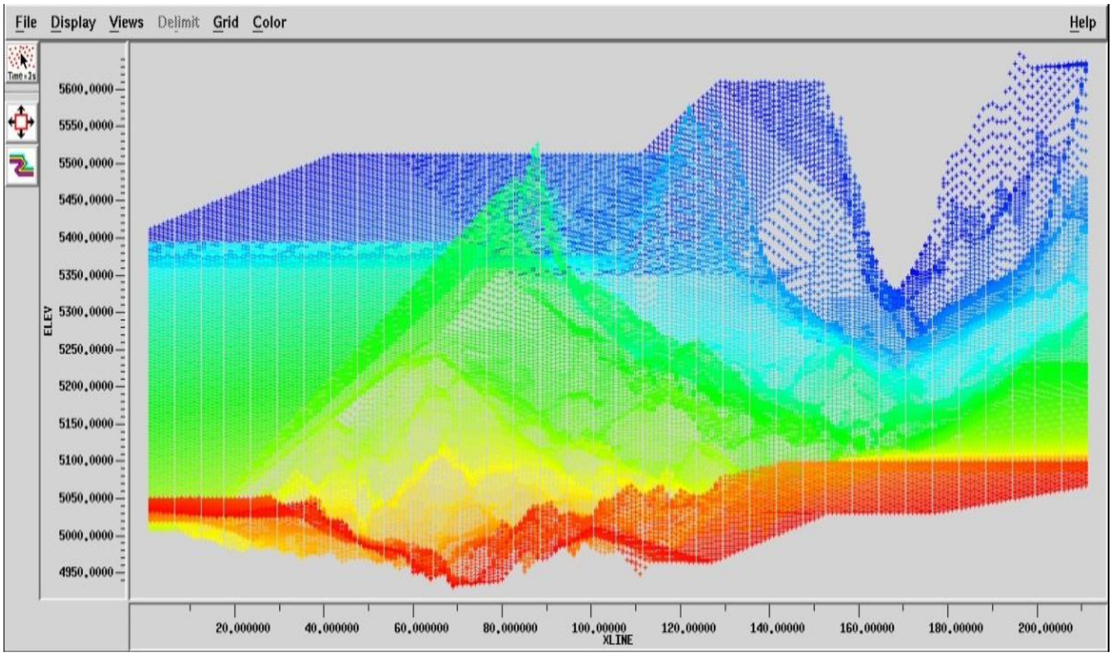
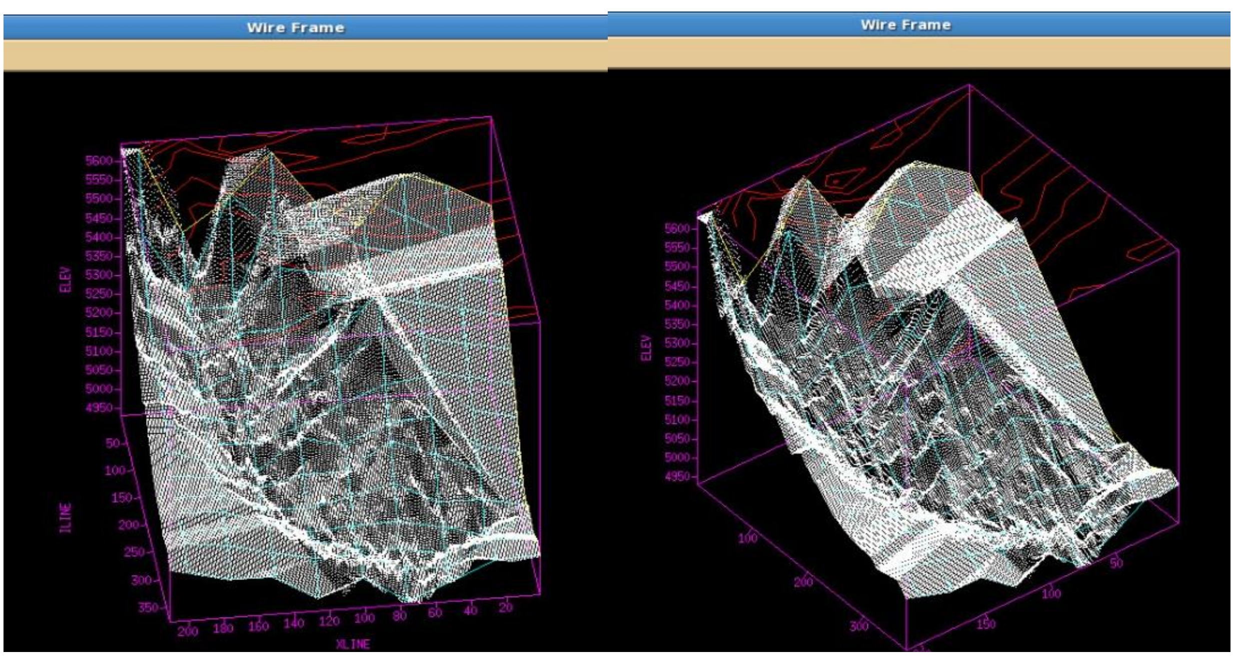
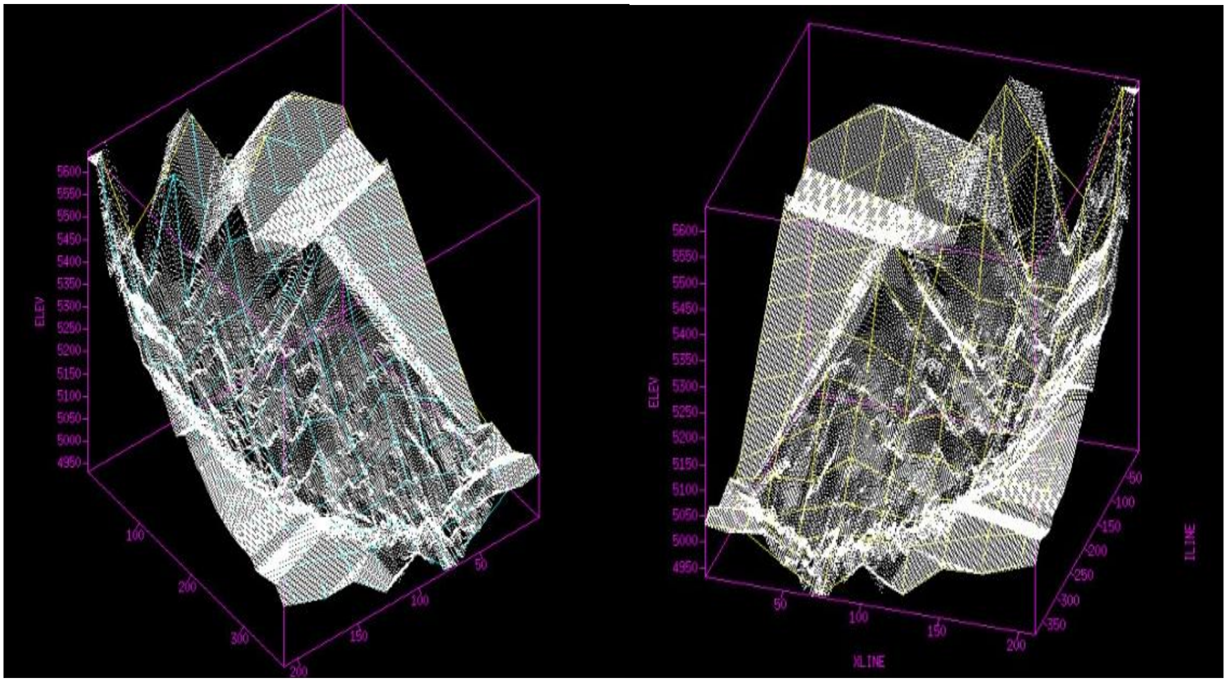


Figure 4.3: A Plot showing elevation view over the survey area in the cross-line (x-line) direction

Wireframe diagrams, Figure 4.4 (a), (b), (c) and (d) were equally generated for the investigated prospect (SOKU) to reveal the block elevation patterns and trend. As previously established, the elevation is un-even and non-uniform as seen from the wireframe diagrams from the respective positions.



(a) (b)



(c) (d)

Figure 4.4: Wire Frame Diagrams Showing the Elevation over the Survey area.

The Refraction technique which provides a means for utilizing the travel-times of critically refracted seismic waves,to compute the depth and velocity structure of the near-surface layers over areas for which a survey is carried out was deployed. It indirectly estimated intercept time and bedrock velocity using the first-arrival times which were used to estimate a velocity and depth model over the survey area in conjunction with uphole derived models. Four (4) major layers were identified based on their velocity trends; a top most weathering layer and three underlying consolidated layers. Figure 4.5 shows an interactive velocity picking tool bar that was used during the 1st and 2nd velocity analysis in the processing sequence.

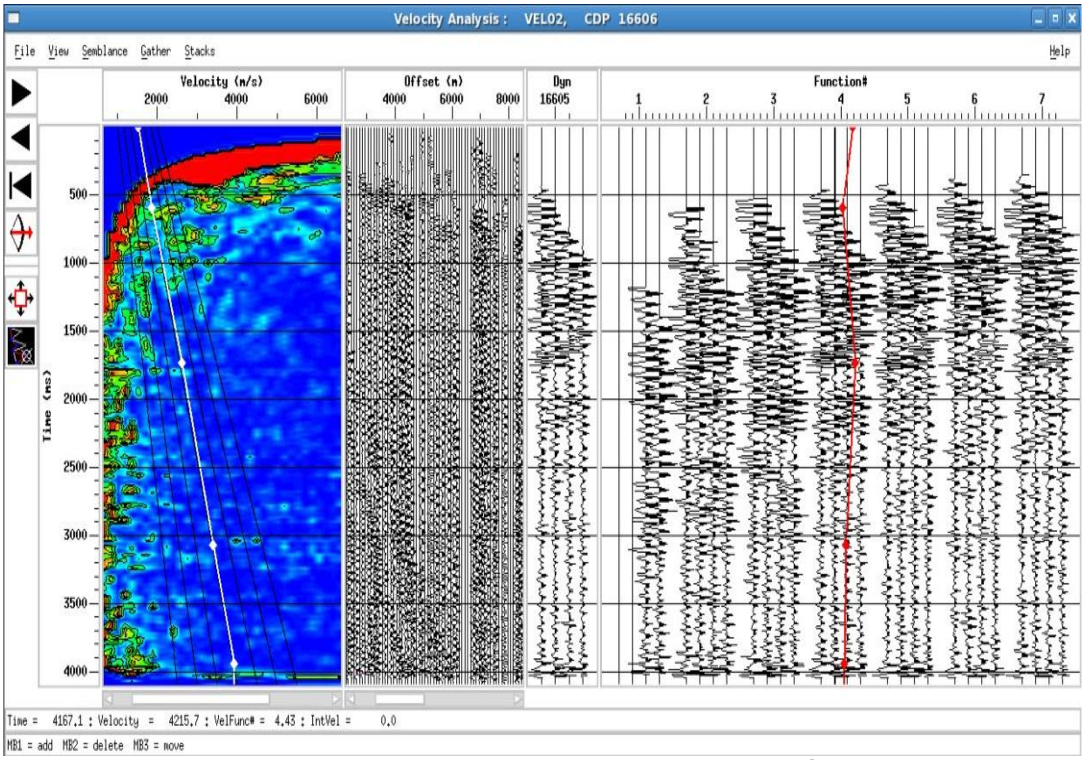


Figure 4.5: Velocity picking tool bar used during 1st and 2nd velocity analysis

Figure 4.6 and Figure 4.7 show the velocity field of the near-surface over the SOKU area after 1st and 2nd velocity analysis respectively. On close examination of both velocity fields, it is observed that there are sharp demarcations in the velocity field after the 1st velocity analysis. This sharp demarcation now blends better after slight adjustments were made to picked parameters during the 2nd velocity analysis. The velocity field (profile) after 2nd velocity analysis becamethe optimal velocity field for the investigated prospect.

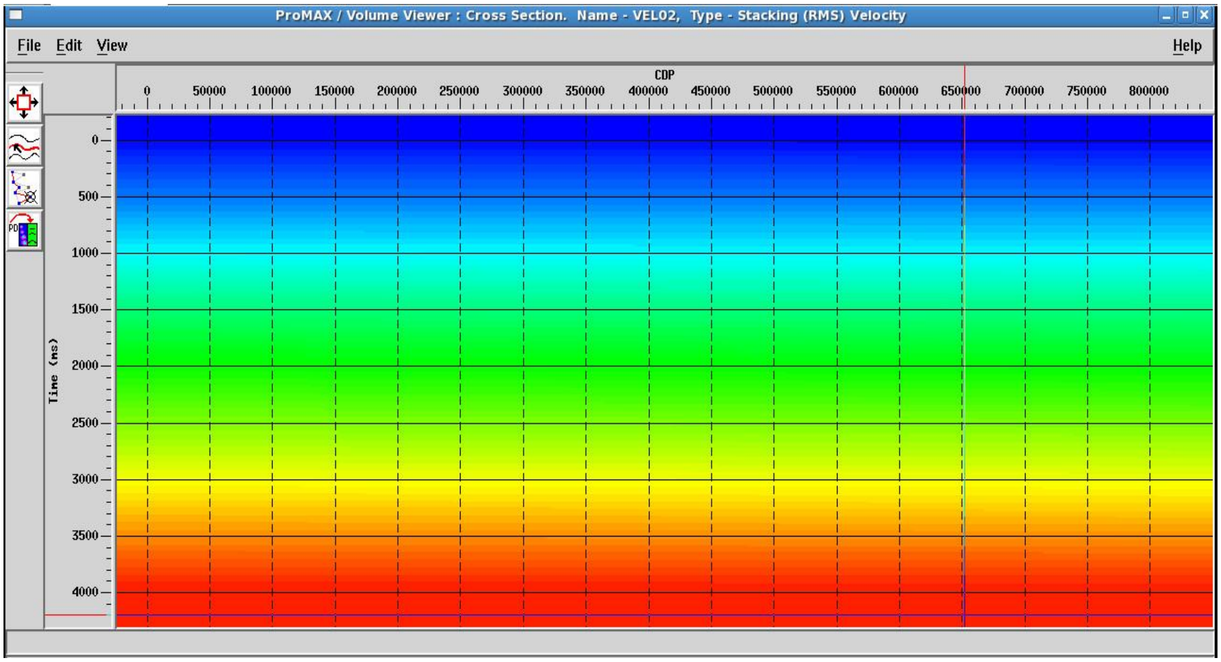


Figure 4.6: Velocity Field Obtained after 1st Velocity Analysis

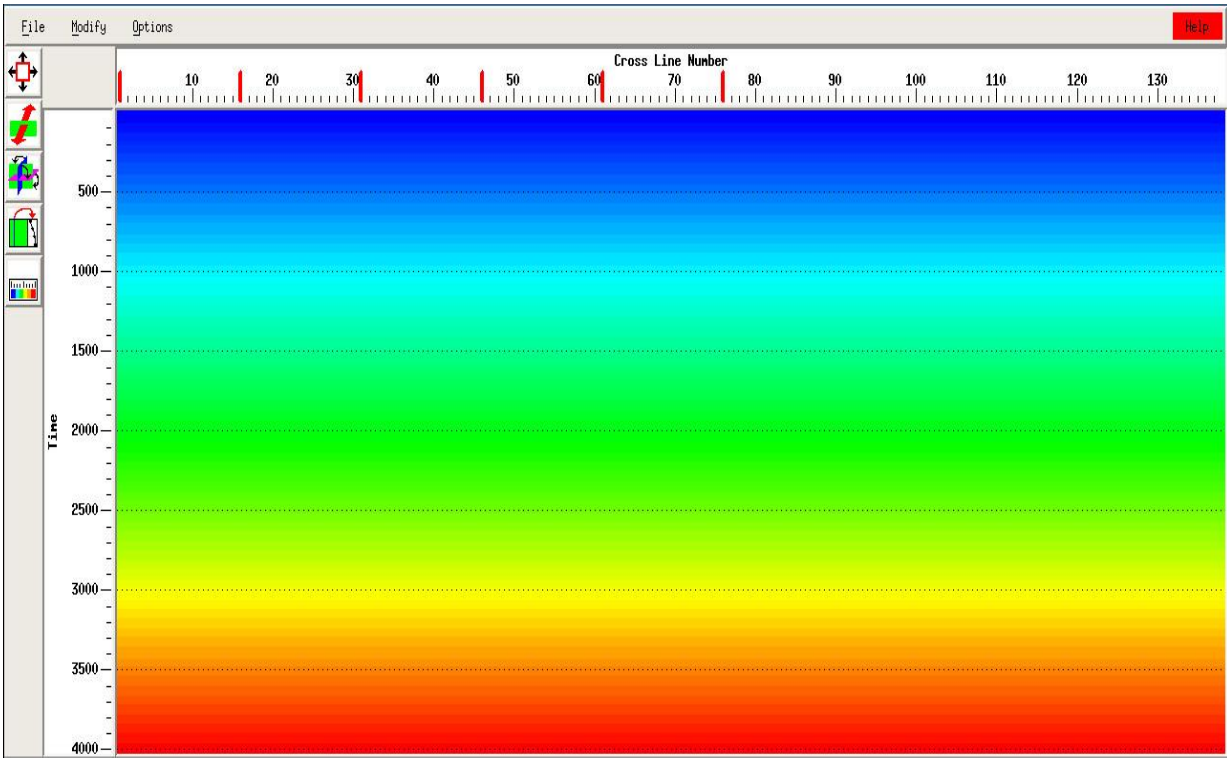
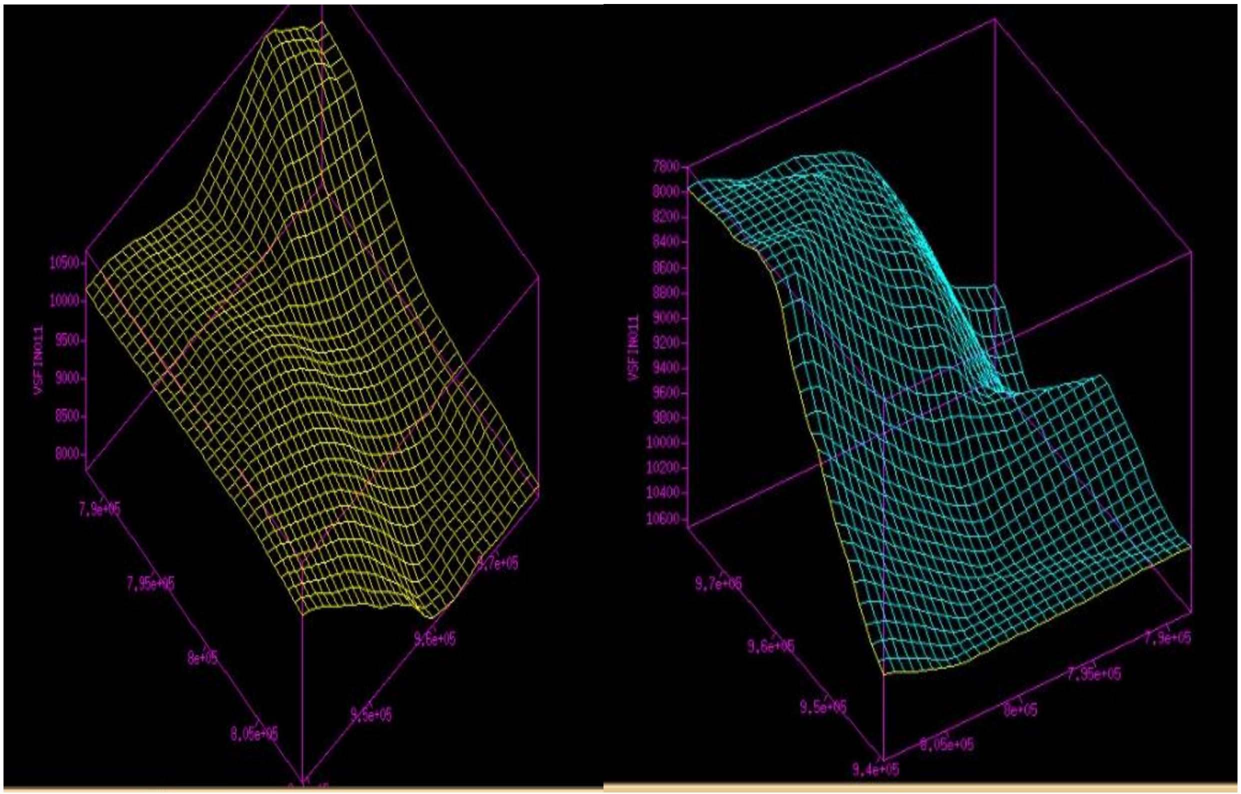


Figure 4.7: Velocity Field Obtained after 2ndVelocity Analysis

A refractor velocity wireframe diagram (Figure 4.8) was equally generated in different orientations for the SOKU area. The diagram basically shows the velocity field view over the area. This velocity field view is crucial in the build up to the much sought after comprehensiverefraction statics solution.



(a) (b)

Figure 4.8 Refractor velocity wireframe diagram

The obtained velocity field for the near-surface was equally generated in both In-line and X-line directions (Figure 4.9 and Figure 4. 10). The velocity trend obtained agrees with geology as velocities increased with increasing depths (Mares, 1984). This is an anticipated trend because increasing depths of burial would result into more compaction of sediments which would in turn increase velocities of seismic waves propagating at such zones or depths. The velocity fields over both the in-line and x-line directions are very similar and this is desirable for our target objective which is to adapt this near-surface velocity depth model to derive a refraction statics solution that would completely solve the statics problem of SOKU for meaningful and accurate structural/stratigraphic interpretations.

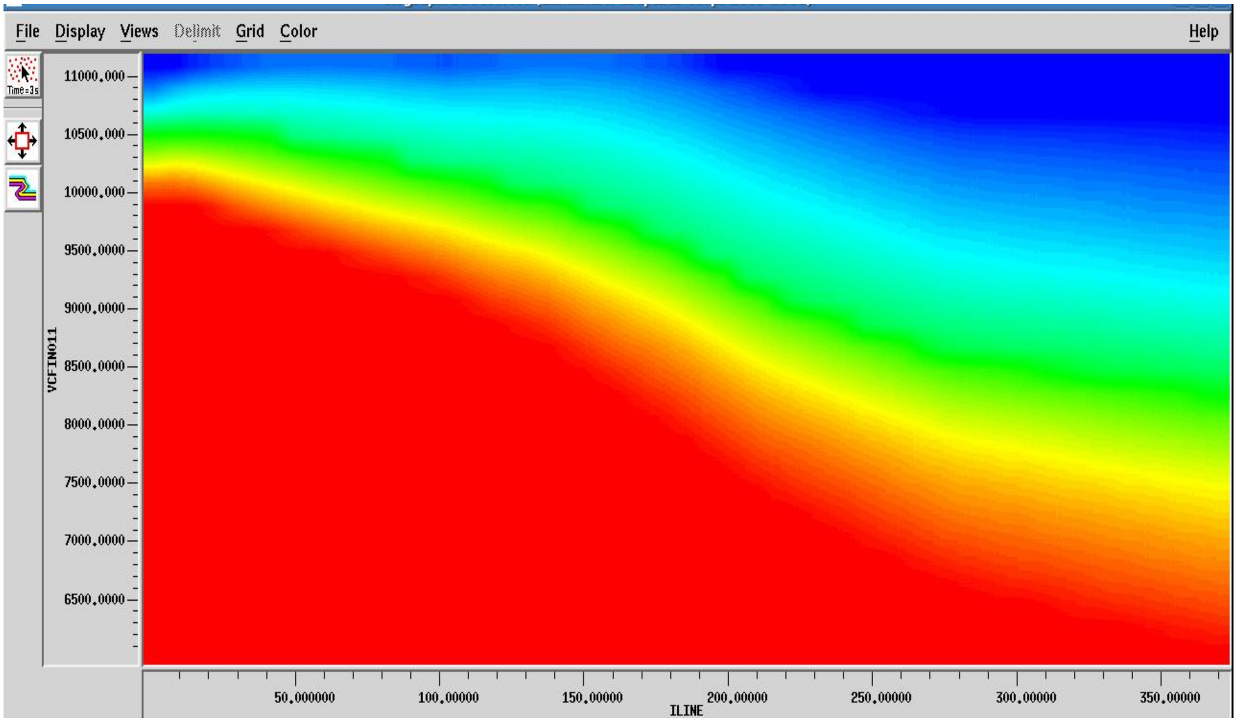


Figure 4.9: Velocityfield in In-line Direction showing the various layers mapped

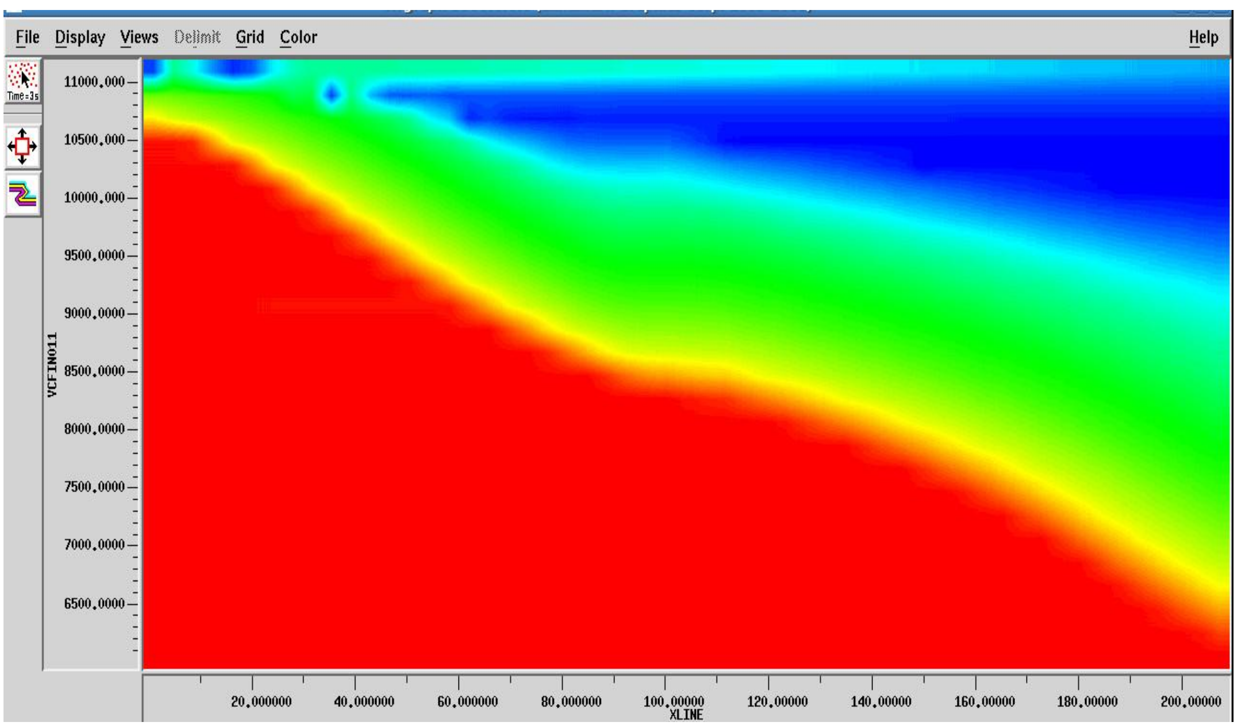


Figure 4.10: Velocityfield in Cross-line (X-line) Direction showing the various layers mapped

Apart from the display of the velocity field in both the in-line and x-line directions, a generalized velocity field plot (Figure 4.11) over the SOKU area was obtained.

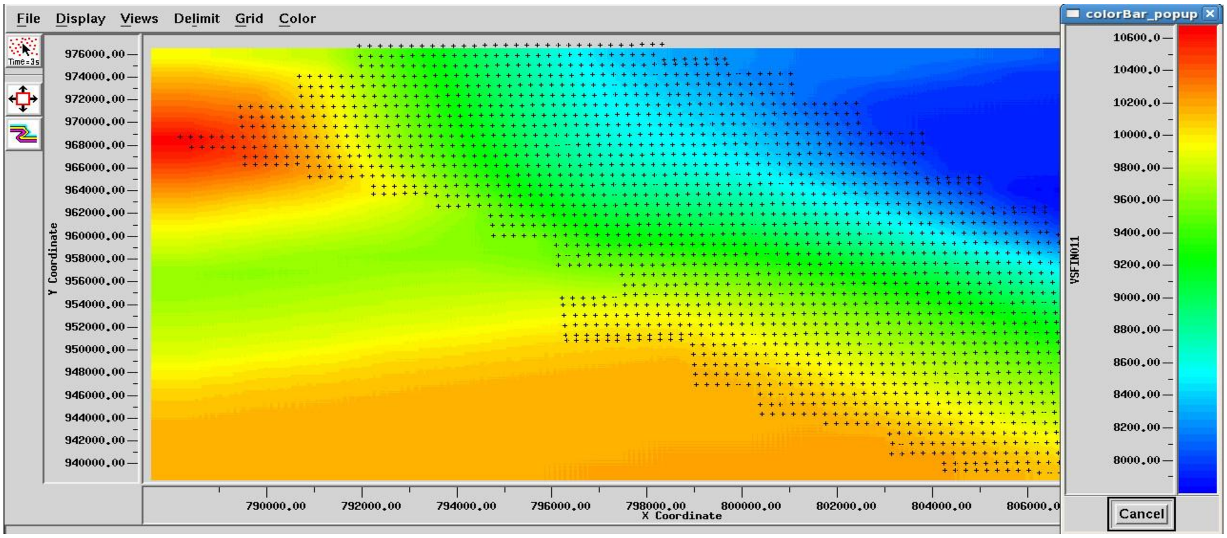
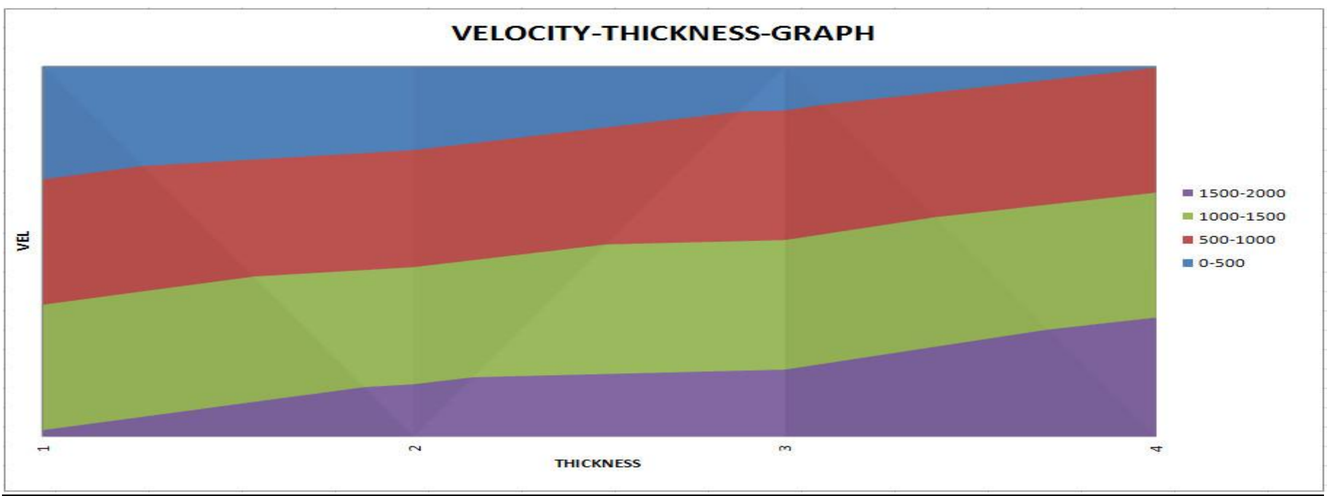


Figure 4.11: Generalized Velocity field over a part of the survey area showing the layers mapped

After successfully imaging the near-surface, the four (4) identified layers were modeled in terms of their velocity and thickness ranges in the form of a bar graph. This model is presented in Figure 4.12.



Bar Code	Annotation	Thickness (Depth) Range (m)	Velocity Range (m/s)
	Weathering Layer	3 – 18	520
	First Consolidated Layer	14 – 124	1614 – 1723
	Second Consolidated Layer	62 – 322	1708 – 1758
	Third Consolidated Layer	248 – 493	1950 – 1976

Figure 4.12: Velocity – Thickness Model with Appropriate Annotation

These values obtained were in close proximity with values obtained from a recent literature on near-surface characterization, imaging and velocity model building in the Niger Delta Basin

(Opara *et al.*, 2017 and 2018). The velocity model of the near-surface was ideal. It increased progressively with increasing depth of burial. This trend is further highlighted by the graphs plotted for thickness versus velocity (Figure 4.13) and velocity versus thickness (Figure 4.14).

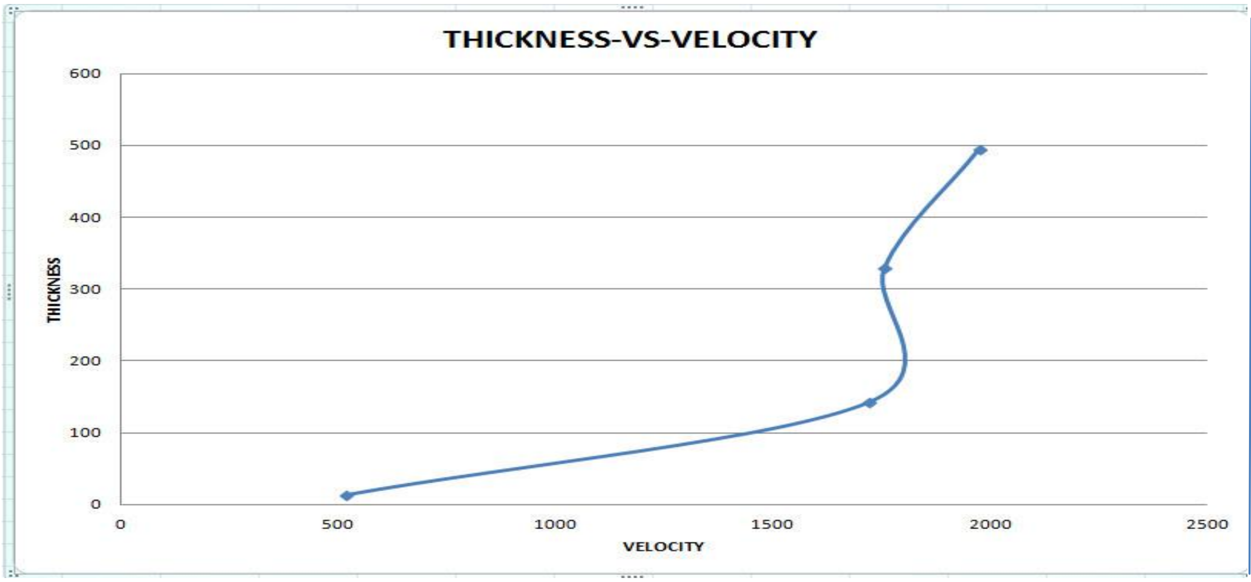


Figure 4.13: Thickness (m) Versus Velocity(m/s) Plot for the different layers over SOKU.

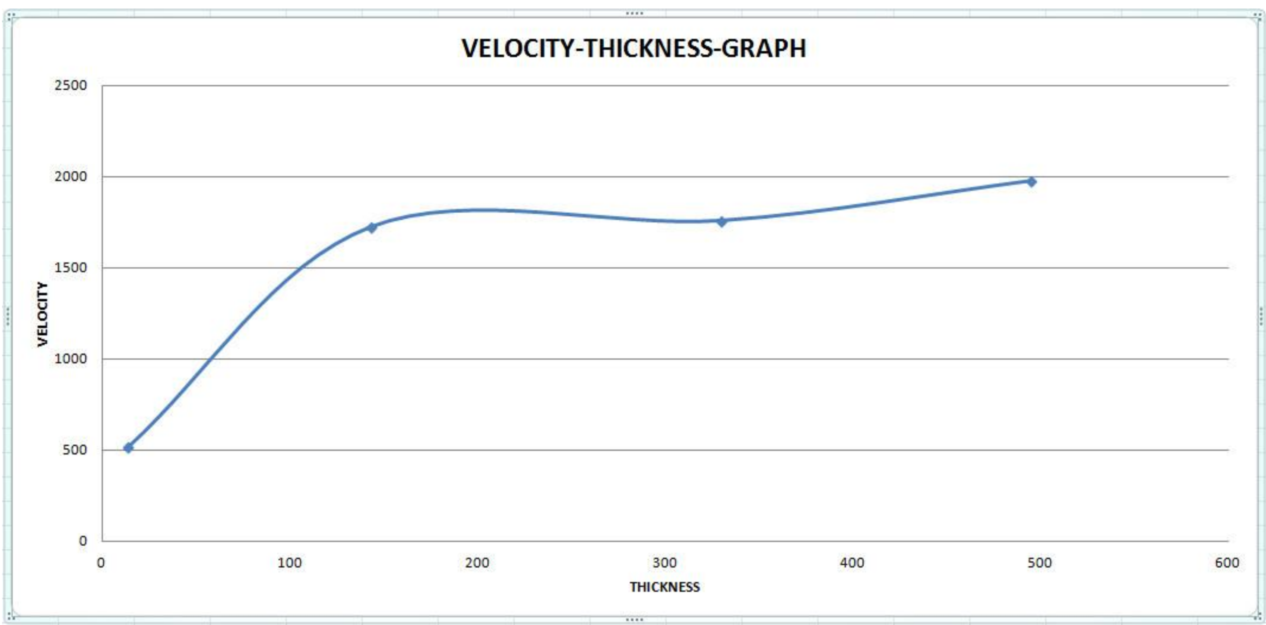


Figure 4.14: Velocity (m/s) – Thickness (m) graph showing mapped near-surface properties over SOKU.

A block representation of the imaged near-surface in terms of velocity and thickness ranges is summarized in Table 4.1.

Table 4.1: Velocity – Thickness (Depth) in In-line and Cross-line direction over SOKU

	In-line		Cross-line	
	Velocity(m/s)	**Thickness (m)**	**Velocity(m/s)**	**Thickness(m)**
WeatheringLayer	520	5-14	520	3-18
1stConsolidated Layer	1614-1723	10-143	1568-1748	14-124
2ndConsolidated Layer	1708-1758	71-330	1736-1786	62-322
3rdConsolidated Layer	1950-1976	314-495	1923-1942	248-493

4.2 Adapting the Near-Surface Model to derive the Refraction Statics Solution

The near-surface model that was generated was used as input together with some field header information to derive a comprehensive refraction statics solution that would correct the statics problem of the SOKU prospect. The comprehensive statics solution comprised of the field statics, refraction statics and the residual statics. The field statics catered for the elevation statics (sometimes called datum statics) problem and a part of the short wave and long wave statics problem associated with the near-surface inhomogeneity situation of the SOKU area. The refraction statics took care of the problem of the Low Velocity Layer (LVL) and a part of both short wave and long wave statics, while the residual statics solved the remnant unresolved short wave and long wave statics problem that the field and refraction statics could not resolve.It was implemented twice on the dataset to achieve optimal result. It is insightful to note that the approach to refraction statics derivation and implementation differs from one processing software tool to the other. Slight differences in terminology thus exist, for some terms encountered during the processing on Promax™ and Vista™ platforms, for example Vista™recognizes short wave and long wave statics whereas in Promax™both statics are embedded in refraction statics.

A set of solutions are now presented which when collectively combined together using appropriate flow commands would constitute the complete statics solution that addresses the statics problem already identified for SOKU. Figure 4.15 is the source elevation statics solution which is intended to resolve the uneven elevation problem.

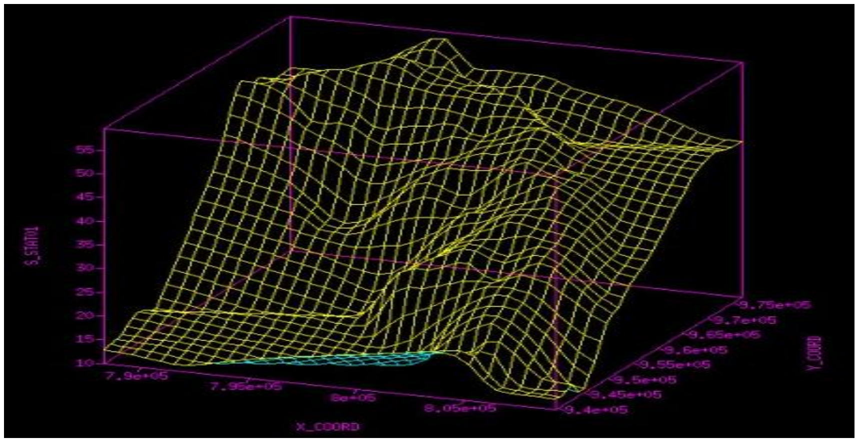


Figure 4.15: Source – Elevation Statics Solution

Figure 4.16 is a schematic diagram showing the Source – Refraction statics solution derived for the SOKU area. On close observation, it is noticed that the source and receivers are now being moved to the reference datum plane (the zero time mark) on the vertical axis. The objective here is for all the source and receivers to be at the same datum plane.

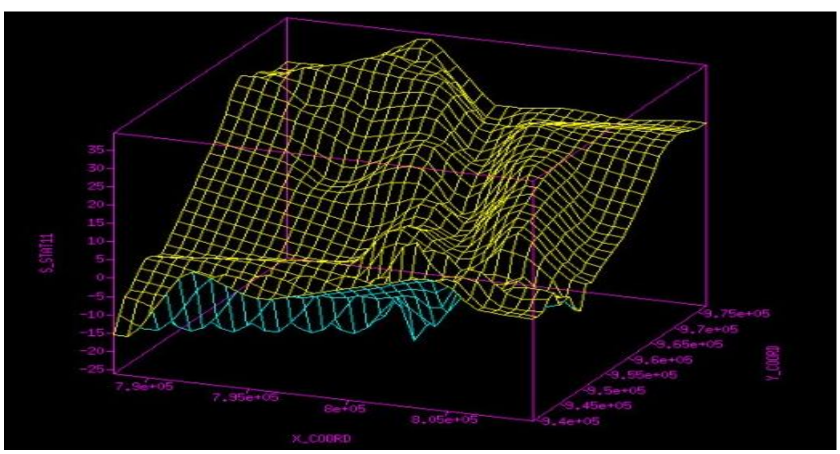


Figure 4.16: Source – Refraction Statics Solution

Figure 4.17 is a schematic of the source statics from the refraction statics which basically gives the source positioning and orientation across the prospect under investigation which must be corrected or moved to the reference datum.

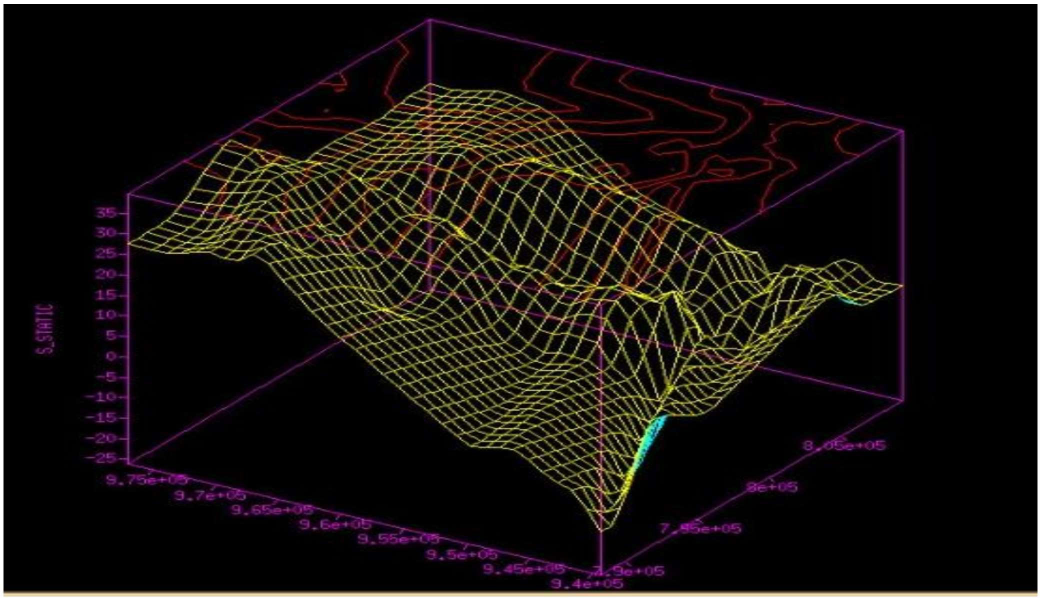


Figure 4.17: Source – Statics from Refraction Statics

The solutions so far derived were all adapted to build a complete refraction statics solution to final datum (Figure 4.18)

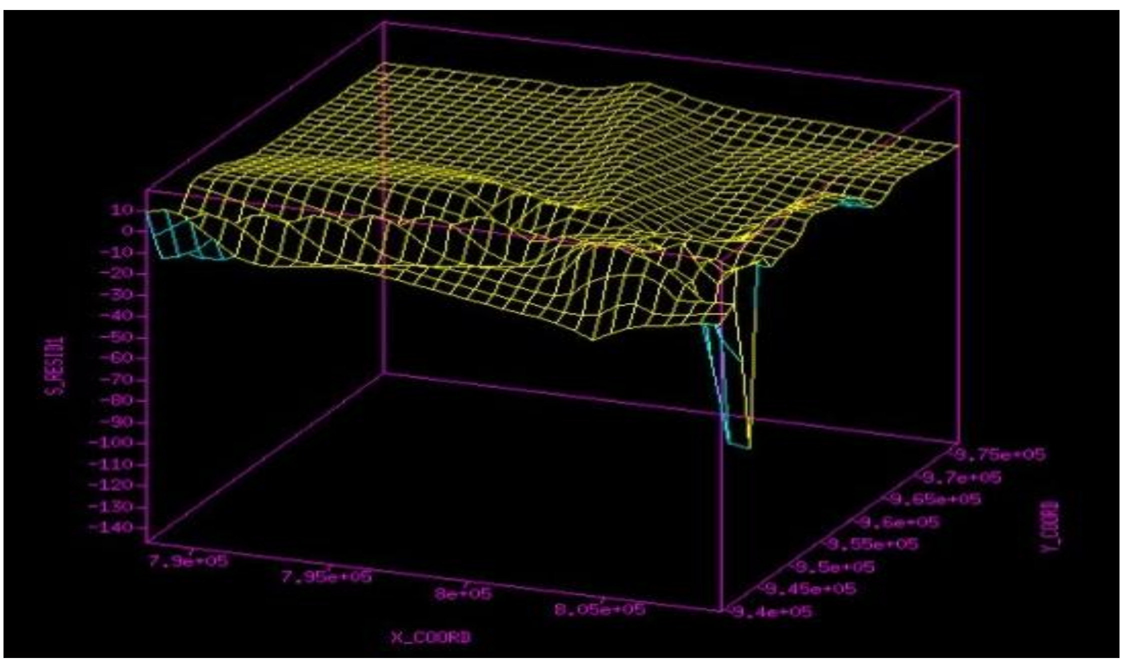


Figure 4.18: Refraction Statics Solution to Final Datum

It is very visible to see that sources and receivers are almost aligned now at the reference datum except for some trough like structures encountered at the edges of the grid. These anomalies account for unresolved short wave and long wave statics problems. These unresolved anomalies would subsequently be resolved (moved to the reference datum) when the first and second residual statics workflow would be applied, thereby enabling the source and receivers to be at a common datum plane which is the ultimate target.

4.3 Quantitative Field (Source and Receiver) Statics Results

The field statics derived and implemented corrected for the undulating, rugged and non-uniform topography of OML-23 SOKU. It was implemented to move source(s) and receiver(s) to a common datum. The operational domain for this component of the comprehensive statics solution was source (source statics) and receiver (receiver statics) based.

Tables 4.2 and 4.3 gives quantitative statics (time shift) values for the field statics component (source and receiver statics) derived and implemented for inline 79, showing the magnitude of statics in milliseconds (ms), at selected Source Index Number (SIN) points and receiver station locations respectively, along the chosen inline before statics application and after statics have been derived and applied.

Table 4.2: Quantitative values of the source statics components of the field statics solution before statics implementation and after statics have been derived and applied.

S/N	BEFORE		AFTER	
	SOURCE INDEX NUMBER	**SOURCE-STATICS (ms)**	**SOURCE INDEX NUMBER**	**SOURCE-STATICS (ms)**
1	22	38	22.1	31
2	24	34	24.4	29
3	41	29	40.6	23
4	118	32	117.8	32
5	139	32	139.4	30
6	159	34	159.5	28
7	320	11	320	15
8	374	23	374.1	23
9	390	17	390.3	18
10	433	15	432.7	11
11	472	13	472.1	11
12	515	15	514.6	7
13	594	5	594.1	6
14	626	13	625.7	2
15	679	4	679	1

Table 4.3: Quantitative values of the receiver statics components of the field statics solution before statics implementation and after statics have been derived and applied.

S/N	BEFORE		AFTER	
	RECEIVER STATION	RECEIVER-STATICS (ms)	RECEIVER STATION	RECEIVER-STATICS(ms)
1	118	50	118.3	35
2	159	36	158.6	22
3	181	52	180.7	52
4	211	25	210.9	27
5	235	47	235.1	40
6	362	22	361.9	40
7	430	52	430.3	39
8	475	21	474.6	23
9	533	19	532.9	20
10	978	35	978.8	24
11	1000	6	999.9	22
12	1016	33	1016	36
13	1135	30	1134.8	28
14	1258	22	1257.5	20
15	1408	26	1408.5	19

The statics values presented above show appreciable static shifts for the seismic traces for each source and receiver location at defined Source Index Number (SIN) locations and receiver stations respectively. These quantitative values are now modeled into receiver statics plots

(Figure 4.19) and source statics plots (Figure 4.20) to highlight at a quick glance the contribution of the source and receiver components of the field statics that was sought, derived and applied.

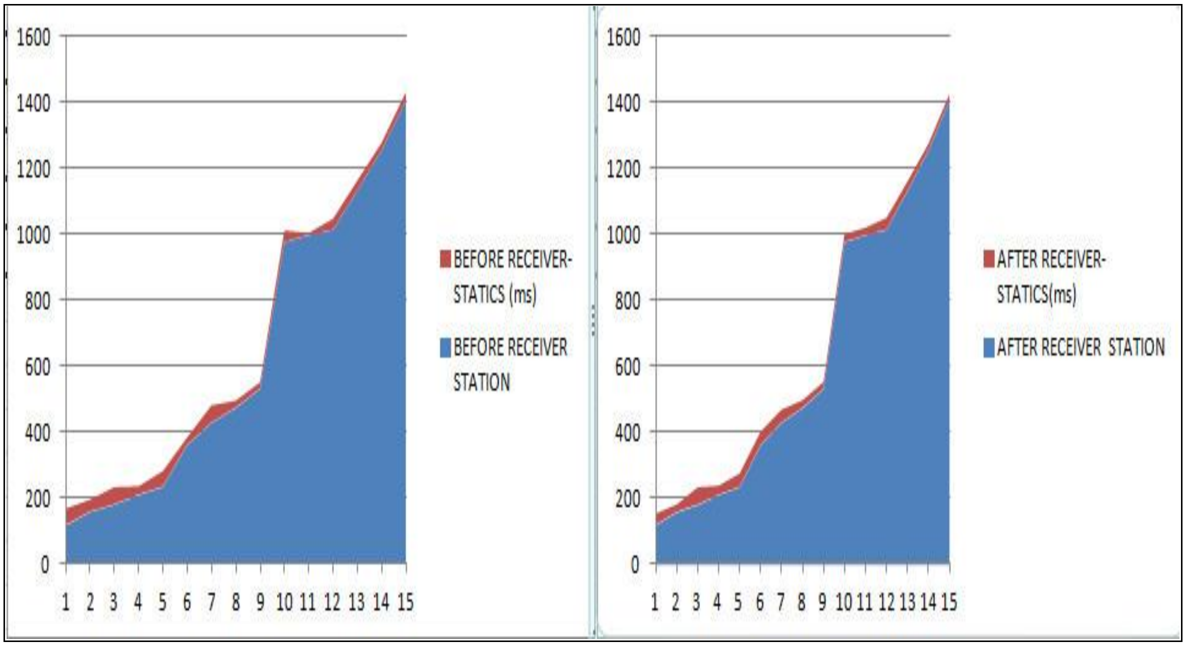


Figure 4.19: Receiver – statics plot of receiver statics values in (ms) versus receiver stations before and after application of the sought statics

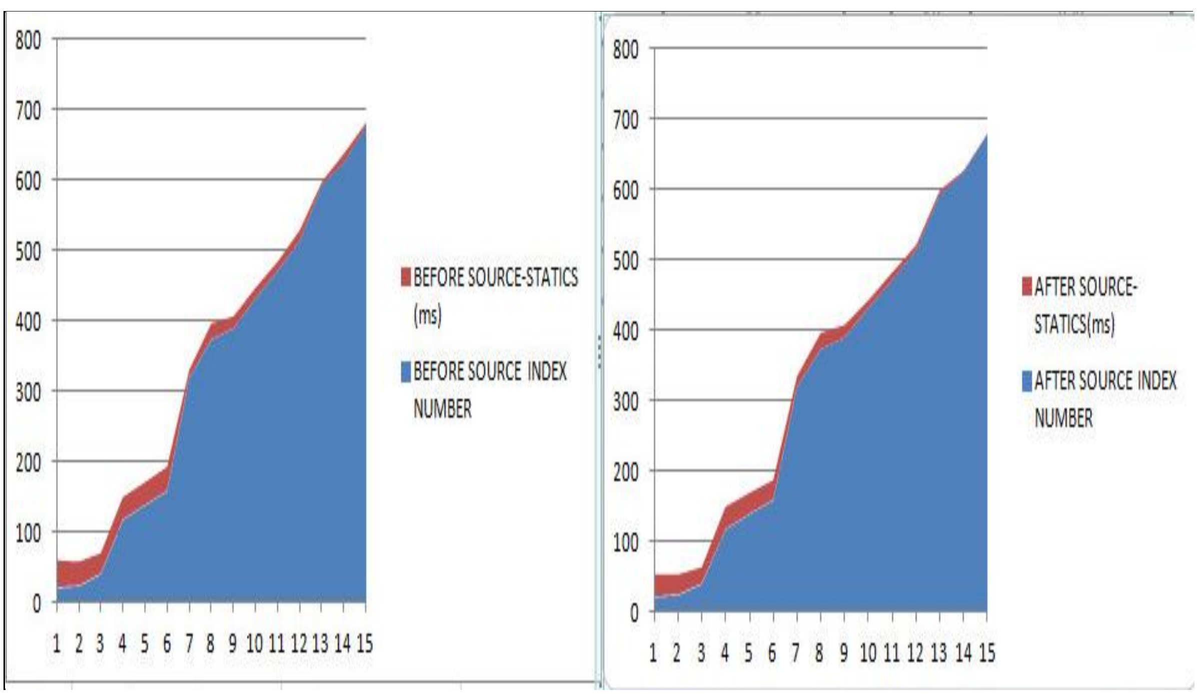


Figure 4.20: Source – statics plot of source statics values in (ms) versus Source Index Numbers (SIN) before and after application of the sought statics

After implementing field statics, refraction statics then 1st and 2nd residual statics were equally derived and applied to the SOKU dataset. The principle adopted to derive refraction statics relied on supplying the first break times of all traces along each FFID (field file identification) into VISTA and PROMAX modules to perform refraction statics. The software module then corrects for time in this operation and the corrected time(s) were in sync with those in the table earlier presented. The operational domain for refraction statics is also source and receiver based. The 1st and 2nd residual statics was implemented also to cater for effects (spatial short and long wavelength) along the common depth points (CDP). Unlike the previous two statics solution which are strictly source and receiver domain operational (based), the residual statics in addition to being operational in the source and receiver domain also incorporates the CDP (common depth point) domain. This bridges potential gaps in the build up to the comprehensive statics solution which the field and refraction statics components alone may not be able to resolve.

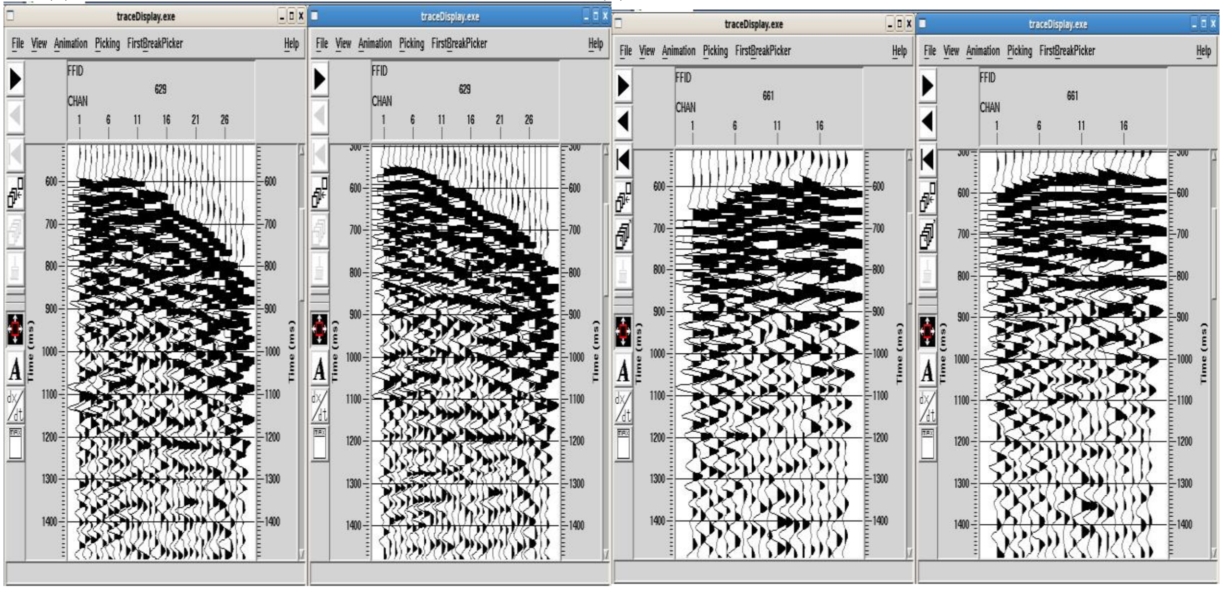
4.4 Application of the Derived Refraction Statics Solution on the Dataset

This section shows the results achieved after the derived refraction statics solution was applied. The results achieved are sequentially presented and clearly affirms the effectiveness of the derived and implemented refraction statics solution. The results presented here aregrouped into three sub-sections; the first shows the effectiveness of the derived refraction statics solution on shot gathers, the second determines the effectiveness of the solution on a stacked seismic section and the final section determines the overall success of the derived solution on a migrated section of the data.

4.4.1 Derived Refraction Statics Solution applied to Seismic Shot Gathers

Thissection shows before and after refraction statics application results on seismic shot gathers in Field File Identification (FFID) configurations. The before and after result for each FFID shot gather were placed side by side so that on close examination, the problem of the statics would be seen (on the before panel) and the same panel now corrected for the statics problem (on the after panel). The approach was basically to first display the seismic data in their respective shot gathers configuration in FFID before any form of processing and after the comprehensive refraction statics solution was applied to the data, they were again displayed in their respective shot gathers using the same FFID, as our primary focus was to mirror and compare the same shots in their gathers to demonstrate how the refraction statics solution derived and applied has solved the statics challenge for SOKU. Figure 4.21 shows before and after refraction statics displays for FFID's 629, 661, 668 and 693. On close observation, it is very evident that reflections were becoming more continuous and regular with better energy (amplitude) focus in after displays when the refraction statics solution was applied than in before displays with no refraction statics solution.

(a) FFID 629 - Before and After Refraction Statics (b) FFID 661- Before and After Refraction Statics



(c) FFID 668 - Before and After Refraction Statics (d) FFID 693- Before and After Refraction Statics

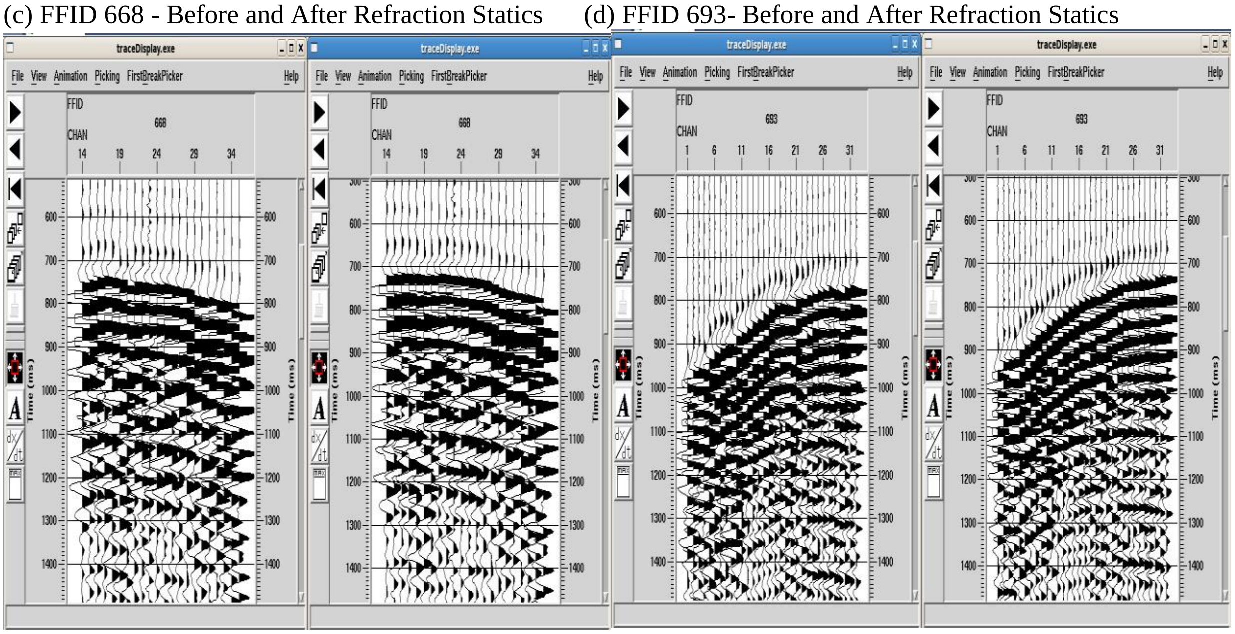
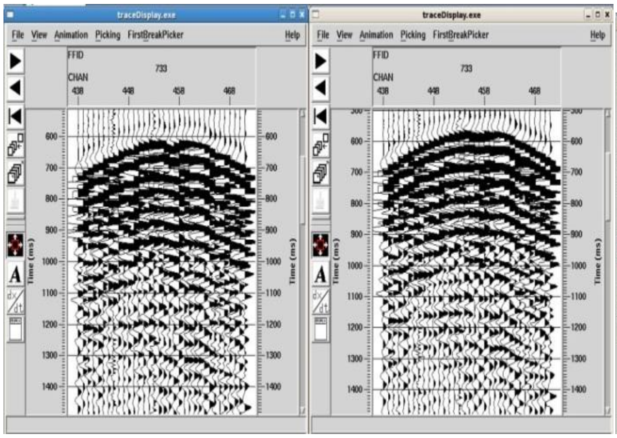


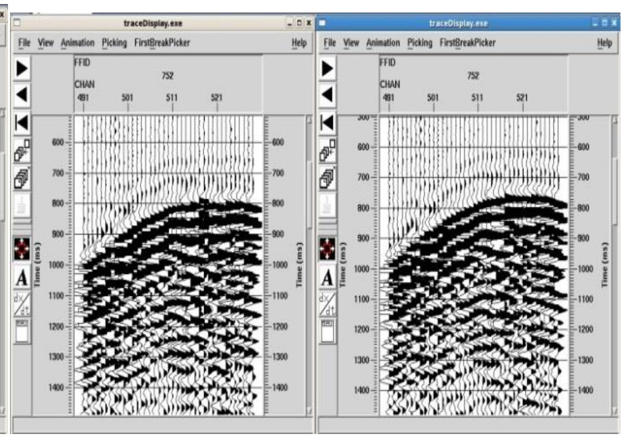
Figure 4.21: Derived refraction statics solution applied to shot gathers - FFID 629, FFID 661, FFID 668 and FFID 693

Similarly, Figure 4.22 and Figure 4.23 shows the before and after display of shot gathers in FFID's (733, 752, 758, 764, 793, 797) and (800, 853, 859) respectively. As earlier stated, on close examination of the shot gathers, it is observed that reflections are now properly moved out and aligned in their proper directions as it ought to. Failure to correct for these distortions in reflection patterns would eventual impede the success of other processing procedures like stacking and migration and would ultimately lead to a false image of the subsurface structures that would be at variance with actual geology of the area (SOKU in this case).

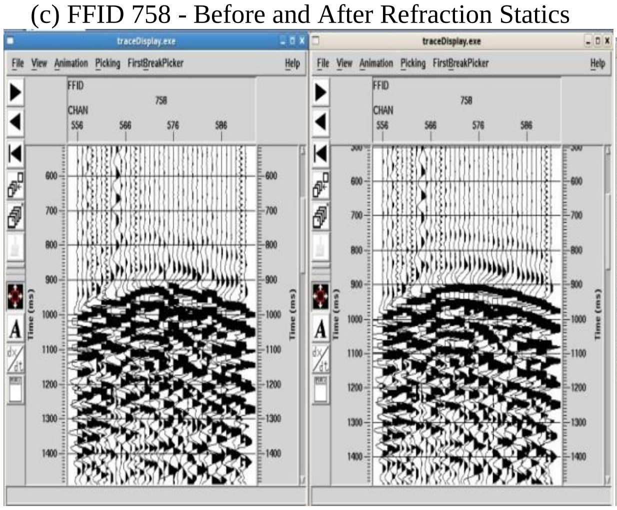
(a) FFID 733 - Before and After Refraction Statics



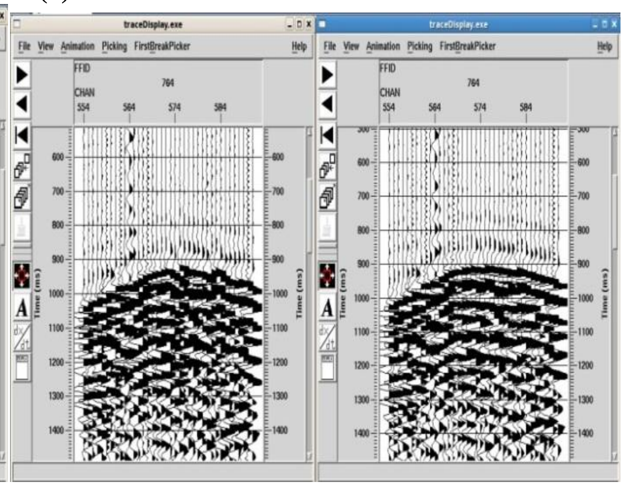
(b) FFID 752- Before and After Refraction Statics



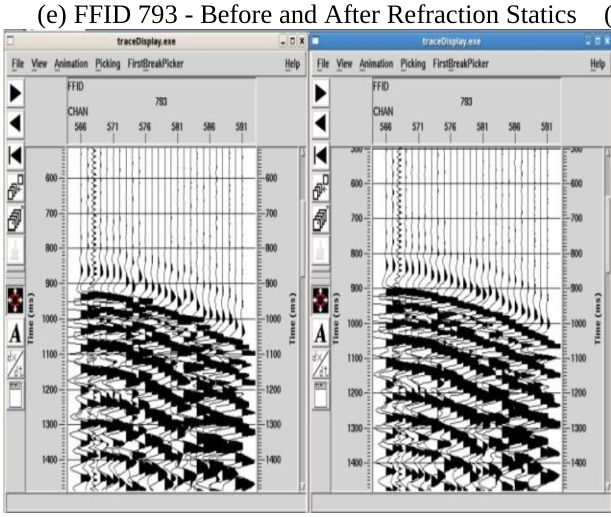
(c) FFID 758 - Before and After Refraction Statics



(d) FFID 764- Before and After Refraction Statics



(e) FFID 793 - Before and After Refraction Statics



(f) FFID 797- Before and After Refraction Statics

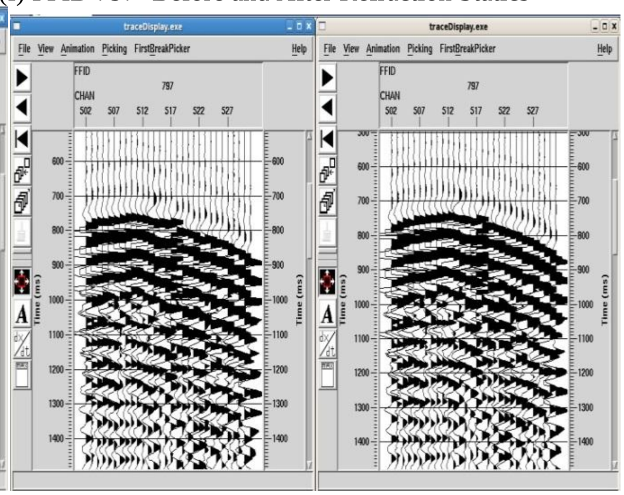
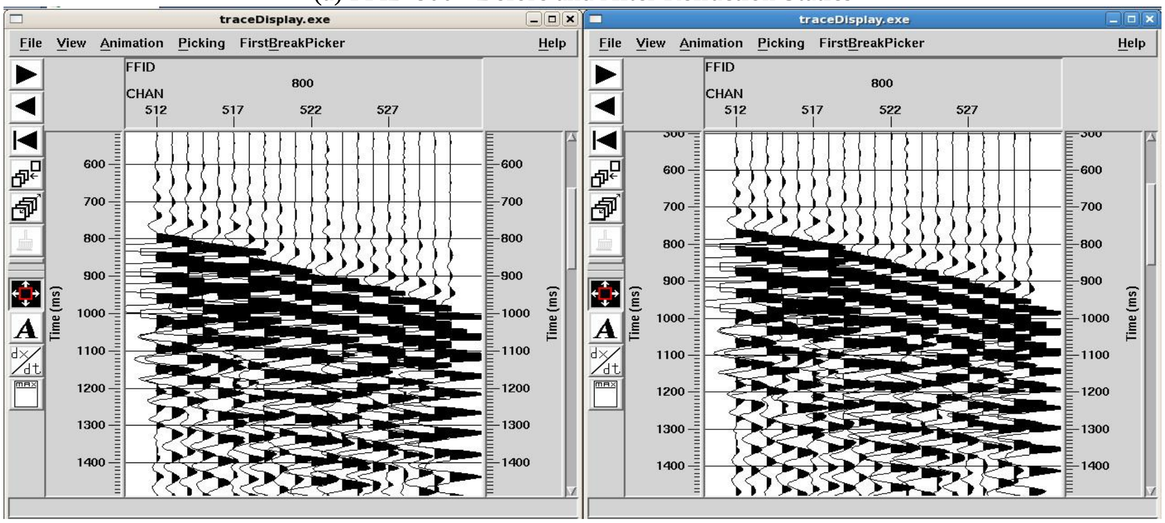
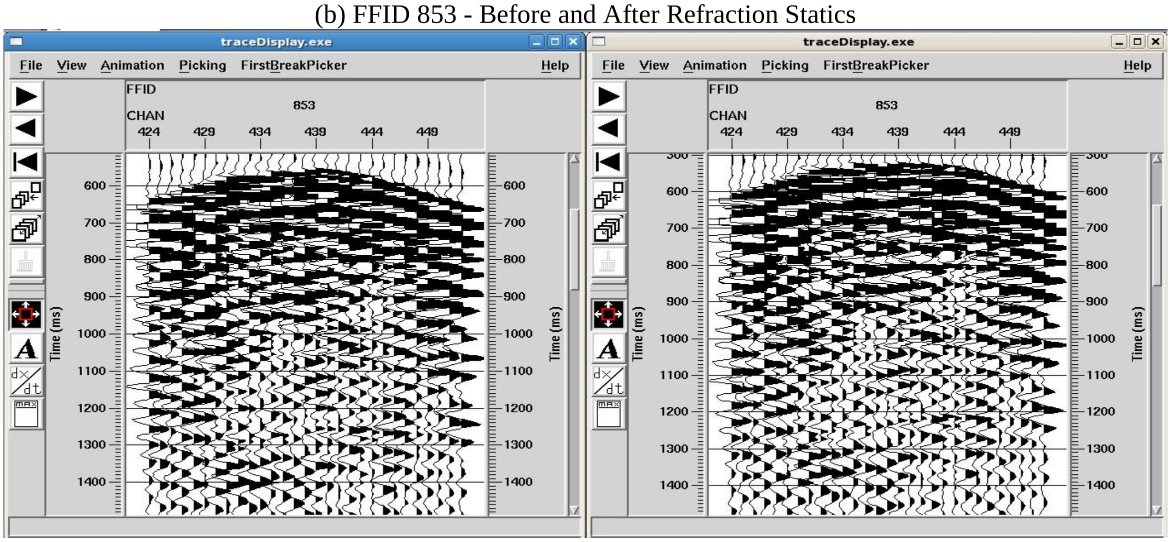


Figure 4.22: Derived statics solution applied to shot gathers - FFID 733, FFID 752, FFID 758, FFID 764, FFID 793 and FFID 797

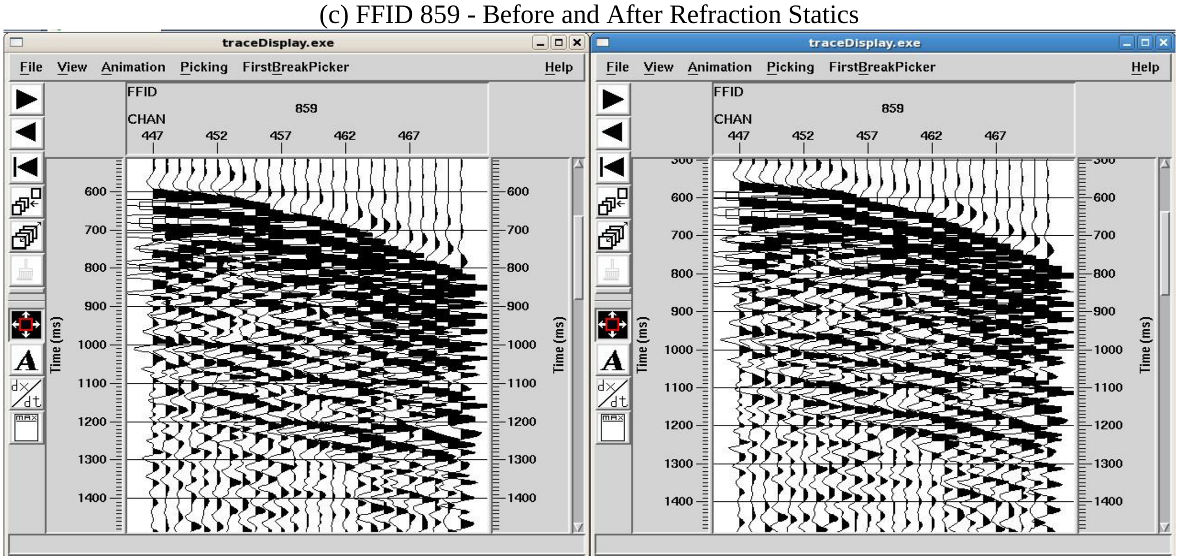
(a) FFID 800 - Before and After Refraction Statics



(b) FFID 853 - Before and After Refraction Statics



(c) FFID 859 - Before and After Refraction Statics



B

Figure 4.23: Derived statics solution applied to shot gathers - FFID 800, FFID 853 and FFID 859

Figure 4.24 now displays a collection of selected shots with included markers to show regions were the effect or impact of the application of the derived refraction statics solution is most visible.

Figure 4.24: Selected collection of shots showing with markers (arrows) the resultant effect of the applied refraction statics solution derived on the shot gathers.

The quality of results achieved at this stage of the processing sequence was superior to those achieved by Opara *et al.*, 2017 and 2018, (Figure 4.25) when both outcomes were compared.

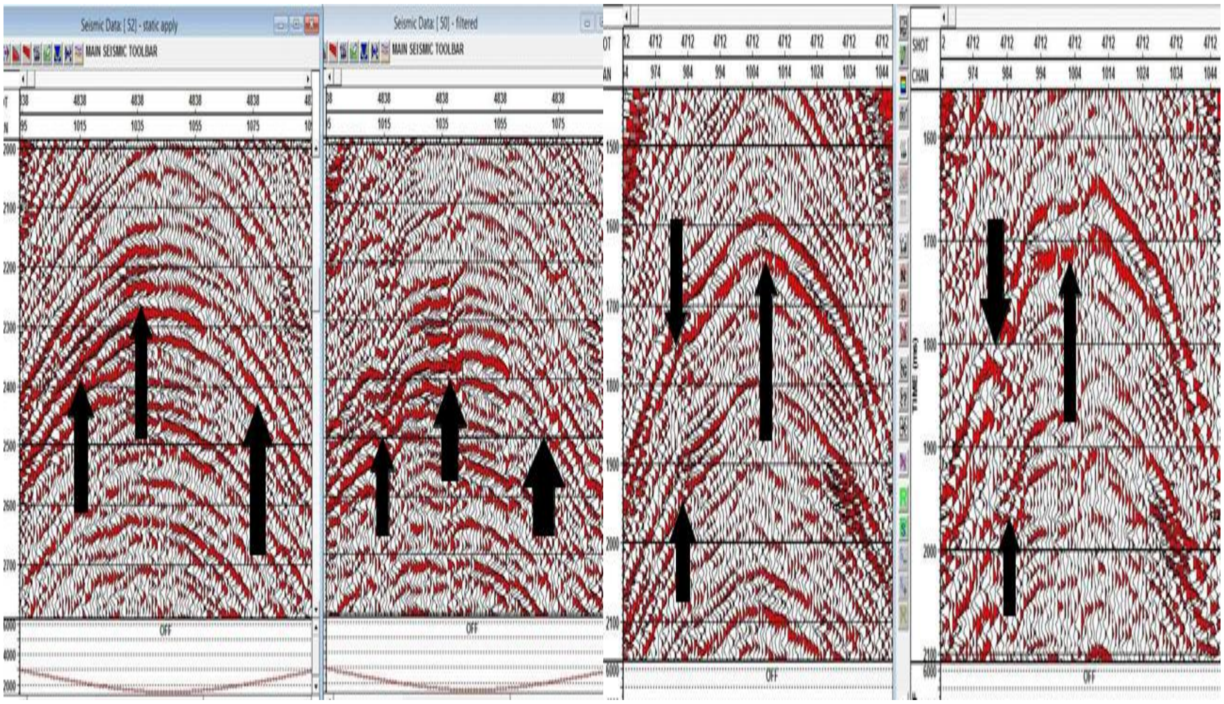


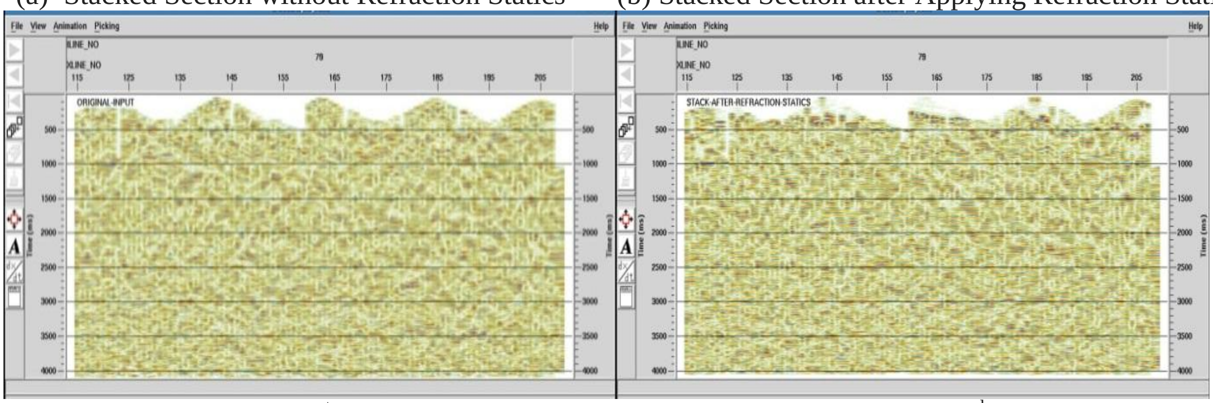
Figure 4.25: Juxtaposed view of partial statics corrected shot (left) and uncorrected shot (right) for shot gather 4838 and 4712 respectively showing the impact of their derived and implemented statics (From Opara et al., 2017 and 2018).

This superior result achieved at this processing stage of the present study is attributed to the more accurate and robust near-surface modeling algorithm we adopted (for the study) upon which the refraction statics solution was sought, derived and applied.

4.4.2 Derived Refraction Statics Solution applied to Stacked Section

After the demonstration of the effectiveness of the derived and applied refraction statics solution on the shot gathers, a further step was taken by stacking the data. Stacking is basically a data compression procedure. The approach adopted was the common midpoint (CMP) stack, which sums all offsets of a CMP gather into one block trace. To demonstrate the effectiveness of the derived refraction statics solution, we displayed a stacked CMP in a specific in-line direction without any form of refraction statics correction applied and then we applied the derived refraction statics solution to the data and stacked. After stacking, the same in-line was equally extracted and displayed, to mirror the same events to see how the refraction statics solution has improved the alignment of reflection events and overall data quality of the stacked section. Figure 2.26 (a) shows a stacked section (in-line 79) without refraction statics, (b) shows the stacked section after the application of the derived refraction statics solution. The (c) part shows the stacked section after 1st residual statics and (d) the same stacked section after 2nd residual statics.

(a) Stacked Section without Refraction Statics (b) Stacked Section after Applying Refraction Statics



(c) Stacked Section after 1st Residual statics (d) Stacked Section after 2nd Residual statics

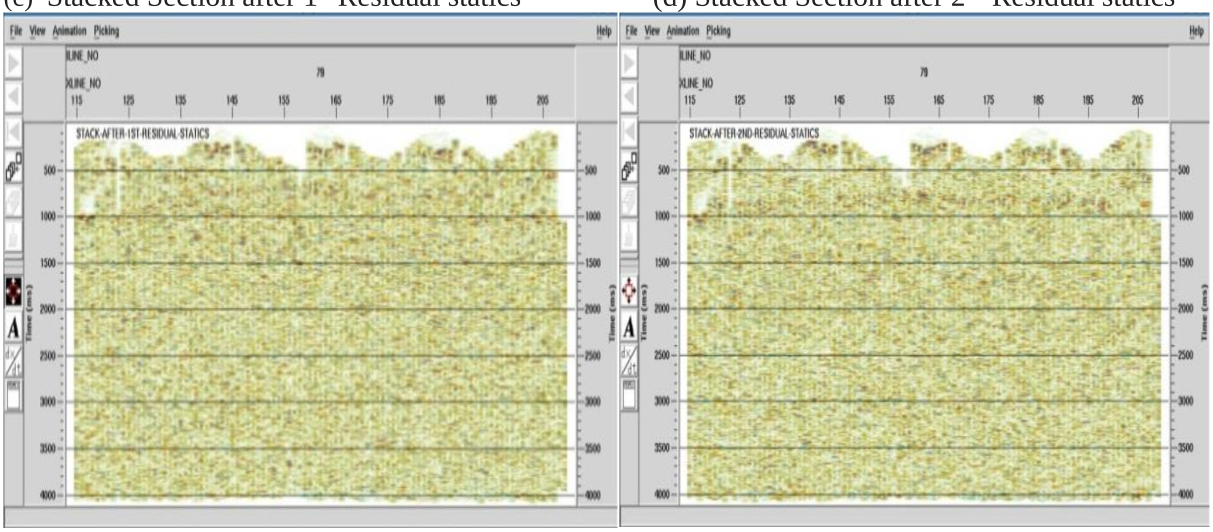


Figure 4.26: Selected slides showing stacked section without refraction statics (a), stacked section after the application of refraction statics (b), the stacked section after 1st residual statics (c) and the same stacked section after 2nd residual statics(d)

On first examination of Figure 4.26, the problems of refraction statics which have been resolved after the derived refraction statics solution was applied may not be easily seen by aninexperienced (novice) seismic data processor/interpreter. This now makes Figure 4.27 (a) and (b) more instructive as efforts have now been made to enlarge the already presented stacked section with annotations and markers inscribed to reveal areas were the stacked section has improved in its resolution as a result or consequence of the applied refraction statics solution as well as the 1st and 2nd residual statics corrections.

(a) Refraction statics problem is resolved as reflectors are moved backed to their actual positions

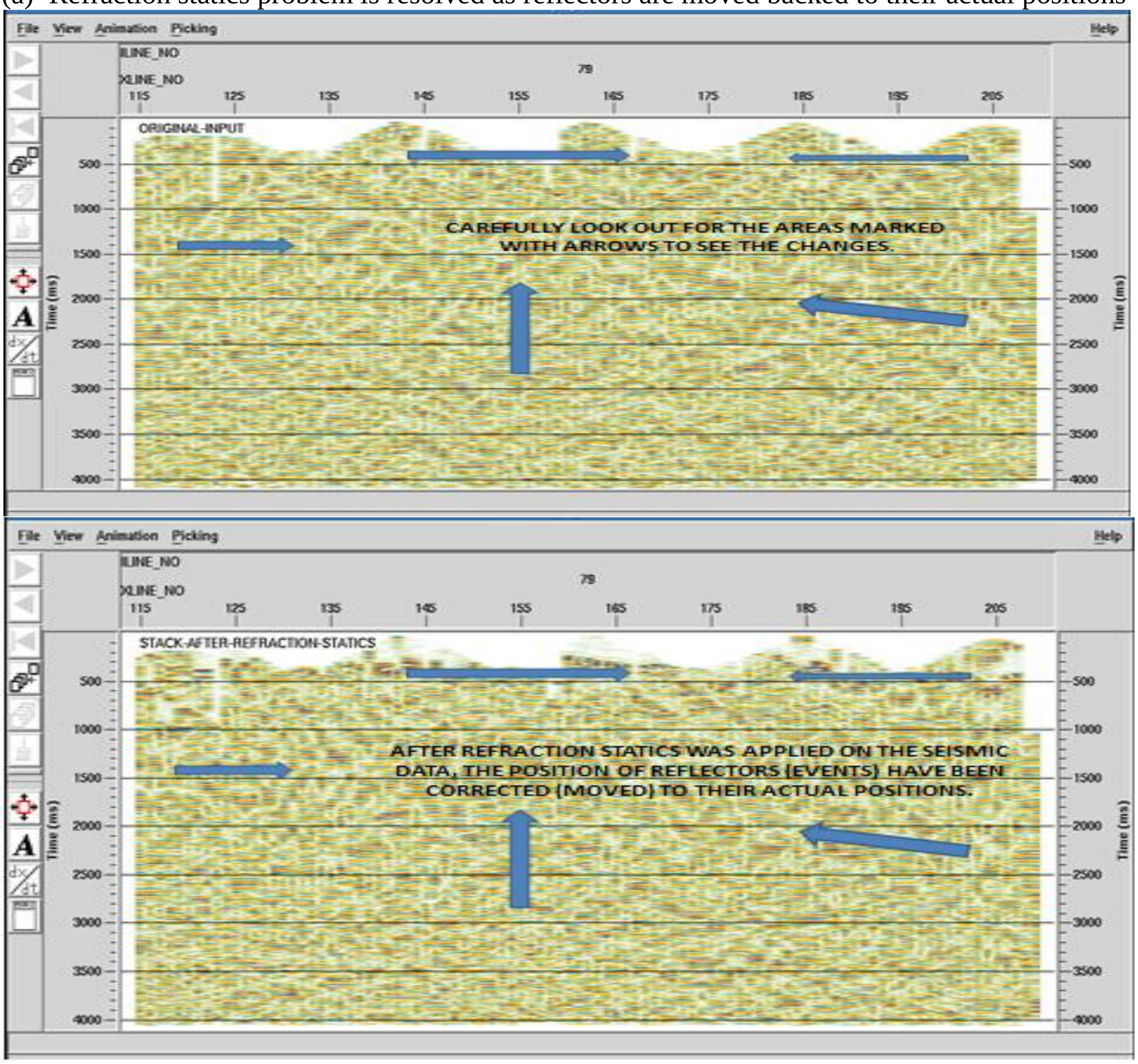


Figure 4.27: (a) Selected slides showing with marked arrows and annotation of the resultant effect of the applied refraction statics solution on the stacked seismic section.

(b) Remaining refraction statics problems are resolved with 1st and 2nd Residual Statics integrated into the refraction statics solution

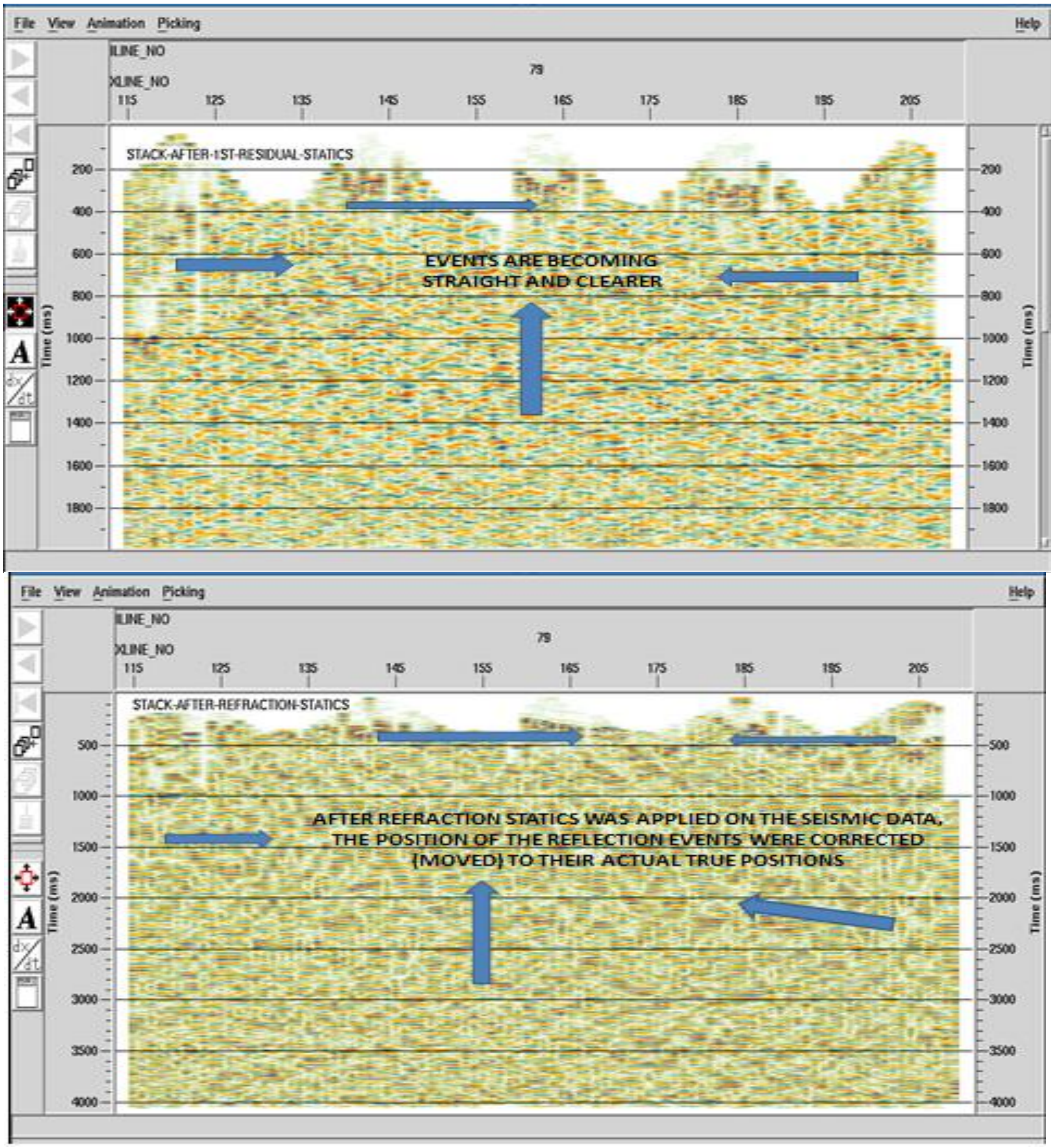
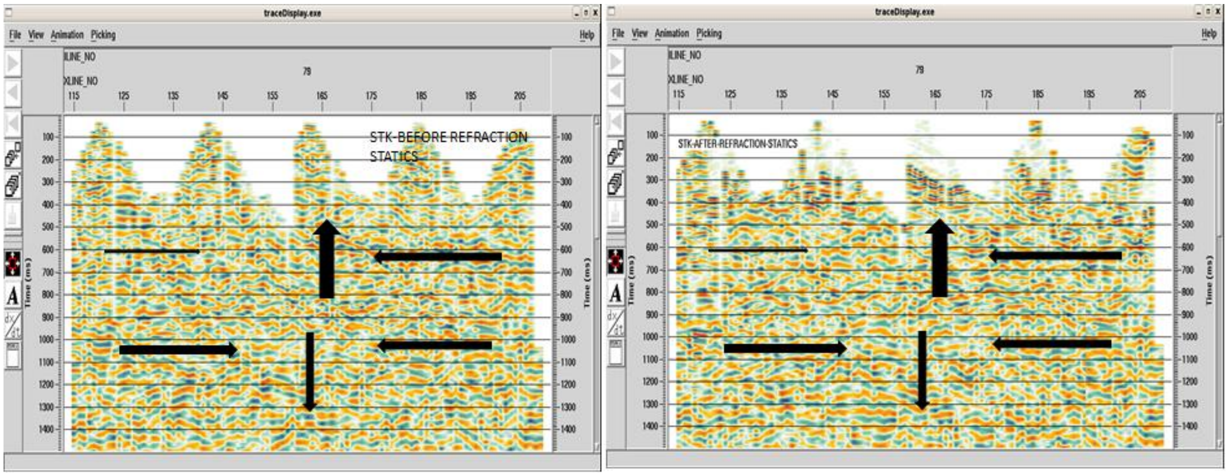


Figure 4.27(b): Selected slides showing with marked arrows and annotation of the resultant effect of 1st and 2nd residual statics correction added to the already applied refraction statics solution on the same stacked seismic section.

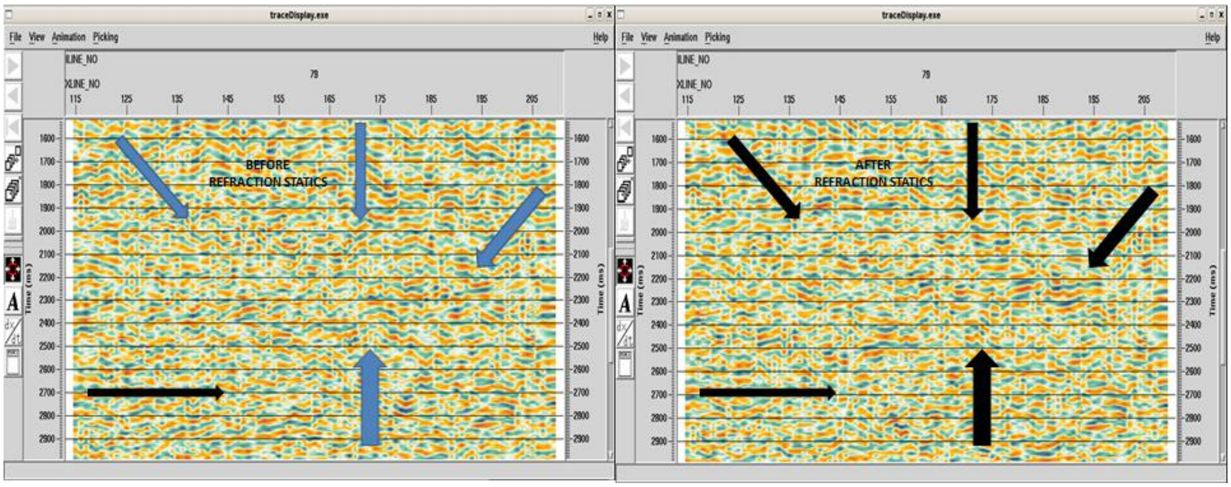
On close examination of the original input; the stacked section without refraction statics solution applied, spurious reflections or events at positions that are not true representation of the geology of the area being imaged are seen. After refraction statics was applied as seen on the stack after refraction statics, events occurring at 500ms, 1500ms and 2000ms are seen to align properly and are exhibiting better continuity. This is a positive indication that the derived and applied refraction statics solution is the most appropriate for the SOKU prospect, and more importantly, that the solution is surface consistent. Similarly, on close examination of the section after 1st and 2nd residual statics correction (Figure 4.27 (b)), it is equally observed that events (reflectors/refractors) are more straight or continuous and certain portions of the stacked sections with strong pseudo amplitudes (energy) were tapered to their actual amplitudes, thus improving the reliability and integrity of the dataset. This type of stacked section is the most desirable (input data type) for QC checks and detailed interpretation.

Our conviction that the derived and applied refraction statics solution has tremendously improved the data quality and integrity of the stacked section is further supported in Figure 4.28 in which a final step which entailed decomposition of the stacked section into time frame displays of (0 – 1.5 seconds), (1.5 – 3 seconds) and (3 – 4 seconds) was extracted and displayed for this corrections to be made more visible in support of the assertion that the derived refraction statics solution as presented is the optimal solution to address the statics challenge for SOKU.The (a) part of Figure 4.25 represents the stacked section display before and after statics correction at time frame (0 – 1.5 seconds), the (b) part is the display for time frame (1.5 – 3 seconds) while the (c) part is for time frame (3 – 4 seconds)

(a) Stacked section before and after implementing refraction statics for time frame (0 - 1.5 seconds)



(b) Stacked section before and after implementing refraction statics for time frame (1.5 - 3 seconds)



(c) Stacked section before and after implementing refraction statics for time frame (3 - 4 seconds)

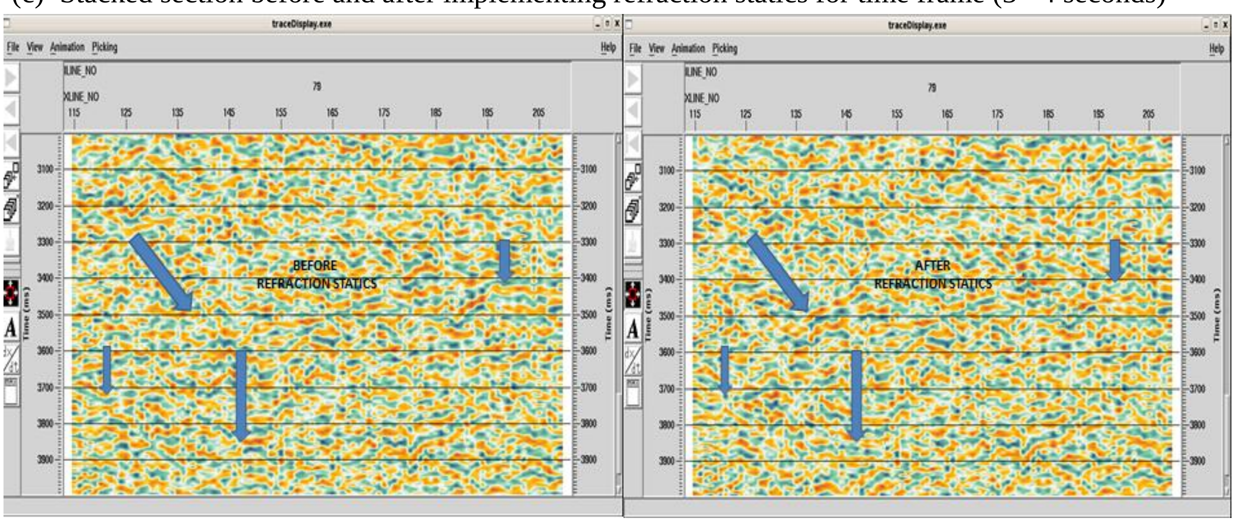


Figure 4.28: Decomposed/Time stretched slides of stacked section before and after application of refraction statics. Time frame of 0–1.5 seconds is shown in (a), Time frame 1.5–3.0 seconds in (b) and Time frame 3–4 seconds in (c). The effects of refraction static are now very evident and clearly visible.

4.3.3 Derived Refraction Statics Solution applied in Migrated Section

Migration of seismic data is a crucial (if not the most) important processing stage in the seismic data processing workflow, it is performed to move dipping events to their correct positions, collapse diffractions and increase the spatial resolution of the data being processed. Migration is a technology driven (dependent) procedure and could be achieved in time or depth domains. Computer power, time factor, resources and peculiarity of acquired datasets are key variables to consider when deploying a migration method/type. A time migration algorithm (an Explicit Finite Difference 3D Time Method, FX (Explicit) Type) was applied. This choice was guided by the processing power of our workstation, time, data specifications or peculiarity and the fact that time migration routines are relatively less complex to perform than depth migration routines.

The migration algorithm on Promax™ used explicit F – XY spatially – variant extrapolators to perform time migrationfor the 3D seismic dataset. The migration caters for complex dips up to a maximum of 70 degrees. The migration used a vertical and spatially – variant interval velocity field in time, $V_{int}(x, y, t)$ as input. The deployed migration type is modern with a high degree of accuracy in achieving successes for time migration procedures. It solves the wave equation by applying spatially varying convolution operators in the F-X domain. Figure 4.29 is a time migrated stacked section of the area under consideration (in-line 79) without refraction statics implementation.

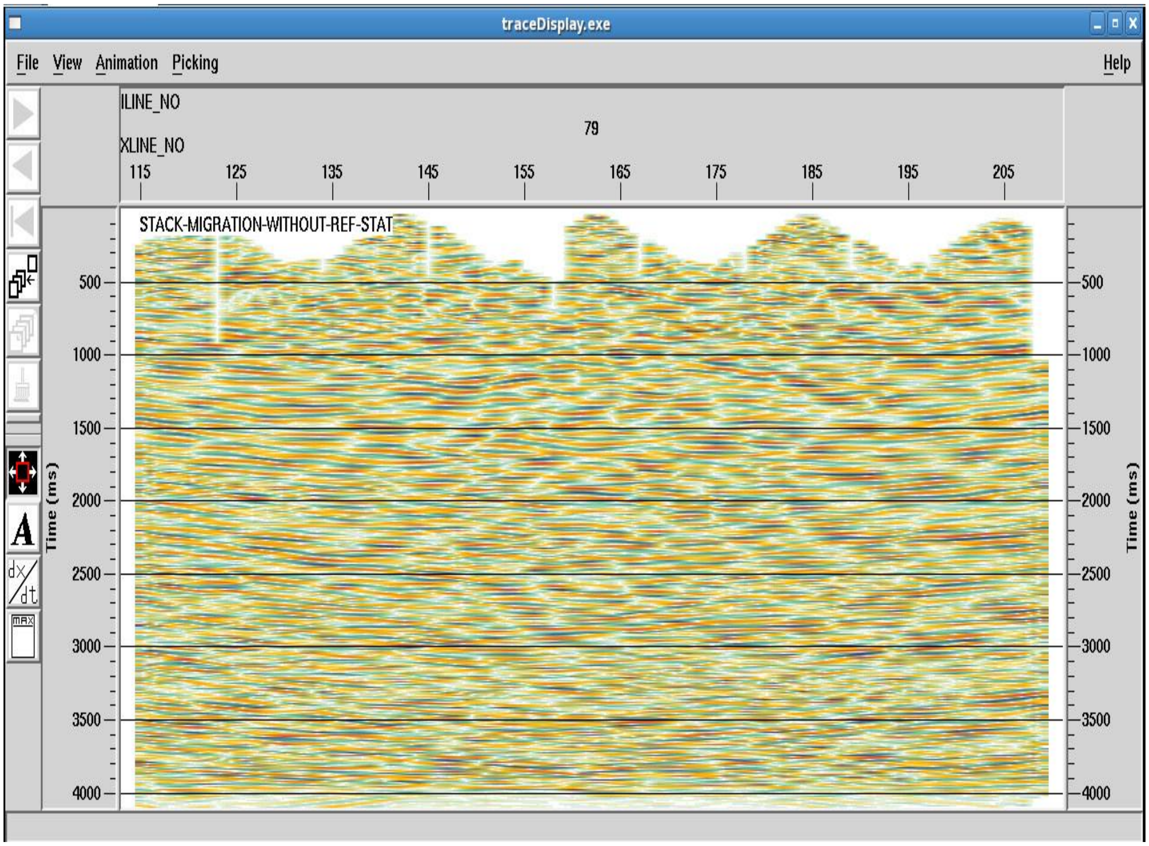


Figure 4.29: Migrated stacked seismic section without the application of refraction statics

Figure 4.30 is a time decomposed display of the migrated stacked section in intervals of 0 – 1 seconds, 1 – 2 seconds and 3 – 4 seconds for a clearer view of reflection events.

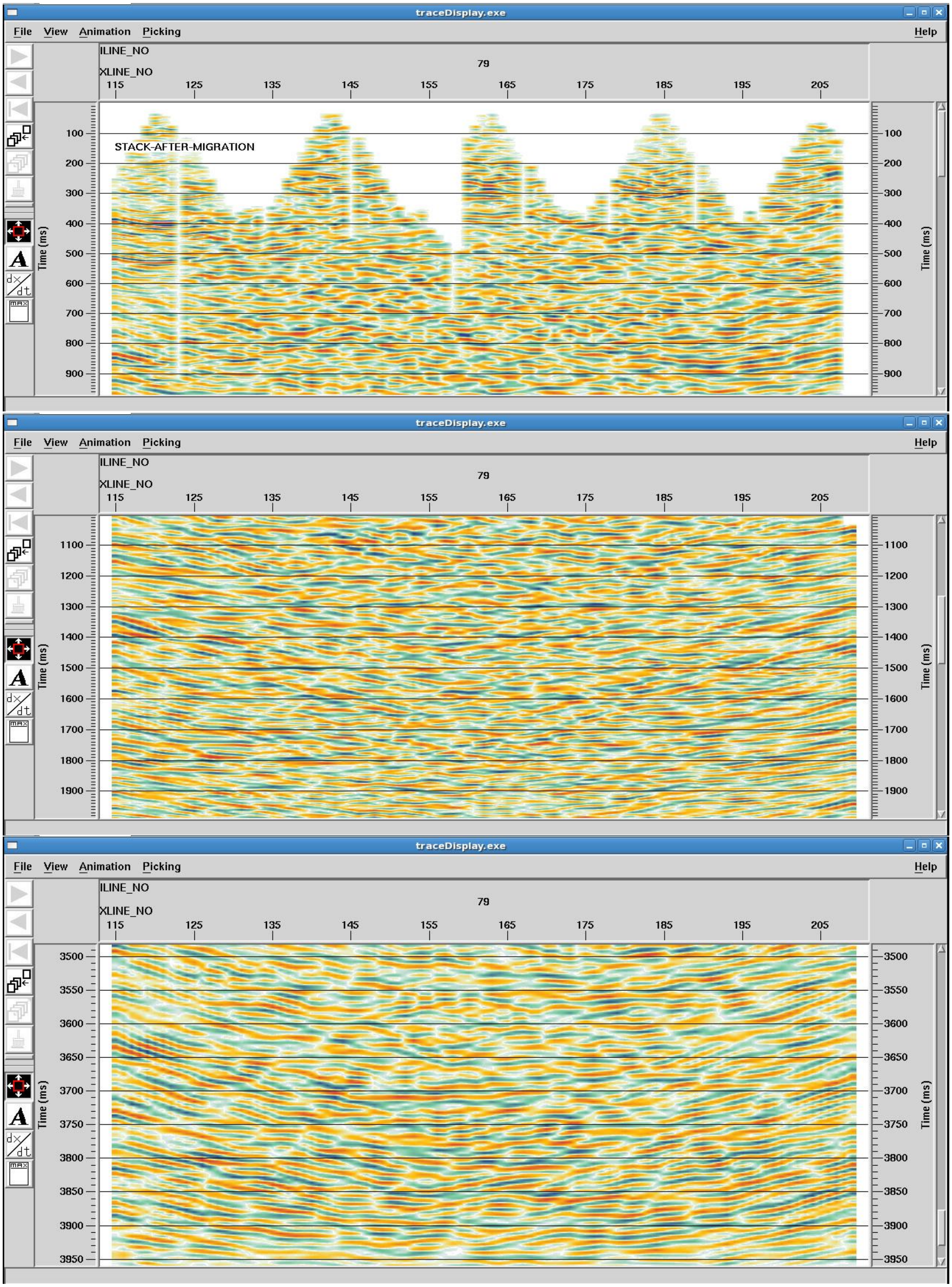


Figure 4.30: Stacked seismic section after migration decomposed into time frames to improve lateral and temporal resolution but without the application of refraction statics.

Figure 4.31 is also a time decomposed display of the same section within the same time interval but after the derived refraction statics solution was implemented then followed by migration.

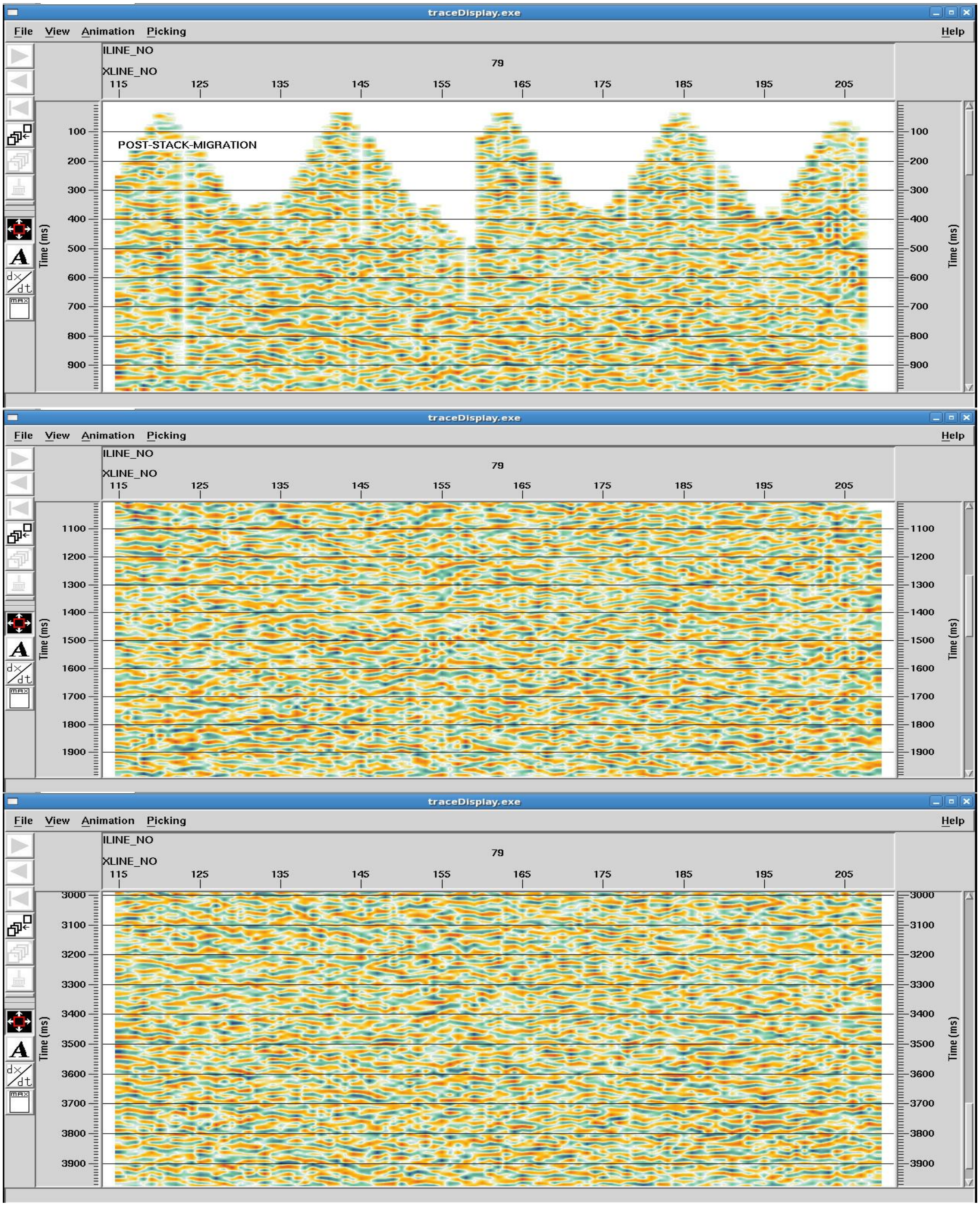


Figure 4.31: Stacked seismic section after migration decomposed into time frames to improve lateral and temporal resolution after the application of refraction statics

Upon close examination, it is observed that the imaging quality (spatial and temporal resolution, reflectors continuity and true amplitude display) has remarkably improved on the migrated stacked section (post migration display) after the refraction statics solution was applied. This equally, is an indication that the refraction statics solution derived for SOKU was optimal and has satisfactorily addressed the statics problem for the prospect. Figure 4.32 is a juxtaposed display of the before and after results achieved in the migration stage of the processing sequence to further buttress our present position.

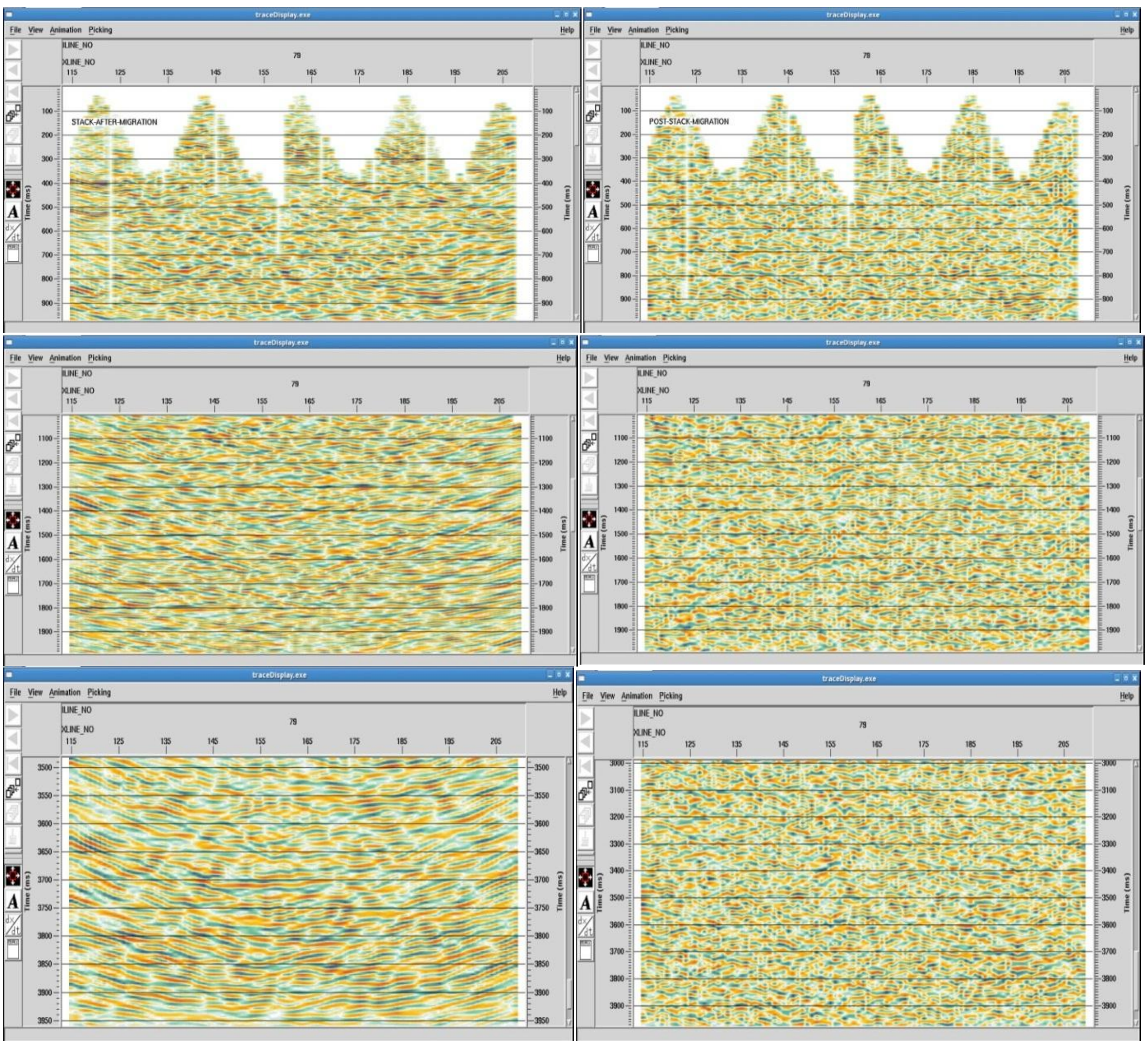


Figure 4.32: Migrated seismic sections before and after application of refraction static juxtaposed for easy assessment of the effectiveness of the derived and applied refraction statics solution.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 Summary

Staticscorrection involves basically a constant timeshiftoftheseismictrace, as opposed to dynamic correction, which involves a set of time variable shifts. As with most seismic data processing steps, staticscorrectionrepresents a slight simplification to physical reality. That notwithstanding, statics corrections have a dramatic effect on the final quality of the seismic section if derived and applied carefully as have been demonstrated for the SOKU dataset in this dissertation.Staticscorrection isimportantin theseismicprocessing sequence due toanumber of reasons;

i) They place source and receiver atacommon datum orplane.

ii) Theyensure that reflection events on intersecting lines willbeat thesame time which tackles the problem of mis-ties of reflection events on the seismic section.

iii) They improve the quality of other key processing steps like velocity analysis, stacking and migration.

The effectiveness of applying a properly derived refraction statics solution (statics correction) in the overall 3D seismic data processing flow has been demonstrated in three key dimensions; on the seismic shot gathers, on a stacked section of the seismic section and finally on a migrated section of the data. It is pertinent to note that no one method in itself can solvethe completestatics problem. In the pre-digital era of seismic data processing, field statics and datum statics were considered as complete solutions to resolve statics problems on seismic data. This view however, changed when refraction statics and residual statics programs evolved. The consensus point to be reiterated is that each method has its own place in adding to the complete statics solution. In this study, we deployed all these approachesin arriving at the comprehensive solution which wasapplied in solving the statics problem of OML-23, SOKU. The field statics supplied the solution that resolved the elevation, near-surface inhomogeneity and a part of the long wavelength and short wavelength components of the statics problem,the refraction statics resolved bulk of the long wavelength and short wavelength component of the statics problem, while the residual statics addressed the remnant long and short wavelength components of the statics problemwhich the refraction statics alone could not resolve. It was by the iteration of these methods that the geological model of the subsurface was obtained which is strongly believed to be in close agreement with the actual geology of the SOKU area. It is only such valid geological model that can be interpreted for possible hydrocarbon accumulations with a high degree of accuracy.

5.2 Conclusion

The refractions extracted from a reflection survey (first-breaks) was inverted jointly with up-hole measurements using a special plugin and algorithm to image and characterize the uppermost 400 – 500 m (the near-surface) of the prospect (OML-23 SOKU), in terms of weathering and sub-weathering layer thicknesses and velocities. The obtained near-surface model was subsequently used to derive refraction statics solution for the SOKU dataset to address the identified statics problem of the area. The effectiveness of the derived refraction statics solution was evident as already demonstrated. The impact of the derived and applied refraction statics solution was first shown for shot gathers in their respective Field File Identification (FFID) arrays. Subsequently, it was demonstrated for the stacked section of the seismic data and finally on the migration result of the processing sequence affirming the effectiveness of the derived and applied refraction statics solution. The impact of the solution was remarkable and evident as reflection events were beginning to have greatercontinuity and generalflatness.Our conclusion therefore, is that, therefraction statics solution for the prospect (OML-23, SOKU) was derivedto a reasonablehigh degree of accuracy.Thisposition wassupported bythebefore (without refraction statics applied) and after (with refraction statics applied) appearanceoftheshot gathers, final stacked section and the migrated sections.The derived and implemented refraction statics solution hastherefore successfully solved the statics problem of SOKU as it corrected for apparent reflection times on the sections displayed. It has equally enhanced the continuityof reflection events andhasreinforced the true amplitudes of the reflection events for a better energy focus.

5.3 Recommendation

The aim and target objectives of this dissertation have all be accomplished, however, it is necessary to note certain points which we wish to put forward as recommendations for those interested in this line of research. The recommendations are;

i) Travel-time inversion has an inherent non-uniqueness problem as is the case with all geophysical techniques, for this non-uniqueness problem to be minimal depends largely onthequalityof thepickedfirstarrivalsandthedegreeofnear-surface lateral velocityvariations. Hence, caution shouldbeappliedinpickingsucharrivals toensureaccuracyandconsistency, which by extension would result to amore realistic near-surface model.

ii) It is recommended that for a more thorough and exhaustive investigation of the subjectmatter, the tomographic/tomostatics near-surface modeling approach isimplemented and compared with the approach we have deployed. The models obtained could complement each other when in agreement or could be averaged when they vary.

iii) Similarly, for the migration stage of our study, we recommend that a depth migration algorithm be deployed as more structural features,perhaps, would be revealed and it would be much easier to relate with depth than time if the end goal is for the interpretation and identification of potential reservoirs. This approach would however be more expensive and couldtake as long as 10 times more in seismic processing turnaround time to achieve.

5.4 Contribution to Knowledge

The dissertation has successfully solved the refraction statics (statics correction) problem of OML-23 SOKU. In the course of the study, we have arrived at some positions that we feel will become contributions to the pool of knowledge;

i) From available published literatures, this could be the first documented (pioneering)research on the subject of deriving a refraction statics solution, and applying same to seismic data up to the stacking and migration stages to demonstrate the effectiveness of the derived and applied statics solution in the Niger Delta Basin.

ii) An integrated (new hybrid) algorithm of iteratively combining both refracted arrival inversion with uphole measurements, have been deployed in this study, to build a very robust and more reliable near-surface model, which was subsequently used to derive and implement the statics.

iii) This study has successfully shown the impact and role of the derivation of refraction statics solution in enhancing the seismic imaging process, from shot gathers – stacked section – migrated section of datasets in this single but comprehensive study.

iv) Processing parameters, strategies and workflow have been carefully documented in the dissertation. These processing workflows would form a pool of resource that could be used for future related work. Consequently, research journal articles (papers) on the successes achieved at the different stages of the dissertation have been published in reputable peer reviewed journals and now serve as reference materials for the global research community.

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Appendix

SOURCE INDEX FILE (SPS) (A Full Listing of Source Index File for Dynamite Shots)

```
H00 Sps format version num.     SPS003,13.10.10;
H01 Description of survey area  NIGERIA,XXXX,(SOKU,OML23);
H02 Date of survey              X.X.XXXX,X.X.XXXX;
H021Post-plot date of issue     00.00.XXXX;
H022Tape/disk identifier        3D-SOKU-10;
H03 Client                      XXXXXXXX;
H04 Geophysical contractor      XXXX/XXX Crew XXXX;
H05 Positioning contractor      XXXX/XXX Crew XXXX;
H06 Pos. proc. contractor       XXXX;
H07 Field computer system(s)    SN408 XL Software V6.1,SN408+Link,DOS disks;
H08 Coordinate location         Center of source and receiver patterns;
H09 Offset to coord. location   0.0m;
H10 Clock time w.r.t  GMT       +1;
H11 Swath No.                   Swath 11;
H12 Geodetic datum,-spheroid    Minna Datum,84,Clarke 1880,6378249.145,293.46500
H13 Spare                       ;
H14 Geodetic datum parameters   111.916 87.852 -114.499 -1.875-0.202-0.219-0.032
H15 Spare                       ;
H16 Spare                       ;
H17 Vertical datum description  Nigeria Lagos;
H18 Projection type             Transverse Mercator(t.m.);
H19 Projection zone             Nigeria Mid Belt;
H20 Description of grid units   Meter;
H201Factor to metres            1.00000000;
H220Long. of central meridian   0083000.000E;
H231Grid origin                 0040000.000N0083000.000E
H232Grid coord.at origin       0670553.98E      0.00N;
H241Scale factor                0.9997500000;
H242Lat., long. scale factor    0040000.000N0083000.000E;
H256LAT., LONG. INITIAL LINE    0040000.000N 083000.000E0140000.000N0083000.000E
H257CIRCULAR BEARING OF H256    0000000.0000
H258QUADRANT BEARING OF H256    N000000.000S
H259ANGLE FROM SKEW             0000000.0000
H26 PM,DEFINITION OF CODES
H26 SA: SATELLITE PT. PM: PERMA NENT MARKER
H26 PROSPECT GRID ORIGIN        13374696(X:449924.4,Y:62754.8);
H26 SOURCE, RECEIVER DIGIT      4,4
H26 RCV,SRC LINE INCREMENT      350,400;
H26 RCV,SRC POINT INCREMENT     50,50;
H30 Project code and descriptionSOKU OML 23,S3D;
H31 Line number format          Block(1:6),Strip(7:4),Line Number(12:5);
H400Type,model,polarity         1,SN408XL+Link,CM408,SEG;
H401Crew name,comment           1,XXXX/XXX Crew XXXX(Seismic 3);
H402Sample int.,record len.     1,2.00 MSEC, 8.00 SEC;
H403Number of channels          1,1440;
H404Tape type,format,density    1,IBM 3590 Cartridge, SEG-D 8058, 75742;
H405Filter_alias hz,db pnt,slope1,200 HZ, 3.00 DB, 84.00 DB/OCT;
H406Filter_notch hz,-3db points 1,Out, None;
H407Filter_low hz,db pnt,slope  1,Out, None;
H408Time delay FTB-SOD app Y/N  1,0.00 Msec, Not Applied;
H409Multi component recording   1,Z;
H410Aux. channel 1 contents     1,50Hz;
H411Aux. channel 2 contents     1,Uphole Time;
H412Aux. channel 3 contents     1,Confirmation TB;
H413Aux. channel 4 contents     1,TB;
H600Type,model,polarity         G1,Marsh,JFS-1,20DX,SEG;
H26 Type of Receiver points     G1,18 geophones in 2 strings in 4D;
H601Damp coeff,natural freq.    G1,0.7,10HZ;
H602Nunits,len(x),width(y)      G1,18,47.26m,00m;
H603Unit spacing x,y            G1,2.78m,00m;
H610Type,model,polarity         G2,Marsh,JFS-1,20DX,SEG;
H26 Type of Receiver points     G2,Bunched Geophone in 4D;
H611Damp coeff,natural freq.    G2,0.7,10HZ;
H612Nunits,len(x),width(y)      G2,18,00m,00m;
H613Unit spacing x,y            G2,00m,00m;
H620Type,model,polarity         H1,Hydrophone,MP24-13,SEG;
H26 Type of Receiver points     H1,single hydrophone in 4D;
H621Damp coeff,natural freq.    H1,None,10Hz;
H622Nunits,len(x),width(y)      H1,1,00m,00m;
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H623Unit spacing x,y           H1,00m,00m;
H630Type,model,polarity        G3,Marsh,JFS-1,20DX,SEG;
H26 Type of Receiver points    G3,18 geophones in 2 strings in 3D;
H631Damp coeff,natural freq.   G3,0.7,10HZ;
H632Nunits,len(x),width(y)     G3,18,47.26m,00m;
H633Unit spacing x,y           G3,2.78m,00m;
H640Type,model,polarity        G4,Marsh,JFS-1,20DX,SEG;
H26 Type of Receiver points    G4,Bunched Geophone in 3D;
H641Damp coeff,natural freq.   G4,0.7,10HZ;
H642Nunits,len(x),width(y)     G4,18,00m,00m;
H643Unit spacing x,y           G4,00m,00m;
H650Type,model,polarity        H2,Hydrophone,MP24-13,SEG;
H26 Type of Receiver points    H2,single hydrophone in 3D;
H651Damp coeff,natural freq.   H2,None,10Hz;
H652Nunits,len(x),width(y)     H2,1,00m,00m;
H653Unit spacing x,y           H2,00m,00m;
H700Type,model,polarity        E1,Explosive,Seismex,SEG;
H26 Type of shot points        E1,30m single deep hole in 4D;
H701Size,vert. stk fold        E1,2000g,1;
H702Nunits,len(x),width(y)     E1,1,00m,00m;
H703Unit spacing x,y           E1,00m,00m;
H711Nom. shot depth,charge len. E1,42m,0.15m;
H712Nom. soil,drill method     E1,Clay Silt Sand;Flushing;
H713Weathering thickness       E1,1.5-7m;
H720Type,model,polarity        E2,Explosive,Seismex-1,SEG;
H26 Type of shot points        E2,5*6m linear pattern in 4D;
H721Size,vert. stk fold        E2,2000g,1;
H722Nunits,len(x),width(y)     E2,5,40m,00m;
H723Unit spacing x,y           E2,10m,00m;
H731Nom. shot depth,charge len. E2,6m,0.15m;
H732Nom. soil,drill method     E2,Clay Silt Sand;Flushing;
H733Weathering thickness       E2,1.5-7m;
H740Type,model,polarity        E3,Explosive,Seismex,SEG;
H26 Type of shot points        E3,5*3.5m linear pattern in 4D;
H741Size,vert. stk fold        E3,2000g,1;
H742Nunits,len(x),width(y)     E3,5,40m,00m;
H743Unit spacing x,y           E3,10m,00m;
H751Nom. shot depth,charge len. E3,3.5m,0.15m;
H752Nom. soil,drill method     E3,Clay Silt Sand;Thumping;
H753Weathering thickness       E3,1.5-7m;
H760Type,model,polarity        E4,Explosive,Seismex,SEG;
H26 Type of shot points        E4,5*3.5m circular pattern in 4D;
H761Size,vert. stk fold        E4,2000g,1;
H762Nunits,len(x),width(y)     E4,5,00m,00m;
H763Unit spacing x,y           E4,00m,00m;
H771Nom. shot depth,charge len. E4,3.5m,0.15m;
H772Nom. soil,drill method     E4,Clay Silt Sand;Thumping;
H773Weathering thickness       E4,1.5-7m;
H780Type,model,polarity        E5,Explosive,Seismex,SEG;
H26 Type of shot points        E5,5*6m circular pattern in 4D;
H781Size,vert. stk fold        E5,2000g,1;
H782Nunits,len(x),width(y)     E5,5,00m,00m;
H783Unit spacing x,y           E5,00m,00m;
H791Nom. shot depth,charge len. E5,6m,0.15m;
H792Nom. soil,drill method     E5,Clay Silt Sand;Flushing;
H753Weathering thickness       E5,1.5-7m;
H800Type,model,polarity        E6,Explosive,Seismex,SEG;
H26 Type of shot points        E6,42m single deep hole in 3D;
H801Size,vert. stk fold        E6,2000g,1;
H802Nunits,len(x),width(y)     E6,1,00m,00m;
H803Unit spacing x,y           E6,00m,00m;
H811Nom. shot depth,charge len. E6,42m,0.15m;
H812Nom. soil,drill method     E6,Clay Silt Sand;Flushing;
H813Weathering thickness       E6,1.5-7m;
H820Type,model,polarity        E7,Explosive,Seismex,SEG;
H26 Type of shot points        E7,5*6m linear pattern in 3D;
H821Size,vert. stk fold        E7,2000g,1;
H822Nunits,len(x),width(y)     E7,5,40m,00m;
H823Unit spacing x,y           E7,10m,00m;
H831Nom. shot depth,charge len. E7,6m,0.15m;
H832Nom. soil,drill method     E7,Clay Silt Sand;Flushing;
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H833Weathering thickness        E7,1.5-7m;
H840Type,model,polarity         E8,Explosive,Seismex,SEG;
H26 Type of shot points         E8,5*3.5m linear pattern in 3D;
H841Size,vert. stk fold         E8,2000g,1;
H842Nunits,len(x),width(y)      E8,5,40m,00m;
H843Unit spacing x,y            E8,10m,00m;
H851Nom. shot depth,charge len. E8,3.5m,0.15m;
H852Nom. soil,drill method      E8,Clay Silt Sand;Thumping;
H853Weathering thickness        E8,1.5-7m;
H860Type,model,polarity         E9,Explosive,Seismex,SEG;
H26 Type of shot points         E9,5*3.5m circular pattern in 3D;
H861Size,vert. stk fold         E9,2000g,1;
H862Nunits,len(x),width(y)      E9,5,00m,00m;
H863Unit spacing x,y            E9,00m,00m;
H871Nom. shot depth,charge len. E9,3.5m,0.15m;
H872Nom. soil,drill method      E9,Clay Silt Sand;Thumping;
H873Weathering thickness        E9,1.5-7m;
H800Type,model,polarity         A1,Sleevegun,MK2,SEG;
H26 Type of Airgun              A1,Airgun shot,taken 12.5m eachside of peg in 4D
H881Size,vert. stk fold         A1,460 CU IN,1;
H882Nunits,len(x),width(y)      A1,5,40m,0m;
H886P-P Bar/m,Prim/Bubble       A1,22.2MPa.m,9.1;
H887Air Pressure PSI            A1,2000PSI;
H888NO. SUB ARRAYS,NOM DEPTH    A1,4,2.0M;
H880Type,model,polarity         A2,Sleevegun,MK2,SEG;
H26 Type of Airgun              A2,Airgun shot,taken at the peg position in 4D;
H891Size,vert. stk fold         A2,670 CU IN,1;
H892Nunits,len(x),width(y)      A2,5,40m,0m;
H896P-P Bar/m,Prim/Bubble       A2,35.1MPa.m,18.4;
H897Air Pressure PSI            A2,2000PSI;
H898NO. SUB ARRAYS,NOM DEPTH    A2,4,2.0M;
H900Type,model,polarity         A3,Sleevegun,MK2,SEG;
H26 Type of Airgun              A3,Airgun shot,taken 12.5m eachside of peg in 3D
H901Size,vert. stk fold         A3,460 CU IN,1;
H902Nunits,len(x),width(y)      A3,5,40m,0m;
H9036P-P Bar/m,Prim/Bubble      A3,22.2MPa.m,9.1;
H904Air Pressure PSI            A3,2000PSI;
H905NO. SUB ARRAYS,NOM DEPTH    A3,4,2.0M;
H910Type,model,polarity         A4,Sleevegun,MK2,SEG;
H26 Type of Airgun              A4,Airgun shot,taken at the peg position in 3D;
H911Size,vert. stk fold         A4,670 CU IN,1;
H912Nunits,len(x),width(y)      A4,5,40m,0m;
H913P-P Bar/m,Prim/Bubble       A4,35.1MPa.m,18.4;
H915Air Pressure PSI            A4,2000PSI;
H916NO. SUB ARRAYS,NOM DEPTH    A4,4,2.0M;
H990R,s,x file quality control  XXXXXXXXX,1830,XXXXXXX;
H991Co-ord. status final/prov   Final,XXXXXXXXX,2000,XXXXXX;
S2185               55981E1                   472474.4   83954.8      147114433
S2233               56761E1                   474424.4   85154.8      147114622
S2489               55961E1                   472424.4   91554.8      147114701
S2265               56241E1                   473124.4   85954.8      147114746
S2505               55961E1                   472424.4   91954.8      147114835
S2145               56201E1                   473024.4   82954.8      147114909
S2185               56021E1                   472574.4   83954.8      147114932
S2169               56181E1                   472974.4   83554.8      147115005
S2489               55981E1                   472474.4   91554.8      147115029
S2233               56701E1                   474274.4   85154.8      147115114
S2265               56261E1                   473174.4   85954.8      147115338
S2505               55981E1                   472474.4   91954.8      147115356
S2185               56041E1                   472624.4   83954.8      147115431
S2277               57561E1                   476424.4   86254.8      147115508
S2489               56001E1                   472524.4   91554.8      147115527
S2169               56401E1                   473524.4   83554.8      147120043
S2233               56601E1                   474024.4   85154.8      147121314
S2265               56281E1                   473224.4   85954.8      147121345
S2505               56021E1                   472574.4   91954.8      147121429
S2281               57541E1                   476374.4   86354.8      147121524
S2587               57241E1                   475624.4   94004.8      147121607
S2489               56021E1                   472574.4   91554.8      147121739
S2233               56541E1                   473874.4   85154.8      147121801
S2505               56041E1                   472624.4   91954.8      147124040
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S2217	56361E1	473424.4	84754.8	147124252
S2201	55981E1	472474.4	84354.8	147124335
S2585	57221E1	475574.4	93954.8	147124411
S2489	56041E1	472624.4	91554.8	147124443
S2233	56521E1	473824.4	85154.8	147124526
S2265	56321E1	473324.4	85954.8	147124609
S2505	56061E1	472674.4	91954.8	147124626
S2217	56321E1	473324.4	84754.8	147124653
S2489	56061E1	472674.4	91554.8	147124758
S2265	56361E1	473424.4	85954.8	147130158
S2201	56021E1	472574.4	84354.8	147130244
S2163	56261E1	473174.4	83404.8	147130425
S2233	56261E1	473174.4	85154.8	147130542
S2489	56081E1	472724.4	91554.8	147130604
S2505	56081E1	472724.4	91954.8	147130713
S2219	57161E1	475424.4	84804.8	147130839
S2489	56101E1	472774.4	91554.8	147131152
S2233	56241E1	473124.4	85154.8	147131214
S2505	56101E1	472774.4	91954.8	147131353
S2215	57181E1	475474.4	84704.8	147131429
S2489	56121E1	472824.4	91554.8	147131504
S2265	56481E1	473724.4	85954.8	147131539
S2489	56141E1	472874.4	91554.8	147131655
S2265	56501E1	473774.4	85954.8	147131720
S2505	56121E1	472824.4	91954.8	147131741
S2489	56161E1	472924.4	91554.8	147131833
S2265	56561E1	473924.4	85954.8	147132110
S2489	56181E1	472974.4	91554.8	147132132
S2489	56201E1	473024.4	91554.8	147132545

SOURCE INDEX FILE (SPS) FOR AIRGUN SHOTS (A full listing for Air gun Shots)

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H00 Sps format version num.     SPS003,13.10.10;
H01 Description of survey area  NIGERIA,XXXXXXXXXX,SOKU,OML23;
H02 Date of survey              XX.XX.XXXX,XX.XX.XXXX;
H021Post-plot date of issue     00.00.2010;
H022Tape/disk identifier        3D-SOKU-10;
H03 Client                      XXXXXXXXX;
H04 Geophysical contractor      XXXX/XXX Crew XXXX;
H05 Positioning contractor      XXXX/XXX Crew XXXX;
H06 Pos. proc. contractor       XXXX;
H07 Field computer system(s)    SN408 XL Software V6.1,SN408+Link,DOS disks;
H08 Coordinate location         Center of source and receiver patterns;
H09 Offset to coord. location   0.0m;
H10 Clock time w.r.t  GMT       +1;
H11 Swath No.                   Swath 11;
H12 Geodetic datum,-spheroid    Minna Datum,84,Clarke 1880,6378249.145,293.46500
H13 Spare                       ;
H14 Geodetic datum parameters   111.916 87.852 -114.499 -1.875-0.202-0.219-0.032
H15 Spare                       ;
H16 Spare                       ;
H17 Vertical datum description  Nigeria Lagos;
H18 Projection type             Transverse Mercator(t.m.);
H19 Projection zone             Nigeria Mid Belt;
H20 Description of grid units   Meter;
H201Factor to metres            1.00000000;
H220Long. of central meridian   0083000.000E;
H231Grid origin                 0040000.000N0083000.000E
H232Grid coord.at origin       0670553.98E      0.00N;
H241Scale factor                0.9997500000;
H242Lat., long. scale factor    0040000.000N0083000.000E;
H256LAT., LONG. INITIAL LINE    0040000.000N 083000.000E0140000.000N0083000.000E
H257CIRCULAR BEARING OF H256    0000000.0000
H258QUADRANT BEARING OF H256    N000000.000S
H259ANGLE FROM SKEW             0000000.0000
H26 PM,DEFINITION OF CODES
H26 SA: SATELLITE PT. PM: PERMA NENT MARKER
H26 PROSPECT GRID ORIGIN        13374696(X:449924.4,Y:62754.8);
H26 SOURCE, RECEIVER DIGIT      4,4
H26 RCV,SRC LINE INCREMENT      350,400;
H26 RCV,SRC POINT INCREMENT     50,50;
H30 Project code and descriptionSOKU OML 23,S3D;
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H31 Line number format          Block(1:6),Strip(7:4),Line Number(12:5);
H400Type,model,polarity         1,SN408XL+Link,CM408,SEG;
H401Crew name,comment           1,XXXX/XXX Crew XXXX(Seismic 3);
H402Sample int.,record len.     1,2.00 MSEC, 8.00 SEC;
H403Number of channels          1,1440;
H404Tape type,format,density    1,IBM 3590 Cartridge, SEG-D 8058, 75742;
H405Filter_alias hz,db pnt,slope1,200 HZ, 3.00 DB, 84.00 DB/OCT;
H406Filter_notch hz,-3db points 1,Out, None;
H407Filter_low hz,db pnt,slope  1,Out, None;
H408Time delay FTB-SOD app Y/N  1,0.00 Msec, Not Applied;
H409Multi component recording   1,Z;
H410Aux. channel 1 contents     1,50Hz;
H411Aux. channel 2 contents     1,Uphole Time;
H412Aux. channel 3 contents     1,Confirmation TB;
H413Aux. channel 4 contents     1,TB;
H600Type,model,polarity         G1,Marsh,JFS-1,20DX,SEG;
H26 Type of Receiver points     G1,18 geophones in 2 strings in 4D;
H601Damp coeff,natural freq.    G1,0.7,10HZ;
H602Nunits,len(x),width(y)      G1,18,47.26m,00m;
H603Unit spacing x,y            G1,2.78m,00m;
H610Type,model,polarity         G2,Marsh,JFS-1,20DX,SEG;
H26 Type of Receiver points     G2,Bunched Geophone in 4D;
H611Damp coeff,natural freq.    G2,0.7,10HZ;
H612Nunits,len(x),width(y)      G2,18,00m,00m;
H613Unit spacing x,y            G2,00m,00m;
H620Type,model,polarity         H1,Hydrophone,MP24-13,SEG;
H26 Type of Receiver points     H1,single hydrophone in 4D;
H621Damp coeff,natural freq.    H1,None,10Hz;
H622Nunits,len(x),width(y)      H1,1,00m,00m;
H623Unit spacing x,y            H1,00m,00m;
H630Type,model,polarity         G3,Marsh,JFS-1,20DX,SEG;
H26 Type of Receiver points     G3,18 geophones in 2 strings in 3D;
H631Damp coeff,natural freq.    G3,0.7,10HZ;
H632Nunits,len(x),width(y)      G3,18,47.26m,00m;
H633Unit spacing x,y            G3,2.78m,00m;
H640Type,model,polarity         G4,Marsh,JFS-1,20DX,SEG;
H26 Type of Receiver points     G4,Bunched Geophone in 3D;
H641Damp coeff,natural freq.    G4,0.7,10HZ;
H642Nunits,len(x),width(y)      G4,18,00m,00m;
H643Unit spacing x,y            G4,00m,00m;
H650Type,model,polarity         H2,Hydrophone,MP24-13,SEG;
H26 Type of Receiver points     H2,single hydrophone in 3D;
H651Damp coeff,natural freq.    H2,None,10Hz;
H652Nunits,len(x),width(y)      H2,1,00m,00m;
H653Unit spacing x,y            H2,00m,00m;
H700Type,model,polarity         E1,Explosive,Seismex,SEG;
H26 Type of shot points         E1,30m single deep hole in 4D;
H701Size,vert. stk fold         E1,2000g,1;
H702Nunits,len(x),width(y)      E1,1,00m,00m;
H703Unit spacing x,y            E1,00m,00m;
H711Nom. shot depth,charge len. E1,42m,0.15m;
H712Nom. soil,drill method      E1,Clay Silt Sand;Flushing;
H713Weathering thickness        E1,1.5-7m;
H720Type,model,polarity         E2,Explosive,Seismex-1,SEG;
H26 Type of shot points         E2,5*6m linear pattern in 4D;
H721Size,vert. stk fold         E2,2000g,1;
H722Nunits,len(x),width(y)      E2,5,40m,00m;
H723Unit spacing x,y            E2,10m,00m;
H731Nom. shot depth,charge len. E2,6m,0.15m;
H732Nom. soil,drill method      E2,Clay Silt Sand;Flushing;
H733Weathering thickness        E2,1.5-7m;
H740Type,model,polarity         E3,Explosive,Seismex,SEG;
H26 Type of shot points         E3,5*3.5m linear pattern in 4D;
H741Size,vert. stk fold         E3,2000g,1;
H742Nunits,len(x),width(y)      E3,5,40m,00m;
H743Unit spacing x,y            E3,10m,00m;
H751Nom. shot depth,charge len. E3,3.5m,0.15m;
H752Nom. soil,drill method      E3,Clay Silt Sand;Thumping;
H753Weathering thickness        E3,1.5-7m;
H760Type,model,polarity         E4,Explosive,Seismex,SEG;
H26 Type of shot points         E4,5*3.5m circular pattern in 4D;
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H761Size,vert. stk fold         E4,2000g,1;
H762Nunits,len(x),width(y)      E4,5,00m,00m;
H763Unit spacing x,y            E4,00m,00m;
H771Nom. shot depth,charge len. E4,3.5m,0.15m;
H772Nom. soil,drill method      E4,Clay Silt Sand;Thumping;
H773Weathering thickness        E4,1.5-7m;
H780Type,model,polarity         E5,Explosive,Seismex,SEG;
H26 Type of shot points         E5,5*6m circular pattern in 4D;
H781Size,vert. stk fold         E5,2000g,1;
H782Nunits,len(x),width(y)      E5,5,00m,00m;
H783Unit spacing x,y            E5,00m,00m;
H791Nom. shot depth,charge len. E5,6m,0.15m;
H792Nom. soil,drill method      E5,Clay Silt Sand;Flushing;
H753Weathering thickness        E5,1.5-7m;
H800Type,model,polarity         E6,Explosive,Seismex,SEG;
H26 Type of shot points         E6,42m single deep hole in 3D;
H801Size,vert. stk fold         E6,2000g,1;
H802Nunits,len(x),width(y)      E6,1,00m,00m;
H803Unit spacing x,y            E6,00m,00m;
H811Nom. shot depth,charge len. E6,42m,0.15m;
H812Nom. soil,drill method      E6,Clay Silt Sand;Flushing;
H813Weathering thickness        E6,1.5-7m;
H820Type,model,polarity         E7,Explosive,Seismex,SEG;
H26 Type of shot points         E7,5*6m linear pattern in 3D;
H821Size,vert. stk fold         E7,2000g,1;
H822Nunits,len(x),width(y)      E7,5,40m,00m;
H823Unit spacing x,y            E7,10m,00m;
H831Nom. shot depth,charge len. E7,6m,0.15m;
H832Nom. soil,drill method      E7,Clay Silt Sand;Flushing;
H833Weathering thickness        E7,1.5-7m;
H840Type,model,polarity         E8,Explosive,Seismex,SEG;
H26 Type of shot points         E8,5*3.5m linear pattern in 3D;
H841Size,vert. stk fold         E8,2000g,1;
H842Nunits,len(x),width(y)      E8,5,40m,00m;
H843Unit spacing x,y            E8,10m,00m;
H851Nom. shot depth,charge len. E8,3.5m,0.15m;
H852Nom. soil,drill method      E8,Clay Silt Sand;Thumping;
H853Weathering thickness        E8,1.5-7m;
H860Type,model,polarity         E9,Explosive,Seismex,SEG;
H26 Type of shot points         E9,5*3.5m circular pattern in 3D;
H861Size,vert. stk fold         E9,2000g,1;
H862Nunits,len(x),width(y)      E9,5,00m,00m;
H863Unit spacing x,y            E9,00m,00m;
H871Nom. shot depth,charge len. E9,3.5m,0.15m;
H872Nom. soil,drill method      E9,Clay Silt Sand;Thumping;
H873Weathering thickness        E9,1.5-7m;
H800Type,model,polarity         A1,Sleevegun,MK2,SEG;
H26 Type of Airgun              A1,Airgun shot,taken 12.5m eachside of peg in 4D
H881Size,vert. stk fold         A1,460 CU IN,1;
H882Nunits,len(x),width(y)      A1,5,40m,0m;
H886P-P Bar/m,Prim/Bubble       A1,22.2MPa.m,9.1;
H887Air Pressure PSI            A1,2000PSI;
H888NO. SUB ARRAYS,NOM DEPTH    A1,4,2.0M;
H880Type,model,polarity         A2,Sleevegun,MK2,SEG;
H26 Type of Airgun              A2,Airgun shot,taken at the peg position in 4D;
H891Size,vert. stk fold         A2,670 CU IN,1;
H892Nunits,len(x),width(y)      A2,5,40m,0m;
H896P-P Bar/m,Prim/Bubble       A2,35.1MPa.m,18.4;
H897Air Pressure PSI            A2,2000PSI;
H898NO. SUB ARRAYS,NOM DEPTH    A2,4,2.0M;
H900Type,model,polarity         A3,Sleevegun,MK2,SEG;
H26 Type of Airgun              A3,Airgun shot,taken 12.5m eachside of peg in 3D
H901Size,vert. stk fold         A3,460 CU IN,1;
H902Nunits,len(x),width(y)      A3,5,40m,0m;
H9036P-P Bar/m,Prim/Bubble      A3,22.2MPa.m,9.1;
H904Air Pressure PSI            A3,2000PSI;
H905NO. SUB ARRAYS,NOM DEPTH    A3,4,2.0M;
H910Type,model,polarity         A4,Sleevegun,MK2,SEG;
H26 Type of Airgun              A4,Airgun shot,taken at the peg position in 3D;
H911Size,vert. stk fold         A4,670 CU IN,1;
H912Nunits,len(x),width(y)      A4,5,40m,0m;
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H913P-P Bar/m,Prim/Bubble	A4,35.1MPa.m,18.4;			
H915Air Pressure PSI	A4,2000PSI;			
H916NO. SUB ARRAYS,NOM DEPTH	A4,4,2.0M;			
H990R,s,x file quality control	XXXXXXXXX,1830,XXXXXX;			
H991Co-ord. status final/prov	Final,XXXXXXXXX,2000,XXXXXX;			
S2333	57281A1	475724.4	87654.8	147094813
S2333	57282A1	475724.4	87654.8	147094917
S2333	57301A1	475774.4	87654.8	147094957
S2333	57302A1	475774.4	87654.8	147095028
S2457	57321A1	475824.4	90754.8	147102206
S2457	57322A1	475824.4	90754.8	147102259
S2457	57301A1	475774.4	90754.8	147102326
S2457	57302A1	475774.4	90754.8	147102453
S2457	57303A1	475774.4	90754.8	147102528
S2457	57281A1	475724.4	90754.8	147102553
S2457	57282A1	475724.4	90754.8	147102617
S2457	57261A1	475674.4	90754.8	147102643
S2457	57262A1	475674.4	90754.8	147102708
S2457	57241A1	475624.4	90754.8	147102734
S2457	57242A1	475624.4	90754.8	147102759
S2457	57221A1	475574.4	90754.8	147102824
S2457	57222A1	475574.4	90754.8	147102849
S2457	57201A1	475524.4	90754.8	147102915
S2457	57202A1	475524.4	90754.8	147102941
S2457	57181A1	475474.4	90754.8	147103006
S2457	57182A1	475474.4	90754.8	147103213
S2457	57161A1	475424.4	90754.8	147103244
S2457	57162A1	475424.4	90754.8	147103309
S2457	57141A1	475374.4	90754.8	147103335
S2457	57142A1	475374.4	90754.8	147103401
S2457	57121A1	475324.4	90754.8	147103427
S2457	57122A1	475324.4	90754.8	147103616
S2457	57101A1	475274.4	90754.8	147103654
S2457	57102A1	475274.4	90754.8	147103717
S2457	57081A1	475224.4	90754.8	147103739
S2457	57082A1	475224.4	90754.8	147103802
S2457	57061A1	475174.4	90754.8	147103825
S2457	57062A1	475174.4	90754.8	147103849
S2457	57041A1	475124.4	90754.8	147103912
S2457	57042A1	475124.4	90754.8	147103935
S2457	57021A1	475074.4	90754.8	147103957
S2457	57022A1	475074.4	90754.8	147104021
S2457	57001A1	475024.4	90754.8	147104044
S2457	57002A1	475024.4	90754.8	147104107
S2457	56981A1	474974.4	90754.8	147104130
S2457	56982A1	474974.4	90754.8	147104153
S2457	56961A1	474924.4	90754.8	147104217
S2457	56962A1	474924.4	90754.8	147104240
S2457	56941A1	474874.4	90754.8	147104303
S2457	56942A1	474874.4	90754.8	147104325
S2457	56921A1	474824.4	90754.8	147104349
S2457	56922A1	474824.4	90754.8	147104412
S2457	56901A1	474774.4	90754.8	147104434
S2457	56902A1	474774.4	90754.8	147104457
S2457	56881A1	474724.4	90754.8	147104519
S2457	56882A1	474724.4	90754.8	147104541
S2457	56861A1	474674.4	90754.8	147104603
S2457	56862A1	474674.4	90754.8	147104625
S2457	56841A1	474624.4	90754.8	147104646
S2457	56842A1	474624.4	90754.8	147104708
S2457	56821A1	474574.4	90754.8	147104729
S2457	56822A1	474574.4	90754.8	147104751
S2457	56801A1	474524.4	90754.8	147104812
S2457	56802A1	474524.4	90754.8	147104833
S2457	56781A1	474474.4	90754.8	147104853
S2457	56782A1	474474.4	90754.8	147104915
S2457	56761A1	474424.4	90754.8	147104936
S2457	56762A1	474424.4	90754.8	147104957
S2457	56741A1	474374.4	90754.8	147105547
S2457	56742A1	474374.4	90754.8	147110318
S2457	56721A1	474324.4	90754.8	147110451

S2457	56722A1	474324.4	90754.8	147110534
S2457	56701A1	474274.4	90754.8	147110600
S2457	56702A1	474274.4	90754.8	147113455
S2457	56681A1	474224.4	90754.8	147113530
S2457	56682A1	474224.4	90754.8	147113601
S2457	56661A1	474174.4	90754.8	147113631
S2457	56662A1	474174.4	90754.8	147113700
S2465	56801A1	474524.4	90954.8	147120106
S2465	56802A1	474524.4	90954.8	147120132
S2459	56801A1	474524.4	90804.8	147122313
S2459	56802A1	474524.4	90804.8	147122404
S2459	56821A1	474574.4	90804.8	147122430
S2459	56822A1	474574.4	90804.8	147122501
S2459	56841A1	474624.4	90804.8	147122531
S2459	56842A1	474624.4	90804.8	147122557
S2459	56861A1	474674.4	90804.8	147122625
S2459	56862A1	474674.4	90804.8	147122654
S2459	56881A1	474724.4	90804.8	147122720
S2459	56882A1	474724.4	90804.8	147122748
S2459	56901A1	474774.4	90804.8	147122813
S2459	56902A1	474774.4	90804.8	147122839
S2459	56921A1	474824.4	90804.8	147122904
S2459	56922A1	474824.4	90804.8	147122930
S2459	56941A1	474874.4	90804.8	147122956
S2459	56942A1	474874.4	90804.8	147123023
S2459	56961A1	474924.4	90804.8	147123123
S2459	56962A1	474924.4	90804.8	147123255
S2459	57221A1	475574.4	90804.8	147124824
S2459	57222A1	475574.4	90804.8	147124853
S2459	57201A1	475524.4	90804.8	147124918
S2459	57202A1	475524.4	90804.8	147124945
S2459	57181A1	475474.4	90804.8	147125006
S2459	57182A1	475474.4	90804.8	147125030
S2459	57161A1	475424.4	90804.8	147125058
S2459	57162A1	475424.4	90804.8	147125117
S2459	57141A1	475374.4	90804.8	147125139
S2459	57142A1	475374.4	90804.8	147125158
S2459	57121A1	475324.4	90804.8	147125217
S2459	57122A1	475324.4	90804.8	147125247
S2459	57101A1	475274.4	90804.8	147125316
S2459	57102A1	475274.4	90804.8	147125338
S2459	57081A1	475224.4	90804.8	147125426
S2459	57082A1	475224.4	90804.8	147125919
S2459	57061A1	475174.4	90804.8	147125943
S2459	57062A1	475174.4	90804.8	147130011
S2459	57041A1	475124.4	90804.8	147130033
S2459	57042A1	475124.4	90804.8	147130100

Receiver File (SPS) for selected Shots (Geophone and Hydrophone)
(A full listing is too large and extensive to fully display)

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H000SPS format version num.     SPS001,05.06.12;
H010Description of survey area  <untitled>,,N/A,N/A;
H020Date of survey              XX.XX.XX,XX.XX.XX;
H021Post-plot date of issue     XX.XX.XX;
H022Tape/disk identifier        N/A;
H030Client                      N/A;
H040Geophysical contractor      N/A,N/A;
H050Positioning contractor      N/A;
H060Pos. proc. contractor       N/A;
H070Field computer system(s)    N/A,N/A,N/A;
H080Coordinate location         N/A;
H090Offset to coord.location   N/A,N/A;
H100Clock time w.r.t. GMT       N/A;
H110Spare                       N/A;
H120Geodetic datum,-spheroid    N/A,N/A,N/A,N/A;
H130Spare                       N/A;
H140Geodetic datum parameters   N/A,N/A,N/A,N/A,N/A,N/A,N/A;
H150Spare                       N/A;
H160Spare                       N/A;
H170Vertical datum description  N/A,N/A,N/A,N/A;
H180Projection type             N/A;
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H190Projection zone             N/A,N/A;
H200Description of grid units   Metres;
H201Factor to metre             1.00000000;
H210Lat. of standard parallel(s);
H220Long. of central meridian   ;
H231Grid origin                 ;
H232Grid coord.at origin       ;
H241Scale factor                ;
H242Lat., long. scale factor    ;
H256Lat., long. initial line    ;
H257Circular bearing of H256    ;
H258Quadrant bearing of H256    ;
H259Angle from skew             ;
H300Project code and description;
H310Line number format          ;
H400Type,Model,Polarity         ;
H401Crew name,Comment           ;
H402Sample int.,Record Len.     1,0.000000,N/A;
H403Number of channels          1,1;
H404Tape type,format,density    ;
H405Filter_alias Hz,dB pnt,slope;
H406Filter_notch Hz,-3dB points ;
H407Filter_low Hz,dB pnt,slope  ;
H408Time delay FTB-SOD app Y/N  ;
H409Multi component recording   ;
H410Aux. channel 1 contents     ;
H411Aux. channel 2 contents     ;
H412Aux. channel 3 contents     ;
H413Aux. channel 4 contents     ;
H414Spare                       ;
H415Spare                       ;
H416Spare                       ;
H417Spare                       ;
H418Spare                       ;
H419Spare                       ;
H600Type,model,polarity         G1,geophone 1;
H601Damp coeff,natural freq.    ;
H602Nunits,len(X),width(Y)      ;
H603Unit spacing X,Y            ;
H604Spare                       ;
H605Spare                       ;
H606Spare                       ;
H607Spare                       ;
H608Spare                       ;
H609Spare                       ;
H700Type,model,polarity         A1,air gun 1;
H701Size,vert. stk fold         ;
H702Nunits,len(X),width(Y)      ;
H703Unit spacing X,Y            ;
H716P-P bar m,prim/bubble       ;
H717Air pressure psi            ;
H718No. sub arrays,Nom depth    ;
H719Spare                       ;
H720Type,model,polarity         E1,explosive 1;
H721Size,vert. stk fold         ;
H722Nunits,len(X),width(Y)      ;
H723Unit spacing X,Y            ;
H620Type,model,polarity         EI;
H621Damp coeff,natural freq.    ;
H622Nunits,len(X),width(Y)      ;
H623Unit spacing X,Y            ;
H624Spare                       ;
H625Spare                       ;
H626Spare                       ;
H627Spare                       ;
H628Spare                       ;
H629Spare                       ;
R5645               667.51G1                  473649.4   62729.8
R5645               668.51G1                  473649.4   62779.8
R5645               669.51G1                  473649.4   62829.8
R5645               670.51G1                  473649.4   62879.8
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R5645	671.51G1	473649.4	62929.8
R5645	672.51G1	473649.4	62979.8
R5645	673.51G1	473649.4	63029.8
R5645	674.51G1	473649.4	63079.8
R5645	675.51G1	473649.4	63129.8
R5645	676.51G1	473649.4	63179.8
R5645	677.51G1	473649.4	63229.8
R5645	678.51G1	473649.4	63279.8
R5645	679.51G1	473649.4	63329.8
R5645	680.51G1	473649.4	63379.8
R5645	681.51G1	473649.4	63429.8
R5645	682.51G1	473649.4	63479.8
R5645	683.51G1	473649.4	63529.8
R5645	684.51G1	473649.4	63579.8
R5645	685.51G1	473649.4	63629.8
R5645	686.51G1	473649.4	63679.8
R5645	687.51G1	473649.4	63729.8
R5645	688.51G1	473649.4	63779.8
R5645	689.51G1	473649.4	63829.8
R5645	690.51G1	473649.4	63879.8
R5645	691.51G1	473649.4	63929.8
R5645	692.51G1	473649.4	63979.8
R5645	693.51G1	473649.4	64029.8
R5645	694.51G1	473649.4	64079.8
R5645	695.51G1	473649.4	64129.8
R5645	696.51G1	473649.4	64179.8
R5645	697.51G1	473649.4	64229.8
R5645	698.51G1	473649.4	64279.8
R5645	699.51G1	473649.4	64329.8
R5645	700.51G1	473649.4	64379.8
R5645	701.51G1	473649.4	64429.8
R5645	702.51G1	473649.4	64479.8
R5645	703.51G1	473649.4	64529.8
R5645	704.51G1	473649.4	64579.8
R5645	705.51G1	473649.4	64629.8
R5645	706.51G1	473649.4	64679.8
R5645	707.51G1	473649.4	64729.8
R5645	708.51G1	473649.4	64779.8
R5645	709.51G1	473649.4	64829.8
R5645	710.51G1	473649.4	64879.8
R5645	711.51G1	473649.4	64929.8
R5645	712.51G1	473649.4	64979.8
R5645	713.51G1	473649.4	65029.8
R5645	714.51G1	473649.4	65079.8
R5645	715.51G1	473649.4	65129.8
R5645	716.51G1	473649.4	65179.8
R5645	717.51G1	473649.4	65229.8
R5645	718.51G1	473649.4	65279.8
R5645	719.51G1	473649.4	65329.8
R5645	720.51G1	473649.4	65379.8
R5645	721.51G1	473649.4	65429.8
R5645	722.51G1	473649.4	65479.8
R5645	723.51G1	473649.4	65529.8
R5645	724.51G1	473649.4	65579.8
R5645	725.51G1	473649.4	65629.8
R5645	726.51G1	473649.4	65679.8
R5645	727.51G1	473649.4	65729.8
R5645	728.51G1	473649.4	65779.8
R5645	729.51G1	473649.4	65829.8
R5645	730.51G1	473649.4	65879.8
R5645	731.51G1	473649.4	65929.8
R5645	732.51G1	473649.4	65979.8
R5645	733.51G1	473649.4	66029.8
R5645	734.51G1	473649.4	66079.8
R5645	735.51G1	473649.4	66129.8
R5645	736.51G1	473649.4	66179.8
R5645	737.51G1	473649.4	66229.8
R5645	738.51G1	473649.4	66279.8
R5645	739.51G1	473649.4	66329.8
R5645	740.51G1	473649.4	66379.8
R5645	741.51G1	473649.4	66429.8

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R5645	743.51G1	473649.4	66529.8
R5645	744.51G1	473649.4	66579.8
R5645	745.51G1	473649.4	66629.8
R5645	746.51G1	473649.4	66679.8
R5645	747.51G1	473649.4	66729.8
R5645	748.51G1	473649.4	66779.8
R5645	749.51G1	473649.4	66829.8
R5645	750.51G1	473649.4	66879.8
R5645	751.51G1	473649.4	66929.8
R5645	752.51G1	473649.4	66979.8
R5645	753.51G1	473649.4	67029.8
R5645	754.51G1	473649.4	67079.8
R5645	755.51G1	473649.4	67129.8
R5645	756.51G1	473649.4	67179.8
R5645	757.51G1	473649.4	67229.8
R5645	758.51G1	473649.4	67279.8
R5645	759.51G1	473649.4	67329.8
R5645	760.51G1	473649.4	67379.8
R5645	761.51G1	473649.4	67429.8
R5645	762.51G1	473649.4	67479.8
R5645	763.51G1	473649.4	67529.8
R5645	764.51G1	473649.4	67579.8
R5645	765.51G1	473649.4	67629.8
R5645	766.51G1	473649.4	67679.8
R5645	767.51G1	473649.4	67729.8
R5645	768.51G1	473649.4	67779.8
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R5645	770.51G1	473649.4	67879.8
R5645	771.51G1	473649.4	67929.8
R5645	772.51G1	473649.4	67979.8
R5645	773.51G1	473649.4	68029.8
R5645	774.51G1	473649.4	68079.8
R5645	775.51G1	473649.4	68129.8
R5645	776.51G1	473649.4	68179.8
R5645	777.51G1	473649.4	68229.8
R5645	778.51G1	473649.4	68279.8
R5645	779.51G1	473649.4	68329.8
R5645	780.51G1	473649.4	68379.8
R5645	781.51G1	473649.4	68429.8
R5645	782.51G1	473649.4	68479.8
R5645	783.51G1	473649.4	68529.8
R5645	784.51G1	473649.4	68579.8
R5645	785.51G1	473649.4	68629.8
R5645	786.51G1	473649.4	68679.8
R5645	787.51G1	473649.4	68729.8
R5645	788.51G1	473649.4	68779.8
R5645	789.51G1	473649.4	68829.8
R5645	790.51G1	473649.4	68879.8
R5645	791.51G1	473649.4	68929.8
R5645	792.51G1	473649.4	68979.8
R5645	793.51G1	473649.4	69029.8
R5645	794.51G1	473649.4	69079.8
R5645	795.51G1	473649.4	69129.8
R5645	796.51G1	473649.4	69179.8
R5645	797.51G1	473649.4	69229.8
R5645	798.51G1	473649.4	69279.8
R5645	799.51G1	473649.4	69329.8
R5645	800.51G1	473649.4	69379.8
R5645	801.51G1	473649.4	69429.8
R5645	802.51G1	473649.4	69479.8
R5645	803.51G1	473649.4	69529.8
R5645	804.51G1	473649.4	69579.8
R5645	805.51G1	473649.4	69629.8
R5645	806.51G1	473649.4	69679.8
R5645	807.51G1	473649.4	69729.8
R5645	808.51G1	473649.4	69779.8
R5645	809.51G1	473649.4	69829.8
R5645	810.51G1	473649.4	69879.8
R5645	811.51G1	473649.4	69929.8
R5645	812.51G1	473649.4	69979.8

R5645	813.51G1	473649.4	70029.8
R5645	814.51G1	473649.4	70079.8
R5645	815.51G1	473649.4	70129.8
R5645	816.51G1	473649.4	70179.8
R5645	817.51G1	473649.4	70229.8
R5645	818.51G1	473649.4	70279.8
R5645	819.51G1	473649.4	70329.8
R5645	820.51G1	473649.4	70379.8
R5645	821.51G1	473649.4	70429.8
R5645	822.51G1	473649.4	70479.8
R5645	823.51G1	473649.4	70529.8
R5645	824.51G1	473649.4	70579.8
R5645	825.51G1	473649.4	70629.8
R5645	826.51G1	473649.4	70679.8
R5645	827.51G1	473649.4	70729.8
R5645	828.51G1	473649.4	70779.8
R5645	829.51G1	473649.4	70829.8
R5645	830.51G1	473649.4	70879.8
R5645	831.51G1	473649.4	70929.8
R5645	832.51G1	473649.4	70979.8
R5645	833.51G1	473649.4	71029.8
R5645	834.51G1	473649.4	71079.8
R5645	835.51G1	473649.4	71129.8
R5645	836.51G1	473649.4	71179.8
R5645	837.51G1	473649.4	71229.8
R5645	838.51G1	473649.4	71279.8
R5645	839.51G1	473649.4	71329.8
R5645	840.51G1	473649.4	71379.8
R5645	841.51G1	473649.4	71429.8
R5645	842.51G1	473649.4	71479.8
R5645	843.51G1	473649.4	71529.8
R5645	844.51G1	473649.4	71579.8
R5645	845.51G1	473649.4	71629.8
R5645	846.51G1	473649.4	71679.8
R5645	847.51G1	473649.4	71729.8
R5645	848.51G1	473649.4	71779.8
R5645	849.51G1	473649.4	71829.8
R5645	850.51G1	473649.4	71879.8
R5645	851.51G1	473649.4	71929.8
R5645	852.51G1	473649.4	71979.8
R5645	853.51G1	473649.4	72029.8
R5645	854.51G1	473649.4	72079.8
R5645	855.51G1	473649.4	72129.8
R5645	856.51G1	473649.4	72179.8
R5645	857.51G1	473649.4	72229.8
R5645	858.51G1	473649.4	72279.8
R5645	859.51G1	473649.4	72329.8
R5645	860.51G1	473649.4	72379.8
R5645	861.51G1	473649.4	72429.8
R5645	862.51G1	473649.4	72479.8
R5645	863.51G1	473649.4	72529.8
R5645	864.51G1	473649.4	72579.8
R5645	865.51G1	473649.4	72629.8
R5645	866.51G1	473649.4	72679.8
R5645	867.51G1	473649.4	72729.8
R5645	868.51G1	473649.4	72779.8
R5645	869.51G1	473649.4	72829.8
R5645	870.51G1	473649.4	72879.8
R5645	871.51G1	473649.4	72929.8
R5645	872.51G1	473649.4	72979.8
R5645	873.51G1	473649.4	73029.8
R5645	874.51G1	473649.4	73079.8
R5645	875.51G1	473649.4	73129.8
R5645	876.51G1	473649.4	73179.8
R5645	877.51G1	473649.4	73229.8
R5645	878.51G1	473649.4	73279.8
R5645	879.51G1	473649.4	73329.8
R5645	880.51G1	473649.4	73379.8
R5645	881.51G1	473649.4	73429.8
R5645	882.51G1	473649.4	73479.8
R5645	883.51G1	473649.4	73529.8

R5645	884.51G1	473649.4	73579.8
R5645	885.51G1	473649.4	73629.8
R5645	886.51G1	473649.4	73679.8
R5645	887.51G1	473649.4	73729.8
R5645	888.51G1	473649.4	73779.8
R5645	889.51G1	473649.4	73829.8
R5645	890.51G1	473649.4	73879.8
R5645	891.51G1	473649.4	73929.8
R5645	892.51G1	473649.4	73979.8
R5645	893.51G1	473649.4	74029.8
R5645	894.51G1	473649.4	74079.8
R5645	895.51G1	473649.4	74129.8
R5645	896.51G1	473649.4	74179.8
R5645	897.51G1	473649.4	74229.8
R5645	898.51G1	473649.4	74279.8
R5645	899.51G1	473649.4	74329.8
R5645	900.51G1	473649.4	74379.8
R5645	901.51G1	473649.4	74429.8
R5645	902.51G1	473649.4	74479.8
R5645	903.51G1	473649.4	74529.8
R5645	904.51G1	473649.4	74579.8
R5645	905.51G1	473649.4	74629.8
R5645	906.51G1	473649.4	74679.8
R5645	907.51G1	473649.4	74729.8
R5645	908.51G1	473649.4	74779.8
R5645	909.51G1	473649.4	74829.8
R5645	910.51G1	473649.4	74879.8
R5645	911.51G1	473649.4	74929.8
R5645	912.51G1	473649.4	74979.8
R5645	913.51G1	473649.4	75029.8
R5645	914.51G1	473649.4	75079.8
R5645	915.51G1	473649.4	75129.8
R5645	916.51G1	473649.4	75179.8
R5645	917.51G1	473649.4	75229.8
R5645	918.51G1	473649.4	75279.8
R5645	919.51G1	473649.4	75329.8
R5645	920.51G1	473649.4	75379.8
R5645	921.51G1	473649.4	75429.8
R5645	922.51G1	473649.4	75479.8
R5645	923.51G1	473649.4	75529.8
R5645	924.51G1	473649.4	75579.8
R5645	925.51G1	473649.4	75629.8
R5645	926.51G1	473649.4	75679.8
R5645	927.51G1	473649.4	75729.8
R5645	928.51G1	473649.4	75779.8
R5645	929.51G1	473649.4	75829.8
R5645	930.51G1	473649.4	75879.8
R5645	931.51G1	473649.4	75929.8
R5645	932.51G1	473649.4	75979.8
R5645	933.51G1	473649.4	76029.8
R5645	934.51G1	473649.4	76079.8
R5645	935.51G1	473649.4	76129.8
R5645	936.51G1	473649.4	76179.8
R5645	937.51G1	473649.4	76229.8
R5645	938.51G1	473649.4	76279.8
R5645	939.51G1	473649.4	76329.8
R5645	940.51G1	473649.4	76379.8
R5645	941.51G1	473649.4	76429.8
R5645	942.51G1	473649.4	76479.8
R5645	943.51G1	473649.4	76529.8
R5645	944.51G1	473649.4	76579.8
R5645	945.51G1	473649.4	76629.8
R5645	946.51G1	473649.4	76679.8
R5645	947.51G1	473649.4	76729.8
R5645	948.51G1	473649.4	76779.8
R5645	949.51G1	473649.4	76829.8
R5645	950.51G1	473649.4	76879.8
R5645	951.51G1	473649.4	76929.8
R5645	952.51G1	473649.4	76979.8
R5645	953.51G1	473649.4	77029.8
R5645	954.51G1	473649.4	77079.8