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GiantfossilmasswastingoffthecoastofWestIndia: TheNatarajasubmarineslide

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Abstract

Weusetwodimensionalprestackdepthmigratedseismic reflectionprofilesandseafloor bathymetrytodescribe the continentalmarginstructureanda massivemasstransportdeposit off the westcoastofIndia.ThisgiantsliderunsfromtheGujurat–SaurashtramargintotheLaxmiBasin.Itisover330km long,amaximumof190kmwideanditsrunoutbasalgradientis1.2°.Wenamethisgiantmasswastingdepositthe NatarajaSubmarineSlide.Thisslidecovers49±16×10^{3}km^{2}andrepresentsavolumeof 19×10^3±4×10^3 km^3,makingitthesecondbyvolumeofanypassivemarginlandslide/masstransport deposit.Seismicfaciesanalysisallowstheinternalstructureofthemasstransportdeposittobedescribedasfaras thetoe.Thisslidehasbeenabletocircumventmassiveseamounts,thushighlightingthecapacityoftheflowandits potentialenergyduringemplacementinafunnelbetweentheslopeoftheWesternIndianpassivemarginandtheL axmiRidge.Stratigraphically,theemplacementoftheNatarajaSlidepredatesthemainpulseof sedimentation duringthe lateMiocene–Recentassociatedwith the IndusFanbutfollowsrapidsedimentationacrossSandSEAsiaduringtheEarly–MiddleMiocene.Themarginarchitectureattheheadofthisslideisassociatedwithagravitycontrolledfoldandthr ustbeltthatmayhavecausedslopesteepeningandtriggeringoftheslide.

*Keywords:*masswastingslideseismicreflectionWestIndiamarginArabianSea

1. Introduction

Landslidesoccuronandoffshore,andrangein volumefromdm^{3}to×10^{3}km^3. Triggeringmechanismsareoftenunknownandalmostcertainlydifferbetweensettings(Hamptonetal.,1996).Masswasting/masstransportdepositsrepresentsomeofthemostchallengingandimportantsedimentaryandmechanicalfeaturesforgeoscientistsandstructuralengineerstounderstand(e.g.,Massonetal.,2006).Offshore,alongbothpassiveoractivemargins(MoscardelliandWood,2015),masswastingplaysanimportantroleinshapingmostcontinentalslopesthatleadtodeepabyssalplainsandhelpstoformthearchitectureofdeepwatersedimentarysystemswhenassociatedwithturbiditycurrents(Embley,1976;Woodcock,1979;Bellaicheetal.,1986).Massmovementscan,incertaincircumstances,affectmanmadeinstallations,suchasdeepseacablesorsubseaoffshorestructures(Gennesseauxetal.,1980;Piperetal.,1988).Movementoftheoverlyingwatercolumnduringemplacementmaygenerate tsunamis,asdocumentedforthewellknownHoloceneStoreggaSlideintheNorthAtlanticoffshoreNorway(Jansenetal.,1987;Buggeetal.,1988;Yamadaetal.,2012).Despitethenumerousseafloorfeaturesdescribedandtheproposedmechanismsfortriggeringslides(e.g.,overpressure,fluid/sedimentremobilization,earthquake)thelimitednumberofgiantslidesintherockrecordthathavebeenstudiedindetaildonotallowadefinitiveanalogytobemadebetweenthesemodernandancientexamples.

Themorphologyofthepresentdaymarginofwestern India(NainiandKolla,1982;Chakrabortyetal.,2006)ischaracterizedbyaseriesofarcuateconcaveupandconcavedownfeaturesattheshelftoslopetransition(Fig.1).Atthisscalewecandefinethemarginasbeingassociatedwithaseriesofprogradingsedimentarywedgesand/orretrogradingerosiveslopes(Steffensetal.,2003).ThemainsedimentarybodywithinthispartofthewesternIndianOceanistheIndusFan(Fig.1B)thatcontainsupto 11kmofsediments(Exxon,1985;Clift etal.,2001).Thesurficialshapesfoundalongthemargincanbesummarizedbythreedipbathymetricprofiles(Fig.1C).ThenorthernprofilecorrespondstotheIndusFanandshowsaconvexupwardprofilereflectingtheexcessofPlio–Pleistocenesedimentsaccumulatedbythisthicksedimentarybody(Fig.1B).Althoughtheinfluenceofdeltaicsedimentarysystemsdiffersbetweenthethreeareas,wenotethattheprofilealongtheGujurat–Saurashtrasectorshowsaconcaveupwardgeometrycomparedtoitsneighbors,suggestiveofmasswasting(ColemanandPrior,1998;AdamsandSchlager,2000).SlopefailureofPlio–Pleistocenedepositsspatiallyassociatedwithhydrates,rapidsedimentationratesorseismicityhasbeendocumentedalongtheslopeoftheWesternIndianmargin(Raoetal.,2002).

TheLaxmiandGujurat–SaurashtraBasinshavebeenextensivelydescribedandanalyzedinrelationtotheriftinghistoryofGondwana,withparticularattentionhavingbeenpaidtothecontinentoceantransition(e.g.Bhattacharyaetal.,1994a;TodalandEdholm,1998;Chaubeyetal.,2002;Krishnaetal.,2006;Calvèsetal.,2008,2011;Misraetal.,2015).Nonetheless,detaileddescriptionofthedriftsequencesoftheGujurat–SaurashtraandLaxmiBasinshasnotbeenperformedpreviouslybecauseofthelimitedavailableseismicreflecti oncoverageandmodestnumberofwells/boreholesdrilledinthearea.Ourstudybuildsonpreviousstudiesandus estwo dimensionalPreStackDepthMigrated(PreSDM)seismicreflectiondatatodescribethelargescalegeometryoft hemargin.Weidentifysomekeyfaciesthatformamajorsedimentvolumeandrepresenttheproductofamajorlate Mioceneeventinthehistoryof thismargin.Wedefinethespatialextent,theinternalstructureandtectonicoriginofthispreviouslyundescribedse dimentarybody.ThisseismicallyobservedstructurehasrecentlybeencalibratedduringInternationalOceanDis coveryProgram(IODP)Expedition355(Pandeyetal.,2015).PreliminaryresultsfromSitesU1456andU1457(Fi g.1A),supportourinitialinterpretationsthatwerecompletedbeforedrilling.

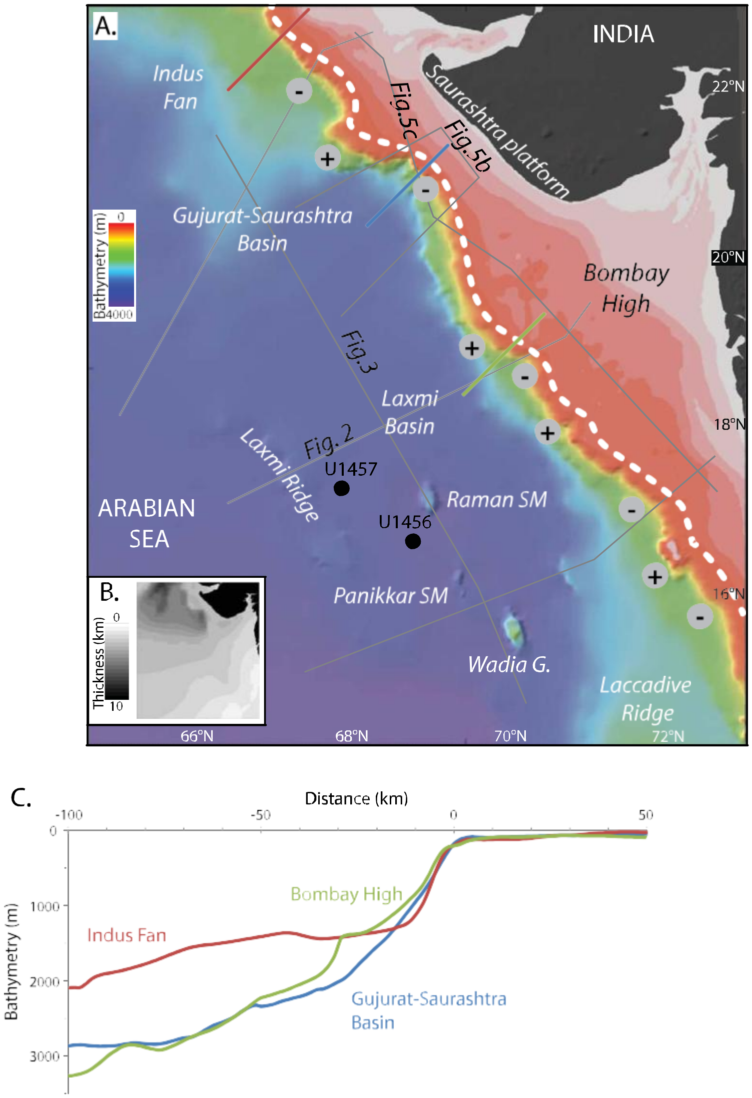

Fig.1.A.RegionalsettingoftheWesternIndiamarginandadjacentArabianSeaBasin.Theseismicdatausedforthisstudyaremarkedbygreylines.Alongmargin,convexupandconvexdownmorphologyofshelftoslopeareexpressedbypositiveandnegativegreysymbols,respectively.B.Thicknessmapofsedimentswithinthestudyarea(Exxon,1985),notetheextentoftheIndusfandepocentrenorthofthestudyarea.C.Bathymetricprofilesacrossshelfandslopefromthreelocationsalongthemargin,theseprofilesareeitherconvexup(IndusFan,i.e.highsedimentrateandimportantdeepseafan)orconcaveup(BombayHighorGujurat–SaurashtraBasin).ThetwoIODPdrillsitesU1456andU1457arelocatedinthesouthwesternpartofthestudyare(Pandeyetal.,2015).

2. Materialsandmethods

Theapproximately3500kmofseismicreflectiondatausedinthisstudy(Fig.1A)arepartofthemuchlargerregi onalIndiaSPAN™surveyacquiredandprocessedbyIONGXTechnologyin2006–2007.Theacquisitionwasdesignedforcrustalscaleimagingbyusingalongreceivercablewitha10.1kmmaximumoffsetandalargesourcesizeof7480cuin.Crustalscaleimagingisachievedbyan18stwowaytimerecord(equivalenttoaround40kmdepth).Theprestackdepthmigrateddataweremigrated(KirchhoffPreSDM)usingvelocitiesderivedfromiterativetomographicvelocitymodeling.VintagesinglechannelseismicreflectionprofileRC1707fromtheLamont–DohertyEarthObservatoryhasalsobeenused(Fig.1;accessedbytheGeoMapApp3.3.9–link:http://www.geomapapp.org/).

Weanalyzedtheseseismicreflectionlinesattwodifferentscales,fromthemega(basin)scaletothearchitecturalelementscale.Atthescaleofthearchitecturalelements,seismicfaciesanalysis(Mitchumetal.,1977)wasusedtodocumentanddescribethekinematicindicatorsofthemasstransportcomplexes(MTC)asdefinedbyBulletal.(2009).Identificationoftheheadwall,extensionaldomain,translationaldomainandcontractionaltoedomains(Prioretal.,1984)isbasedontheexternalandinternalgeometryofthemasswastingpackage,asimagedbytheseismicreflectiondata.Theclassificationofattached/detachedMTCfollowstheschemeofMoscardelliandWood(2008).TheregionalGEBCO(BritishOceanographicDataCentre,2003)bathymetricdataareusedtodescribethemarginandlocatethevariousstructureswheretheslideispresent.

Inspring2015,twoIODPsitesweredrilledinthesouthwesternpartofourstudyarea(Fig.1A).Werefertothispreliminaryagecontrolandsedimentaryfaciesfromonboardanalysistocalibrateourgeophysicalobservations(Pandeyetal.,2015).

3. Results

3.1. *Marginscalestructure–Natarajaslidelocation*

ThepresentdaystructureofthewesternIndianmarginismainlydominatedbyaseriesofinfilledriftbasinsspanningfromthelandwardGujurat–SaurastrahmargintotheLaxmiBasinandboundedtothewestbytheLaxmiRidge,whereseawarddippingreflectors(SDR)markthetransitionbetweenabortedoceanicbasincrusttothetrueoceanicaccretiongeneratedalongtheCarlsbergRidge(e.g.NainiandTalwani,1982;Calvèsetal.,2011;Misraetal.,2015).ThissettingistheresultofrepeatedridgejumpmarkedbySDRsequencesonbothsidesoftheLaxmiRidge.

ThemaingeodynamiceventtohaveshapedtheonshorepartofthemarginistheDeccanLargeIgneousProvince(e.g.WellmanandMcElhinny,1970;Mahoney,1988).Thiseventismarkedseawardbyaprominentseismicreflectionpackageoverlainbycarbonateplatforms(Calvèsetal.,2008,2011)andinturnburiedbyCenozoicsiliciclasticdepositslargelysourcedfromtheIndiancontinentandHimalayaviatheIndusRiver(e.g.,Cliftetal.,2001)(Fig.2A).TheflatlyingfloodbasaltsareintransitionwithseawarddippingreflectionpackagesintheLaxmiBasin(Calvès,2009;Misraetal.,2015;Fig.2A).

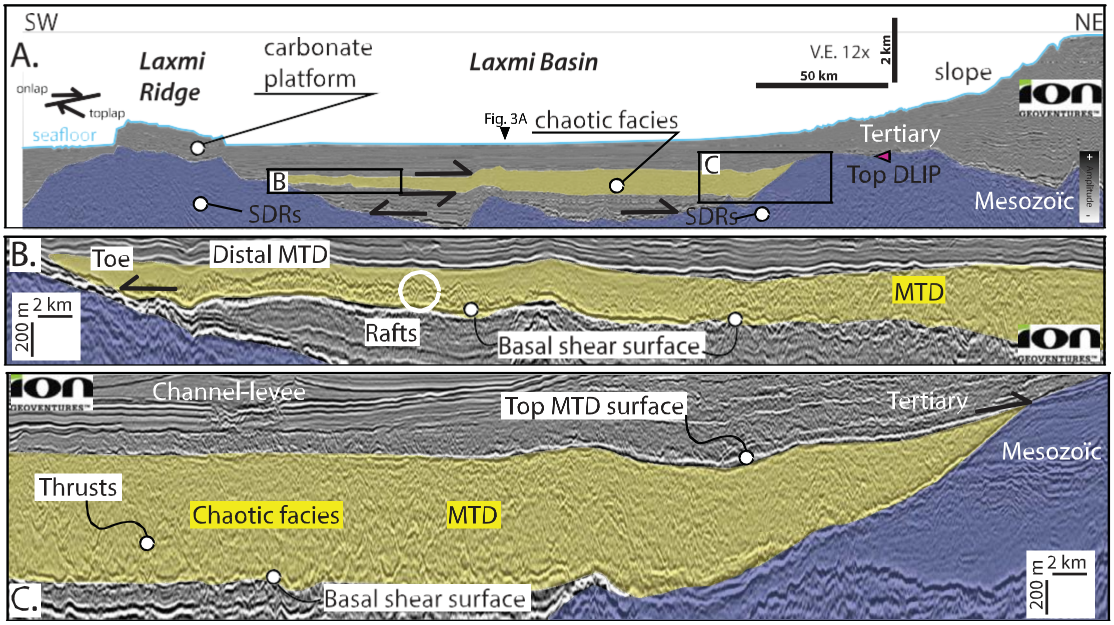

Fig.2. Regionalprestackdepthmigratedseismicreflectionprofilesacrossthe BombayHigh,LaxmiBasintoLaxmiRidge.A.ThisseismicreflectionprofileofthemarginshowsthewidthofanextensivechaoticseismicfacieswithintheCenozoicsection.TheMeso–Cenozoictransitionbelowtheslopeofthemarginismarked(purplefiledarrow)bythetopoftheDeccanLargeIgneousProvince(topDLIP)seismichighamplitudereflectiveevent.SeawardDippingReflector(SDR)sequencesareobservedonbothsidesoftheLaxmiBasin.B.Thechaoticseismicfaciesismarkedbymassivethrustandonlaplandwardonthe Mesozoicsequence.C.TowardtheLaxmiRidgethechaoticseismicfaciesthinslaterally.D.TowardthePanikkarSeamountthefaciesislesschaoticandtheslidethinsandonlapsagainstthestructuralbasementhighs,seeFig.1Aforprofilelocation.

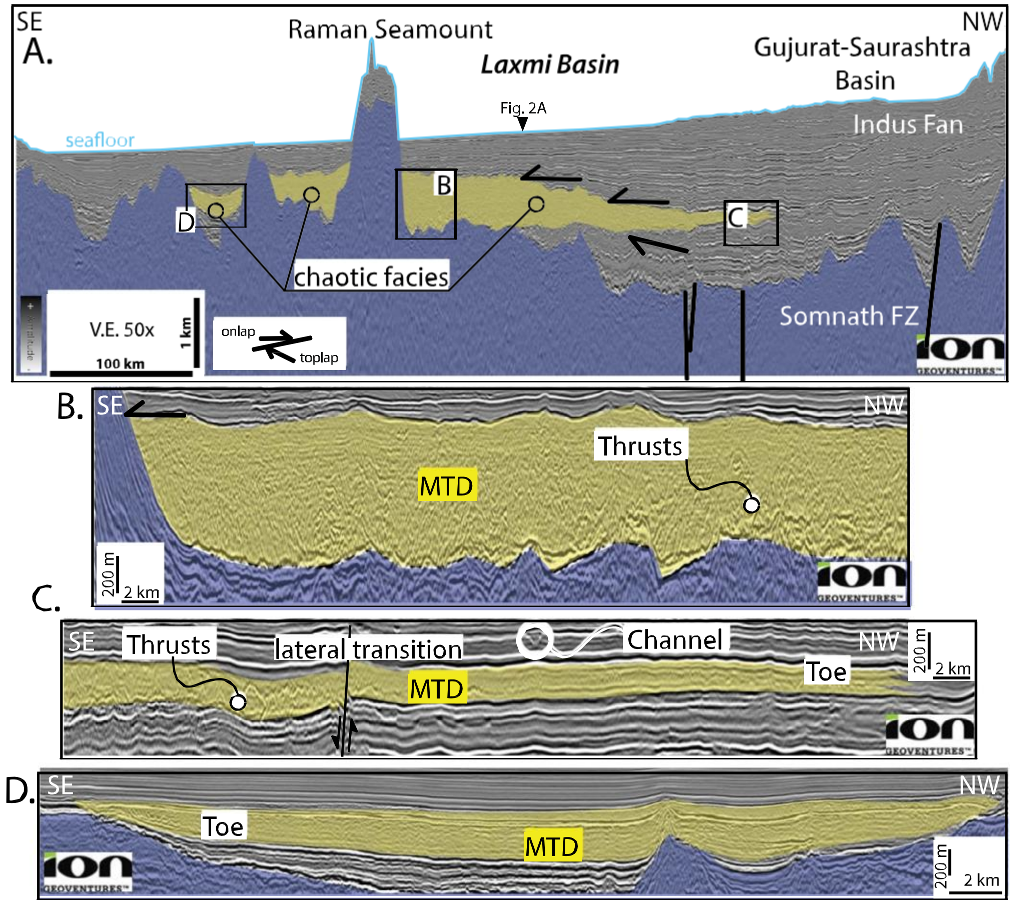

Fig.3. RegionalprestackdepthmigratedseismicreflectionprofilesNW–SEacrossthe LaxmiBasinand RamanSeamount and, Gujurat–SaurashtratoLaxmibasinsB.,thechaoticseismicfaciesisthickertowardtheSW,notetheportionoftheIndusFananditsgiantchannellevees.Thechaoticseismicfaciesrunsfurthersouth,beyondtheRamanSeamount.Notechangeofscalebetweendisplays,seeFig.1Aforprofilelocation.

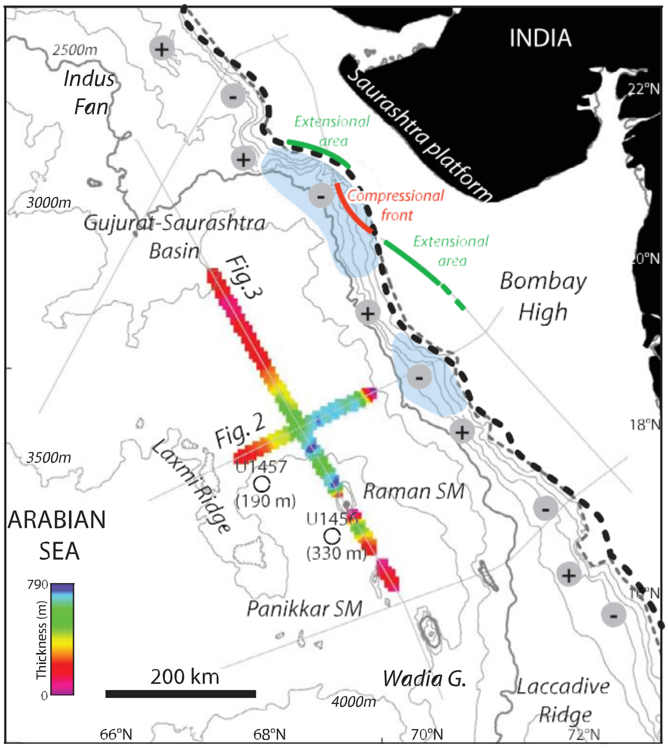

Fig.4. IsopachmapoftheNatarajaslide.Theseafloorcontoursarespacedevery500meters.ThegeomorphologicalelementsoftheseafloorsurfacearesimilartoFig.1.ThicknessofthemasswasteddepositsofthetwodrillIODPsiteU1456andU1457aremarkedinbrackets(Pandeyetal.,2015).Twoconcavedownmorphologiesofthemarginaremarkedintheslopebyblueshadedareas.Thesearemarkingpotentialmassmissingtotheirlateralsectionalongthedownslopeofthe WestIndianmargin.Theshelfmargingeometryisrelatedtolargescalegravityspreadingoftheslopewithconcavedownareasunderlainbycontractionaldeformation(seeFig.5).(Forinterpretationofthereferencestocolorinthisfigure,thereaderisreferredtothewebversionofthisarticle.)

TheCenozoicIndusFansequenceiscomposedatitsbasebycontinuousparallelseismicreflectionsthatonlapontostructuralhighs(Figs.2B,2C,and3A).Abovethissequenceapackagedefinedbychaoticfaciesofregionalextentcoversmostofthe LaxmiBasin.Thispackagethinstowardsandeventuallyonlapsthe LaxmiRidgetotheSE(Fig.2A).ItisthickertowardstheNE,whereitis>750mthick(Fig.4).Theinternalorganizationofthissequenceiscomposedofchaotictodiscontinuousseismicfaciespackages,brightsteeplydippingreflections,rotateddiscontinuousstratalreflectionsandlowamplitudestructurelessfacies(insetsFigs.2Aand2B).Eachofthesefaciescanbeinterpretedasmasstransportdepositsandhelpustodefinethepotentiallocationoftheultimateheadscarpandtoe(e.g.,Bulletal.,2009)(Figs.2,3,4and5).The2Dgriddoesnotallowcompletemappingofthemasstransportdeposit,buttheoverallextentandlargescalethicknessvariation,andthusvolume,isconstrainedwithreasonablecertainty. Theseismicreflectionprofilesinthedeepbasinallowonlytheidentificationofthetoeregionoftheslide(Figs.2B,3C,and3D).Weareabletodefinetheedgeoftheseawardpartoftheslidewherethindepositsandlesschaoticfacies(

Figs.2B,3C,and3D)areexpressedtotheNW,SWandSE(Fig.4).TheNEtoSpolarityoftheslideandespeciallyitstoehasbeendrilledatbothIODPSitesU1456andU1457(Pandeyetal.,2015).Regionalslopestothebasement,aswellasthemodernbathymetryarealsoconsistentwithemplacementtowardsthesouth.ThechaoticfaciesonlapsthefootoftheRamanSeamount(Figs.3Aand3B).TheRamanandPannikarSeamounts,locatedinLaxmiBasin(Figs.1Aand3B;Bhattacharyaetal.,1994b),constitutedbarrierstotheflowoftheslidedeposit,whichflowedaroundthesefeaturestowardsthesouth(Fig.3B).Thecoredmasstransportdeposit(Fig.4)thicknessvariesfrom~330m atSiteU1456to~190m atSiteU145(Pandeyetal.,2015).ThesethicknessvariationsintheSWpartoftheNatarajaslideareinagreementwiththeisopachmapcomputedfromthetopandbaseoftheseismicallydefinedchaoticfaciesinthisregion(Fig.4).

ThearchitectureoftheproximalpartofthemarginoffshoretheSaurashtraplatform(Figs.3,5Band5C)iscomposedofadeepwaterfoldandthrustbeltthatinvolvestheCenozoicsedimentarypackage.TheNWpartofthestudyareashowsathinsedimentarycover,comparedtotheadjacentareas,withatransitionintoamajortroughwheretwoburiedstackedcompressionalfeaturesareidentifiedandwhichareseentoemanatefromdetachmentsthatrunintotheslopeofthemargin.Thesetectonicstructuresarelinkedtoextensionalstructuresthatseesignificantpilesofsedimentextendingtowardthe SE(Fig.5C).ThemaindepocenteroffthewesternmarginofIndiaisassociatedwiththeBombayHigh(e.g.,Biswas,1982;Rao,1991;Figs.1Band5A).

TheheadwalldomainofthismasswastingcomplexislocatedintheslopeoftheGujurat–SaurashtraBasin.Basedonthemorphologyofthemargin,twoconcaveupareasarelocatedupslopeoftheNatarajaSlide(blueshadedareas,Fig.4).BasedonthepolarityoftheseismicfaciesanddrillingresultsfromIODPExpedition355,wefavorthenorthernpolygon(northof20°N,Fig.4)aspotentialheadwallsourceforthefollowingreasons:Basedonbathymetry/slopegradientandseismicprofiles,theheadwallisinferredtorunalongtheslopeandshelfbreak(Figs.1and5A).Thetruncatedreflectionsattheshelfedge/slopetransitionmarkstheheadofthescar(Fig.5B).Slopegradientsintheheadscarpregionrangefrom1.6°to2.7°,whicharetypicalofthedécollementlevelinupperslopeandheadscarpregionsalongpassivemargins(HarrisandWhiteway,2011).Thedistalbasallowerhalfgradientofthemasstransportdepositsliesatagradientof1.2°.Thisvalueisconsistentwiththelargestslidesthattendtooccuronthelowestsurfaceslopes(McAdooetal.,2000).

BeforetherecentdrillingofSitesU1456andU1457,therewasnopreciseageinformationforthelandslidefaciesitself.However,itsageisbracketeddownwardbythepresenceofupto1150mofbasinfilldepositbetweentheslideandthetopofthevolcanicbasementandoverlyingPaleogenecarbonateplatforms(Calvèsetal.,2008),andupwardbythechannelleveecomplexesoftheIndusFan,whicharedatedasEarlyMioceneandyoungerfurthernorth(Cliftetal.,2001).ThestratigraphicpositionofthemasstransportdepositsiscalibratedfurthernorthwhereitstopandbasemarkerscorrelatewithhemipelagicsedimentsfromaboreholewithpoorlyresolvedagesfromearlytolateMiocene(~15Ma)(http://www.dghindia.org;well:GSDW11A)(Figs.2Aand3A).AtSiteU1456(Fig.1A),thesedimentlyingimmediatelyaboveandwithinthemasstransportdepositisdatedat<10.8Ma,whereassedimentlyingdirectlyunderneaththedepositis datedas13.5–17.7Ma(Pandeyetal.,2015).TheagegapbetweenthetworepresentserosionatthedrillsitelinkedtoMTCemplacementaround10.8Maanddoesnotindicateslowsedimenttransport.ThebestageestimatefortheNatarajaslideisthusbetweenaround10.8Ma(lateMiocene).

3.2. *SizeandvolumetricsoftheNatarajaMTD*

ThesizeoftheheadscarpintheGujurat–SaurashtraBasinis~100kmalongtheNW–SEaxisand~90kmalongitsNE–SWaxis(Figs.4and5A).Itspresentdayminimumheightis~2300m,thiscorrespondstothetopofthetruncatedreflectionsontheshelfedgetransitiontothebaseoftheslopewherecontinuousreflectionbegins(Fig.5B).Theestimatedvolumeoftheheadscarpcanbecomputedasthequarterofanellipsoid,sothatitsvolumeis estimatedat~11×10^3km^3. TheNatarajaSlidehasa surfaceextentof~$49\pm16\times10^3$km^{2}and a volumeofsome$19\times10^3\pm4\times10^3$km^3, whichmakesthis oneofthelargestknownmasstransportcomplexdepositsalonganypassivemarginsofardocumentedonEarth.Atthescaleofthemargin,thesliderepresents8%±3%oftheCenozoicsedimentdepositedintheGujurat–SaurastrahandLaxmiBasins(Fig.1B;Exxon,1985,wholevolumeof~600×10^3km^3).TheminimumvolumeofthescarpobservedonthebathymetryandtheestimatesoftheNatarajaSlidedepositareofthesameorder.Thearealsize>100km^{2}andvolume>1km^{3}oftheNatarajaSlideallowustoclassifyitasanattachedmasstransportdepositintheterminologyofMoscardelliandWood(2008,2015).

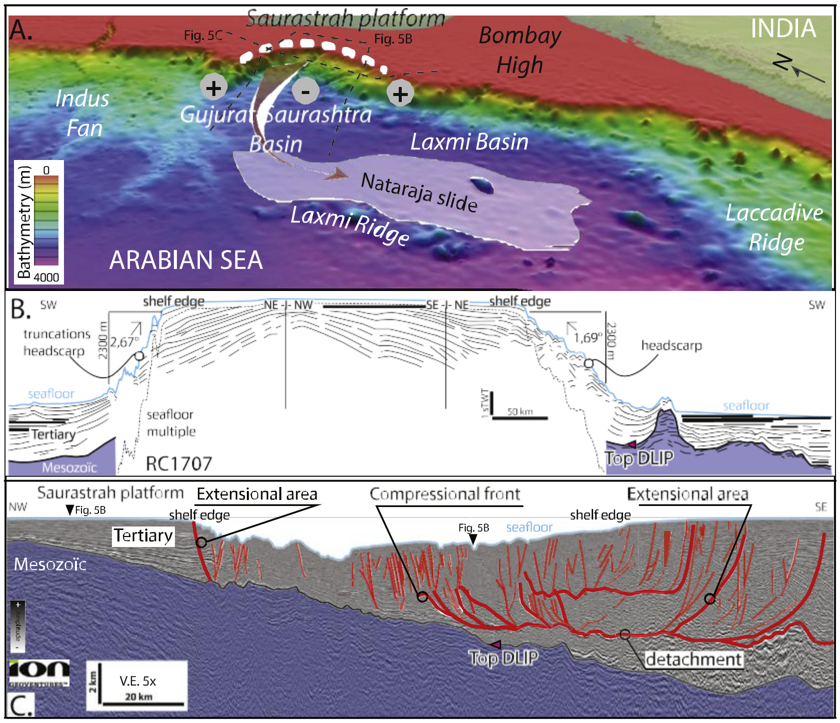

Fig.5.A.ExtensionoftheburiedNatarajaslideandpotentialsourcearea.Therunoutdistanceisabout550kmforalengthof338kmandamaximumwidthof193km,volumetricestimatesis$19\times10^3\pm4\times10^3$km^3.B.LinedrawingofseismicsinglechannelRC1707(Columbia–Lamont–DohertyEarthObservatory,GeoMapApp).C.RegionalNW–SEprestackdepthmigratedseismicreflectionprofileacrosstheshelfandslopeoftheWestIndiacontinentalmarginoffshoretheSaurashtraplatform.Thestructural styleoftheTertiarysectionisassociatedwithastackoftwocompressionaldeepwaterfoldandtrustbelt.DeccanLargeIgneousProvinceismarkedwithapurplearrow(topDLIP).

Table1

Volumetricandheightoffallhorizontalrunoutratioofthe‘giant’submarinelandslides(i.e.volume>10^3km^3) andassociatedreferences.

Slidename	Runoutlengt	Height*H*	*H/l*ratio	Vol	Reference
Nuuanu	230	5000	0.022	5000	Normarketal.,1
IsraelSlumpComplex	150	2000	0.013	1000	FreyMartinezet
Saharaslide	780	3300	0.004	1100	Embley,1976
Bruneislide	120	2300	0.019	1200	Geeetal.,2007
HinlopenSlide	300	1400	0.005	1350	Vannesteetal.
CapeFearSlide	420	4250	0.010	1400	Popenoeetal.
EasternAmazonFanMTCs	275	3300	0.012	1500	Pineretal.,199
WesternAmazonFanMTCs	245	3000	0.012	2000	Pineretal.,199
Storeggaslide	770	3720	0.005	3000	Canalsetal.,20
AvabacasFormation	500	500	0.001	10000	Callotetal.,200
SouthMakassarStraitMTC	120	1700	0.014	2438	Armanditaetal.
Makranaccretionarycomp	150	600	0.004	42000	Burgetal.,2008
AgulhasSlump	750	800	0.001	20331	Dingle,1977
GiantChaoticBody	255	3000	0.012	50000	Torellietal.,199
Nataraja	550	3150(±15	0.006	18745(±4	Thisstudy

4. Discussion

4.1. *SignificanceoftheNatarajaSlide*

Wehavecompiledfromvarioussourcestheheightoftheratiooftheoriginatingslopeheighttohorizontalrunoutofsubmarineslidesasafunctionofthevolumeofeachmasswastingdeposit(e.g.,EdgersandKarlsrud,1982;DeBlasioetal.,2006).Globally,theNatarajaSlideisthesecondlargestmarinemasstransportdepositalongapassivemarginbyvolume, onlysmallerthantheAgulhasslump(Dingle,1977)(Table1,Fig.6).Basedonthesizeandshapeofthisbody,thelongrunoutofthismasstransportdepositacross a gentleslope,coveringlongdistancesandthedevelopmentofathickdepositfurtherpushestheenvelopeproposedby DeBlasioetal.(2006),aswellastheempiricalcurvesofsubmarinelandslidesofEdgersandKarlsrud(1982)totheirlimits.Thisslidehasasourcelocatedinamixedsedimentarymarginsequenceanditssinkisstructurallyboundedbymajorbathymetricfeatures,whichwearguehavefacilitateditsrunoutdistancebyfocusingit.ThepotentialmixedlithologiessourcedfromtheslopeoftheWestIndianMargincouldexplainthevariousfeaturesobservedwithinthecoredslidedeposits(Pandeyetal.,2015).TheobservedolistostromesintheMakran(onshorePakistan,Burgetal.,2008)ortheGiantChaoticBody(offshoreGibraltar,Torellietal.,1997)arethelargestchaoticsedimentarybodiesyetobserved.Thesetwosedimentarybodiesshareaspecificgeodynamicandstructuralsetting,anaccretionaryprism,whichisdifferentfromthepassivemarginstructuralframeworkoftheWestIndianMarginwhereweobservetheNatarajaSlide(e.g.NainiandTalwani,1982).

4.2. *GeneticfactorsoftheNatarajaSlide*

Atthemarginscale,thestratigraphicandstructuralsettingoftheproximalsourceareaallowsustoproposeaspatialassociationoftheheadwallandthecompressionalfrontbelowtheslopeofthemargin(Fig.5C).Thisconfiguration,whichisfoundalongmanypassivemargins,accretionaryprismsandtransformmargins,isasourceofmanyslidesandofmasswastinggenesis(e.g.,Morley,2009;Morleyetal.,2011).Atthescaleoftheslidethekinematicevidencefora singleeventassociatedwiththisslideisrelatedtothegeometryofthecompressional/extensionalfeaturesfromitsbodyintoitstoe.Theabsenceofmultiplestackedcompressionalfeaturesin this slide(Figs.2B,2Cand3B)arguefor a singlemassmovement. A basalshearsurfaceisonlyidentifiedatthebottomofthemasstransportcomplex(Fig.2B). ThepotentialperiodofemplacementoftheNatarajaSlideiscoincidentwithmajorchangesinsouthernAsia(Clift, 2006).OnefactoristheclimaticevolutionandchangeinsedimentaryproductionandsedimentationaroundthecontinentalmarginsofSandSEAsiaatthattime.DuringtheearlyPaleogenethemarginrecordedcarbonateplatformgrowthfollowedby astressshiftexpressedbyfocalclasticsedimentaryloading(Whitingetal.,1994)thathasplayedanimportantroleonbuildingsequencesofsedimentarygravitationalsliding.ThisisobservedonothermarginsaroundtheIndianOceansuchastheKrishna–GodavariBasin(Rao,2001)andRovumaBasin(MahanjaneandFranke,2014).TheMiddletoEarlyMiocenewasatimeofrapidsedimentdeliverytothecontinentalmarginsofIndia,drivenbyfasterosioncausedbyaheavysummermonsoon.Developmentofa majorclasticwedgemayhaveresultedingravitationalinstabilitythatresultedincollapse~10.8Ma.

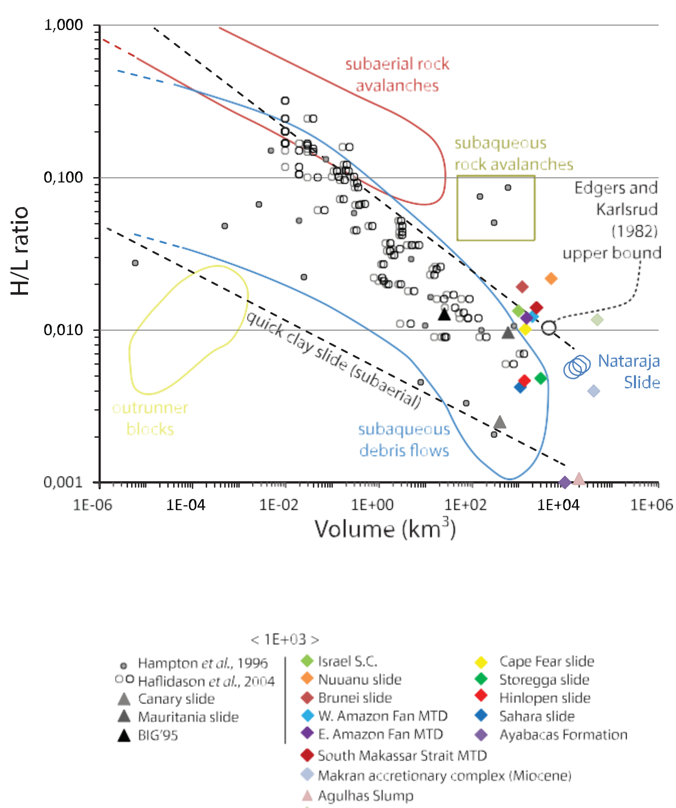

Fig.6. Heightoffalltohorizontalrunoutratioofthe slide as a functionof thevolumeofthemasswastingdeposits.ThecoloredenvelopesarefromDeBlasioetal.(2006,seewithinfor compileddata).IndividualslidesarefromHaflidasonetal.(2004)fortheStoreggaslideoffNorwayandfromv ariousslidesintheglobalocean(Hamptonetal.,1996).Giantslidesaredepictedbytrianglesorcoloreddiam ondsforvolumes>10^3km^3(seeTable1forreferences).CurvesfromEdgersandKarlsrud(1982),theupper boundvaluesforsubmarinelandslidesandsubaerialquickclayslidesareplottedforreference.(Forinterpre tationofthereferencestocolorinthisfigurelegend,thereaderisreferredtothewebversionofthisarticle.)

4.3. Perspectives

Regionally,theNatarajaSlide,ifassociatedwithasinglecatastrophicevent,couldhaveleftitsmarkonthecoas talrecordoftheArabianSeaintheformoftsunamigenicdeposits,althoughthe>10.8Maageofthedepositmaym akepreservationanissuewhensearchingforequivalentsedimentsonshore.Thestructuralanalysisofdensergr idofdataontheslideshouldallowdeterminationofthekinematicsofthisslideandthepotentialmechanismsofitse mplacement(catastrophicorcreeping).ThelongrunoutandtherelationshipwiththeseamountsintheLaxmiBa sinhowevercouldarguesfromcatastrophicemplacement.Specificcharacterizationofthesedimentsassociat edwiththeslideisneededtoinferanyroleplayedbybaselevelvariation,hydratedissociation,localtectonicsorev enbasinfluidmigrationinrelationwithhydrocarbongeneration.Comingafteratimeofrapidmarginsedimentatio nmayargueinfavorofgravitationalinstabilityastheunderlyingcause.

IntheArabianSeathepresentdayriskofcoastaltsunamisisanalyzedassumingasourceofmassmovementsf romtheMakranaccretionaryprism,oreventheAndamantoJavaarcinthecaseoffarfieldsources(e.g.Heidarza dehetal.,2008;OkalandSynolakis,2008).Thisapproachisassociatedwiththelimitedoccurrenceofearthquak esalongthewesterncontinentalmargin(Chandra,1977),becausethesearecommoncausesoftsunamisintheI ndianOceanregion.Yetnoriskassessmentisdiscussedinthesestudieswithasourceofmassmovementsandw atercolumndisplacementsrelatedtotheWestIndianContinentalmargin.OurdescriptionoftheNatarajaSlidehi ghlightsthisregionasapotentialsourceofmassmovementsintheWesternIndianOceanandshouldguidefutur eresearchonthismargin.Giventhelargesedimentmassthathasbeenbuiltalongthewesterncontinentalmargi nduringthePlio–Pleistocenephaseofrapidsedimentdeliverythepotentialforfurthermajormasswastingeventsmaywellexist.T hisnewinformationaboutalargeLateMioceneeventiscentraltorefiningourassessmentoftsunamihazardalon gthedenselypopulatedwesterncoastofIndia.Convexupwardareasalongthemarginaremorelikelytoslip,thisri skisunderlinedbythedepthandslopeofthedécollementobservedbelowtheSaurashtrashelfthat isdeeperthanitformedoriginally.

5. **Conclusions**

Thispaperreportsthediscoveryandfirstdescriptionandquantificationofthegiant NatarajaSlideoffshoreMumbai,thesecondlargestlandslidesofardiscoveredalonganypassivemarginworldwide.Thelandslidecoversar ound5×10^4km^{2}andcomprisessome2×10^4km^{3}sediment.ItislateMioceneinage.TheNatarajaSlide'sroleinf ormingatopographicalhighfortheeasternborderoftheIndusFancanbe questioned.Inbothactiveandpassivemarginsweshouldconsiderthatmasswastinghasimportancealongside carbonateaccumulationandfluvialinputinshapingtheseafloorofsedimentarybasins.TheNatarajaSlidewillre quirefurtherstudiestofullyunderstanditsstructureandspatialorganization,whichmaybeachievedinpartwithf utureworkonthecoresrecoveredbyIODPExpedition355.

6. Author contributions

G.C.hasframedthestudyoftheNatarajaSlide,andallauthorshavecontributedtothemainideadescribedinthi smanuscriptandtoitswriting.

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