



UNIVERSIDADE DE BRASÍLIA
INSTITUTO DE GEOCIÊNCIAS - IG
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS APLICADAS E GEODINÂMICA

VITTO CÉSAR MIRANDA DE ARAÚJO

**IMAGEAMENTO SÍSMICO DA LITOSFERA SOB A BACIA DO
PARNAÍBA: ESTUDO DE REFRAÇÃO PROFUNDA E FUNÇÃO
DO RECEPTOR COM ESTAÇÕES DE PERÍODO CURTO**

Tese de Doutorado n° 52

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Tese apresentada ao Programa de Pós-Graduação em Geociências Aplicadas e Geodinâmica do Instituto de Geociências da Universidade de Brasília como parte dos requisitos para obtenção do título de Doutor em Geociências.

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Palavras-chave: Sísmica de refração profunda, função do Receptor, Bacia do Parnaíba, Tomografia Sísmica, Litosfera

" Se, a princípio, a ideia não é absurda, então não há esperança para ela."

Albert Einstein

*À minha esposa, meus filhos (Ravi e Maitê) e a meus pais,
Afrânio Bruno Aranha de Araújo (in memorian)
e Maria de Lourdes Miranda de Araújo*

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Resumo

A Bacia do Parnaíba é uma depressão intracratônica localizada nas regiões norte e nordeste do Brasil, abrange parte dos estados do Pará, Maranhão, Piauí, Tocantins, Ceará, Bahia e recobre uma área de aproximadamente 660.000 km². Seus limites apresentam contato tectônico com os crátons Amazônico (oeste) e São Luis (norte) e erosivo com as unidades da Província Borborema (leste), o Cráton São Francisco e a Província Tocantins (sul). Com objetivo de detalhar a estrutura da litosfera sob a Bacia do Parnaíba e melhor entender sua gênese e evolução tectônica, o presente trabalho apresenta resultados obtidos com os métodos geofísicos de sísmica de refração profunda e função do receptor. O levantamento sísmico foi realizado ao longo de uma transecta de 1.150 km de extensão. A linha se inicia no Cráton Amazônico, atravessa a Província Tocantins (Faixa Araguaia), cruza os limites oeste e leste da bacia (Blocos Grajaú e Teresina) e finaliza na Província Borborema. O experimento de refração foi realizado com 600 sensores espaçados de dois em dois quilômetros, com cargas explosivas de 3.000 kg nos extremos (distribuídos em dois poços) e 1.500 kg nos tiros intermediários. A técnica função do receptor foi aplicada em registros telessísmicos de 40 estações de 3 componentes de período curto, espaçadas a cada 30 km, coincidentes com a transecta sísmica. Os resultados da sísmica de refração mostram a geometria das principais descontinuidades crustais e a distribuição de velocidades (V_p , V_s e V_p/V_s). O modelo traz importantes informações como a caracterização do *front* de sutura Amazônico, a geometria assimétrica da bacia, espessura máxima de 3.2 km no depocentro e alta velocidade de ondas sísmicas na crosta inferior, provavelmente atribuída à presença de intrusões magmáticas máficas. Os dados de Função do Receptor mostram diferentes padrões de V_p/V_s para a crosta, marcados por degraus na interface de *Mohorovicic*, os quais corroboram a presença de diferentes blocos crustais no embasamento da bacia, amalgamados durante a consolidação do Gondwana Oeste. Os valores de espessura crustal são positivamente correlacionáveis aos de sísmica de refração, com tendência ao afinamento crustal na medida que se aproxima da Província Borborema. Os dados mostram ainda que o domínio central da transecta (domínio do Bloco Grajaú) foi, de fato, afetado por intenso magmatismo, o qual teria desempenhado importante papel na evolução da Bacia do Parnaíba. A presença de intrusões máficas na base da crosta nessa região a tornariam mais competentes e menos suscetíveis a deformações Cretáceas significativas na abertura do Oceano Atlântico, haja vista a presença de uma placa fóssil subductada e a presença de estrutura crustal espessa e preservada, destoante de modelos conceituais de rifte, que sugerem afinamento crustal e *uplift* litosférico.

Palavras Chave:

1 - Sísmica de Refração Profunda; 2 - Função do Receptor; 3 - Bacia do Parnaíba;
4 - Tomografia Sísmica; 5 - Litosfera

Abstract

The Parnaíba Basin is an intracratonic depression located in northern and northeastern regions of Brazil, encompassing parts of the states of Pará, Maranhão, Piauí, Tocantins, Ceará, Bahia and an area of approximately 660.000 km². Its limits present tectonic contact with Amazonian (westwards) and São Luis (southwards) Cratons and erosive with São Francisco Craton (eastwards) and Tocantins Province (southwards). With the proposal to detail the lithosphere structure beneath the Parnaíba Basin and better understand its genesis and tectonic evolution, the present work shows the first results of the research project that uses deep seismic refraction and receiver function. The seismic survey was performed along an 1150 km long profile. The line starts in Amazonian Craton, crosses Tocantins Province (Araguaia Belt), traverse west and east limits of Parnaíba Basin (Grajaú and Teresina blocks) and ends in Borborema Province. The deep refraction experiment was carried out with 600 sensors spaced 2 km each, with bursting charges of 3.000 kg (distributed in two wells) in the extremes and 1.500 kg in intermediary shots. The receiver function technique was applied on Teleseismic registers of 40 three component short period stations, spaced every 30 km. The deep refraction seismic results show the geometry of the main crustal discontinuities and the distribution of velocities (V_p , V_s and V_p/V_s). The model brings important information like the asymmetric shape of the basin, maximum depth of 3.2 km in its depocenter and high seismic wave velocities in lower crust, probably attributed to the presence of mafic magmatic intrusion on the base of lower crust. Receiver function data present different crust V_p/V_s patterns, marked by steps on *Mohorovicic* interface, which corroborate the presence of different crustal blocks beneath the Parnaíba's Basin domain, amalgam during the consolidation of West Gondwana. The crustal thickness values are positively correlated to deep seismic data, with a tendency for crustal thinning as it approaches the Borborema Province. The data even show that the central domain of the transect (Grajaú Block) was, indeed, affected by intense magmatism, which would have played an important role during the evolution of the Parnaíba Basin. The presence of mafic intrusion within the base of the crust would make it more reliable in that region and less susceptible to Cretaceous deformations related to the opening of Atlantic Ocean, due to the preservation of a fossil subducted plate and the presence of a thick and preserved crustal structure, dissonant from rift concepts, which suggest crustal thinning and lithospheric uplift.

Keywords:

1 - Deep Seismic Refraction; 2 - Receiver Function; 3 - Parnaiba Basin;
4 - Seismic Imaging; 5 - Lithosphere.

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Estrutura da Tese

A presente tese de doutorado contém cinco capítulos. O Capítulo 1 contextualiza o tema de pesquisa e a área de estudo, os métodos e justifica a finalidade da tese. Por último apresenta sucintamente os métodos geofísicos empregados, a logística operacional de campo, o banco de dados e descreve as rotinas de processamento.

O Capítulo 2 apresenta o manuscrito " *Structure of the crust and upper mantle beneath the Parnaíba Basin, Brazil, from wide-angle reflection–refraction data* " publicado no dia 04 de abril de 2018 no periódico da Geological Society of London - GEOLSOC/UK. O artigo mostra o modelo de ondas P para todo domínio do perfil de refração. Nesse artigo buscou-se determinar as principais heterogeneidades da crosta abaixo do perfil, assim como a geometria da descontinuidade de Moho e principais implicações. O artigo representa a base dos dados da pesquisa na Bacia do Parnaíba e os materiais suplementares, compostos pelos dados de modelagem dos 20 tiros, podem ser encontrados no link: <https://doi.org/10.6084/m9.figshare.c.4058582>.

O Capítulo 3 é relativo ao manuscrito " *Crustal Structure and Vp/Vs Ratio of Parnaíba Basin - Brazil: Evidences of Neoproterozoic Amalgamation in West Gondwana* ". O artigo apresenta os dados de função do receptor obtidos no perfil da Bacia do Parnaíba. Os resultados mostram detalhes da compartimentação tectônica que atravessa o perfil, apresenta a disposição dos valores de Vp/Vs e destaca a geometria da Moho, que mostra correlação positiva com os dados de refração. O material suplementar encontra-se nos Apêndices A e B, que apresentam uma tabela com os dados de função do receptor, os eventos utilizados em cada estação, os traços empilhados segundo parâmetro de raio, o empilhamento radial de cada estação e a solução H-k Stacking, com resultados e estatísticas.

O Capítulo 4 apresenta os dados da modelagem de ondas S, os quais serão utilizados para compor o manuscrito " *S Wave characteristics and Vp/Vs ratio of Parnaíba Basin - Brazil: insights from receiver function and deep seismic refraction* ". O artigo evidenciará os principais resultados da modelagem das ondas S, as principais

correlações do perfil V_p/V_s obtido com dados de função do receptor, além das implicações acerca da evolução tectônica da bacia.

O Capítulo 5 discorre sobre as principais conclusões do trabalho. São elencadas as discussões acerca dos métodos geofísicos empregados e as principais contribuições da pesquisa na Bacia do Parnaíba.

O Apêndice A apresenta a tabela-resumo dos dados de sismologia utilizados, com as coordenadas de todas as 40 estações sismográficas, distância em relação à origem, tempo de chegada das ondas Ps e número de funções do receptor utilizadas por estação.

O Apêndice B é referente ao material suplementar utilizado no manuscrito de função do receptor. Nos documentos é possível visualizar os traços estaqueados separados por parâmetro de raio, a solução Hk-stacking e suas estatísticas, a componente radial representativa e o mapa de eventos telessísmicos utilizados no cálculo da função do receptor.

O Apêndice C apresenta o manuscrito " *Characterization of the crustal structure by reflectivity patterns of WARR and DSR seismic data from the Parnaíba Basin, Brazil* ", publicado na Geophysical Journal International, como desdobramento dos estudos de refração e função do receptor na Bacia do Parnaíba.

1. INTRODUÇÃO

A plataforma continental da América do Sul apresenta importantes feições geológicas e tectônicas do ciclo Brasileiro e de ciclos orogênicos anteriores, embora vastas regiões estejam escondidas por grandes sinéclises paleozoicas (Castro *et al.*, 2014).

O entendimento dos mecanismos de formação e evolução tectônica dessas grandes bacias (Paleozóicas), compostas por extensas pilhas de sedimentos continentais a marinhos e longa história de subsidência, passa pelo conhecimento da estrutura e composição da litosfera subjacente.

As propriedades da litosfera são bem determinadas por dados sísmicos e sismológicos, devido principalmente à sensibilidade dos métodos sísmicos às variações de velocidade das ondas no meio tanto lateralmente quanto em profundidade (Prodhel & Mooney, W. D., 2012). Modelos de velocidade obtidos a partir de dados sísmicos podem ser interpretados em termos de composição e estado físico da subsuperfície, além de fornecer informações sobre a forma e espessura das camadas.

Nesse contexto, nas últimas décadas estudos sísmicos e sismológicos têm sido realizados no Brasil (Assumpção *et al.*, (2002); Assumpção, (2004); Berrocal *et al.*, (2004), Soares, (2005); Soares *et al.*, (2006); Ventura, (2010); Daly *et al.*, (2014); Evain *et al.*, (2015); Lima *et al.*, (2015); Tozer *et al.*, (2017); Soares *et al.*, (2018); Coelho *et al.*, (2018), Pinheiro *et al.*, (2018), Queiroz, (2019) visando a determinação da estrutura da litosfera e o aprimoramento dos modelos de evolução tectônica da placa Sul-Americana.

Este trabalho mostra os principais resultados obtidos com o experimento sísmico de refração profunda da Bacia do Parnaíba (do inglês *Wide Angle Reflection-Refraction*), que integrou resultados sísmicos e sismológicos. O levantamento de dados foi conduzido pelo LabLitos/IG/UnB, em parceria com o grupo de tectônica da Universidade de Aberdeen/UK, ao longo de uma transecta E-W aproximadamente coincidente com a transecta de reflexão sísmica profunda realizada por Daly *et al.*, (2014).

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1.1 - Localização da Área de Estudo

O estudo foi desenvolvido na Bacia do Parnaíba, localizada na porção norte/nordeste do Brasil. O perfil sísmico foi realizado em uma transecta de direção E-W com aproximadamente 1.150 km de extensão, situado entre as cidades de Marabá-PA e Independência-CE e cruza a Bacia do Parnaíba e seus limites leste e oeste (Fig. 1).

1.2 - Objetivos

O objetivo do trabalho é determinar o modelo da estrutura crustal e do manto superior sob a região ocupada pelo domínio da Bacia do Parnaíba, a geometria das principais descontinuidades e a composição e estado físico da litosfera, a partir da modelagem de ondas P e S obtidas com o método de refração sísmica profunda e com a técnica da função do receptor.

Os objetivos específicos são: i) aplicar a técnica função do receptor em registros de telessismos para obter a primeira aproximação da espessura e V_p/V_s médias da crosta sob o perfil; ii) definir modelo de velocidade V_p e V_s da crosta processando e modelando dados de refração profunda dos (~ 20) tiros da linha; iii) obtenção do modelo integrado de refração e função do receptor e iv) analisar o modelo de refração com base no perfil sísmico de reflexão profunda (*Deep Seismic Reflection*) apresentado por Daly *et al.* (2014);

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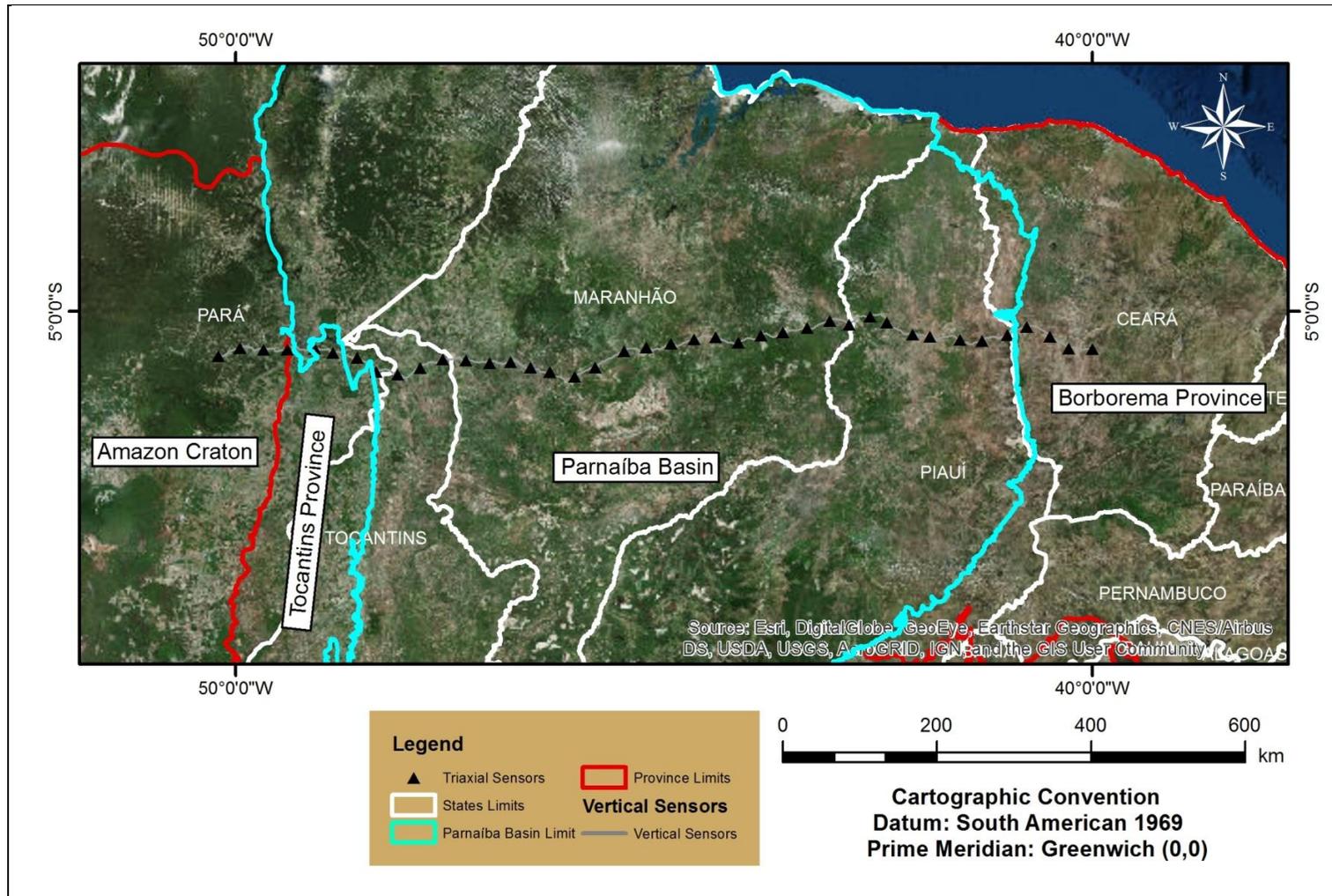


Figura 1: Mapa geográfico da localização da transecta sísmica de refração profunda e respectivas estações triaxiais de período curto utilizadas para cálculo da função do receptor.

1.3 - Contexto Geológico

A área de pesquisa se insere no contexto geológico da Bacia do Parnaíba, uma vasta depressão intracratônica aprisionada na porção centro-oriental da América do Sul. A bacia compreende uma região de complexa evolução tectônica/litoestrutural resultante de colisões envolvendo blocos cratônicos e extensivos cinturões de dobramentos neoproterozóicos, com evolução tectono-sedimentar estabelecida durante a transição do Neoproterozóico ao Eopaleozóico.

O Neoproterozóico foi marcado, de forma geral, por um período de rifteamento e extensão continental mundial (Tafrogenia Toniana 900 - 800 Ma.), seguido de sucessivas colisões continuadas de blocos e fragmentos continentais previamente dispersos (Brito Neves *et al.*, 2000). Essa etapa de convergência resultou na aglutinação de diferentes blocos e incorporação de complexos acrecionários na forma de cinturões móveis, culminando com a formação do continente Gondwana, o qual perdurou até o Cambriano (520 Ma.; Urung, 1997).

Os principais episódios orogênicos Neoproterozóicos são referidos, na América do Sul, como Brasileiro, e na África, como Pan-Africano (Trompette, 1994). As faixas móveis formadas nesses sistemas orogênicos são sítios que acomodam a maior parte dos esforços tectônicos de convergência litosférica, seja por subducção de crosta oceânica, na fase pré-colisional ou por empilhamento de escamas tectônicas como produto da fase colisional (Almeida, 1990) e desempenham importante papel na amalgamação de blocos cratônicos no curso dos processos de colisão.

A evolução da era Neoproterozóica foi acompanhada de extensão pós orogênica disseminada, iniciando-se a fragmentação da margem proto-Andina do Gondwana e a consequente origem do antigo oceano Iapetus. No fim do Cambriano, mudanças no estado de *stress* da litosfera continental causaram extensão crustal e rifteamento, os quais foram acompanhados de abundantes intrusões magmáticas. As fases de rifte e magmatismo ocorreram preliminarmente ao longo de zonas de fraquezas pré-existentes do Gondwana Oeste, entretanto, os processos extensionais não se conduziu à total quebra continental, originando-se uma série de riftes abortados. Nesse contexto, bacias cratônicas paleozoicas se formaram e ocuparam vastas regiões na América do Norte (bacias do Michigan, Illinois e Hudson Bay), África (bacias do Congo, Chad e Taoudeni) e América do Sul (Amazonas, Parecis, Paraná e Parnaíba; Castro *et al.*, 2016).

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O presente capítulo discorre acerca das principais unidades geotectônicas que fazem parte do contexto geológico do perfil sísmico de refração profunda da Bacia do Parnaíba. O perfil sísmico se inicia sobre o Cráton Amazônico, cruza parte norte da Província Tocantins (Faixa Araguaia), a Bacia do Parnaíba e termina na Província Borborema.

1.3.1 - Cráton Amazônico

O Cráton Amazônico, localizado no norte da América do Sul, é uma das maiores regiões cratônicas do mundo. Possui uma área aproximada de 4.300.000 km² dividida nos escudos do Guaporé e das Guianas, os quais são separados pelas coberturas sedimentares da Bacia Amazônica. O cráton tem se mantido estável desde 1.0 Ga. e é limitado por cinturões orogênicos neoproterozóicos do Tucavaca, na Bolívia, Araguaia-Cuiabá e Tocantins, no Brasil.

A evolução tectônica do cráton (Cordani *et al.*, 1979; Tassinari, 1981; Cordani & Brito Neves, 1982; Teixeira *et al.*, 1989 e Tassinari *et al.*, 1996) remonta a uma sucessão de arcos magmáticos do arqueano, paleoproterozóico e mesoproterozóico, os quais definiram Províncias Geocronológicas e envolveram a formação de material juvenil, como também processos subordinados de retrabalhamento crustal.

As principais Províncias Geocronológicas descritas por Tassinari & Macambira (1999), definidas como áreas cratônicas com propriedades geoquímicas/geocronológicas semelhantes, são denominadas, em ordem cronológica, como: Província Amazônia Central (2.5 Ga.); Província Maroni-Itacaiunas (2.25 a 2.0 Ga.); Província Ventuari-Tapajós (1.95 - 1.8 Ga.); Província Rio Negro - Juruena (1.8 - 1.55 Ga.); Província Rondoniana - San Ignácio (1.55 - 1.3 Ga.) e Província Sunsás (1.3 - 1.0 Ga.).

Uma das particularidades dos dados de proveniência mineral mostram que o crescimento da crosta continental e do Cráton Amazônico, durante o Proterozóico, envolveu a adição de materiais pré-existentes (Sato & Tassinari, 1996). A evolução cratônica considerou tanto materiais provenientes de manto superior, a partir de sucessivos arcos de ilhas (Províncias Ventuari-Tapajós, Rio-Negro Juruena e parte da Província de Maroni-Itacaiunas), como materiais de colisão continental.

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1.3.2 - Província Tocantins

A Província Tocantins (Almeida et al. 1981; Marini *et al.*, 1984) é um grande sistema orogênico Neoproterozóico situado entre os crátons Amazônico (a oeste), São Francisco-Congo (a leste) e um terceiro bloco - Paranapanema (a sul) - desenvolvido a partir das colisões que resultaram na amalgamação do supercontinente Gondwana no final do Neoproterozóico. Menores porções de fragmentos continentais, os quais também foram envolvidos no desenvolvimento da Província Tocantins se encontram atualmente recobertos pela presença da Bacia do Parnaíba (Cordani et al., 1984; Brito Neves et al., 1984; Fuck et al., 2008).

A província homônima é composta de três faixas ou cinturões orogênicos diacrônicos com diferentes vergências: a Faixa Paraguai, Faixa Araguaia e Faixa Brasília. Segundo Fuck et al. (2007), a Província Tocantins possui cerca de 2.000 km de comprimento, largura de 800 km e faz contato com o Cráton Amazônico (ao longo das margens leste e sudeste do craton) e o Cráton São Francisco, em sua borda oeste.

As Faixas Araguaia e Paraguai fazem contato com a borda leste do Cráton Amazônico, ao passo que a Faixa Brasília faz contato em sua borda leste com o Cráton São Francisco. A Faixa Brasília se estende por mais de 1000 km com orientação aproximada N-S e constitui um dos orógenos Brasileiros mais bem conservados e completos da América do Sul.

Suas principais características indicam importante anomalia gravimétrica diagnóstica de sutura entre os blocos continentais envolvidos (Pereira and Fuck, 2005) e que a diferenciação estrutural final da Faixa de Brasília resultou do fechamento de uma ampla bacia oceânica durante a Orogenia Brasileira Neoproterozóica (Pimentel e Fuck, 1992; Pimentel et al., 2000; Soares et al., 2006).

1.3.3 - Bacia do Parnaíba

A Bacia do Parnaíba é uma das cinco bacias cratônicas da plataforma Sul-Americana desenvolvida na região oeste do continente Gondwana. Possui formato aproximadamente circular, ocupa uma área de aproximadamente 660.000 km² e está localizada acima de um embasamento complexo compreendendo diversos terrenos arqueanos e proterozóicos amalgamados durante a orogenia Brasileira (Cordani, 1984; Cordani *et al.*, 2009; Brito Neves *et al.*, 1984).

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Situada entre o Cráton Amazônico/Província Tocantins em sua borda oeste, Cráton São Luis/ Arco do Gurupi em sua porção norte, Cráton São Francisco/Província Borborema em seu limite leste/sul, a Bacia do Parnaíba (Fig. 2) é classificada como do tipo *sag* (intracontinental) e mostra registro sedimentar do Ordoviciano ao Cenozóico.

Por correlação com as entidades geológicas circundantes à bacia supracitada, se deduz que seu substrato é constituído de rochas metamórficas, ígneas e sedimentares, cujas idades abrangem um longo intervalo – do Arqueano ao Ordoviciano; porém, possivelmente predominem rochas formadas entre o final do proterozóico e o início do paleozóico, que corresponde ao tempo de consolidação da Plataforma Sul-Americana.

Fortes (1978) postulou que a forma e evolução tectônica da Bacia do Parnaíba está relacionada com a reativação de estruturas do embasamento pré-existentes. Com base em dados de geologia regional e estudos de isótopos de amostras de testemunhos, Brito Neves *et al.*, (1984) propuseram a existência de um distinto, mas não exposto embasamento rochoso abaixo da porção oeste da bacia, aprisionado entre o cráton Amazônico e a Província Borborema.

A sucessão das coberturas sedimentares se deu sobre os riftes cambro-ordovicianos de Jaibaras, Jaguarapi, Cococi/Rio Jucá, São Julião e São Raimundo Nonato (Brito Neves, 1998) e pode ser compartimentada em cinco grandes sequências deposicionais, das quais três iniciaram o processo de deposição no Paleozóico (Siluriana, Mesodevoniana - Eocarbonífera e Neocarbonífera-Eotriássica), e duas foram depositadas no Mesozoico (Jurássica e Cretácea; Góes & Feijó 1994). Essas sequências são delimitadas por discordâncias que representam importantes hiatos deposicionais e se estendem por toda a bacia ou abrangem extensas regiões (Vaz *et al.*, 2007).

O Grupo Serra Grande (Sequência Siluriana) representa um ciclo transgressivo-regressivo completo, está repousado sobre as rochas proterozóicas ou sobre depósitos cambro-ordovicianos. Em subsuperfície, ocorre praticamente em toda a extensão da bacia. Contudo, sua área de afloramento consiste quase que exclusivamente de uma estreita faixa na extremidade leste da bacia, bordejada por rochas do embasamento. Compreende as Formações Ipu, Tianguá e Jaicós. Góes e Feijó (1994) interpretam os ambientes de deposição do Grupo Serra Grande como flúvioglacial e glacial, passando a transicional (nerítico) e retornando às condições continentais (fluvial entrelaçado).

O Grupo Canindé (Sequência Mesodevoniana - Eocarbonífera) é composto pelas Formações Itaim – em muitos trabalhos considerada como membro inferior da

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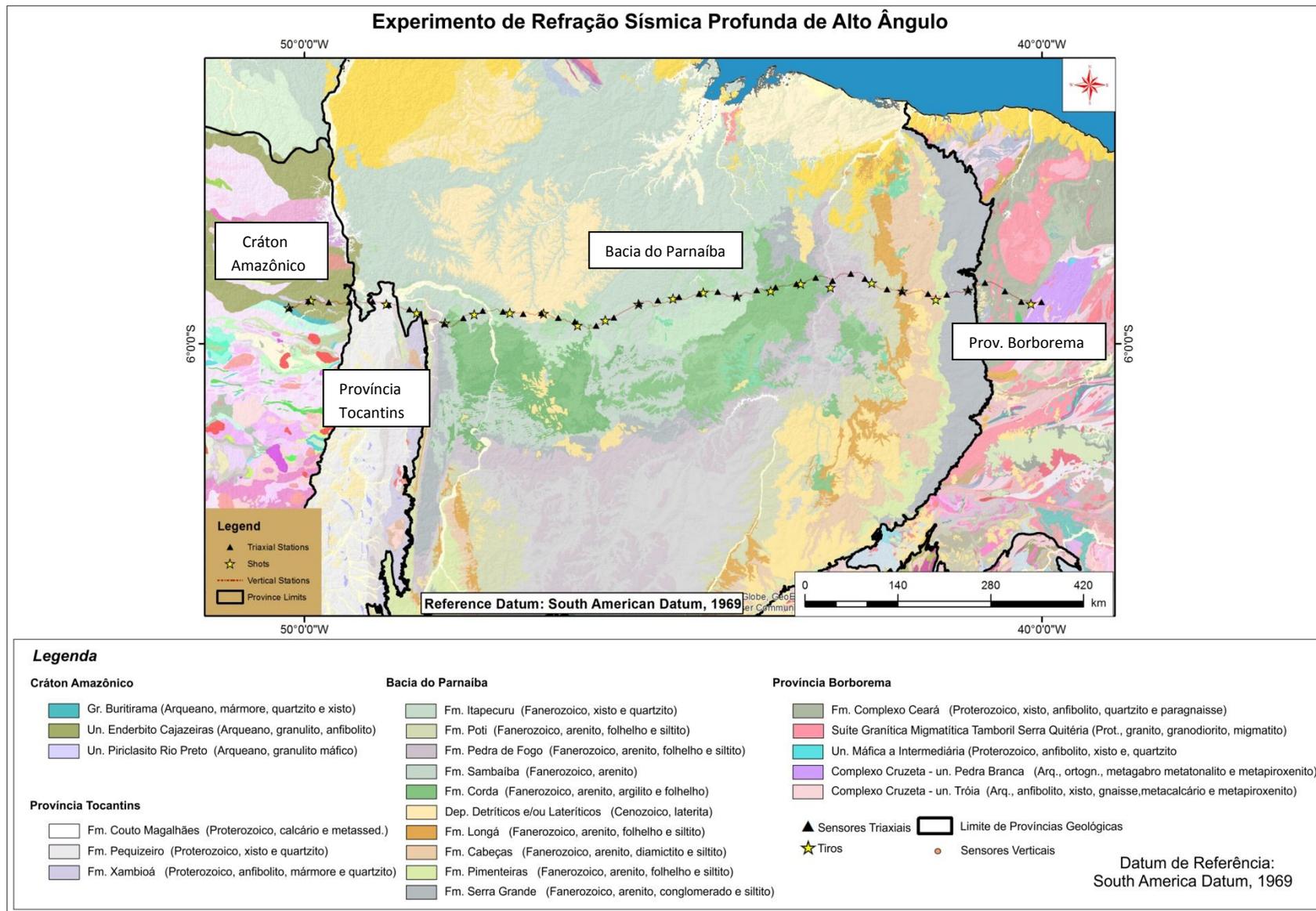


Figura 2: Mapa geológico (CPRM 1:1.000.000) que abrange o contexto da transecta sísmica da Bacia do Parnaíba-Brasil.

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Formação Pimenteiras – Pimenteiras, Cabeças, Longá e Poti. A Formação Itaim apresenta arenitos e folhelhos de ambiente de plataforma rasa. A Formação Pimenteiras está bem exposta nos arredores da cidade de Picos (PI) e é composta por arenitos com níveis de folhelhos, depositados em ambientes dominados por marés e tempestades.

A Formação Cabeças é composta por arenitos com geometria sigmoidal abaulada e localmente intercalações de diamictitos; Góes e Feijó (1994) a interpretam como depósito de ambiente nerítico plataformar, com ação de correntes e influência periglacial.

A Formação Longá é composta arenitos finos e siltitos, interpretados pelos autores supracitados como depósitos plataformais dominados por tempestades. O Grupo Canindé é encerrado pela Formação Poti para a qual Góes *et al.* (1997) interpretaram os ambientes de deposição como *shoreface* submaré inferior e superior, canal flúvio-estuarino e planície de maré, sob condições climáticas de aridez, conforme evidenciado por *tepees* e concreções do tipo “rosa do deserto”.

A Sequência Neocarbonífera-Eotriássica da Bacia do Parnaíba foi designada por Góes & Feijó (1994) como correspondente ao terceiro grande ciclo sedimentar, sobreposta discordantemente à Sequência Mesodevoniana Eocarbonífera. Essa sequência corresponde ao Grupo Balsas e representa uma sucessão de rochas depositadas em um complexo ambiente clástico/evaporítico de mar raso, gradando para um ambiente continental dominado por sistemas lacustre e desértico. Litoestratigraficamente, o Grupo Balsas é composto por quatro formações: Piauí, Pedra de Fogo, Motuca e Sambaíba.

As rochas que compõem a Formação Piauí representam o início da deposição sedimentar do Grupo Balsas ainda durante o Pensylvaniano (Vaz *et al.*, 2007). Lima & Leite (1978) interpretaram que tais rochas foram depositadas a partir de um sistema fluvial com contribuição eólica e breves incursões marinhas, sob condições de aridez climática. Essa formação foi descrita por Ribeiro (2000) como sendo constituída principalmente por rochas areníticas e, subordinadamente, por rochas conglomeráticas e siltíticas. Essa unidade possui contato erosivo com a formação subjacente (Formação Poti).

A Sequência Jurássica é representada por um estágio tectônico ativado,

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relacionado a ruptura do Megacontinente *Pangea*, que levou à abertura do oceano Atlântico. Eventos distensionais, remobilização de falhas antigas, surgimento de fraturas e intenso magmatismo básico caracterizaram essa etapa mesozóica evolutiva da Plataforma Sul-Americana (Almeida & Carneiro, 2004; Zálan, 2004).

Esse magmatismo básico é atribuído às rochas da Formação Mosquito, constituída por derrames basálticos e intercalações arenosas que afloram no rio homônimo, ao sul da cidade de Fortaleza dos Nogueiras/MA, segundo Aguiar (1971).

A sequência deposicional jurássica Pastos Bons, originada após subsidência provocada pelo peso das rochas básicas da Formação Mosquito e das rochas da própria bacia, apresentam diferentes litotipos podem ser divididos em três partes: basal, intermediária e superior.

Na base predomina arenito branco ou com tonalidades esverdeadas, amareladas, fino a médio, grãos subarredondados e, geralmente, apresentam estratificação paralela e raras lentes de calcário. Na parte média da seção ocorrem siltito, folhelho/argilito cinza a verdes, comumente intercalados com arenito. A porção superior é formada de arenito vermelho/cor-de-rosa, fino, gradando para siltito, contendo níveis de folhelho (Caputo, 1984). De leste para oeste, a Formação Pastos Bons jaz discordantemente sobre as Formações paleozóicas Poti, Piauí, Pedra de Fogo e Motuca (Lima e Leite, 1978).

Com base no conteúdo fossilífero (peixes, conchas, ostracodes) atribui-se idade jurássica média a superior à Formação Pastos Bons, depositada em paleo-depressões continentais, lacustrinas, com alguma contribuição fluvial, em clima semiárido a árido. O final dessa fase sedimentar teria sido uma consequência das atividades tectônicas concernentes à abertura do Atlântico Equatorial (Vaz *et al.*, 2007).

A sequência Cretácea se desenvolveu em regime tectônico extensional, ocasionado pela abertura do Atlântico, a qual promoveu intenso magmatismo e o deslocamento dos depocentros da região central para as proximidades do extremo norte e noroeste da bacia (Vaz *et al.*, 2007). Os afloramentos ocorrem principalmente na porção noroeste/norte da bacia e sobrepõem-se discordantemente sobre as rochas das sequências Jurássica e as mais antigas. As principais unidades são: Formação Sardinha, Codó, Corda, Grajaú e Itapecuru.

A Formação Sardinha é atribuída a corpos de basalto, preto a roxo, ocorrentes como grandes diques, pequenas soleiras e mapeados entre as cidades de Fortaleza dos

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Nogueiras e Barra do Corda. A espessura média em afloramento é de 20 m e o nome da unidade homenageia o local da primeira observação, a Aldeia do Sardinha.

O termo Formação Corda refere-se, essencialmente, a arenitos vermelhos, castanho-avermelhados, muito finos/finos e médios, seleção regular a boa, semifriáveis a semicoesos, ricos em óxidos de ferro e zeólitas. Quando ocorrem sobrepostos a basaltos, é abundante a presença de fragmentos dessa rocha como arcabouço. Estratificações cruzadas de grande porte, *climbings* transladantes e *ripples*, fluxos de grãos e outras estruturas típicas de dunas eólicas são comuns nessa unidade. Estratificações cruzadas de baixo ângulo e cruzadas acanaladas também ocorrem. A análise conjunta das particularidades dessa formação permitem a classificar como depositada num sistema desértico.

O conteúdo litológico da Formação Grajaú pode ser representado pelas rochas aflorantes nas cercanias da cidade homônima - arenitos creme-claro/esbranquiçado, creme-amarelado ou variegados, médios/grossos, subangulosos/angulosos, mal selecionados, sendo comum a presença de seixos e de níveis conglomeráticos. Eventualmente observam-se camadas de arenitos finos/muito finos e de pelitos. Estratificações cruzadas acanaladas e marcas de carga são abundantes. Também no caso da Formação Grajaú constata-se que quando existem basaltos subjacentes, estes fornecem material para os corpos areníticos.

Na Formação Codó, folhelhos, calcários, siltitos, gipsita/anidrita e arenito são os principais litotipos e são freqüentes níveis de sílex e estromatolito. Na Mina do Chorado, nas cercanias de Grajaú, o relevo cárstico está refletido em inúmeras dolinas, com deslocamentos de blocos. Os jazimentos de gipsita são recobertos abruptamente por folhelho bege a cinza/preto esverdeado, revelando uma ampla inundação (transgressão) do mar/lago Codó. Rossetti et al. (2001b) declaram que as Formações Grajaú e Codó, ambas do Neo-aptiano-Eo-albiano, foram depositadas em ambientes marinho raso, lacustre e flúvio-deltaico. Interdigitação ou equivalência cronoestratigráfica entre essas duas formações é asseverada também por Lima e Leite (1978).

A Formação Itapecuru recobre discordantemente as Formações Grajaú e Codó, (Rossetti et al. (2001a), é formada por estratos arenosos pelíticos, de idade Mesoalbiano-Neocretáceo e corresponde a seis ciclos deposicionais atribuídos a sistemas de vales estuarinos incisos. Para esta unidade, na região de Açailândia,

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prepondera um sistema estuarino-lagunar episodicamente atingido por ondas de grande escala, no qual foram observados os seguintes ambientes: canal fluvial, laguna, canal de maré e litorâneo.

Os depósitos mostram uma natureza transgressiva, e o litotipo mais freqüente é formado de arenitos variegados, finos, friáveis, com estruturas diversas, como, por exemplo, estratificações cruzadas *hummocky*, acanalada, tabular, *mud couplets* e escorregamento de massa. Pelitos e arenitos conglomeráticos ocorrem, mas subordinadamente (Anaisse Junior et al. 2001). A figura 3 mostra a carta estratigráfica proposta para a Bacia do Parnaíba.

1.3.3.1 - Aspectos Tectônicos

A Bacia do Parnaíba como um todo registra um complexo histórico de deposição e pode ser subdividida em Parnaíba (Siluriano-Carbonífero), Alpercatas (Permiano - Jurássico) e Grajaú (Cretáceo – Sub-bacias cenozóicas; Vaz et al. 2007). Estritamente falando, a Bacia do Parnaíba consiste apenas da sucessão Siluriana-Carbonífera, embora o termo seja usado para conotar o conjunto de sucessão sedimentar da bacia, incluindo a sobreposição das sequências do Permiano-Jurássico e Cretáceo-Cenozóico (conhecidas como bacias Alpercatas e Grajaú, respectivamente; Fig. 4).

Atualmente, a Bacia do Parnaíba apresenta um abrupto contato de falha com a Província Tocantins (Cinturão Araguaia) no oeste (Daly *et al.*, 2014), um contato tectônico / erosional com a Província Tocantins ao sul e um singelo contato sedimentar ao norte com o Cráton São Luís e com o Cráton São Francisco para a SE. Ao longo da fronteira leste, o limite da bacia com o bloco Borborema é erosional, com presença de sedimentos basais silurianos da bacia expostos.

A origem e forma de evolução da bacia ainda é controverso e tema de debate. Devido à complexidade da evolução tectônica e interesse na exploração de recursos minerais inerentes à bacia, esforços têm sido envidados para mapeamento de suas estruturas e embasamento. As principais feições são descritas por caracterizações geológicas (Cordani *et al.*, 1984; Cordani *et al.*, 2009; Vaz *et al.*, 2007) e geofísicas, com dados potenciais (Nunes, 1993; Castro *et al.*, 2014, 2016), sísmicos (Daly *et al.*, 2014; Tozer *et al.*, 2017; Soares *et al.*, 2018) e sismológicos (Assumpção *et al.*, 2013a, b; Feng *et al.*, 2004).

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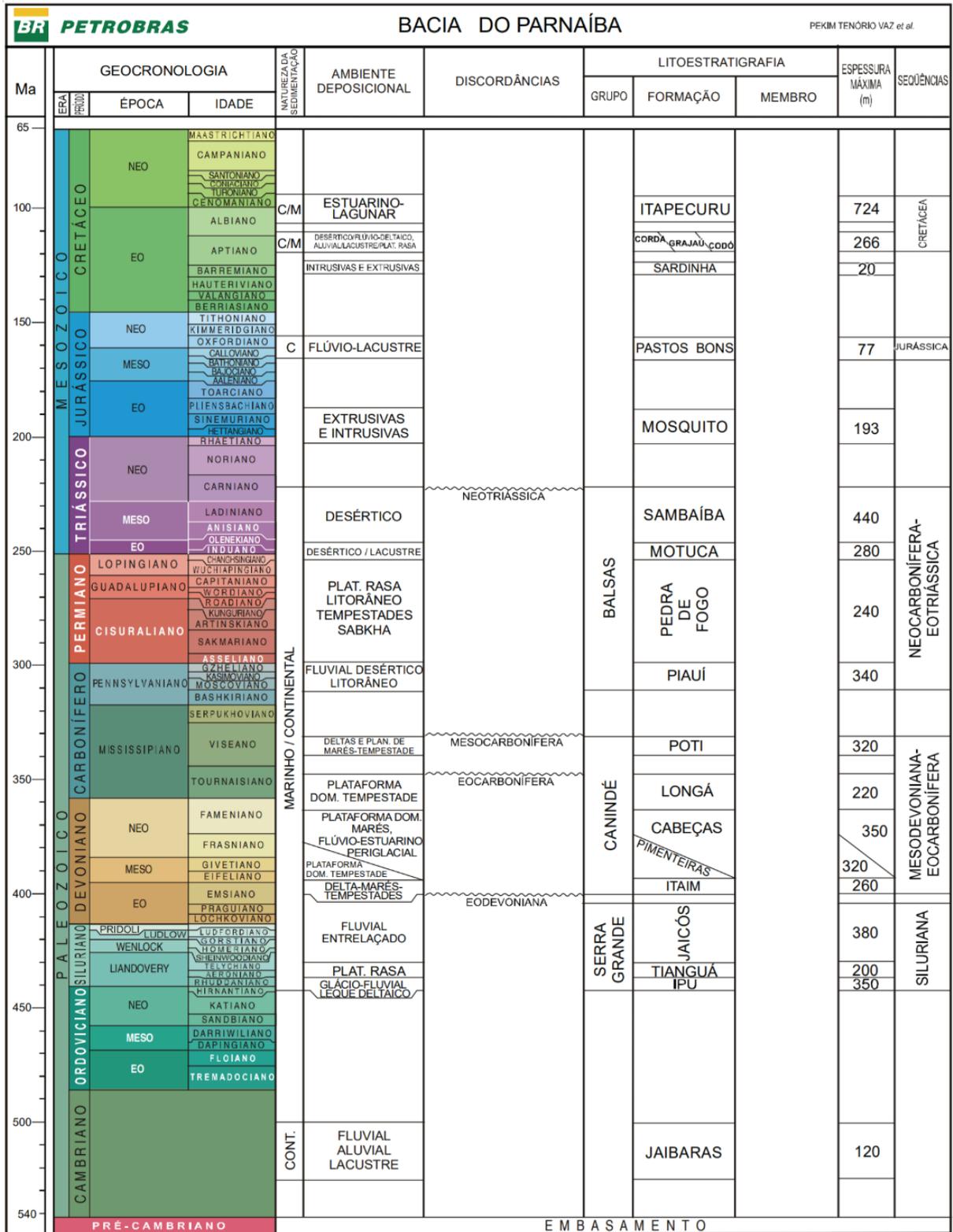


Figura 3: Carta estratigráfica da Bacia do Parnaíba. (Vaz et al., 2007)



Figura 4: Mapa geológico das sub-bacias que compõem a Bacia do Parnaíba, considerando-se a sequência Siluriana - Carbonífera (Parnaíba), sequência Permiana - Jurássica (Alpercatas) e sequência Cretácea / sub-bacias Cenozóicas correspondentes (Grajaú).

O embasamento da Bacia do Parnaíba consiste em uma colagem de pelo menos três domínios principais, classificados como bloco Amazônia, Parnaíba e Borborema, marcados por bruscos contatos entre si (Daly *et al.*, 2014; Castro *et al.*, 2014). A origem ou subsidência inicial da Bacia do Parnaíba provavelmente está ligada às deformações, eventos térmicos e pós-orogênicos do Ciclo Brasileiro (Almeida & Carneiro, 2004). Diferentemente de outras grandes bacias cratônicas da plataforma Sul-Americana

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(Amazonas-Solimões, Paraná e Parecis), a bacia não apresenta um *trend* preferencial de rifteamento que controle as sequências deposicionais de preenchimento. Entretanto, seu embasamento apresenta uma série de pequenos riftes de direção NW-SE e NE-SW, preferencialmente definidos por análises de dados potenciais, os quais tem sido considerados como estruturas precursoras da bacia *sag* (Nunes 1993; Oliveira & Mohriak 2003; Pedrosa Jr et al. 2015, 2017; Castro et al. 2016). Estruturas grabeniformes interpretadas no substrato da Bacia do Parnaíba teriam exercido forte controle no depocentro inicial e sucessões sedimentares.

Carozzi *et al.* (1975); Fortes (1978) e Cunha (1986) reconheceram as grandes estruturas do Ciclo Brasileiro que atuaram na compartimentação da Bacia, durante o Paleozóico. Dentre essas estruturas, destacam-se o Lineamento Picos-Santa Inês (NE-SE), Lineamento Tocantins-Araguaia (N-S) e o Rife do Jaibaras (Oliveira & Mohriak 2003; Pedrosa Jr *et al.*, 2015, 2017), exposto e aparentemente controlado pelo Lineamento Transbrasileiro (Schobenhau Filho *et al.*, 1975).

O Lineamento Transbrasileiro corta a bacia em sua porção sudeste e representa uma zona de cisalhamento continental que cruza a placa da América do Sul e continua na placa africana (onde é conhecido como o Lineamento Kandi) e é definida como a cicatriz de uma colagem transcontinental como parte da formação de Gondwana Oeste (Cordani et al. 2013; Brito Neves & Fuck 2014), no fim do Neoproterozóico.

Com o encerramento do Ciclo Brasileiro (Cambro-Ordoviciano), por subsidência termomecânica, os grabens foram preenchidos pelo progressivo afundamento ao longo das faixas tectonicamente instáveis, a partir do final do Ordoviciano (Caputo & Lima, 1984), servindo de substrato às sequências vulcano-sedimentares da bacia.

O magmatismo máfico regional da formação Mosquito, relacionado à abertura do Oceano Atlântico Central, e por diques e intrusões parentais cretáceas da Formação Sardinha, ligada à abertura do Oceano Atlântico Sul, teriam desempenhado forte influência em termos de subsidência. O primeiro depocentro da bacia paleozóica inicial deslocou-se para a parte central da bacia durante o início do período carbonífero-jurássico e migrou novamente para noroeste, no cretáceo (Vaz et al. 2007), sugerindo uma relação temporal magmática entre as formações Mosquito e Sardinha, respectivamente. O ambiente deposicional da bacia era inicialmente mais amplo do que

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é hoje, com uma conexão para as bacias do Amazonas e do Paraná e possivelmente até com a bacia do Congo na África (Melo, 1988).

1.3.4 - Província Borborema

A Província Borborema, localizada na porção nordeste do Brasil, é considerada um mosaico de faixas móveis metassedimentares e maciços separados por um sistema complexo de zonas de cisalhamento (Almeida *et al.*, 1981). Sua formação foi marcada por acreção tectonoestratigráfica, conforme mostram os principais modelos de evolução tectônica (Brito Neves *et al.*, 1995; Brito Neves *et al.*, 2000) propostos para a região.

A província de Borborema é caracterizada e por uma rede de cisalhamento dúctil transcorrente (Vauchez *et al.*, 1995), a qual teria sido desenvolvida dentro da placa continental para acomodar a deformação imposta pela colisão oblíqua ativa em sua margem. As características estruturais e tipos de rochas da Província Borborema foram desenvolvidas principalmente do Mesoproterozóico ao início do Neoproterozóico (evento Cariris Velhos) e do fim do Neoproterozóico ao Cambriano (Brasiliano / Pan Orogenia africana; Brito Neves *et al.*, 2000; 2003).

O Ciclo Brasiliano (670-570 Ma) promoveu retrabalhamento da crosta formada durante o evento anterior (Cariris Velhos) e foi o principal evento tectonotermal na província de Borborema, com presença de grande volume e diversidade de magmatismo granítico (~ 30% das rochas expostas) que foi adicionado à crosta durante este evento (Brito Neves *et al.*, 2000).

Duas das zonas de cisalhamento com *trend* E-W da província - zonas de cisalhamento Dextral Pernambuco e Patos, destacam-se pelas suas grandes dimensões, que atingem mais de 500 km e 2 km em largura, ligada a discretas zonas de cisalhamento N-NE (Neves *et al.*, 1996). A província é dividida em três domínios, (a) Domínio Setentrional, ao norte da zona de cisalhamento de Patos, (b) Domínio da Zona Transversal, entre as duas zonas de cisalhamento e (c) o Domínio Meridional, localizado ao Sul da Zona de cisalhamento de Pernambuco. Esses domínios são interpretados como representando uma colagem de domínios litotectônicos menores (Brito Neves *et al.*, 2000).

1.4. Métodos Geofísicos

O presente capítulo descreve os dois métodos geofísicos utilizados na pesquisa da bacia do Parnaíba: o método da Sísmica de Refração Profunda e da Função do Receptor. Ambos são bastante aplicáveis no estudo da litosfera, tendo em vista o forte controle de velocidade de propagação das ondas e a vasta ocorrência de eventos telessísmicos naturais do *stress* das placas tectônicas.

A sísmica de refração é um método de fonte ativa, o qual utiliza o tempo de trânsito e o percurso de ondas para determinação da velocidade média do meio e o posicionamento das principais descontinuidades em profundidade.

A técnica da função do receptor é um método que utiliza fontes passivas, que permite isolar a estrutura de velocidade da Terra abaixo de uma estação sismográfica dos efeitos da fonte e de estruturas distantes. A técnica foi desenvolvida por Langston (1977, 1979) denominada *P wave equalization* e, atualmente, é conhecida como Função do Receptor (Owens et al.; 1984 e Ammon, 1991). O método é comumente aplicado em estudos da estrutura da crosta e eficaz na estimativa da espessura crustal e composição, haja vista a sensibilidade do método ao conteúdo de sílica.

1.4.1 - Sísmica de Refração Profunda de Ângulo Amplo

O método da sísmica de refração de ângulo amplo (do inglês *Wide Angle Reflection-Refraction, WARR*) se destaca por quantificar com precisão a velocidade de propagação das ondas sísmicas nas camadas constituintes do meio. Constitui, historicamente, um dos principais métodos utilizados no estudo das crosta continental (Mooney & Meissner, 1991; Holbrook *et al.*, 1992; Christensen & Mooney, 1995). A profundidade de investigação sísmica é proporcional ao tamanho do arranjo dos receptores, necessitando-se nos estudos de crosta arranjos de centenas de quilômetros ou sete a dez vezes maiores que a profundidade prevista de investigação (Soares, 2005).

A refração sísmica é utilizada, também, para estudos petrofísicos da crosta profunda, comparando-se velocidades de campo com aquelas obtidas em laboratório. A composição crustal é inferida pela determinação da razão V_p/V_s , que mantém relação unívoca com a razão de Poisson e é um adimensional particularmente sensível ao

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conteúdo de sílica das rochas (Holbrook *et al.*, 1992; Zandt e Ammon, 1995; Christensen, 1996; Musachio *et al.*, 1997).

O método da refração sísmica ocorre com a propagação de ondas mecânicas no meio rochoso geradas através de uma fonte controlada, para determinar os valores de velocidade e descontinuidades de diferentes impedâncias em subsuperfície. A utilização de ondas elásticas ou sísmicas, propagadas através da Terra, é baseada em três premissas fundamentais: i) as ondas se propagam com diferentes velocidades, de acordo com o estrato geológico; ii) é necessário o contraste de impedância entre as camadas de rochas para as ondas refletirem e refratarem; iii) a velocidade dos estratos deve aumentar com a profundidade. Se as condições de velocidade do meio supracitadas não ocorrerem, o método da refração sísmica terá dificuldade de aplicação (Sjögren, 1984).

O fenômeno da refração ocorre quando atingido o ângulo de reflexão crítico pela frente de onda. Antes do ângulo crítico, a frente de onda transpassa a interface entre os meios, aproximado-se da interface divisora dos meios e afastando-se da normal segundo o contraste de velocidade entre as camadas. Na incidência crítica, o raio é transmitido paralelamente à interface entre as camadas e a energia sísmica retorna à superfície na forma de uma frente de onda plana designada *Headwave* ou frente de onda refratada. O fenômeno é regido pela lei de *Snell* (Equação 1), que descreve o comportamento da trajetória do raio na presença de mudança de meio físico (Sheriff & Geldart, 1985).

EQUAÇÃO 1

$$\frac{\text{sen}\theta_1}{V_1} = \frac{\text{sen}\theta_2}{V_2} = \rho$$

onde θ_1 é o ângulo de incidência, θ_2 é o ângulo de refração, V_1 é a velocidade de propagação na camada 1, V_2 é a velocidade de propagação na camada 2, subjacente à camada 1 e ρ é o parâmetro de raio.

A aplicação do método se dá pela teoria do raio sísmico (Červený *et al.*, 1977; Červený, 2001, e referências ali contidas) e é aplicada com base no cálculo do tempo de trânsito do alinhamento de fases das ondas sísmicas (onda direta, refletida e refratada) no ângulo crítico e acima deste, por meio de um determinado meio homogêneo e isotrópico. O método é utilizado para simplificar o cálculo do caminho que uma onda percorre através de um meio com regiões de diferentes velocidades de propagação.

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Segundo o algoritmo cada onda pode ser modelada como um conjunto de feixes estreitos (raios) que avançam através do meio por distâncias discretas, ajustadas por intermédio de derivadas locais do meio, para o cálculo de suas novas direções de propagação, até que o traçado do raio completo seja atingido, entre a fonte e o receptor.

As fases mais proeminentes (onda direta, refração da crosta superior, refração interface de *Mohorovičić* e reflexões de ângulo crítico; Fig.5) são classificadas como primeiras "chegadas" e marcam as principais discontinuidades internas da crosta e da *Moho*. A discontinuidade de *Moho* define importante interface de referência crustal e é identificada pelo forte contraste de impedância acústica entre os meios, o que faz com que suas ondas tenham amplitude de destaque quando visualizadas em sismogramas.

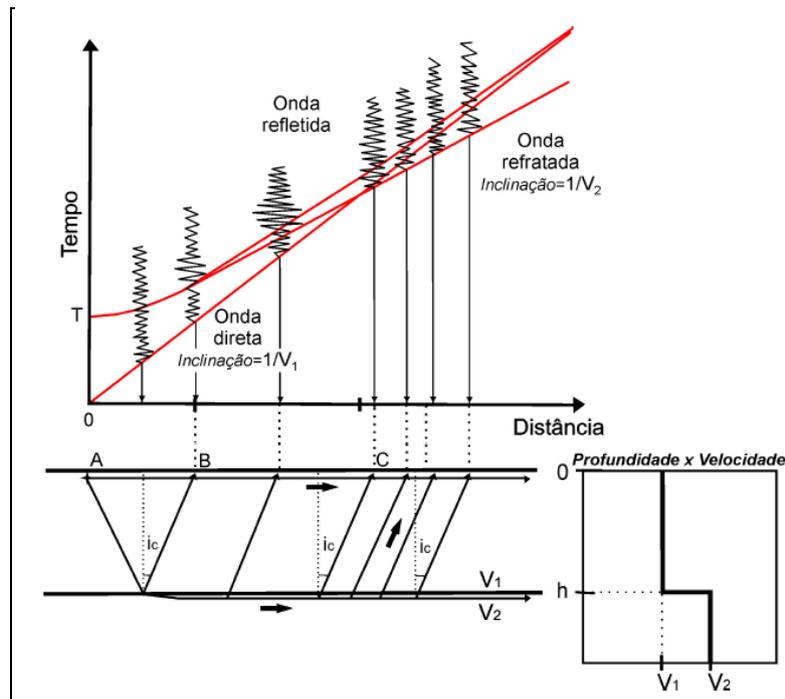


Figura 5: Sismograma hipotético mostrando as relações das curvas tempo x distância entre as ondas direta, refratada e refletida para um modelo de uma interface. B marca o ponto crítico e C o ponto onde a refração se torna primeira chegada. A onda direta é uma reta passando pela origem dos eixos com coeficiente angular igual ao inverso da velocidade da primeira camada. A onda refletida é uma hipérbole assintótica à onda direta para grandes distâncias. ($x \gg h$), e a onda refratada uma reta com início a partir de uma incidência crítica da frente de onda. Nesse ponto, a reflexão e a refração são tangentes (Modificado de Soares, 2005).

A propagação dessas ondas em meios homogêneos e isotrópicos são regidas pelas seguintes equações (Giese 1976; Sheriff & Geldart, 1982):

EQUAÇÃO 2

$$t = \frac{x}{V_1}$$

EQUAÇÃO 3

$$t^2 = \frac{x^2}{V^2} + \frac{(2H)^2}{V^2}$$

EQUAÇÃO 4

$$t = \frac{x}{V_2} + \frac{2h \cos \theta_c}{V_1}$$

EQUAÇÃO 5

$$t = \frac{x}{V_{n+1}} + \sum_{i=1}^n \frac{2H_i}{V_i} \cdot \sqrt{V_{n+1} + V_i^2 / V_{n+1}}$$

onde t é o tempo de trânsito, x a distância do geofone até o ponto de tiro, V_i a velocidade na i -ésima camada, V a velocidade média acima do refletor, H é a profundidade do refletor, θ_c o ângulo crítico, n o número da interface refletora e H_i a espessura da i -ésima camada.

As equações 2 a 4 são relativas, respectivamente, às ondas direta, refletida e refratada numa interface entre dois meios. A expressão 5 apresenta a equação da onda refratada em uma interface com n camadas. Os alinhamentos de fase da onda direta é uma equação de primeiro grau e resolve a variável da velocidade na camada superior. A derivada da refração em meios com n camadas fornece o inverso da velocidade da camada $n+1$, ou seja, da camada situada abaixo da interface refratora. As reflexões de alto ângulo, relacionadas a equação da hipérbole, ocorrem com amplitudes maiores que as das fases refratadas e fornecem a velocidade média do meio acima do refletor.

O alinhamento de fases refratadas são bem reconhecidas quando estas ocorrem como primeiras "chegadas", haja vista a ocorrência de formas de onda com amplitudes de maior destaque. Entretanto, heterogeneidades e anisotropia do meio podem afetar o alinhamento-padrão esperado das fases sísmicas e desviar o caminho do raio sísmico esperado. Para estudos sísmicos de refração profunda, é necessário o uso de arranjos de centenas de quilômetros para que se obtenha registros de refração da descontinuidade crosta-manto (interface da *Moho*) como primeira "chegada", bem como reflexões de alto ângulo.

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A identificação das fases de reflexão de amplo ângulo ocorrem num *offset* próximo a 100 km, ao passo as que fases de refração da *Moho* como primeiras "chegadas" ocorrem próximas a um *offset* de 200 km da fonte (considerando-se crosta com média de 40 km de espessura). O ponto de inflexão da refração da onda direta com as fases profundas da refração da *Moho* definem um ponto estratégico - *crossover*. Uma vez conhecidas as velocidades das camadas de uma determinada interface e a distância do ponto de tiro até o sensor, é aplicada a seguinte equação para determinação da espessura crustal:

EQUAÇÃO 6

$$H = \frac{x_c}{2} \cdot \sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

onde x_c é definido pelo *offset* do *crossover*, H é a profundidade da interface da *Moho*, V_1 a velocidade da camada 1 e V_2 a velocidade da camada 2.

1.4.1.2 - Aquisição dos dados

O banco de dados de refração consistiu de 20 pontos de tiro, espaçados aproximadamente a cada 50 km, realizados em setembro de 2015 ao longo de toda transecta do experimento (Fig. 1). A transecta sísmica apresenta *trend* aproximadamente linear, posicionado ao longo de rodovias federais pavimentadas ou estradas de terra secundárias. A trajetória acompanha outra transecta sísmica realizada por reflexão sísmica profunda (Daly *et al.*, 2014).

Para realização do experimento (Fig. 6), utilizaram-se 37 registradores da marca RefTek modelo DAS-130 com sensor triaxial Sercel L-4A 3D, do *Pool* de Equipamentos Brasileiros / PEG-BR e 600 estações verticais monocanais (300 registradores Texans com sensores verticais Sercel L-4A, de 2.0 Hz, e 300 registradores Texans acoplados a geofones do *pool* de equipamentos da PASSCAL, de 4.5 Hz) uniformemente espaçados.



Figura 6: Equipamentos e procedimentos de campo do método da sísmica de refração profunda. em a) registrador do pool brasileiro Texan; em b) sensor e registrador acoplados; em c) sensor triaxial da PASSCAL; em d) geofone da PASSCAL; em e) tamponamento do poço com brita; em f) preparação da espoleta para detonação durante a madrugada.

As estações três componentes Sercel foram previamente instaladas às explosões com equipamentos funcionando de forma contínua e amostragem de 100 SPS, por um período de seis meses. As estações verticais foram configuradas para amostragem de 200 SPS e foram instaladas somente para o registro da fonte ativa, durante janelas de tempo pré-programadas para funcionarem durante 10 minutos no intervalo compreendido pelas detonações.

As detonações se deram em poços de 25 cm de diâmetro e profundidade média de 40 m, os quais $2/3$ eram preenchidos com 1.5 toneladas de explosivos e $1/3$ tamponado com solo e cascalho. Os tiros foram realizados durante a madrugada de quatro dias seguidos. Devido dificuldade de permissões superficiais, os tiros 3 e 23 não foram realizados e a carga explosiva dos tiros 2 e 24 foram duplicadas. Após verificação de todos os tiros, constatou-se que os tiros 5 e 8 não obtiveram energia suficiente para serem registrados, restando-se 20 tiros efetivamente.

1.4.1.3 - Processamento dos dados

Após aquisição, os dados foram coletados e submetidos a uma rotina prática de processamento para composição dos sismogramas sequenciais em função dos pontos de

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tiro. O conjunto de operações de processamento visa desde a conversão de dados brutos oriundos dos sismógrafos até montagem final da seção sísmica.

Inicialmente, para análise dos dados em formato adequado, os dados foram convertidos do formato padrão para SEG-Y, por meio dos programas 125_seggy (v 3.0) e rt_mseed. Após essa etapa, os dados foram novamente convertidos para formato do pacote *Seismic Analysis Code* (SAC), com o programa segy2sac e mseed2sac.

Uma vez obtidos os dados no formato SAC, procedeu-se com a edição do *header* dos arquivos dos traços sísmicos, com informações relativas à hora origem do tiro, posicionamento da estação, elevação da estação, posição e profundidade do tiro. Correções foram aplicadas assumindo *drift* instrumental (tempo relativo de percurso gasto pelas ondas entre a explosão e o receptor) linear dos registradores verticais, considerando-se o uso de relógios internos programados sincronizados por intermédio de um computador conectado a uma antena receptora GPS.

Após obtenção dos dados com tempo de deriva corrigido, procedeu-se à seleção e filtragem dos traços. Nessa etapa, os sismogramas são filtrados por inspeção visual, a partir da identificação de traços muito ruidosos ou sem informação de sinal. Uma vez identificados, os traços são removidos do acervo de dados, objetivando-se manter a coerência das fases entre os sismogramas vizinhos.

A etapa final corresponde à montagem da seção sísmica de cada tiro, composta por sismogramas sequenciais. As seções foram montadas a partir do uso de um *script* que utiliza uma sucessão de comandos do pacote SAC. Dentre as operações, o *script* faz a leitura dos arquivos disponíveis e calcula a seção com tempo reduzido para facilitar a visualização das fases (Equação 7)

EQUAÇÃO 7

$$t_R = t - \frac{x}{V_r}$$

onde t_R é o tempo de redução, t é o tempo de trânsito, x o *offset* do geofone e V_r a velocidade de redução. Além dessas operações, o algoritmo inclui o corte do registro do tempo reduzido num intervalo definido pelo usuário, remoção de média e tendência dos traços, filtro passa-banda para isolar o conteúdo de frequência inerente às explosões de ruídos naturais de alta frequência e uso de distintos ganhos. Para dados de ondas P, foi utilizada velocidade de redução de 8,0 km/s e para ondas S, 4,62 km/s.

Após montagem de todos sismogramas, é feita a leitura dos principais alinhamentos de fases identificáveis, considerando-se todas descontinuidades até a

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interface de *Moho*. Com a leitura das fases, procede-se para a etapa final, de modelagem de ondas P e S por meio da técnica do traçado de raio.

O algoritmo empregado neste trabalho para o cálculo do traçado de raios e modelagem dos dados foi desenvolvido por Zelt & Ellis (1988) e posteriormente adicionado ao pacote de programas RAYINVR (Zelt & Smith, 1992). O pacote utiliza o método de traçado de raios em ambiente bidimensional e realiza uma série de cálculos para obtenção de sismogramas sintéticos, amplitude das ondas e inversão do tempo de trânsito das ondas.

Para modelagem dos dados, é necessário realizar a parametrização do modelo proposto. A parametrização consiste na amarração do modelo ao contraste de propriedades observadas, tais como número de camadas, velocidade das ondas, geometria do modelo, descontinuidades e gradiente de velocidades. O procedimento consiste na criação de um modelo que represente as principais descontinuidades observadas na crosta e manto superior, que seja constituído de um número mínimo de variáveis livres (nós) de velocidade e profundidade. Essas variáveis são ajustáveis e podem ser editadas conforme necessidade e qualidade dos dados.

Uma vez obtida a parametrização inicial do modelo, utiliza-se o programa RAYINVR para o traçado de raios e observação das fases calculadas. Por meio de tentativa e erro e diversas iterações, os tempos de trânsito são calculados por integração ao longo da trajetória dos raios (Zelt & Ellis, 1988). O pacote de programas permite ainda a obtenção do cálculo estatístico do modelo para acompanhamento dos ajustes ao longo da modelagem.

Os resultados de sismica de refração de ondas P estão contidos no Capítulo 2 da tese, conforme manuscrito " *Structure of the crust and upper mantle beneath the Parnaíba Basin, Brazil, from wide-angle reflection–refraction data* " e os resultados de ondas S no Capítulo 4.

1.4.2 - Função do Receptor

A função do receptor é uma método que utiliza registros telessísmicos naturais oriundos da própria instabilidade tectônica da Terra. A técnica tem importante relevância na determinação da espessura crustal, razão V_p/V_s (Zandt & Ammon, 1995)

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e é largamente empregada pela simplicidade da teoria e logística operacional dos equipamentos.

Funções do receptor são séries temporais calculadas por operações matemáticas a fim de se obter a estrutura de velocidade da Terra exatamente abaixo de uma estação sismográfica (Langston, 1979; Owens *et al.*, 1984; Owens & Zandt, 1985; Ammon, 1991). O método utiliza frentes de onda P de telessismos incidentes sobre uma descontinuidade abaixo de uma estação sismográfica (Descontinuidade de *Moho*) com um ângulo próximo à vertical. O método baseia-se no preceito de partição de energia de frentes de onda P, quando em contato com a interface de *Moho* se transformam em onda S e múltiplas. O registro desta onda P será predominante na vertical e da onda S (produzida na conversão) será principalmente na radial (Fig. 7).

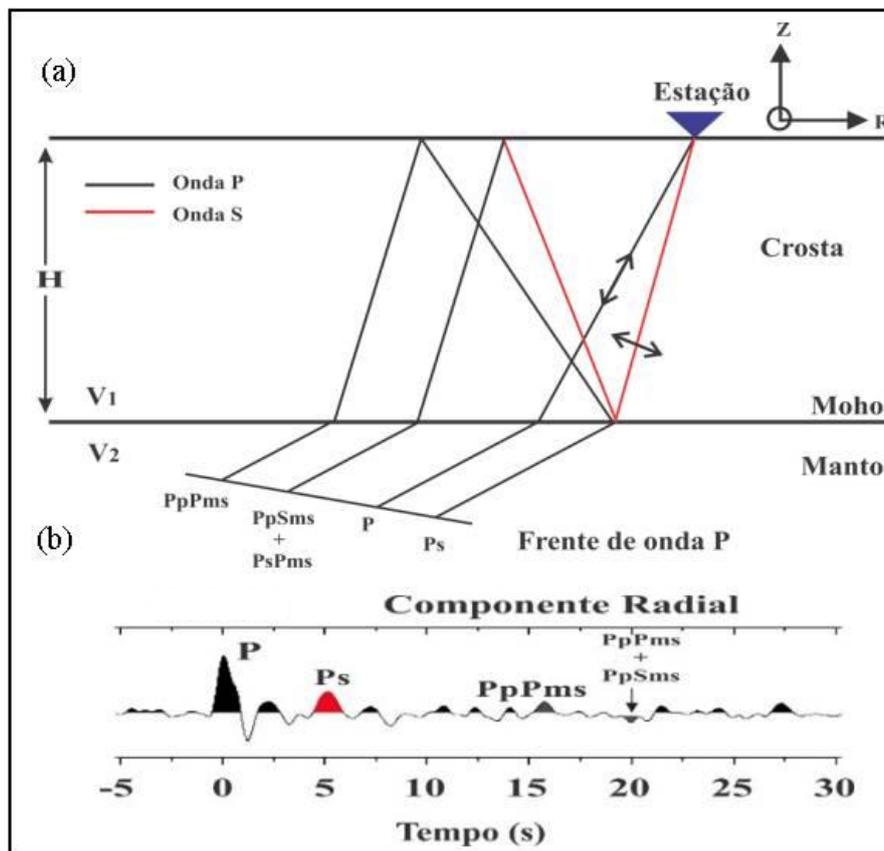


Figura 7: Diagrama de raio da Função do Receptor. Principais conversões da onda P em onda S e reflexões múltiplas. A fase Ps representa a onda P convertida em onda S na Moho, as reflexões múltiplas (PpPms, PsPms + PpSms e PsSms) apresentam a letra m que representa a descontinuidade de Moho. Registro da Função do Receptor na radial (Imagem adaptada de Trindade, 2014).

Os registros telessísmicos são formados pela convolução da assinatura da fonte (*wavelet*), com a estrutura da Terra abaixo da estação sismográfica e a resposta do

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instrumento. As componentes vertical, radial e tangencial do registro são representadas por Owens *et al.*, (1984) pelas seguintes relações:

EQUAÇÃO 8

$$D_V(t) = w(t) * e_v(t) * i(t)$$

EQUAÇÃO 9

$$D_R(t) = w(t) * e_r(t) * i(t)$$

EQUAÇÃO 10

$$D_T(t) = w(t) * e_t(t) * i(t)$$

onde $Dt_{(V,R,T)}$ representa o registro telessísmico em suas componentes, w a assinatura da fonte, $e(t)_{(V,R,T)}$ a estrutura da Terra abaixo da estação sismográfica, $i(t)$ a resposta do instrumento e " * " o operador matemático "convolução". As denominações V, R, T, e t representam, respectivamente, as componentes vertical, radial, transversal do registro sísmico e o tempo.

Aplicando-se a Transformada de Fourier nas equações 8, 9 e 10, a convolução se transforma numa multiplicação espectral conforme as equações abaixo:

EQUAÇÃO.11

$$D_V(w) = W(w) . E_V(w) . I(w)$$

EQUAÇÃO 12

$$D_R(w) = W(w) . E_R(w) . I(w)$$

EQUAÇÃO 13

$$D_T(w) = W(w) . E_T(w) . I(w)$$

onde w é a frequência radial.

A onda P telessísmica tem um ângulo de incidência quase vertical sob a estação, o que gera um pico inicial na componente vertical ($e_v(t)$) seguida por alguns picos menores (picos gerados por reverberações e fases convertidas). Desprezando esses picos menores e supondo que a resposta da estrutura na componente vertical e_v seja somente um pico contendo toda energia da onda P ($e_v(t)$ não influencia no registro vertical),

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podemos representar essa componente por *Delta Dirac* (elemento neutro da deconvolução; Langston, 1979):

EQUAÇÃO 14

$$e_v \approx \delta(t)$$

EQUAÇÃO 15

$$D_V(t) \approx i(t) * s(t)$$

Ao aplicar a deconvolução na componente vertical de registro $D_V(t)$, das componentes horizontais ($D_R(t)$ e $D_T(t)$), isola-se a estrutura abaixo da estação na direção radial $e_r(t)$ e tangencial $e_t(t)$ na forma de uma série temporal com o primeiro pulso contendo a energia da onda P incidente e os demais pulsos de ondas S e múltiplas (Langston, 1979; Owens *et al.*, 1984; Wilson & Aster, 2003). No domínio da frequência, a deconvolução é uma divisão espectral conforme mostra as seguintes relações:

EQUAÇÃO 16

$$E_R(w) = \frac{D_R(w)}{D_V(w)} \approx \frac{\delta(t)I(w)S(w)}{I(w)S(w)}$$

EQUAÇÃO 17

$$E_T(w) = \frac{D_T(w)}{D_V(w)} \approx \frac{D_T(w)}{D_V(w)}$$

onde $E_R(w)$ e $E_T(w)$ definem a função do receptor nas componentes radial e transversal, respectivamente. O registro da FR radial terá o primeiro pico positivo, resultante de toda energia que chega como onda P na estação (reflexões, refrações e reverberações) seguida por picos menores gerados por conversões e reverberações (Fig. 5).

Conhecida a diferença de tempo entre as fases P, Ps e PpPms (obtida dos sismogramas) e a velocidade média da onda P na crosta, a razão V_p/V_s e a profundidade da Moho (h) serão obtidas pelas seguintes equações (Zandt, *et al.*, 1995):

EQUAÇÃO 18

$$t_{Ps} - t_P = h \left[(V_S^{-2} - \rho^2) - \sqrt{(V_P^{-2} - \rho^2)} \right]$$

EQUAÇÃO 19

$$t_{PpPms} - t_P = 2h \left(\sqrt{(V_P^{-2} - \rho^2)} \right)$$

onde t_{Ps} é o tempo de chegada da onda Ps, t_P é o tempo de chegada da onda P e t_{PpPms} é o tempo de chegada da primeira múltipla. A razão entre as equações 3.18 e 3.19 definem a relação entre as velocidades Vp e Vs, segundo:

EQUAÇÃO 20

$$\frac{V_P}{V_S} = \left\{ (1 - \rho^2 V_P^2) \left[2 \left(\frac{t_{Ps} - t_P}{t_{PpPms} - t_P} \right) + 1 \right]^2 + \rho^2 V_P^2 \right\}^{1/2}$$

Notar que não é necessário o valor da espessura crustal para o cálculo da razão Vp/Vs. O cálculo da espessura h pode ser estabelecido pela seguinte relação:

EQUAÇÃO 21

$$h = \frac{V_P(t_{Ps} - t_P)}{\left(\sqrt{\frac{V_P^2}{V_S^2} - \rho^2 V_P^2} - \sqrt{1 - \rho^2 V_P^2} \right)}$$

Uma vez obtidos os valores de h e Vp/Vs, obtidos com as relações propostas por (Zandt, *et al.*, 1995; equações 20 e 21), é possível submeter os dados a um programa de inversão que fornece como saída estimativas da espessura média da crosta em função da razão Vp/Vs (Zhu & Kanamori, 2000).

Algumas observações são importantes acerca da teoria da função do receptor no domínio da frequência. O conhecimento de determinados efeitos são importantes e devem ser considerados, como por exemplo a correção do nível d'água e a distância entre a fonte e o receptor.

No cálculo da função do receptor, a etapa de divisão espectral pode gerar instabilidades causadas por denominadores de baixa amplitude. Para corrigir esse

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problema, os baixos valores de amplitude são substituídos por frações de maior valor de amplitude do denominador (Ammon, 1997), conhecido como Parâmetro de Nível D'Água (c). O valor deve ser definido de tal sorte que possua o maior valor possível em função da estabilidade do sinal (Fig. 8).

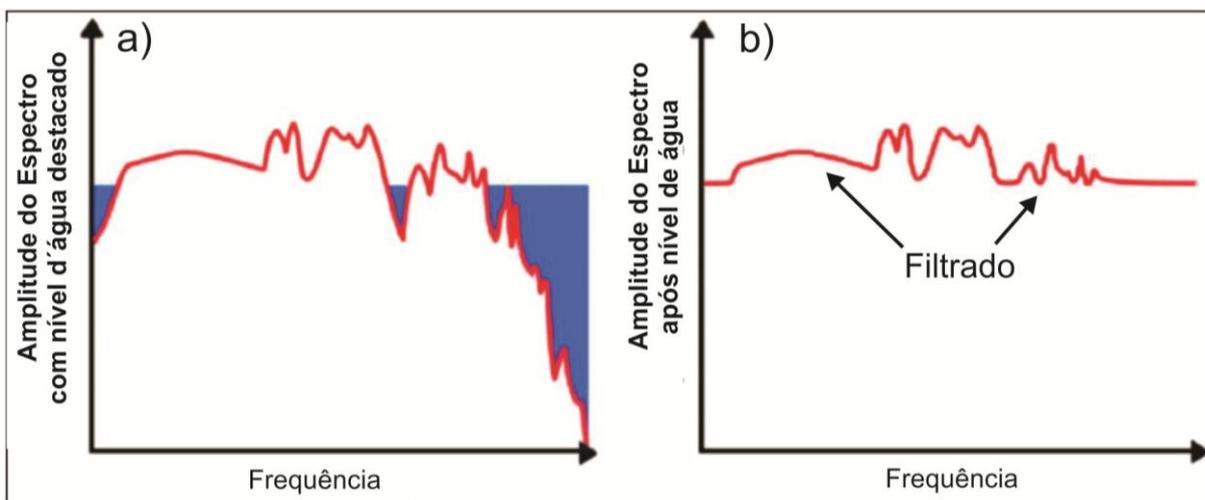


Figura 8: Exemplo do espectro de potência do traço com o uso do parâmetro de Nível d'Água. Notar em a) o espectro do nível d'água destacado e em b) o espectro após o uso do filtro. Adaptado de Ammon, (1997).

A distância entre a fonte e o receptor deve ser considerada na aplicação a técnica da Função do Receptor. Devido às principais descontinuidades da crosta terrestre identificáveis por sismologia (*Moho*, limite da Litosfera/Astenosfera, descontinuidade de 410 km e 670 km; Shearer, 2009), a velocidade das ondas P e S é bruscamente alterada.

No manto superior, as descontinuidades de 410 km ($\sim 20^\circ$) e 670 km ($\sim 30^\circ$) causam a triplicação do sinal sísmico, que dificulta o reconhecimento das ondas (Fig. 9) tendo em vista diferentes fases com diferentes parâmetros de raio e tempo de trânsito de chegada similares. Ademais, a ocorrência de zonas de sombra causadas pela trajetória do raio sísmico impossibilitam o seu reconhecimento em distâncias epicentrais de 103° a 144° , onde não se observam registros de onda P ao longo do manto.

Os efeitos da distância entre a fonte e o receptor afetam diretamente os valores de amplitude e os tempo de chegada das ondas P, que são dependentes da distância epicentral dos eventos à estação. Quanto maior a distância epicentral, menor é a amplitude da fase da onda Ps observada.

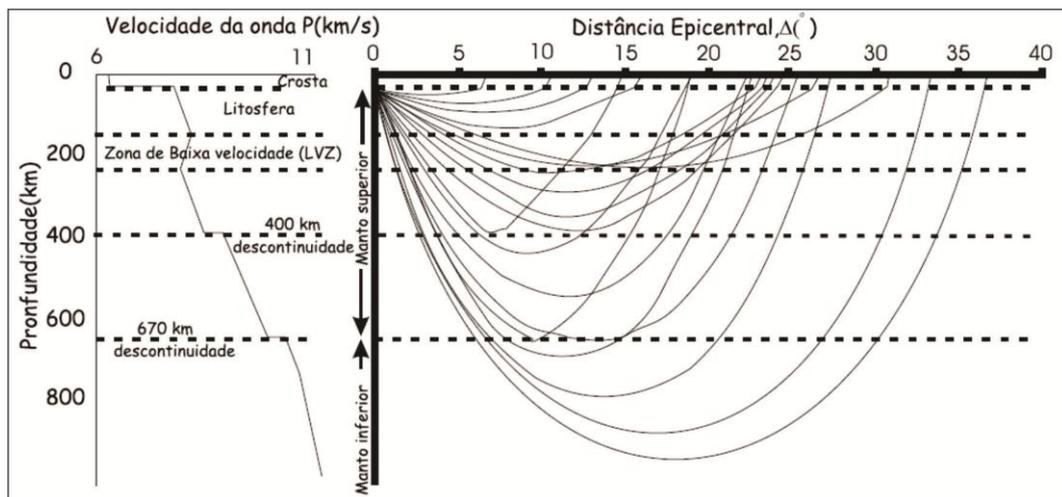


Figura 9: Modelo crustal hipotético, com curva de velocidade conforme descontinuidades. Notar distintos parâmetros de raio concentrando-se na distância epicentral entre 20 e 30 graus, fato que dificulta a identificação; ao acurada das fases de interesse. adaptado de Le Freve & Helmberger, (1989).

1.4.2.1 - Aquisição em Campo

O banco de dados utilizados para cálculo da função do receptor advém das estações triaxiais de período curto descritas no item 3.1.1. As estações são compostas por um registrador, um sensor três componentes (enterrado e orientado ao norte), GPS, regulador de tensão, cabos conectores, bateria e um sistema autônomo de energia recarregável por energia solar (Fig. 10). Os sensores foram instalados ao longo da transecta sísmica, em regiões geológicas estratégicas ao experimento, espaçados por aproximadamente 30 km de distância e registraram telessismos de diferentes parâmetros de raio e diferentes *backazimuths*.

1.4.2.2 - Processamento dos dados

Após coleta, os dados foram submetidos a uma rotina de processamento para se obter a maior quantidade de eventos telessísmicos representativos possíveis e de qualidade. O conjunto de operações de processamento visou desde a conversão de dados brutos oriundos das estações triaxiais até a obtenção da soma e empilhamento dos registros radiais, cálculo da razão V_p/V_s e espessura crustal.

A conversão de dados utilizou os programas `rt_mseed` e `mseed2sac` para conversão de dados no formato SAC. Os procedimentos adotados no SAC implicaram no abastecimento de informações da fonte, aplicação de filtros e correção de sinal. A partir

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de uma lista de eventos originados na janela de tempo de aquisição das estações (total de 505 eventos), foi utilizado o programa *pwaveqn* (Ammon, 1997) para o cálculo da função do receptor no domínio da frequência. O programa utiliza arquivos de entrada no formato SAC e realiza a rotação das componentes verticais e horizontais dos eventos telessísmicos.



Figura 10: Equipamentos e procedimentos de campo para instalar estações triaxiais de período curto. em a) Sensor L4A 3 componentes, modelo Sercel; em b) sensor sendo instalado no campo; em c) dispositivos da estação, compostos por bateria, registrador e GPS; em d) exemplo de estação triaxial montada, alimentada por uma placa solar.

Alguns parâmetros de entrada foram configurados, como filtro gaussiano (passa baixa), para remoção de ruídos de alta frequência e filtro d'água. Em seguida, o programa faz a deconvolução no domínio da frequência para gerar a função do receptor.

O algoritmo foi aplicado a eventos telessísmicos com magnitude a partir de 5,5 M_w e distância epicentral entre 30° e 90° , para cada uma das 40 estações. Foi utilizado Filtro Gaussiano com fator $a = 4$ (2Hz) e Nível D'Água $c = 0,001$. Os traços gerados foram inspecionados, levando-se em consideração aspectos como a qualidade do sinal,

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reconhecimento claro de fases P e S e verificação dos conteúdos de frequência e amplitude das fases primárias e múltiplas.

Após etapa de filtragem, os dados foram somados e empilhados em função do parâmetro de raio (ρ) a partir da lista de eventos gerada. O empilhamento é realizado no programa *HK-Stacking*, que aplica algoritmos de inversão para inspeção em *grid* no banco de dados de função do receptor e calcula estimativas da espessura média da crosta em função da razão V_p/V_s (Zhu & Kanamori, 2000).

As estimativas calculadas no programa são obtidas com a inserção da velocidade média da onda P e pesos para as fases Ps e múltiplas (PpSms e PsPms). O algoritmo se baseia nas equações 20 e 21 e fornece as informações de saída com incertezas estatísticas. A estimativa dessas incertezas é feita por aplicação do método “*bootstrap*” (Efron & Tibshirani, 1991), a partir do conjunto de funções do receptor, o programa cria subconjuntos de traços sorteados aleatoriamente. O método é aplicado a cada subconjunto e resulta num conjunto de parâmetros H e V_p/V_s (Bianchi, 2008) apresentado de forma gráfica.

As vantagens do programa são a grande quantidade de formas de onda que podem ser processadas, empilhamento de funções do receptor com diferentes distância epicentrais, azimutais e estimativas de incertezas, para V_p/V_s e H . Ademais, o conhecimento prévio da espessura crustal (*i.e.* por outro método geofísico) torna o cálculo da V_p/V_s torna-se mais acurado, tendo em vista que é possível eliminar subconjuntos de resultados ambíguos fora do previsto e calculado.

Os resultados dos dados de função do receptor no domínio da frequência das 40 estações sismográficas estão no artigo " *Crustal Structure and V_p/V_s 's Ratio of Parnaíba Basin - Brazil: Evidences of Neoproterozoic Amalgamation in West Gondwana* ", artigo 2 da tese (Capítulo 3).

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CAPÍTULO 2

2. Structure of the crust and upper mantle beneath the Parnaíba Basin, Brazil, from wide-angle reflection–refraction data



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Abstract: The Parnaíba Basin is a Phanerozoic intracontinental basin within the South America plate, lying on top of and within Precambrian terranes. The Parnaíba Basin Analysis Program wide-angle reflection–refraction (WARR) lies east–west and is 1150 km long profile crossing the basin and its margins. The WARR results show that the crust and uppermost mantle along the profile consist of the Amazonian Craton and Borborema Province, and the Grajaú and Teresina domains comprising the Parnaíba block hidden below the sedimentary cover of the basin itself. The lithospheric characteristics of the Parnaíba block and their differences from the adjacent Precambrian Amazonian Craton and Borborema Province elucidate some aspects of the present day existence of the sedimentary basin covering it. Important elements include the presence of a high mantle velocity and high-velocity lowermost crustal region, interpreted as linked to the intrusion of mafic material into the crust underlying the Grajaú domain, and indications that the crust in this area has been intruded since its consolidation in the Neoproterozoic. It is tentatively proposed that magmatism is related to the inferred thinning of the lower crust of the Teresina and Borborema segments of the profile, with this, in turn, linked to Cretaceous extensional tectonics and the opening of the South Atlantic Ocean.

Supplementary material: Datasets and ray-tracing modelling for all 20 shot gather seismic sections from the WARR experiment of the Parnaíba Basin. Available at <https://doi.org/10.6084/m9.figshare.c.4058582>

Together with the Amazonas-Solimões, Parecis and Paraná basins, the Parnaíba Basin is part of a set of Paleozoic intraplate basins within the South America plate. Its depositional history spans Silurian to Cenozoic time and it is typically associated with an extensional event, similar to the formation of Paleozoic intraplate basins around the world such as, among others, the Williston and Illinois basins in North America, the Congo and Taoudeni basins in Africa and the Siberian basin in Russia (Condie 2004; Kearey *et al.* 2009; Allen & Allen 2013). All these basins appear to represent widespread extensional tectonics on the Gondwana supercontinent following

the Brasiliano/Pan-African Orogeny at the end of the Neoproterozoic and early Paleozoic.

The deeper structure of the Parnaíba Basin, until now, has mainly been inferred from geological (e.g. Cordani *et al.* 1984, 2009) and potential field observations (Nunes 1993; Castro *et al.* 2014, 2016) and is poorly constrained by seismological (Assumpção *et al.* 2013a, b; Feng *et al.* 2004) and seismic data (Daly *et al.* 2014). Its structure and genesis are the subject of some controversy and debate.

The petroleum company BP has recently sponsored the multidisciplinary Parnaíba Basin Analysis Program, involving universities and research centres

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from Brazil and the UK, with the aim of investigating the deep structure of the Parnaíba Basin and illuminating its genesis and evolution. As part of this effort, *Daly et al. (2014)* presented a dense CDP image of the Parnaíba Basin crust (range 20 s two-way travel time) along a 1400 km east–west transect, crossing the basin and its western and eastern borders at roughly the latitude 5.35° S (Fig. 1).

The wide-angle reflection–refraction (WARR) experiment presented here was carried out along almost the same path as the *Daly et al. (2014)* CDP profile and has allowed a two-dimensional velocity

model of the crust and upper mantle of the basin to be constructed. Field acquisition was carried out in September 2015 by the Lithosphere Research Laboratory of the University of Brasília, in partnership with the Pampa Federal University (Caçapava do Sul) and the University of Aberdeen.

Tectonic setting

The Parnaíba Basin is a sag basin occupying an area of c. 660 000 km² (*Cordani et al. 1984*) in NE Brazil

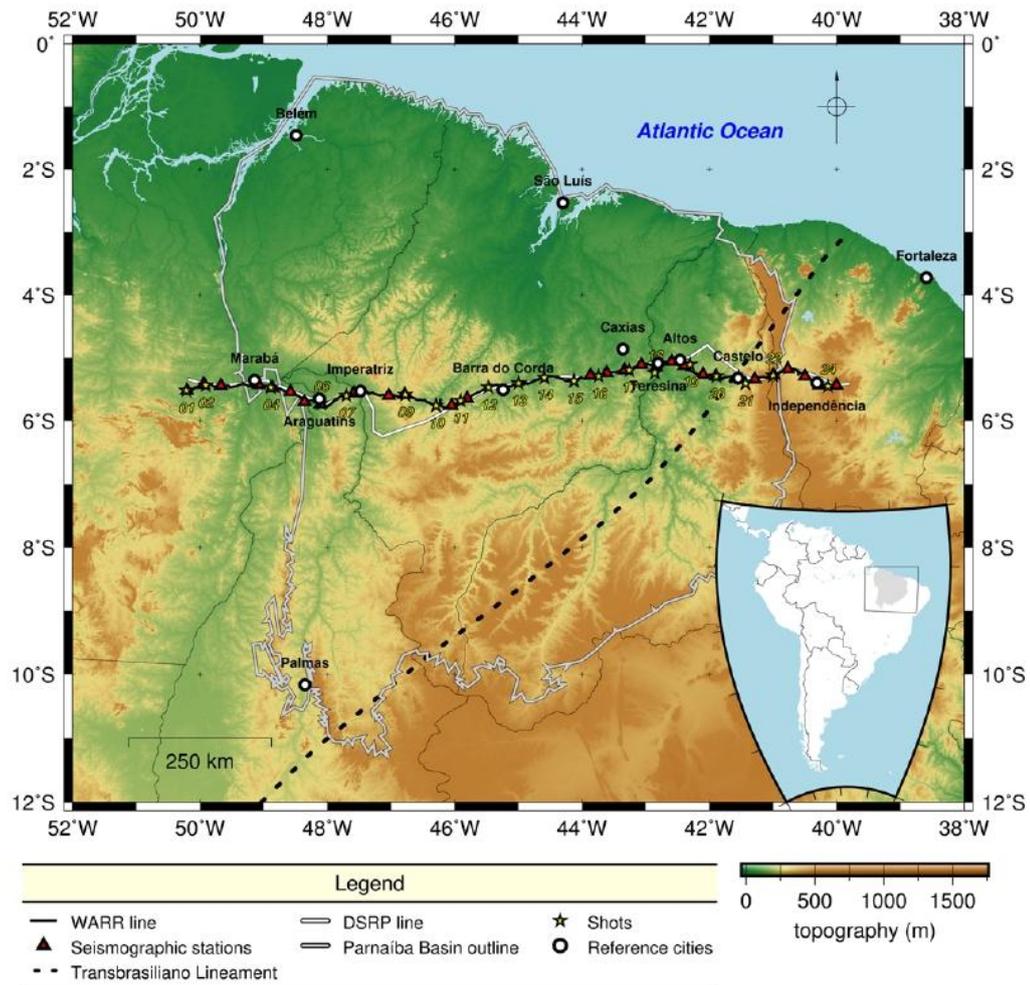


Fig. 1. Physiographic map of north Brazil highlighting the limit of the Parnaíba Basin and showing the paths of the CDP (*Daly et al. 2014*) and WARR profiles. The profiles are coincident except between Imperatriz and Barra do Corda and between Altos and Castelo. Stars indicate the locations of the WARR profile shot points and the triangles are the locations of three-component seismograph stations used for the preliminary receiver function estimates of Moho depth. The dashed line is the inferred location of the Transbrasiliano Lineament (*CPRM 2015*). The inset map shows the Parnaíba Basin in the context of the South American continent (modified from *CIGIAR 2017*).

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and, in contrast with the Amazonas-Solimões, Parecis and Paraná basins, it does not show any preferential rift direction controlling its sedimentary infill. Nevertheless, the basement of the Parnaíba Basin presents a series of small north-south-, NW-SE- and NE-SW-trending rift-like structures, mainly defined by potential field analyses, which have been considered as the precursory structures of the overlying sag basin (Nunes 1993; Oliveira & Mohriak 2003; Castro *et al.* 2016). Among these, the largest is the Jaibaras rift (Oliveira & Mohriak 2003; Pedrosa Jr *et al.* 2015, 2017), exposed along, and apparently controlled by, the Transbrasiliano Lineament, which

cross-cuts the Parnaíba Basin in its SE segment (Fig. 2). The Transbrasiliano Lineament (Schobbenhaus Filho *et al.* 1975) is a continental shear zone crossing the South America plate and continuing into the Africa plate (where it is known as the Kandi Lineament) and is defined as the scar of a transcontinental terrane amalgamation that took place at the end of the Neoproterozoic as part of the formation of West Gondwana (Cordani *et al.* 2013; Brito Neves & Fuck 2014).

The Parnaíba Basin as a whole records a complex history of deposition and can be subdivided into the Parnaíba (Silurian–Carboniferous), Alpercatas

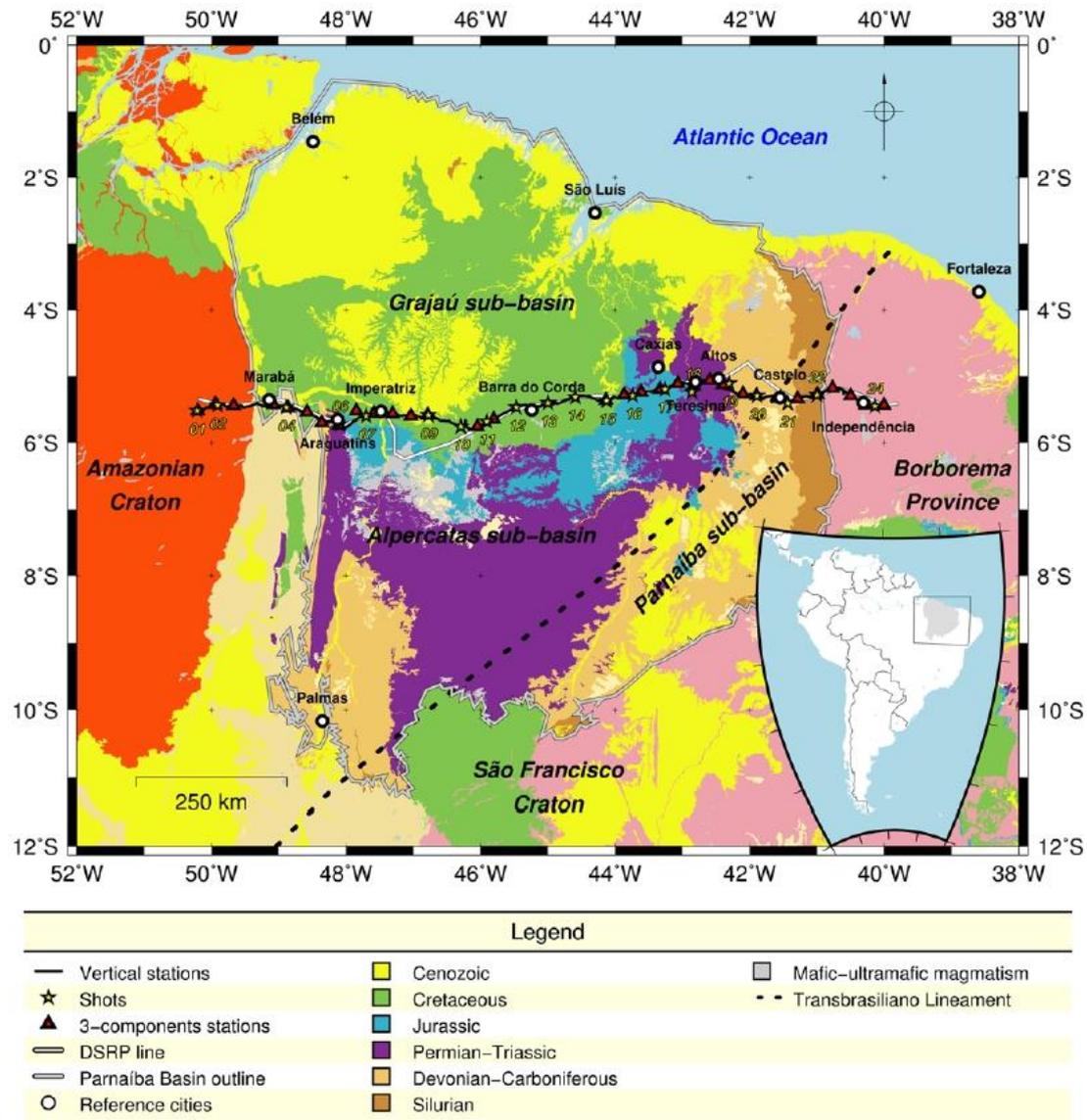


Fig. 2. Geological map of the Parnaíba Basin; see Figure 1 for legend (modified from CPRM 2015).

(Permian–Jurassic) and Grajaú (Cretaceous–Cenozoic) sub-basins (Vaz *et al.* 2007) (Fig. 2). Strictly speaking, the Parnaíba Basin consists only of the Silurian–Carboniferous succession, although the term is used to connote the whole of the sedimentary basin succession, including the overlying Permian–Jurassic and Cretaceous–Cenozoic successions (known as the Alpercatas and Grajaú basins, respectively).

The Parnaíba Basin is marked by regional mafic magmatism of the Triassic–Early Jurassic Mosquito Formation (199±2.4 Ma, Merle *et al.* 2011), related to the opening of the central Atlantic Ocean, and by dykes and sill-like intrusions of the Cretaceous Sardinha Formation (129–124 Ma, Fodor *et al.* 1990), linked to the opening of the South Atlantic Ocean. The total thickness of magmatic rocks derived from these two events is *c.* 600–800 m intruded into a sedimentary pile of maximum 3.5 km thickness (Daly *et al.* 2014).

The initial Early Paleozoic basin depocentre shifted to the central part of the basin realm during Early Carboniferous–Jurassic time and migrated again, northwestwards, in the Cretaceous (Vaz *et al.* 2007 and references cited therein), suggesting a temporal relation with Mosquito and Sardinha magmatism, respectively. The basin realm was initially broader than it is today, with a link to the Amazonas and Paraná basins and possibly even with the Congo basin in Africa (Melo 1988).

At present, the Parnaíba Basin shows a sharp fault contact with the Tocantins Province (Araguaia Belt) in the west (Daly *et al.* 2014), a tectonic/erosional contact with the Tocantins Province to the south, and a smooth northwards sedimentary contact with the São Luis Craton and with the São Francisco Craton to the SE. Along the eastern border, the limit of the basin with the Borborema block is erosional, with the basal Silurian sediments of the basin being exposed.

The basement of the Parnaíba Basin consists of a collage of at least three main domains, classified as the Amazonian, Parnaíba and Borborema blocks, which are marked by steep contacts between them (Daly *et al.* 2014; Castro *et al.* 2014).

WARR experiment

The WARR transect is a 1150 km long east–west profile, beginning over the Amazonian Craton (*c.* 150 km west of Marabá), crossing the Parnaíba Basin and finishing over the Borborema Province, 100 km east of the basin margin, close to Independência (Figs 1 & 2). Its path is regionally almost a straight line, following paved and secondary dirt roads, passing through an isolated, mainly sparsely populated part of NE Brazil. It coincides with the

path of the CDP profile (Daly *et al.* 2014), except between Imperatriz and Barra do Corda and between Altos and Castelo, where the WARR experiment avoided bends in the previous reflection profile.

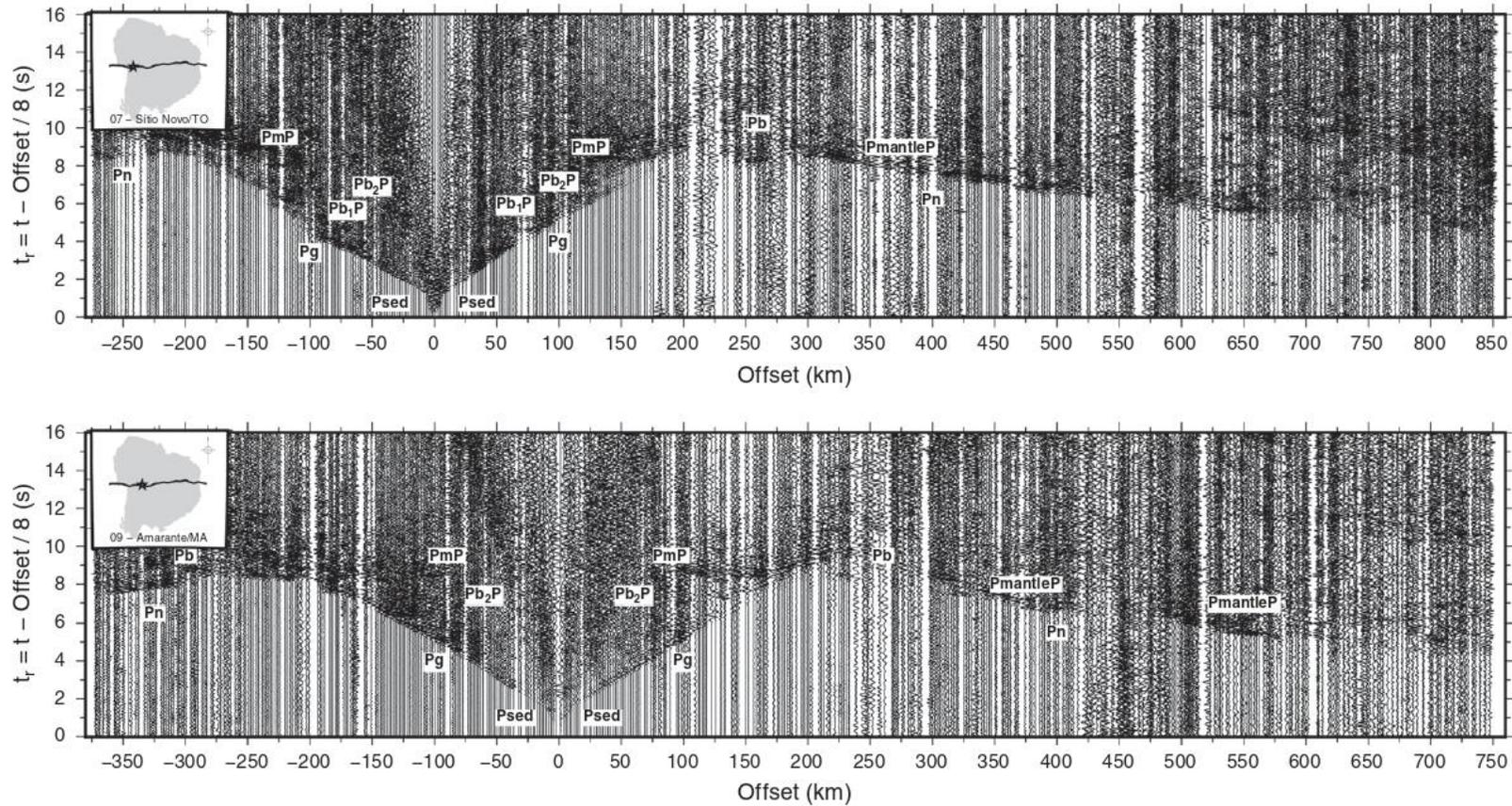
The data were recorded by 36 short-period, three-component stations (recorder model RefTek DAS130 with triaxial sensor model Sercel L-4A 3D from PEG-BR) installed at 30 km intervals, mainly covering the western and eastern parts of the line (cf. Figs 1 & 2), and 600 vertical component stations (300 RefTek Texans with vertical sensor model Sercel L4-A from PEG-BR and 300 Texans with 4.5 Hz vertical geophones from the PASSCAL) evenly distributed along the deployment line (cf. Figs 1 & 2).

The three-component short-period stations were installed before the active source acquisition field-work began, with these instruments working in a continuous recording mode with a sample rate of 100 sps for a period of six months, aimed at obtaining a teleseismic dataset for receiver function studies complementary to the WARR acquisition. The vertical component stations were specifically deployed for the WARR acquisition and recorded during pre-programmed windows of 10 minutes duration, during which shots were detonated, and sampled at a rate of 200 sps. The Texans have very accurate internal clocks, calibrated with global positioning system time before and after deployment.

The shots were loaded in boreholes of 25 cm diameter and 45 m depth with the lower two-thirds (of the boreholes) filled with a chemical emulsion corresponding to 1.5 tonnes of dynamite explosive charge and the upper one-third packed with soil. The experiment was planned with a shot every 50 km along the line, making a total of 24 shots. No eventual permission was granted for shots 3 and 23, so shots 2 and 24 were duplicated, with two boreholes and 3.0 tonnes of explosive for each. The shots were detonated during four nights with shot times controlled with a precision of 10 ms. Shots 5 and 8 did not deliver sufficient energy to be recorded and were discarded. The final dataset consists of 20 shot gather seismic sections (see the supplementary material).

Data processing and data quality

The recorded dataset is of good quality. For most shot gathers it is possible to obtain information to an offset of 350 km, allowing for good control of the crustal structure and Moho discontinuity disposition, as well as the velocity in the uppermost lithospheric mantle. For some shots (e.g. shots 7 and 9; Fig. 3) there are clear phase alignments along the whole profile, which means far offsets up to 850 km (cf. shot 7; Fig. 3). Reflections from a



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Fig. 3. Shot gathers 7 (upper panel) and 9 (lower panel), shot within the Parnaíba Basin and recorded along the whole profile, presenting maximum offsets of 850 and 650 km, respectively. These broad offset recordings provide good constraints on the upper mantle velocity. Examples of seismic phases mentioned in the text are labelled. The reducing velocity on the vertical (time) axis is 8.0 km s^{-1} and a bandpass filter of 2–8 Hz has been applied to the seismic traces. Note that the scale of the horizontal axis differs from shot point to shot point. The inset figure on each shot gather shows the Parnaíba Basin outline (grey shade) and the trace of the WARR profile with the position of the respective shot.

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discontinuity or discontinuities below the Moho (PmantleP) are well recorded by these shots.

The main phases are generated at boundaries in the sediments of the Parnaíba Basin and the Cretaceous sediments and metasedimentary rocks of the Araguaia fold belt (Psed), within the upper crust (Pg) and as a reflection at the base of the upper crust (Pb1P), as a refraction crossing the lower crust (Pb) and as reflected phases at a lower crustal boundary and the Moho (Pb2P and PmP, respectively), and the Moho refraction (Pn) from the uppermost mantle. It is also possible to identify some very deep reflections (i.e. PmantleP), suggesting an interface within the upper mantle below the Moho discontinuity.

In general, the shot gathers of the shots located within the basin display lower signal-to-noise ratios and are more reverberatory than those outside the basin. The seismograms from shots 1, 2 (Amazonian Craton) and 24 (Borborema Block) (Fig. 4), for example, are clean in appearance with clear phase alignments, including the Moho reflected (PmP) and refracted (Pn) phases. By contrast, the constituent seismic traces from shot gathers from shots within the basin present a more scattered aspect (Figs 3 & 5, also see the supplementary material), mainly due to reverberations within the layers of the sedimentary basin itself.

Modelling and results

An initial velocity model is required at the start of the modelling process. This was derived from a direct analysis of the alignment of identifiable phases in the shot gathers in conjunction with a tomographic model along the profile computed from first arrival phases only (carried out by the authors, but not shown here nor published elsewhere), combined with the main features of the deep CDP profile published by *Daly et al. (2014)*. Some consideration was also taken of Moho depth estimates from the preliminary receiver functions results computed (by the authors, but not yet published) from teleseismic data recorded at the three-component stations along the WARR profile (located in Figs 1 & 2). Once a good approximation of the velocity distribution had been achieved via forward modelling, the inversion mode Rayinvr was applied (*Zelt & Ellis 1988*) to improve the geometry and travel time fits of some of the more complex parts of the forward model.

The resulting seismic velocity model is shown in Figure 6 and consists of five layers. The uppermost layer represents sedimentary rock; the next three are upper crust, lower crust and a high-velocity lower crustal layer, respectively; and the lowermost layer is lithospheric upper mantle. The sedimentary layer is up to 3 km thick with a P-wave velocity ranging

from 3.0 to 3.9 km s⁻¹ (top) to 3.5–5.5 km s⁻¹ (bottom). Its boundaries at the surface and base as well as its geometry are well constrained by geological and well data. The bottom of the upper crustal layer ranges in depth from 19.7 to 26.0 km, corresponding to a thickness variation between 17.6 and 24.0 km, respectively. The P-wave velocity varies from top to bottom between 5.9 and 6.3 km s⁻¹ in the central portion of the profile, between 6.27 and 6.40 km s⁻¹ in the easternmost segment, and between 6.1 and 6.5 km s⁻¹ elsewhere. The lower crustal model layer displays a velocity range of 6.6–6.9 km s⁻¹ and has a thickness varying between 13 and 23 km. The base of the crust represents the Moho in the model, except between model distances of 150–650 km, where the WARR data imply the presence of high velocity (7.0–7.45 km s⁻¹) material up to 6 km thick immediately above the Moho. The Moho depth shows highly irregular behaviour along the seismic line, ranging from 51.0 to 33.5 km. Sub-Moho upper mantle P-wave velocities range between 8.0 and 8.4 km s⁻¹. Figure 7 presents the ray-tracing and the fit obtained between the theoretical and observed times for all shots from the shallow part and for shots 1, 6, 12, 20 and 24 for the whole model. The complete modelled dataset is given in the supplementary material.

The statistics summarized in Table 1 give an idea of the quality of the model in terms of replicating the observed and computed phase travel times. It shows the number of observations, the pick uncertainties (assigned qualitatively), the residual T_{rms} of computed times with respect to the observed data and the χ^2 value for each phase separately and for all picks together. The average χ^2 value of 1.4 for the whole dataset seems reasonable in view of the extensive length of the profile and the fact that 20 shot gathers were considered.

The model statistics can also be considered in terms of all phases on individual shots rather than individual phases on all shots and the average values of T_{rms} per shot point are shown in Figure 8. The smallest misfits between the observed and model computed travel times are for shots located outside the Parnaíba Basin (i.e. shots 1–7 within the Amazonian Craton and shots 18–24 within the Borborema block). The shots inside the basin (shots 9–17) present significantly higher T_{rms} values.

Discussion

Parnaíba Basin

The WARR dataset and modelling allow some observations to be made not only on the deeper crustal structure, but also on the shallow part of the crust and on the structure of the Parnaíba Basin itself (Fig. 6, upper panel). The western part of the profile

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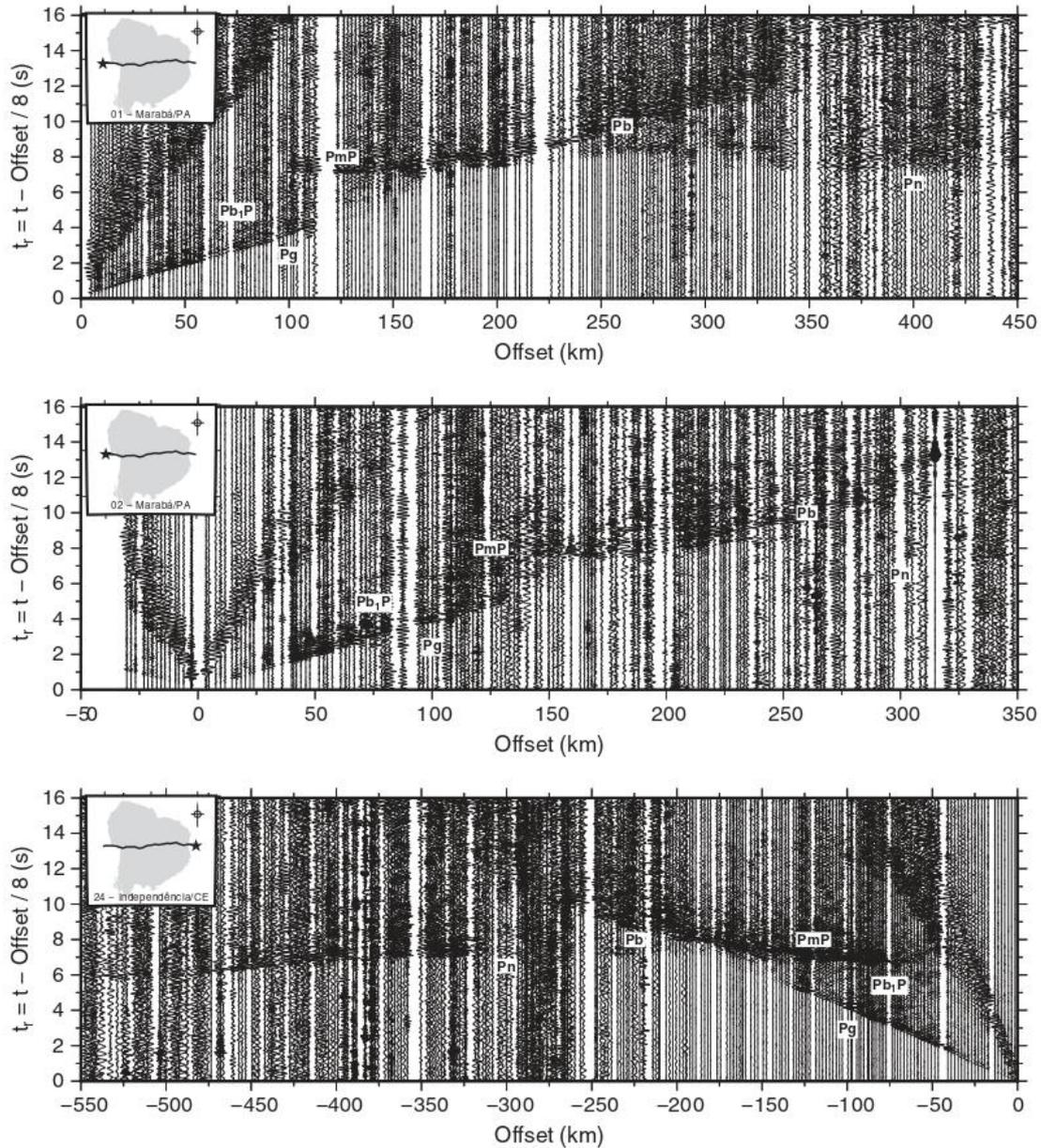


Fig. 4. Shot gathers 1 (upper panel), 2 (middle panel) and 24 (lower panel), shot in the Amazonian Craton (shots 1 and 2) and in the Borborema block (shot 24), presenting well-defined phase alignments. Examples of seismic phases mentioned in the text are labelled. The reducing velocity on the vertical (time) axis is 8.0 km^{-1} and a bandpass filter of 2–8 Hz has been applied to the seismic traces. Note that the scale of the horizontal axis differs from shot point to shot point. The inset figure on each shot gather shows the Parnaíba Basin outline (grey shade) and the trace of the WARR profile with the position of the respective shot.

is characterized by three shallow graben over the Araguaia belt, resolved in the WARR data, resting over the Amazonian Craton basement. They are deeper to the east, with a maximum depth of 1 km. The Cretaceous sedimentary rocks infilling these graben present an average velocity of 3.6 km s^{-1} and the Amazonian Craton basement presents a velocity

of 6.23 km s^{-1} , which is the highest shallow velocity along the profile.

The contact between the Araguaia belt rocks and the sedimentary rocks of the Parnaíba Basin is tectonic and is represented by a sharp fault, as modelled in this work and seen in the CDP profile of Daly *et al.* (2014). The shape of the basin is asymmetrical,

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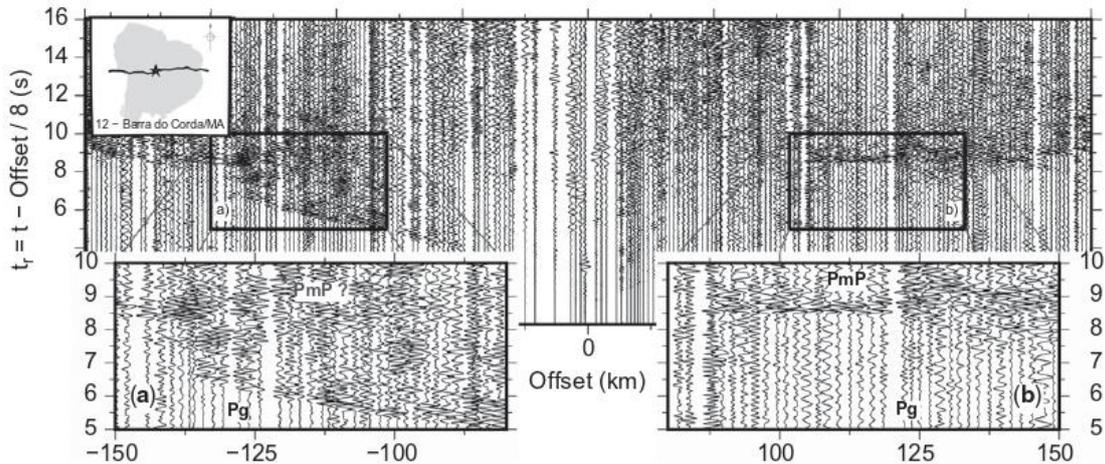


Fig. 5. Shot gather 12 (Barra do Corda; Fig. 1). The zoomed insets show the difference between the (a) negative and (b) positive parts of the section at offsets 50–150 km. The negative side is more reverberatory between the arrivals of the Pg and PmP phases, indicating the presence of mafic intrusions throughout the crust. The shot gather is reduced with 8.0 km s^{-1} and filtered in the bandpass of 1–10 Hz. The inset figure on each shot gather shows the Parnaíba Basin outline (grey shade) and the trace of the WARR profile with the position of the respective shot.

reaching a maximum depth of 3.2 km in its central part (distance 600 km) and thinning strongly eastwards. As the basin as a whole thins, older layers are exposed at the surface until the outcrop of the Silurian succession near the eastern margin of the basin (cf. Figs 2 & 6).

The average velocity of the sedimentary package is *c.* 3.6 km s^{-1} and is $>5.0 \text{ km s}^{-1}$ in the distance range 560–800 km. This increase in P-velocity is associated with the mafic igneous rocks of the Sardinha and Mosquito formations, which are exposed as discontinuous outcrops as well as revealed in the subsurface within abundant boreholes in this area, which has been a target for hydrocarbon exploration. As a result of the lack of resolution of the refraction data, it is not possible to differentiate the type of magmatic rock or to define their position within the sedimentary succession. Nevertheless, the velocity field indicates where magmatic rocks occur in the basin: they were emplaced east of the deepest part of the basin.

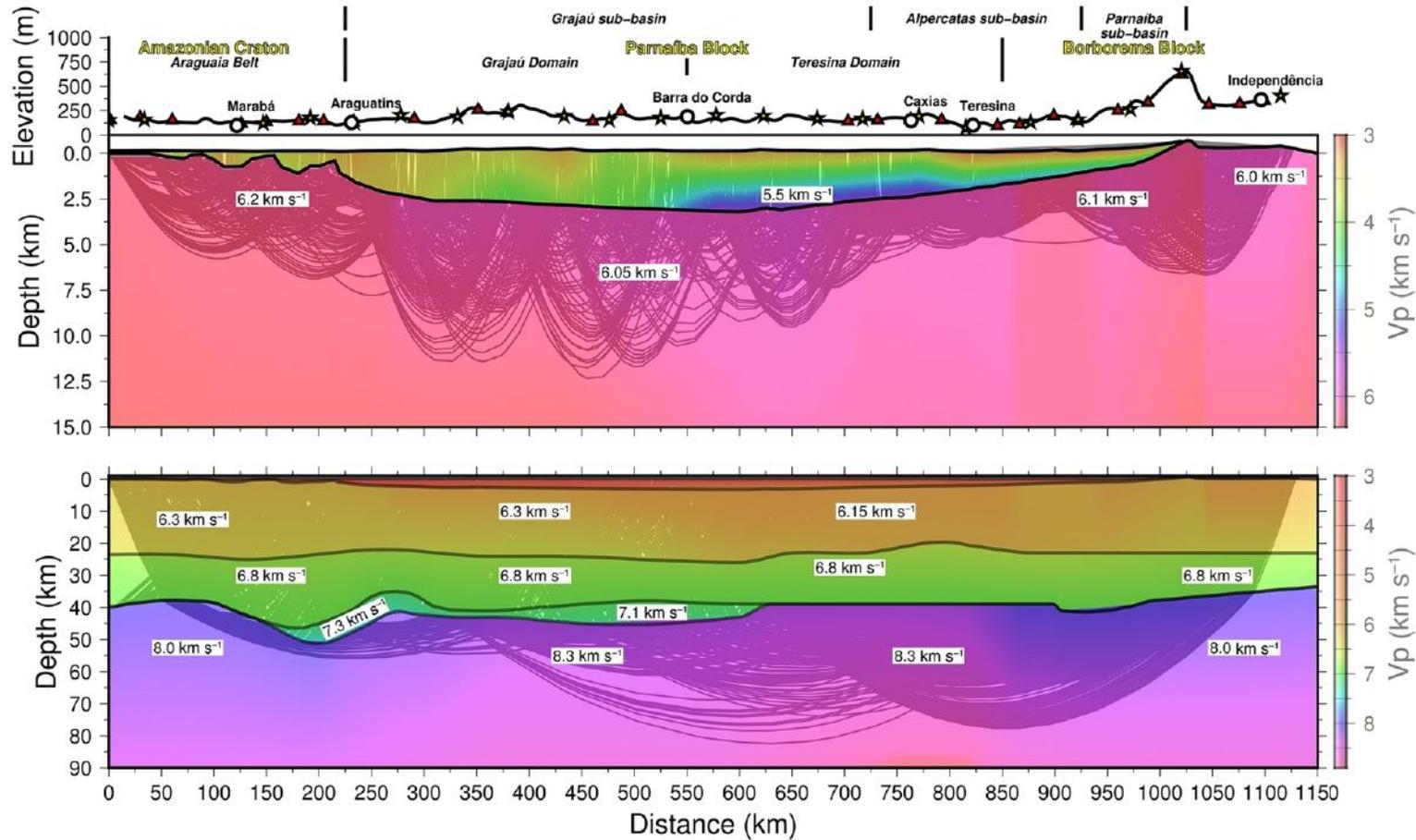
Crustal layers

The basement velocity, immediately below the sedimentary layer, along the WARR profile is $5.9\text{--}6.1 \text{ km s}^{-1}$, increasing to 6.2 km s^{-1} at a distance of 850 km and locally decreasing to 6.1 km s^{-1} between 950 and 1000 km, possibly indicating the Jaibaras graben and the Transbrasiliiano Lineament. The set of early Phanerozoic rifts underlying the Parnaíba Basin recognized from other work (e.g. Nunes 1993; Oliveira & Mohriak 2003; Castro *et al.* 2016), including the Jaibaras graben, are not seen in the

WARR velocity model, probably due to their small dimensions and/or because the velocity of the strata in these rifts is close to the velocity of the adjacent and underlying basement rocks.

The upper crustal layer is almost regular in thickness, with its base at an average depth of 24 km (Fig. 6, lower panel). Beneath the Parnaíba Basin (distances 300–900 km), the upper–lower crust boundary is roughly parallel with the basin basement horizon. Elsewhere, the upper–lower crust boundary is undulating under the Amazonian Craton and more or less flat in the Borborema block. At distances 300–600 km, both the basin and upper crust dip gently eastwards, the depocentre of the basin coinciding with the deepest point of the lower boundary of the upper crustal layer. From this point eastwards until distance 900 km, both the basin–upper crust and upper crust–lower crust layer boundaries become shallower. The latter undulates in the range 600–900 km and follows the top of the high-amplitude body identified in the CDP section and interpreted as a sill-like intrusion by Daly *et al.* (2014). At the western end of the profile the shallow upper crust of the Amazonian Craton is characterized by anomalously high velocities (6.25 km s^{-1} on average) and by a smooth and small velocity gradient, reaching 6.4 km s^{-1} at the base of the upper crust. In contrast with the Amazonian Craton, the west Parnaíba block (labelled the Grajaú domain in Fig. 6) presents a steep upper crustal velocity gradient ranging from 6.1 to 6.5 km s^{-1} . This high gradient coincides with the eastward-dipping upper crust–lower crust boundary (to *c.* 500 km in Fig. 6). To the east the velocity distribution in the upper crustal layer

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Fig. 6. Two-dimensional WARR crustal velocity model across the Parnaíba Basin and its western and eastern margins (lower panel). The upper trace shows the topography along the profile and the locations of shot points (yellow stars) and three-component seismometers (red triangles). The model is divided into four main domains defined from west to east as: (1) the Amazonian Craton (0–250 km); (2) the Grajaú domain (250–550 km); (3) the Teresina domain (550–850 km); and (4) the Borborema block (850–1150 km offset). The middle two domains comprise the Parnaíba block. In general, the model crust thins eastwards, especially through the thinning of lower crust. The upper panel details the shallow part of the model (uppermost 15 km) showing the graben of the Araguaia belt, the asymmetry of the sedimentary basin and a high-velocity region ($>5.0 \text{ km s}^{-1}$) inside the sedimentary basin, indicating that part of the basin along the profile was affected by magmatic intrusions. The ray-trace coverage can be seen in the background of both panels.

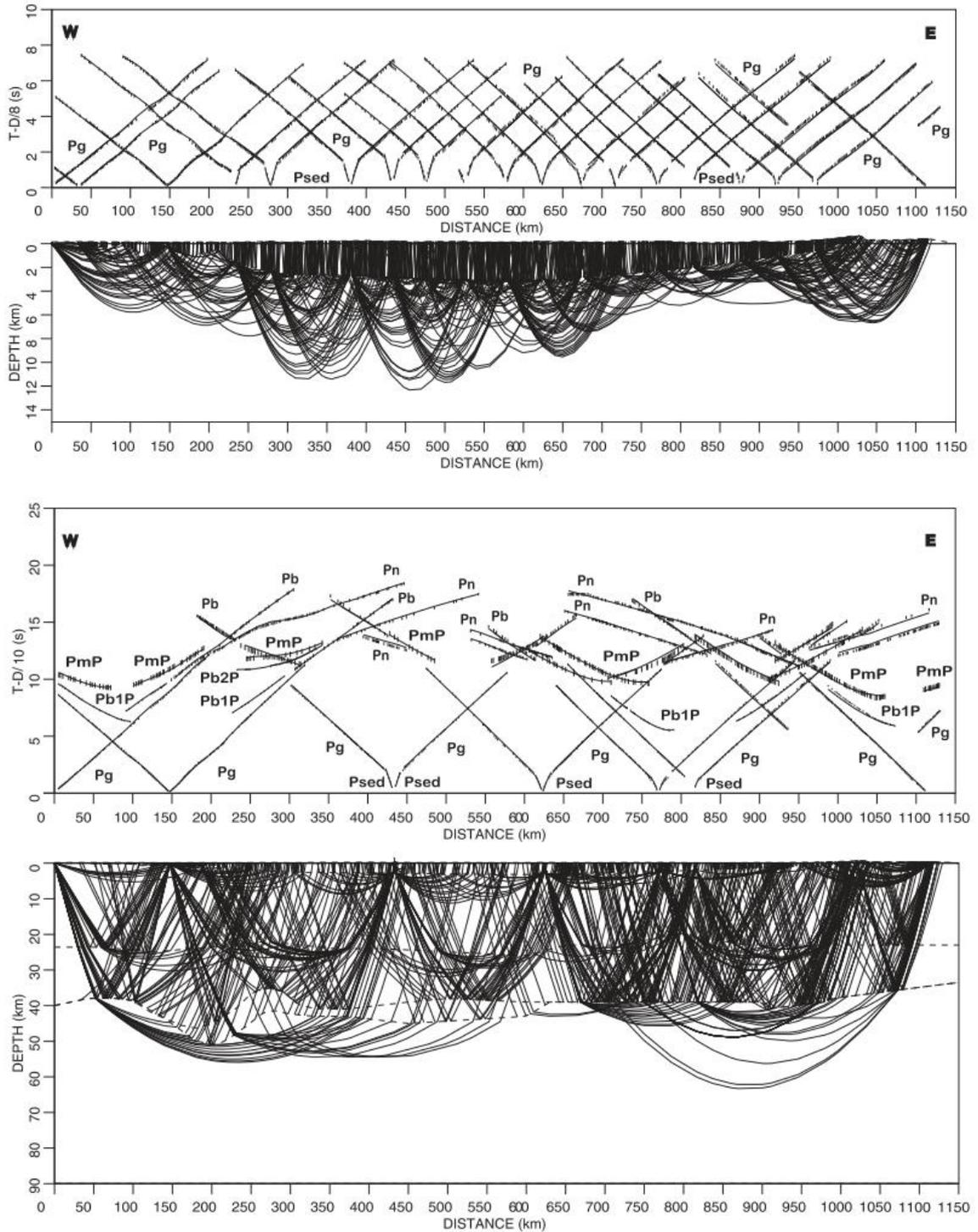


Fig. 7. Ray-tracing and the fit between theoretical and observed travel times for the shallow part of the model (upper panels) and for the deeper crust and upper mantle (lower panels). Fits for all shots are plotted in the former but, for clarity, only those of shots 1, 4, 9, 13, 16, 17, 22 and 24 are shown in the latter. The observed travel times are plotted as error bars (the length being an indication of uncertainty in picking the phase arrival times) and the theoretical travel times computed from the velocity model shown in Figure 6 are continuous lines. The precision of the misfits is shown in Table 1. A complete modelling dataset is presented in the supplementary material.

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Table 1. Statistical analysis of the seismic modelling considering the rms values, the χ^2 values per phase and for all the phases together

Phase	No. of picks	T_{rms} (s)	χ^2
Psed	144	0.112	1.987
Pg	1859	0.093	1.197
Pb	631	0.154	1.274
Pb1P	387	0.073	1.101
Pb2P	77	0.070	1.184
PmP	837	0.255	1.281
Pn	1338	0.140	1.176
All	5273	0.147	1.417

is more irregular, being 5.9–6.1 km s⁻¹ in its upper part and 6.2–6.3 km s⁻¹ in its lower part, presenting a smooth gradient that characterizes the east Parnaíba domain, known as the Teresina block (Castro *et al.* 2014). From 900 km through to the eastern end of the profile, the velocity in the Borborema block is 6.0 km s⁻¹ in the upper part of the basement and 6.4 km s⁻¹ at the bottom and is characterized by a strong velocity gradient. The upper crust–lower crust boundary is flat in this area.

The lower crustal layer in the model has a velocity varying from 6.7 to 6.9 km s⁻¹, except where there is anomalously high-velocity material (7.0–7.4 km s⁻¹) within the lowermost part of the lower crust in the distance range 150–640 km. Excluding this high-velocity material, the P-wave velocity in the lower crust is fairly uniform throughout the profile (6.7 km s⁻¹ at the top of the layer and 6.9 km s⁻¹ at the bottom) and, accordingly, has a similar velocity gradient throughout.

Shot gather 12 (Barra do Corda; Fig. 5) shows that the crust to the west of Barra do Corda presents

a reverberatory aspect between offsets –50 to –150 km and reduced time axis 5–9 s, suggesting that the lower crust, and even the upper crust, in this region may have been intruded and affected by mafic magmatism. Such mafic bodies disturb the propagation of the wave front, generating multiples and discontinuous reflections, and even obscuring the Moho reflection (PmP). By contrast, the same shot gather in its eastern part shows a crust that is not affected in this way.

Moho character and upper mantle

The depth to the Moho along the WARR velocity model is fairly irregular, varying from 51 km in the Amazonian Craton to 33.5 km at the profile’s eastern end within the Borborema block. In general, there is a trend for the Moho depth to shallow, and thus the crust to thin, towards the east along the profile. The eastwards crust-thinning trend is underlined by zones of Moho structure that can be correlated with the crustal domains along the profile labelled in Figure 6.

The most striking structure on the Moho is beneath the Amazonian Craton, where it deepens from 38 to 51 km at the front of the Neoproterozoic Tocantins–Araguaia suture, between 100 and 200 km, before thinning sharply to 41 km at a distance of 300 km. Part of the thickened crust (and hence deeper Moho) in this zone is due to the high-velocity material (7.4 km s⁻¹) added to the lower crustal layer. Together with the seismic fabric imaged in the CDP section (Daly *et al.* 2014), the Moho geometry suggests that this thick crust is formed by lower crustal underthrusting and duplication.

The Moho reflection (PmP) is usually clear, indicating the strong contrast of impedance between the

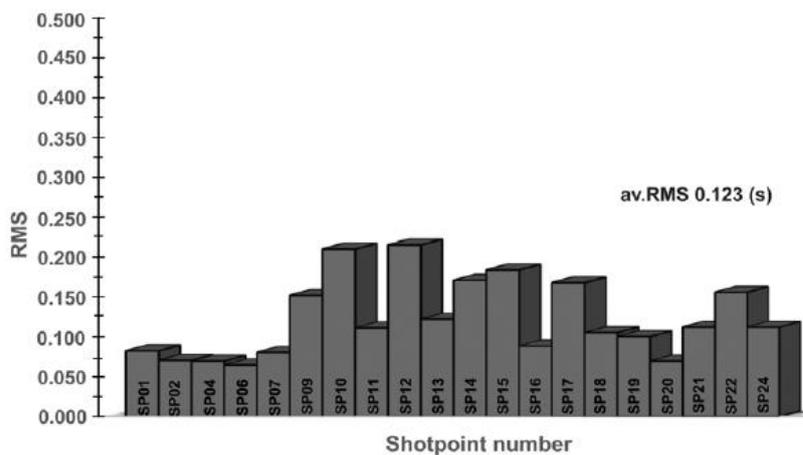


Fig. 8. Histograms showing the quality of the misfit (T_{rms}) between theoretical and synthetic phases per shot. The average T_{rms} of 0.125 s is a good result considering the amount of data and the basin environment, which usually increases uncertainties due to reverberation in the recorded traces.

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rocks of the lowermost crust and the top of the mantle. The PmP phases between shots 4–9 and 17–19 of the present dataset, however, are not well defined. These phases are unclear in the shot gathers (see the supplementary material), suggesting that in both regions the Moho is not a first-order discontinuity. These segments are geographically related to the Amazonian Craton–Parnaíba and Parnaíba–Borborema block sutures, respectively, and are probably an indication of the complexity of the Moho below both these zones. Mafic intrusions within the crust can also affect the Moho reflection. They reduce the velocity and impedance contrasts between the crust and mantle, transforming the Moho into more of a transition layer rather than a first-order boundary and diminishing the PmP phase.

The upper mantle velocity inferred from the WARR dataset is 8.2–8.4 km s⁻¹ under the Parnaíba Basin and around 8.0 km s⁻¹ outside the basin, under the Amazonian Craton and the Borborema block. The anomalously high velocity directly under the basin could represent mantle that has been differentiated, enriched and densified, forming a strong mantle foundation under the Parnaíba Basin and probably isostatically linked to the present day mapped basin limits (that is, a higher density uppermost mantle isostatically compensating the overlying low-density Parnaíba sediments).

Crustal domains along the WARR profile and implications

Any two-dimensional WARR model presents a relatively smooth velocity field geometry defining heterogeneities within the model layers and the lateral variations along the length of the model. Sometimes the differences of interest between geological (or crustal) domains are better expressed by velocity gradients rather than by the absolute velocities themselves. For the present model, a series of velocity–depth profiles, evenly extracted along the model domain, have been stacked and allow the differentiation of four domains along the profile (Fig. 9): the Amazonian and Borborema blocks, exposed outside the basin, and the Parnaíba block hidden below the sedimentary cover, here subdivided into the Grajaú and Teresina domains.

The Grajaú domain is characterized by high-velocity material in the lower crust (6 km thick with a velocity of 7.0–7.2 km s⁻¹), where the Moho is 44 km deep on average (Figs 6 & 9). This region, although modelled as an independent velocity layer coupled to the lower crust, is more likely to be a transitional layer resulting from upper mantle and lower crustal extension, decompression and mafic magma intrusion, affecting the crust as a whole, but mainly expressed in the velocity model as the higher velocity material in the lowermost

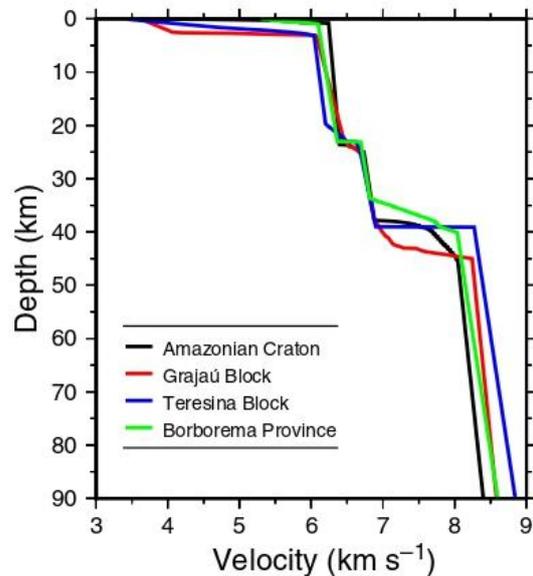


Fig. 9. Average one-dimensional P-velocity curves of the main crustal domains recognized along the profile (as seen in Fig. 6). The main differences are in the velocity gradient of the upper crust, the upper–lower crust transition and lower crust–upper mantle transition. The upper mantle velocity is higher under the basin (up to 8.4 km s⁻¹) than outside the limits of the basin (8.0 km s⁻¹).

lower crust (cf. Christensen & Mooney 1995). A non-abrupt limit is, accordingly, inferred between the lower crust, the high-velocity material and the upper mantle.

The lower crustal accretionary material, considered here as an ‘underplate’ in the sense of Thybo & Artemieva (2013), is geographically coincident with the surface extent of Cretaceous sediments in the Parnaíba Basin (cf. Fig. 2), with this same segment of crust interpreted to have been affected by magmatism, as shown by shot gather 12 (Fig. 5). Considering that this youngest basin depocentre was established in the Cretaceous (e.g. Vaz *et al.* 2007), a genetic link between magmatic underplating (resolved by the velocity model) and crustal depth magmatism (although not enough to have significantly affected crustal velocities) and surface subsidence defining the Cretaceous basin depocentre seems possible.

The Teresina domain is marked by a flat Moho at 39 km depth. It is separated from the Grajaú domain by a step of 4 km in the Moho (600 km), accommodated almost totally by the termination of the high-velocity lower crustal layer (interpreted as being evidence of underplating, as defined here), and from the Borborema block by a step of 2 km (900 km). The nature of the limit between the Grajaú and Teresina domains is not well defined and

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Figure 9 shows that the average velocity of these blocks is similar, the main differences being in the upper crustal velocity gradient and the crust–Moho transition linked to the high-velocity ‘underplate’. Thus it is not clear from the WARR data whether the Grajaú and Teresina domains represent distinct tectonic domains since their amalgamation in the Neoproterozoic, or whether the differences that are now observed are the result of later processes, including magmatism that took place in Jurassic–Cretaceous times. The CDP section of Daly *et al.* (2014) is also inconclusive in this regard given its complete lack of crustal reflectivity in the Grajaú domain.

The contact between the Teresina and the Borborema blocks is tectonic and is considered to be a suture zone, with the former subducted under the Borborema block to the east, as shown in the CDP section of Daly *et al.* (2014). The WARR data resolved the Moho depth at *c.* 39–41 km in the area of this suture zone, suggesting that any Moho structure that was associated with it has since been removed.

The Borborema domain shows the Moho shallowing continuously eastwards, from 41.0 to 33.4 km at the end of the WARR profile. The upper crustal layer does not show similar thinning; its thickness is nearly constant in the Borborema domain, such that at the eastern extremity of the profile the upper crust is more than twice the thickness of the lower crust. The crustal structure of the Borborema block obtained here replicates the structure determined along the NW–SE Borborema deep seismic refraction line (Tavares *et al.* 2012; Lima *et al.* 2015) to the NE of this profile. The Borborema Province, as a whole, displays a thin crust (Soares *et al.* 2011; Lima *et al.* 2015; Luz *et al.* 2015) and a thin lithosphere. Its crust and probably lithospheric mantle were affected by extension linked to the opening of the South Atlantic Ocean in the Cretaceous. This may be linked to marginal uplift of the Borborema Province and the exposure of basement rocks during and after the Cretaceous, and to the present erosional margin of the eastern border of the Parnaíba Basin.

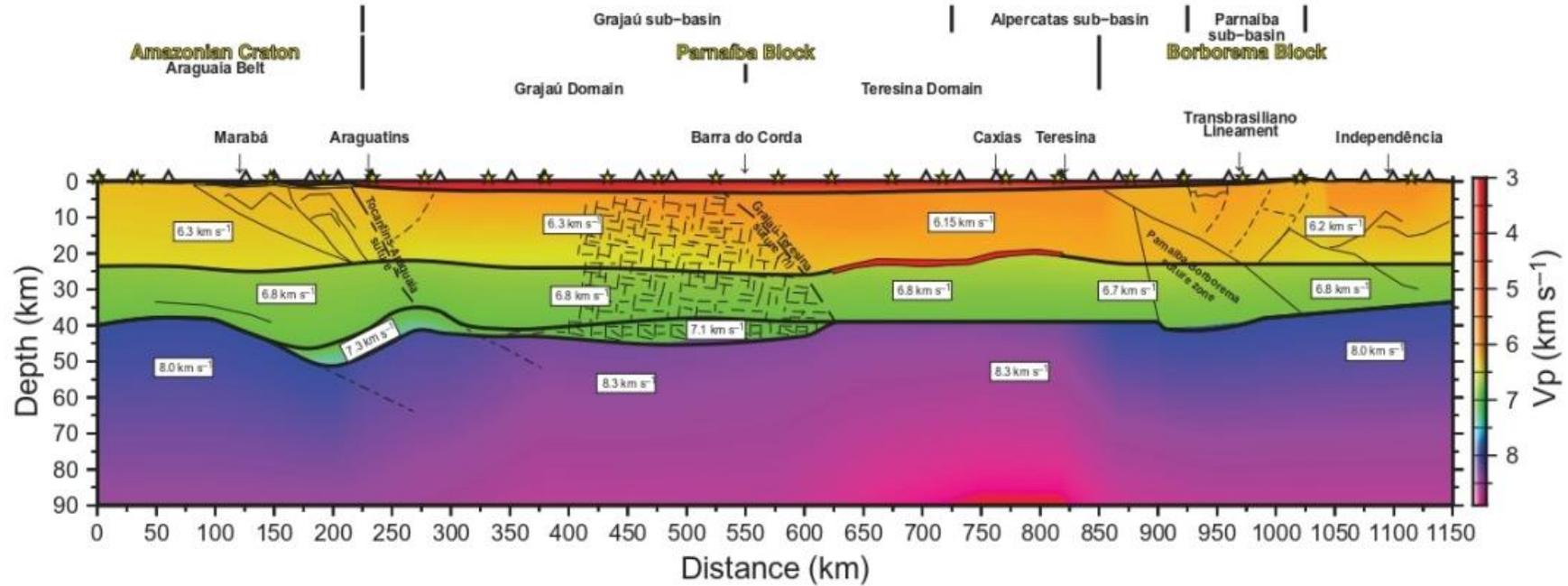
Integrated WARR results and their implications

The main WARR results are integrated in Figure 10. They show that the crust and uppermost mantle along the profile consist of four domains, distinct in their seismic velocities and layering and crustal thicknesses. These are the Amazonian Craton and Borborema Province, to the west and east of the Parnaíba Basin, respectively, and the Grajaú and Teresina domains, together comprising the Parnaíba block hidden below the sedimentary cover of the

Parnaíba Basin itself. The lithospheric characteristics of the Parnaíba block and its constituent domains and their differences from the adjacent Amazonian and Borborema blocks are relevant to the present day existence of the sedimentary basin covering it.

Starting at the base of the model, the upper mantle velocity below both domains of the Parnaíba block is higher (up to 8.4 km s^{-1}) than elsewhere. This isostatically compensates the Early Paleozoic (and, in part, younger) sedimentary succession above the crust and is likely to have been a factor in the initial development of the Early Paleozoic sedimentary basin, subsequent to the Neoproterozoic (and possibly earliest Paleozoic) Brasiliano–Pan-African consolidation of the crust of the Parnaíba block. Regarding the lower crust of the Parnaíba block and its age, it is noted to have been in part reworked eastwards from the Tocantins–Araguaia suture, with the adjacent Amazonian Craton lower crust, in contrast, appearing to have been basically preserved, maintaining Neoproterozoic structures. Nevertheless, the whole of the suturing area also displays the presence of a high-velocity lowermost crustal material, which can be interpreted as caused by magmatic underplating and lower crustal intrusion. The age of this magmatic event is possibly Cretaceous because it spatially coincides with the Cretaceous and younger depocentre of the Parnaíba Basin. In this case, there is a possible genetic link between Cretaceous basin subsidence and magmatism within the sedimentary succession, although the latter is spatially offset from the lower crustal high-velocity body. Since the crust was intruded (as inferred from the character of observed seismic traces) in the Grajaú domain, it is reasonable to suggest that it may also have been stretched at the same time (e.g. Mooney *et al.* 1983). There is strong evidence that the Borborema block was stretched in the Cretaceous (linked to South Atlantic opening; Soares *et al.* 2011; Lima *et al.* 2015; Luz *et al.* 2015), so it follows that the Teresina domain of the Parnaíba block, along with the Grajaú domain, would also have been stretched at this time. There is no remnant structure at the Moho related to the suturing of the Parnaíba and Borborema blocks according to the WARR model; this can be taken as support for Cretaceous stretching of this part of the model and the removal of any such structure. It is also noted that there is no discrete signature of the Transbrasiliano Lineament resolved by the WARR data in the lower crust of the Parnaíba Basin.

The upper crust along the profile does not display any structural effects of extensional tectonics in the Mesozoic, as inferred for the lower crust and Moho, although there was some degree of magmatic intrusion in the Grajaú domain and the upper crust appears to have been uplifted at the eastern border of the Parnaíba Basin, as shown by the erosional



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Fig. 10. Integrated interpretation of the WARR velocity model. Continuous lines are structures (e.g. faults, fractures) interpreted from the CDP session, as are the speculative positions of the Amazonian–Parnaíba and Parnaíba–Borborema sutures, and the dashed lines are the authors’ complementary interpretations. The thick red-coloured body interpreted as a sill in the mid-crust of the Teresina domain was extracted from deep CDP interpretations (Daly *et al.* 2014). The thin line network in the Grajaú domain represents magmatic intrusions throughout the crust inferred from the WARR data.

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margin of the basin there. An extended upper crust usually presents a brittle behaviour. The graben structures recorded in the Araguaia belt, in the westernmost segment of the WARR profile, are a good example of this. However, no rift-like structures or large faults, or strong thickness variations, are resolved in the WARR model of the upper crust beneath the Parnaíba Basin. This includes the set of late Neoproterozoic–early Cambrian rifts (including the Jaibaras rift), which may have played a local part in early basin formation and evolution, but not in the later Mesozoic phase of basin development. As seen at the scale of the WARR data, the crust as a whole beneath the basin has been flexed downwards, in keeping with the sub-parallel basement horizon of the basin itself, and shows no typical rift-type control on basin formation.

Summary and conclusions

The Parnaíba Basin WARR profile is 1150 km long and runs east–west, roughly coincident with the deep seismic reflection profile of Daly *et al.* (2014). Its western terminus is within the Archean–Paleoproterozoic Amazonian Craton *c.* 150 km west of the margin of the Parnaíba Basin and its eastern terminus is within the Brasiliano–Pan-African (Neoproterozoic) Borborema Province, *c.* 100 km east of the margin of the basin.

In particular, the velocity model of the crust and upper mantle beneath the Parnaíba Basin (from ray-tracing of the WARR data) documents lateral velocity changes in the upper mantle – with higher upper mantle velocities beneath the present day preserved Phanerozoic sediments of the Parnaíba Basin – as well as lateral changes in seismic character and velocity within the crust – with higher lower and upper crustal velocities and evidence of magmatic intrusion into the crust beneath the Cretaceous and younger sedimentary depocentre of the Parnaíba Basin.

The existence of high-velocity, high-density lower crust–upper mantle material under the basin itself provides new constraints on the geodynamic history of the Parnaíba Basin and brings new insights for intracontinental basin formation in general.

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3. Crustal Structure and Vp/Vs Ratio of Parnaíba Basin - Brazil: Evidences of Neoproterozoic Amalgamation in West Gondwana

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Abstract

This work presents the results of Receiver Function survey accomplished in the central portion of Parnaíba Basin - Brazil. The seismological stations were deployed along an EW transect, comprising 4 important tectonic provinces of South American Plate: the eastern border of Amazonian Craton, the Tocantins Province, the Parnaíba Basin itself and the western margin of Borborema Province domain, 1.150 km long from the westernmost station. The Receiver Function data were recorded by 40 short period three-components stations, installed mostly within 30 km intervals, working in a continuous mode, during 27 months. Located in the northern portion of Brazil, the Basin lies in a vast intracontinental area and records the Paleozoic sedimentation of West Gondwana, which was the result of crustal collisions involving cratonic blocks and extensive Neoproterozoic fold belts. The receiver function results were analyzed and constrained by previous Wide Angle Reflection Refraction results (Vp and Moho Depth), which provide an accurate mean Vp/Vs determination for the crust using hk-stacking. The data show an heterogeneous crust along the profile, defining four main domains, reinforcing the interpretation of WARR. The Amazonian craton show clear Ps arrivals, with less than 5 s, denoting crust thickness around 39 km, with mean Vp/Vs of 1.75. The Tocantins Province in its proximity with the Parnaíba Basin presents mean Vp/Vs of 1.74 and the higher obtained thickness of the model, registering ~ 50 km thick. The Parnaíba Basin has heterogeneous characteristics, with different patterns along the E-W transect. Grajaú Domain (western portion), which is intensely affected by magmatism, show a not too clear Ps arrival, while Teresina Domain (eastern portion) presents, in general, clearer Ps arrivals, except for remote patches. The mean Vp/Vs in the Parnaíba Basin varies from 1.76, in Grajaú Domain, and 1.73, close to Teresina Domain, reflecting the response of the older sediments of the basin. The transition between the Parnaíba basin and the Borborema Province, marked by an erosive contact, register mean Vp/Vs of 1.71 and crust with 35 km thick. The nature of Vp/Vs along the profile suggests two different domains under Parnaíba Basin, as tipified by potential methods, which elucidated different basement compartmentalization, corroborating with the interpretation that the basement of the Parnaíba Basin is formed by puzzle of minor Pre Cambrian continental blocks amalgamated in Neoproterozoic, as part of West Gondwana formation.

Introduction

The Parnaíba Basin is a Paleozoic intracontinental basin, roughly circular in shape, occupying approximately a 660.000 km² (Cordani *et al.*, 1984) area of northeastern Brazil. As other cratonic basins around the world, it presents thick crust

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northeastern Brazil (Daly *et al.*, 2014; Tozer *et al.*, 2017; Soares *et al.*, 2018), long-lived flat-lying stratigraphic megasequences, deep sourced gravity anomaly (Tozer *et al.*, 2018) and no evidences of rifting or Moho uplift (Daly *et al.*, 2014; Tozer *et al.*, 2018). Its deposition history spans from Silurian to Cenozoic time and register complete regressive-transgressive shallow marine and terrestrial depositional cycles, lying upon a basinal unconformity (Daly *et al.*, 2014; Lima *et al.*, 2019), besides intense magmatism emplaced in its strata and throughout the crust (Daly *et al.*, 2014; Soares *et al.*, 2018). Although recent interdisciplinary studies carried out in the Parnaíba Basin (Daly *et al.*, 2018), where several characteristics of crust and upper mantle were recognized, its genesis and tectonic evolution remain controversial.

During the last decades, intense efforts have been made for the study and comprehension of the Parnaíba Basin formation (Nunes, 1992, Oliveira & Mohriak, 2003; Castro *et al.*, 2014, 2016). Most recent an interdisciplinary studies carried out by universities from Brazil and UK (sponsored by BP; Tozer *et al.*, 2017; Soares *et al.*, 2018, Watts *et al.*, 2018, Daly *et al.*, 2014, 2018; Coelho *et al.*, 2018), let to define several characteristics of crust and upper mantle under the basin and on its neighboring's (Tozer *et al.*, 2017; Soares *et al.*, 2018, Watts *et al.*, 2018, Daly *et al.*, 2014, 2018; Coelho *et al.*, 2018). Even though (these studies) the genesis and tectonic evolution of the Basin remain debatable.

In this context and complementing the previous studies, this work describe the major structural characteristics of the crust under the basin obtained from the analysis of Receiver Function. The data were acquired by a linear array with 40 short period seismographic stations crossing the Parnaíba Basin, extending from the Amazonian Craton to Borborema Province, being an 1,150 km long E–W transect. It has the same path of the WARR experiment performed by Soares *et al.* (2018) and similar to the CDP section of Daly *et al.* (2014) (Figure 1).

The data acquisition was first carried out with 29 stations, which results served as basis for WARR modeling and interpretation, and the other campaigns were performed until December 2018, completing the dataset which is presented in this work.

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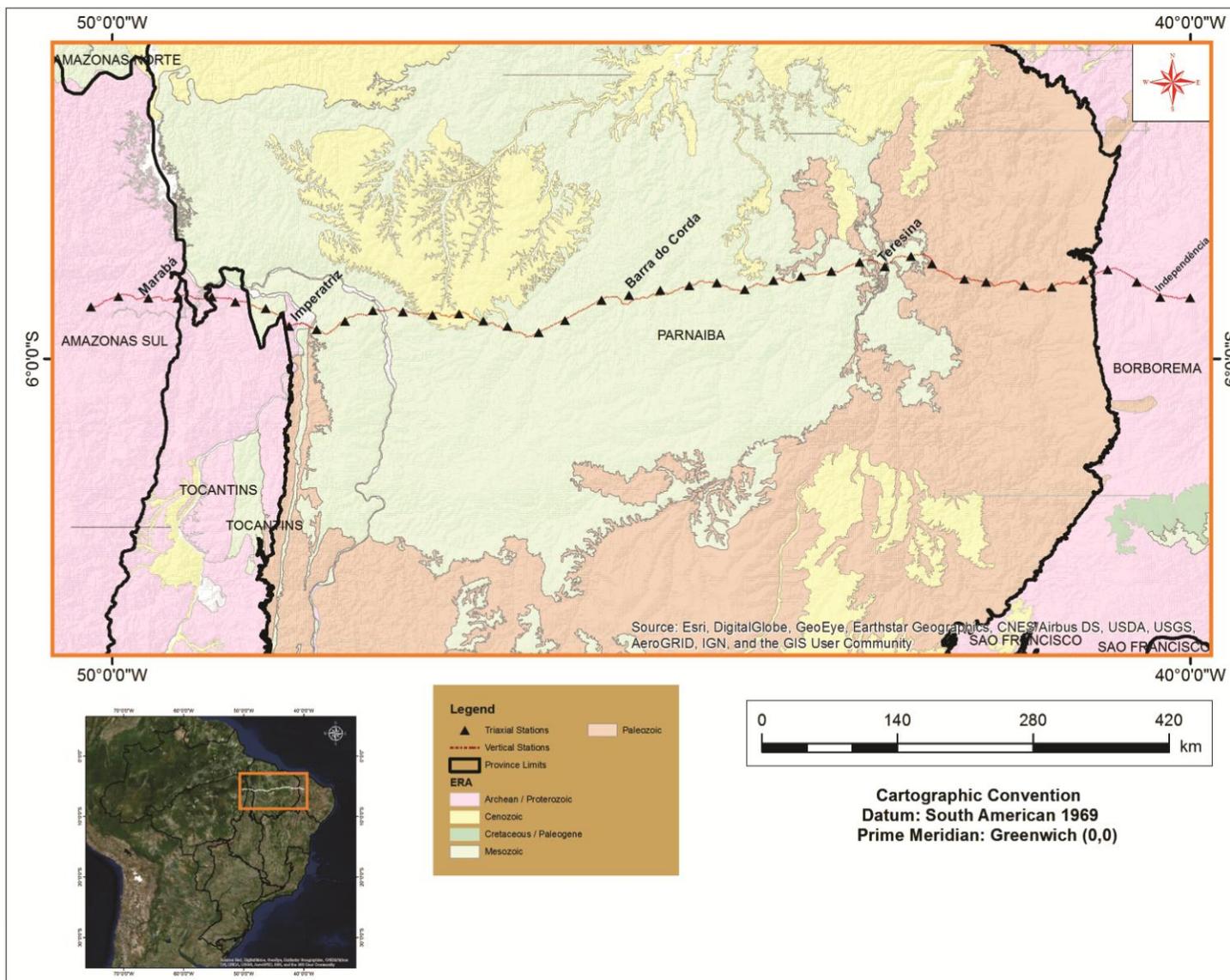


Figure1: Geological map of Parnaíba Basin, following the E - W Receiver Function stations transect.

Geological Context and Tectonic Setting

The Parnaíba Basin is a vast intracratonic depression located in central-eastern portion of South America (Almeida *et al.*, 2000). The basin comprehend a region of intricate tectonic/structural evolution resulting from collisions and extensive Neoproterozoic folded belts, including Achaean and Proterozoic terrain (Cordani, 1984; Cordani *et al.*, 2009; Brito Neves *et al.*, 1984), which stabilized during the transition of Neoproterozoic to Eopaleozoic.

The Neoproterozoic era was marked by global continental extension (Tonian Tafrogeny 900 – 800 M.y.), followed by successive continued collisions of continental blocks and fragments previously dispersed (Brito Neves *et al.*, 2000). This stage of tectonic convergence led to agglutination of different blocks and the incorporation of accretionary complexes into mobile belts, resulting in the formation of the West Gondwana continent, which subsisted until Cambrian (520 M.y.; Urung, 1997).

The west Gondwana continent subsisted until the Cambrian (520 Ma.; Urung, 1997), when changes in the state of stress of continental lithosphere promoted crustal extension and rifting, which was accompanied by local magmatism. The rift and magmatic stage occurred previously in weakness zones in West-Gondwana, however, the extensional processes did not conduct until continental breakup, originating several aborted rifts. In this scenario, Paleozoic intracontinental basins were installed and occupied large regions of South America (Amazonas, Parecis, Paraná and Parnaíba), North America (Michigan, Illinois, and Hudson Bay) and Africa (Congo, Chad, and Taodeni; Hartley and Allen, 1994; Armitage and Allen, 2010).

Situated between the Amazonian Craton - Tocantins Province on its western border, Cráton São Luis - Gurupi Arch in its northern portion, Craton São Francisco - Borborema Province at its eastern - southern boundary, the Parnaíba Basin is one of five intracontinental basins of South-American Plate, showing sedimentary records from Silurian to Cenozoic. The presence of erosive contact in its western limits, besides basal Silurian outcrops in erosive contact with the Borborema Province suggests that the depositional environment would be much broader than the recent limit, with a connection to Amazonas and Paraná Basins and even possibly with the Congo Basin, in Africa (Melo, 1988).

Fortes (1978) postulated that the form and tectonic evolution of Parnaíba Basin

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is linked to the reactivation of pre-existing basement structures. Based on regional geologic data and isotopic analysis from drilling cores, Brito Neves *et al.*, (1984) proposed the existence of a distinct basement rocks below the Parnaíba Basin, corroborating the existence of different geological blocks concealed by the basin's megasequences.

The sedimentary cover started over Cambro-Ordovician rifts (Jaibaras, Jaguarapi, Cococi/Rio Jucá and São Raimundo Nonato) (Brito Neves, 1998) and can be divided into Parnaíba Basin itself (Silurian–Carboniferous), Alpercatas (Permian–Jurassic) and Grajaú (Cretaceous–Cenozoic) sub-basins (Vaz *et al.*, 2007; Figure 1). Besides mega sequences separated by basin-wide unconformities (Goes & Feijó, 1994; Vaz *et al.*, 2007), the basin is marked by two consistent magmatic pulses. The Mosquito Formation related to the opening of Central Atlantic Ocean (early Jurassic) and the Sardinha Formation related to the opening of the South Atlantic Ocean (early Cretaceous), respectively. Mosquito Formation represents a phase of basic extrusive volcanism, composed by black tholeiitic amygdalal basalt, brought to surface through deep fault systems, forming considerable piles (Góes, 1995; Almeida & Carneiro, 2004; Zálan, 2004), whilst Sardinha Formation is related to sill-like structures, emplaced among sedimentary rocks of basin strata (Merle *et al.*, 2001).

Although Parnaíba Basin's long term thermal subsidence postulated by Brito Neves *et al.*, (1984) and Cordani *et al.*, (1984) has been correlated to pre-existing aborted Cambro-Ordovician rift systems, preceding to sag sedimentation, no major rift-like trending is recognized, as observed in other Paleozoic intracontinental basins like Paraná or Amazonas. Besides, exhaustive recent research performed in Parnaíba Basin, specially the contribution of Daly, *et al.*, (2014), Tozer *et al.*, (2017) and later Soares *et al.*, (2018), which performed deep seismic reflection (DSR), gravimetric modeling and deep seismic refraction (WARR), respectively, have shown that the proposed rift model is incompatible. The DSR imaging presented a thick crust, with lack of rupture structures, like normal fault systems, that would have to be supposedly found. Subsidence backstripping of several wells and flexural backstripping performed by Tozer *et al.*, (2017) showed that modal subsidence curves and thick crust do not match rift model. Moreover, Soares *et al.*, (2018) mapped a mafic underplating on Grajaú domain that would be related to the last depocenter shift of the basin, and would have triggered the onset of the former Cretaceous sub basin subsidence.

RF Data Processing

Receiver Function is a method that uses teleseismic events to obtain Earth's structure below a seismic station. The technique was initially named "P-wave-Equalization" (Langston, 1979) and then improved by Owens, (1984), as "Receiver Function". It has important relevance in determining of crustal thickness and bulk composition, from V_p/V_s ratio (Zandt and Ammon, 1995) and is widely applied due to its operational simplicity.

The fundament is based on teleseismic wave partitioning, i.e., when P wave incident upon discontinuities defined by seismic impedance contrast, part of the energy is transformed into P_s phase (S-wave converted phase) and multiples (Figure 2). The record of incident P-wave is predominant in vertical component, while S-wave arrivals (produced in P-wave conversion) is predominant in radial component.

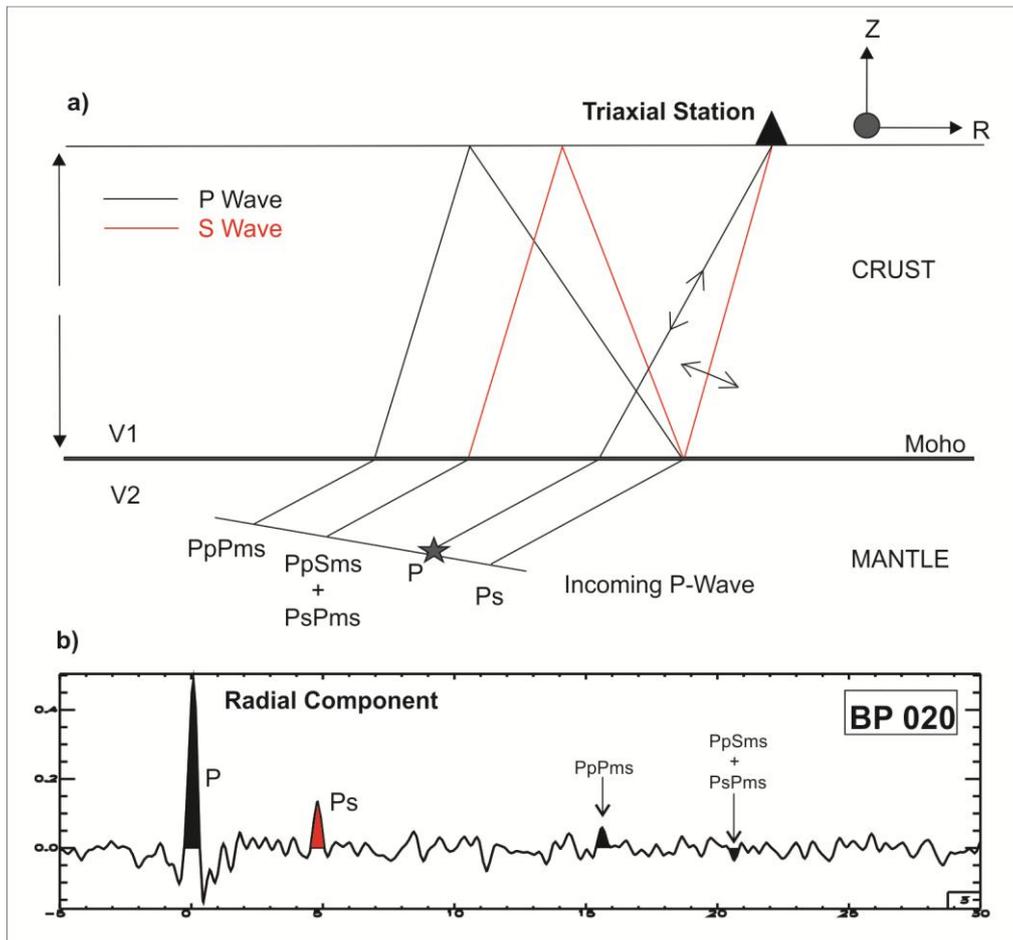


Figure 2: (a) Sketch for P energy partitioning when incident wavefront upon Mohorovicic discontinuity; (b) a stacked RF trace of the station BP020, deployed in the Amazonian Craton. Notice the income P, the converted S wave near 5 s (P_s) and the respective S multiples ($PpPms$, $PpSms+PsPms$).

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The dataset used for Receiver Function calculations derive from 40 short period three-component stations, evenly spaced with an average distance of 30 km between them (Table 1). The data were obtained in four different field campaigns: first, in September 2015, prior to the WARR experiment, which considered 29 stations; second, in July 2017 to reinstall previous stations that didn't record properly or had low signal/noise results and installation of 11 extra stations in inhospitable areas. Third and fourth campaign were used to make maintenance of installed stations until its final recovery, in December 2018, totalizing 40 sites effectively sampled.

The acquisition was performed by recorders RefTek DAS130 and sensor model Sercel L4-A 3D from Brazilian Pool of Equipment (PEG-BR). The stations worked in a continuous recording mode, with sampling rate of 100 samples per second, and 27 months of total estimated period for records, considering all campaigns.

For Receiver Functions estimates, we used teleseismic events with epicentral distances of 30° to 90° , magnitude higher than 5.5 Mb and the RTZ system of rotation. Considering all the campaigns, the computed receiver functions present a good source of events coverage, recording about 505 events, mainly from Andean zone, Atlantic-Pacific Meso Oceanic dorsal, Caribbean Plate and sparse occurrence from North America, Europe and East African Rift (Figure 3).

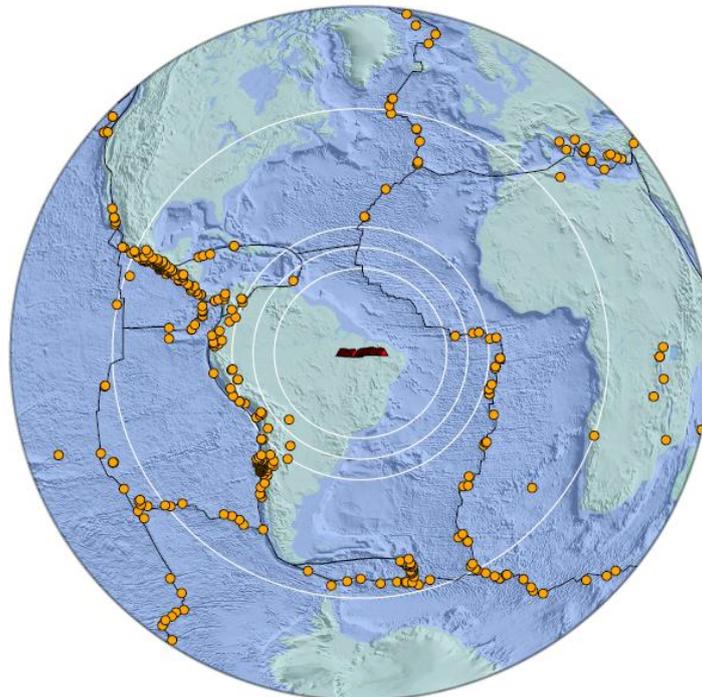


Figure 3: Global map showing the occurrence and coverage of the events used for the estimative of receiver functions in the Parnaíba Basin.

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Table 1: Resume of receiver function stations and events. The table summarize the geographic location and elevation of the seismic stations, distance of each station from the westernmost station, observed Ps arrival at Mohorovicic interface and the number of radial receiver functions used with Gaussian Filter $a = 4$.

Station	Latitude	Longitude	Elevation (m)	Distance (km)	Moho Ps (s)	Number of RF $a = 4$
BP 000	-5,51903	-50,20351	260	0,0	4,749	42
BP 010	-5,42512	-49,94781	200	028,570	4,669	111
BP 020	-5,44005	-49,67061	159	060,056	4,789	54
BP 030	-5,44102	-49,39870	160	090,090	4,898	13
BP 040	-5,42786	-49,07796	139	125,232	5,253	100
BP 050	-5,47653	-48,86055	146	148,660	5,430	93
BP 060	-5,53693	-48,57927	144	180,162	6,143	70
BP 070	-5,69813	-48,36077	175	205,068	5,817	92
BP 080	-5,73157	-48,10600	124	232,900	5,592	103
BP 090	-5,65297	-47,84593	229	262,211	6,258	13
BP 100	-5,55614	-47,58424	176	291,541	5,060	23
BP 110	-5,56494	-47,30866	173	322,309	5,237	21
BP 120	-5,59780	-47,03419	239	352,336	5,522	38
BP 130	-5,58506	-46,78689	237	379,443	5,474	52
BP 140	-5,68900	-46,47201	175	404,385	6,012	06
BP 141	-5,70043	-46,33450	159	430,761	5,842	06
BP 150	-5,75632	-46,04532	211	460,789	5,335	05
BP 160	-5,64585	-45,80336	238	487,546	5,502	37
BP 170	-5,45905	-45,46329	190	525,987	5,730	11
BP 171	-5,41478	-45,20704	177	554,550	5,820	31
BP 172	-5,36994	-44,91978	103	586,775	5,278	09
BP 173	-5,32479	-44,64743	121	616,812	5,350	21
BP 180	-5,29963	-44,39504	125	644,653	4,945	47
BP 190	-5,36015	-44,13615	182	673,337	4,867	42
BP 200	-5,27655	-44,13615	142	702,116	4,695	31
BP 210	-5,23745	-43,61212	157	730,889	4,734	48
BP 220	-5,19278	-43,33032	155	762,737	4,785	65
BP 230	-5,10947	-43,06687	198	791,133	4,972	04
BP 240	-5,15004	-42,83722	082	816,460	5,036	49
BP 250	-5,05624	-42,59166	153	842,938	4,755	25
BP 260	-5,12597	-42,39786	143	865,579	4,915	19
BP 270	-5,26398	-42,09840	225	898,963	5,218	25
BP 280	-5,29237	-41,89689	147	920,070	5,170	42
BP 290	-5,32641	-41,54291	249	959,208	4,923	55
BP 300	-5,33823	-41,28563	329	987,988	4,651	52
BP 310	-5,27260	-40,99248	602	1021,320	4,557	88
BP 320	-5,17623	-40,99248	298	1046,304	4,517	86
BP 330	-5,29115	-40,49734	325	1076,877	4,214	24
BP 340	-5,43164	-40,27947	338	1099,755	4,509	14
BP 350	-5,43617	-40,00283	548	1150,000	4,211	33

In order to remove source and instrument response and obtain the signature of secondary P to S conversion under the installed stations, we deconvolve the vertical component of teleseismic P coda from the corresponding radial component (Langston, 1979; Ammon, 1991) in the frequency domain to obtain the receiver functions. A factor a of Gaussian filter equal 4 (to eliminate frequencies higher than 2 Hz) and water level equal 0.001 were applied to stabilize deconvolution process.

The selected seismograms were cut 60 s before and 90 s after P arrival. For quality control and reliability of the dataset, a visual inspection procedure was

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performed in each radial component seismogram of the receiver function, summarizing 1694 radial component seismograms effectively stacked for the 40 stations.

To estimate the crustal thickness and average Vp/Vs, we performed the *HK-stacking* method (Zhu & Kanamori, 2000), which applies inversion algorithms by grid inspection in receiver function dataset and calculate estimative of the mean depth in function of Vp/Vs. The result is obtained from inputs of Vp and weights in Ps and respective multiples arrivals. Once parameterized the model, the method calculate H and Vp/Vs based on Zandt *et al.*, (1995) relations, which consider the difference time arrival of P, Ps and multiples.

The estimation of the uncertainty is made by the bootstrap method (Efron & Tibshirani, 1991), which computes the mean and standard deviation of uncertainties from an aleatory subset of receiver functions.

The advantages of the *HK-stacking* program is the capability to stack different receiver functions, combining big amount of waveforms, considering different epicentral and azimuthal distances and uncertainties estimative, for H and Vp/Vs.

Depending on frequency content of the wave and the proper geologic complexity, the *HK-stacking* response may be no unique, but showing a trend of H - Vp/Vs maximums that represent possible solutions for the dataset.

In order to reduce this kind of ambiguity, we calculated the *HK-stacking* using the mean Vp crustal velocity obtained from the WARR model (exactly from the position of the station) and choose the *HK-stacking* result which best match the crustal thickness (H) of the WARR model. This additional constraint ensures the calculated Vp/Vs is the most realist one. For example, the Figure 4 presents the receiver function results for the station BP130, the result of the *Hk-stacking* program, the stacked trace representative of the station and the distribution of the teleseismic events considered in the RF analysis. The stacked trace presents the P wave added to basement Ps (which in turn displace P arrival from zero) and successive sets of positive and negative multiples of the basin, giving a ringed aspect to the RF trace. The results for the other stations are displayed in the Appendix I.

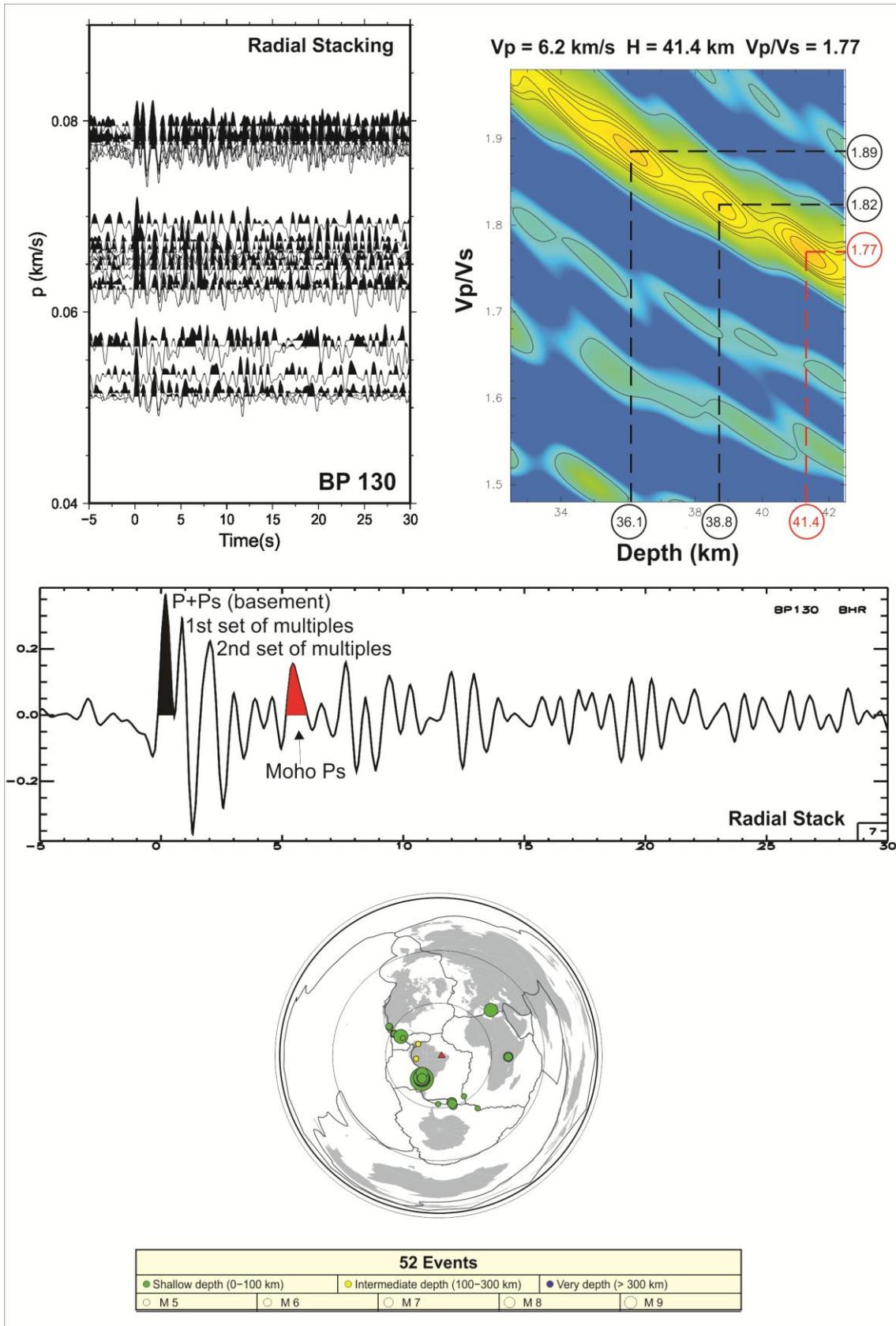


Figure 4: Example of hk-stacking result obtained for station BP-130, in Grajaú Domain. The data show the stacked radial components and multiple Ps peaks responses, due chaotic waveforms arrivals. In this case, the previous obtained WARR model, which marks 43.0 km in that offset, better fits with the diagramed H and Vp/Vs inside red circles, due principally to the waveform amplitude. The station registered 52 events, dispersed in different back azimuths.

Receiver Function Image and Results

The Receiver Function results cover four different tectonic domains (crustal blocks) under the profile and verify Moho's behavior is matching with the previous WARR data. The comparison between WARR and Receiver Function results show high correlation regarding to Moho geometry aspect.

The RF stacked traces, representative of each station, were plotted according the station position along the profile (Figure 5), forming in time a 2D image of the crust, highlighting the geometric form of the Parnaíba Basin, through the alignment of the second set of the multiples phases of the basin basement and the Moho discontinuity under the profile

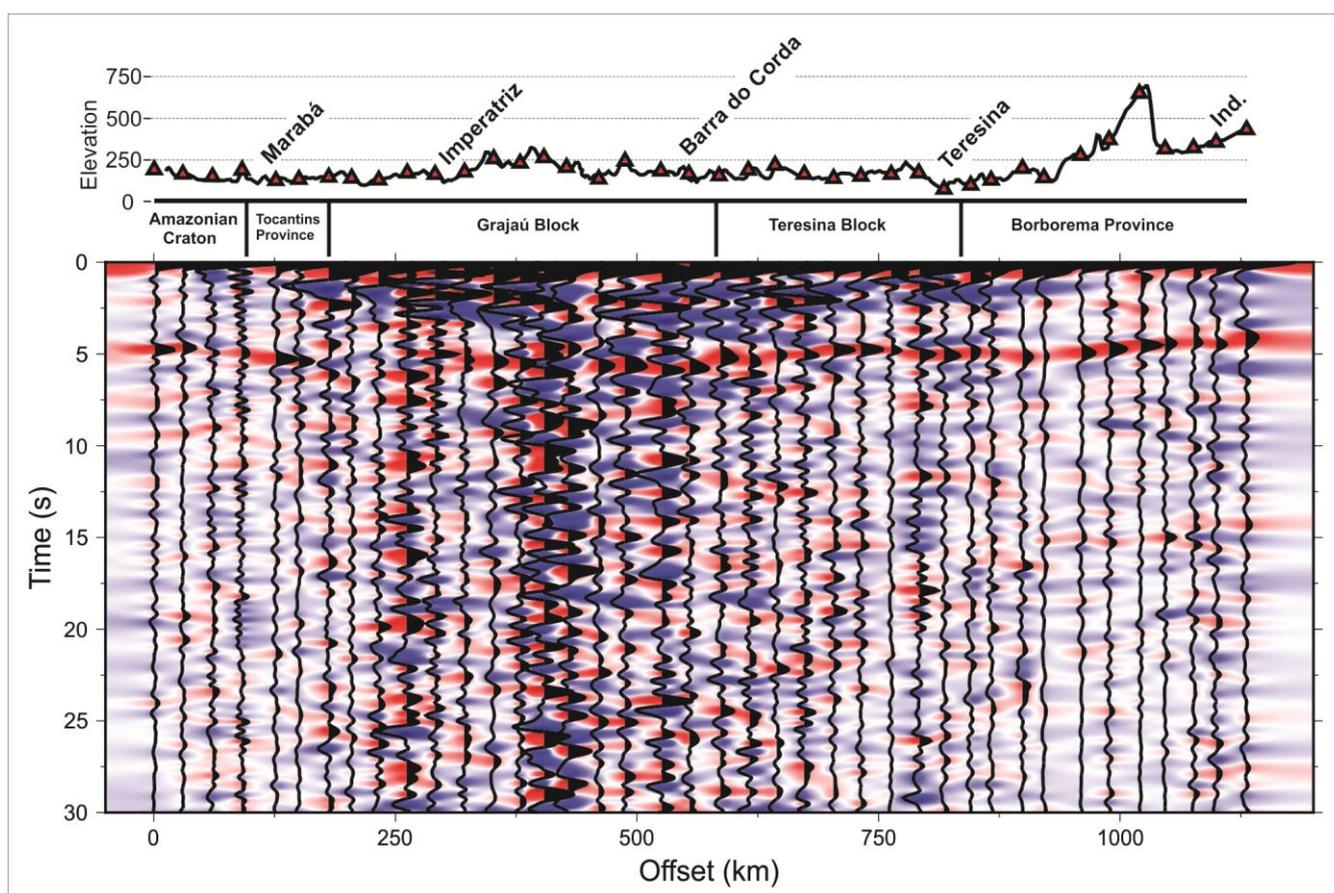


Figure 5: Stacked radial component of each station, summarizing 40 seismograms along 1.150 km. The data allow the mapping of mantle/lower crust interface (Moho) geometry and defines the characteristics of each tectonic site.

The FR section shows Moho Ps incomes around 5s with different signatures and time arrivals, varying its waveforms according to the related tectonic site. In general, the originated Ps conversion vary its amplitude from high (32 stations, $P_s > 25\%$ of P arrival

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amplitude) to moderate (08 stations, Ps between 10% and 25% of P amplitude arrival). The mean Ps/P amplitude registered in Amazonian Craton-Araguaia Belt domain is about 33.16%, while the Parnaíba Basin presents until offset of 600 km (Grajaú Block) a slightly higher mean Ps/P amplitude (37.7%) and from offset 600 to 950 (Teresina Block) mean Ps/P amplitude of 33%. At the easternmost region of the line, in the Borborema Province, the mean Ps/P amplitude rate decrease to 23%, representing the four different tectonic domains present along the profile.

In the Amazonian Craton the mean Ps arrivals register 4.735 s, which denotes crust thickness minor than 40 km, while the Tocantins Province-Amazonian Craton suture front show Ps peak until with 6.258 s, mapping a dipping Moho toward Parnaíba Basin and defining the crust thickness of approximately 50 km. It is the thickest crust along the profile and is interpreted as lower crust duplication.

The Parnaíba Basin itself presents a region of thick crust, with an average P to Ps Moho conversion around 5.0 s (Grajaú domain) while Teresina domain marks 4.45 s, diminishing its thickness gradually toward Borborema Province, where Ps arrival registers 4.2 s, corresponding to the thinner crust along the profile.

Important changes in RF traces due heterogeneities can be entailed (Figure 6). Similar time travel arrival of P and Ps from basin basement (or grabens) shift P arrival offset from 0, displaying interference waveforms (Figure 6 b), c), d) and e).

With respect to the basin domain, it's possible to state that the major stations with reverberating amplitudes are mostly related to Grajaú Block, which presents mafic intrusions, in basal portions of the crust. In this domain, the lower crust / mantle interface is a more transitional layer, where occurs an underplating (Soares *et al.*, (2018). According to Hazarika *et al.*, (2012), the presence of heterogeneities throughout the crust, like an underplating or low velocity zones provoked by an intracontinental basin would "spread" multiple Ps amplitudes, giving a diffuse aspect, compromising its arrivals recognition due multiples reverberation (Figure 6 c, d)

In Teresina Block, differently from Grajaú Block, the traces presents in general clearer Ps arrivals and respective multiples, considering that the region suffers less influence of magmatism than present in Gajaú Block. The clearer P and Ps peaks with well defined amplitudes and reverberated phases, otherwise, comes from Archaean/Proterozoic tectonic sites (Amazonian Craton / Tocantins Province / Borborema Province.

With respect to the basin domain, it's possible to state that the major stations

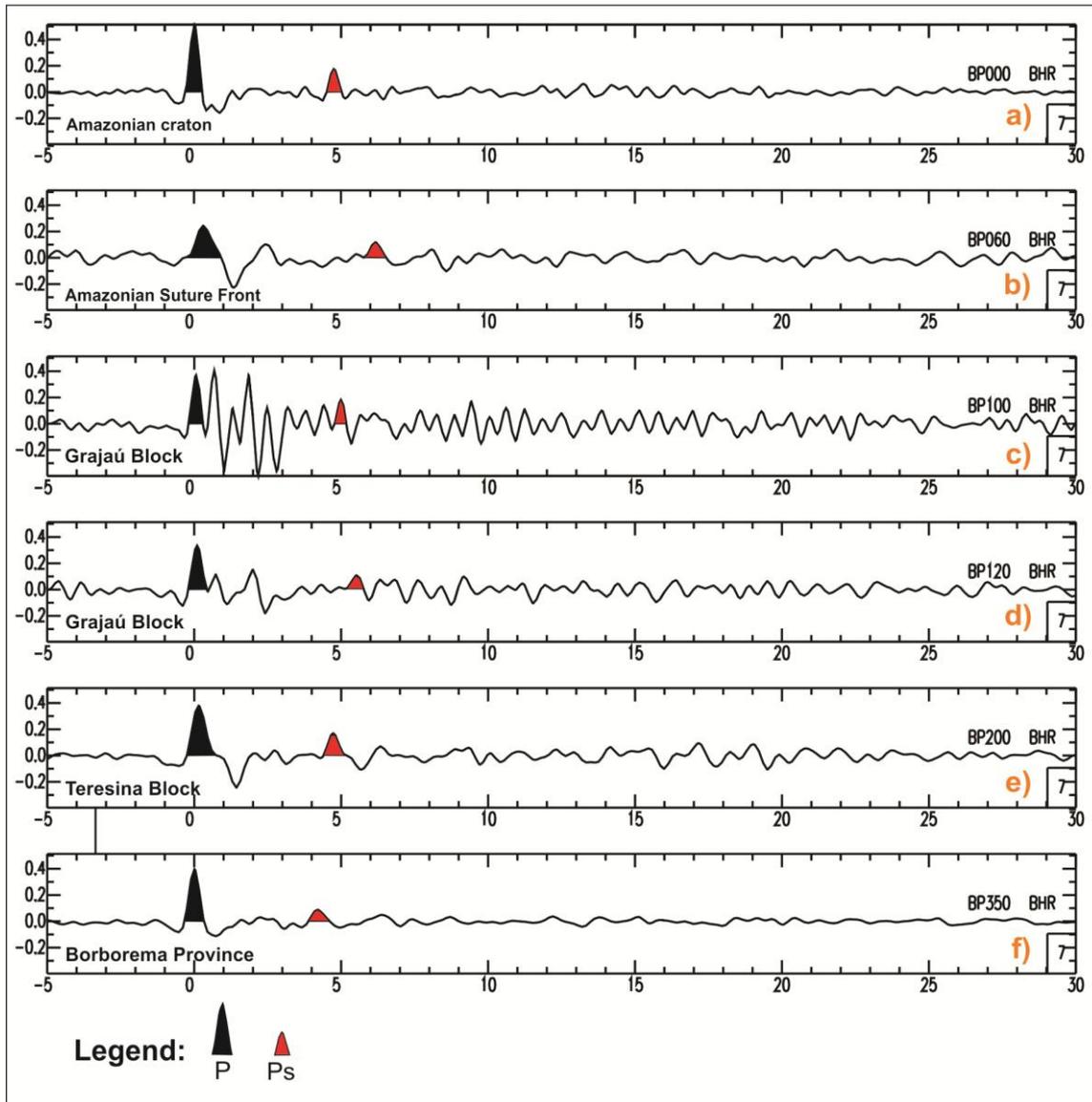


Figure 6: Stacked radial components individualized by similar ray parameter. The figure show in a) Amazonian Craton domain, displaying P arrival at 0 offset, with clear Ps and multiples arrivals; b) the Amazonian Suture Front, with 0 offset shift of P arrival, diffuse Ps and multiples; c) and d) Grajaú Block, showing 0 offset shift of P, reverberated signal and difficult Ps and multiples recognition; e) Teresina Block, with clearer Ps and multiples arrivals with respect to Grajaú block; f) Borborema Province moderate Ps/P ratio amplitude and Ps arrival with less than 5 s.

with reverberating amplitudes are mostly related to Grajaú Block, which presents mafic intrusions in basal portions and throughout the crust, besides a Cretaceous-Cenozoic sediments in surface. In this domain, the lower crust-mantle interface is more transitional where occurs an underplating (Soares *et al.*, 2018). According to Hazarika *et al.*, (2012), the presence of heterogeneities throughout the crust, like an underplating or low velocity zones provoked by an intracontinental basin would "spread" multiple Ps amplitudes, giving a diffuse aspect, compromising its arrivals recognition due multiples reverberation (Figure 6 c, d).

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In Teresina Block, differently from Grajaú Block, the traces present clearer Ps arrivals and respective multiples, considering that the region suffers less influence of magmatism and the soft Cenozoic sediments than present in Gajaú Block. The clearer P and Ps peaks with well defined amplitudes and reverberated phases, otherwise, comes from the domains outside the basin, Amazonian Craton-Tocantins Province and Borborema Province.

With respect to the qualitative analysis, we performed *H-K Stacking* to obtain H and Vp/Vs estimative. For this propose, we plotted the variation of Vp/Vs versus distance in a profile (Fig. 7), gridding Vp/Vs floating along the profile using VMED module of RAYINV package (Zelt & Smith, 1992), considering no vertical gradient. The image presents WARR results together with FR results and the topography variation with the station position throughout the profile. The result expresses the Vp/Vs changes punctually, which are traduced by sharp contrasts between calculated values of the stations.

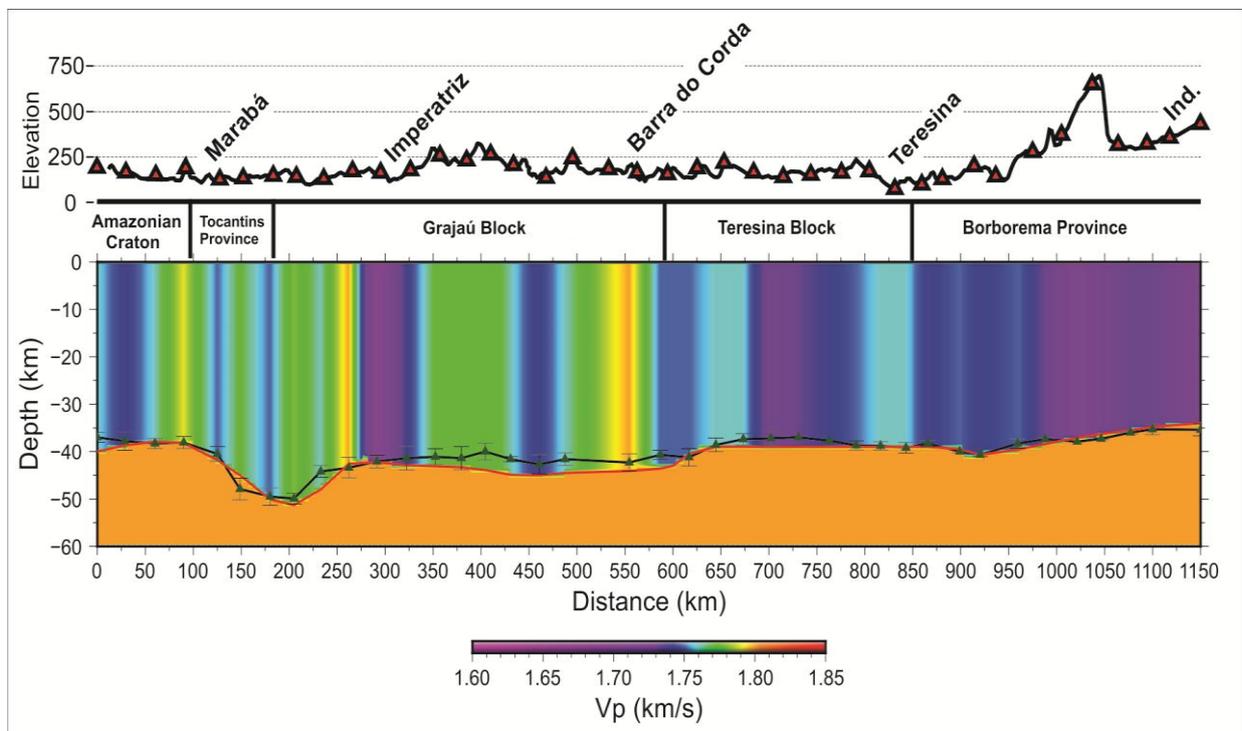


Figure 7: Vp/Vs profile (black line) along Parnaíba Basin, showing its variation in comparison with WARR data (red line delimiting WARR Moho geometry) and geologic province. The data presents quite similar Vp/Vs values in Amazonian Craton and Grajaú domain, and a slightly decrease between Amazonian Craton and Tocantins Province. Note that Grajaú and Teresina domains are marked, respectively, by a shift of mean Vp/Vs from 1.76 to 1.74, while the transition of Parnaíba Basin to Borborema Province show a sharper contrast, from mean Vp/Vs of 1.73 to 1.71. Notice that the higher incertitude values are associated to Grajaú domain, where occur intense magmatism and Cenozoic sediments.

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It's possible to distinguish the four different domains, with respect to the calculated mean V_p/V_s by hk-stacking method. The first 200 km of the profile show the Amazonian Craton and the transition with the Parnaíba Basin basement. The crust is less than 40 km thick in the Amazonian Craton with mean V_p/V_s of 1.76. At this domain, the data has clear Ps and multiples, suggesting an abrupt Moho transition. As consequence, the hk-stacking estimative presents good negative correlation (higher than -99%).

At the Amazonian suture front, the crust thickens sharply to 50 km at the suture front, with mean V_p/V_s of 1.71. (Figure 7). In the Parnaíba Basin, until offset 616 km, the crust presents approximately 40-41 km thick, with V_p/V_s around 1.76. At the surface this segment is closely related to the Cretaceous depositional sequences of the Grajaú sub-basin.

East of it, the crust thins abruptly to 37 km with V_p/V_s of 1.74, and thickens to 42 km close to the eastern limit of the basin. At the surface, this domain is associated with the older sediments of the basin. From this point, the crust thins, reaching 33 km at the easternmost station, with mean V_p/V_s of 1.71, at Borborema Province. The figure 8 illustrate representative stations used as reference for the tectonics' sites analysis.

DISCUSSION

The comprehension of the crustal structure and geophysical proprieties of the Parnaíba Basin has been exhaustively explored during the last years. Vast regional geophysical surveys have been performed, improving the discrimination of the basin basement architecture and compartmentalization.

The Receiver Function results characterized geological provinces described along the Parnaíba Basin profile (Daly *et al.*, 2014; Soares *et al.*, 2018), as well as corroborate the results obtained by potential methods, carried out by Nunes, (1992) and Castro *et al.*, (2014), which proposed a compartmentalization of the Parnaíba Basin. The appending of RF data acknowledge the existence of different blocks within Parnaíba Basin, as expected.

The Amazonian Craton show V_p/V_s varying from 1.74 to 1.79. The results matches that one's calculated by Trindade, (2019), which mapped the northern region of Amazonian Craton / Tocantins Province, obtaining mean V_p/V_s around 1.78 and crustal thickness lower than 40 km.

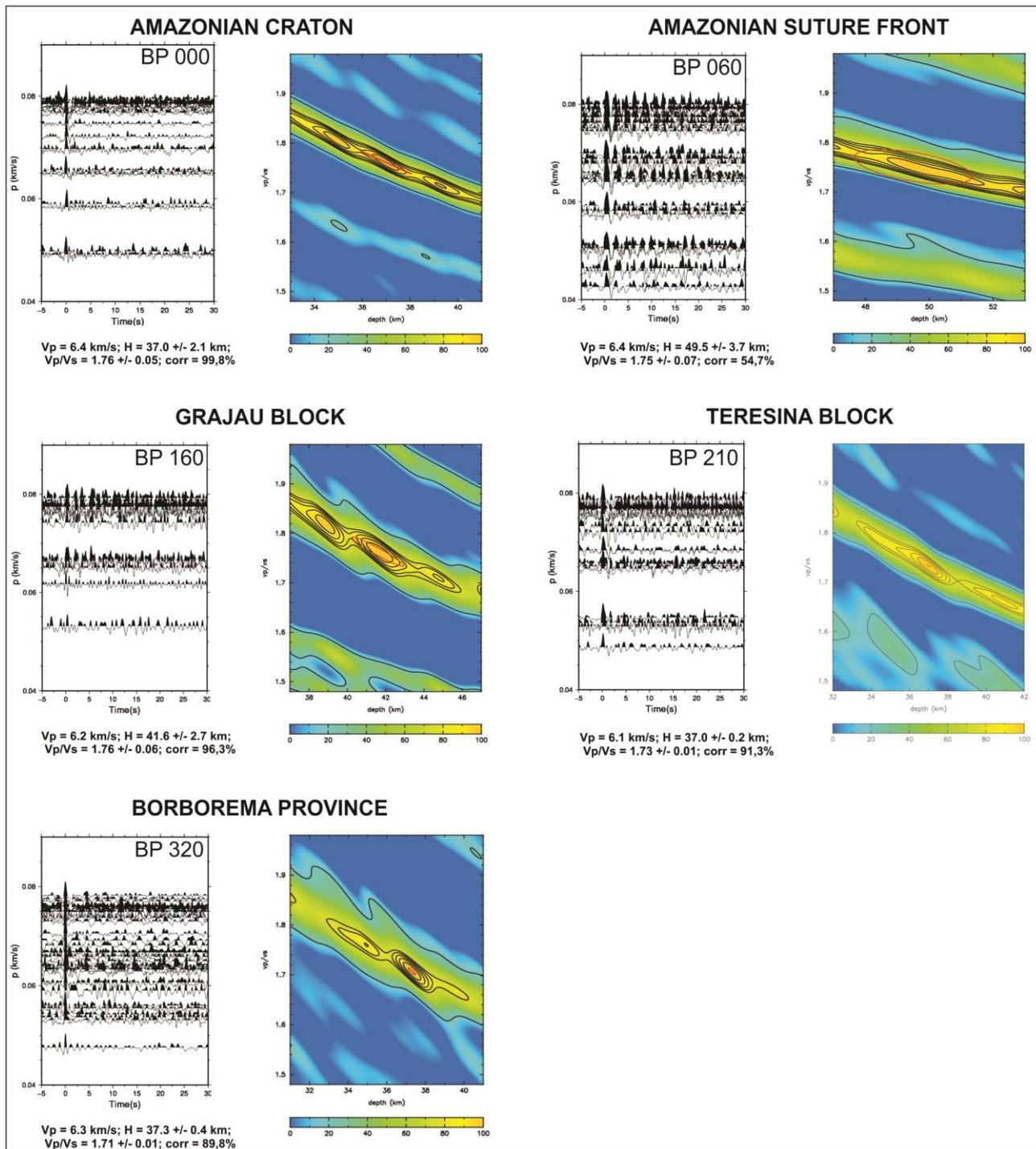


Figure 8: Tectonic domains and principal results obtained with radial component performed in HK-stacking. Note the variation between depth and V_p/V_s along tectonic provinces and the good negative correlation, except for the Amazonian Suture Front, which presents correlation of - 54 %, due tectonic instability related to its geological setting (i.e. subduction zone of Araguaia Belt / Amazonian Craton), besides the proper limitation of the method to resolve tilt interfaces.

The Tocantins Province presents a V_p/V_s decrease in comparison with the Amazonian Craton, with mean V_p/V_s of 1.73. This area is related to the metasediments of the Tocantins Province (Araguaia Belt), which is correlated to the subduction zone of Amazonian Craton with Araguaia Belt.

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At the Parnaíba Basin, the Vp/Vs defines two domains - Grajaú and Teresina Blocks - which reflects different proprieties in the Vp/Vs ratio and waveform. Evidences of presence of intense magmatism spread throughout the crust in Grajaú Block, combined with an underplating, traduce the high Vp/Vs estimative along the profile, reaching values around 1.8 in located stations. The incertitude in this region (Figure 7) is the higher of the whole profile, due presence of magmatism, which disturbs the ray path of Ps arrivals and multiples, and gives a diffuse aspect to the Ps, originating a series of reverberated arrivals that difficult hk-stacking solutions (Figure 6 c) and d).

The Teresina Block, otherwise, presents in general Vp/Vs values lower than the Grajaú domain, varying from 1.70 to 1.76. This portion of the profile is related to Silurian sediments of the basin, which has less influence with respect to significant magmatism piles, as observed in Grajaú Block. The Ps arrivals and multiples are clearer, and differently from Grajaú Block, shows an abrupt lower crust / mantle interface. The Borborema Province presents the lower Vp/Vs results, contrasting to the rest of the profile, varying the results from 1.70 to 1.73. The P, Ps and multiples arrivals show, in general, clearer phases and peaks with less interference of low velocity layers (e.g. Parnaíba Basin), enhancing its recognition consequently (Figure 6 f).

The integration of Receiver Function with WARR model and DSR results allowed a refined interpretation of the basin tectonic context (Figure 9). The image is correlated to the proposed models, adapted to same horizontal and vertical scale, casting RF and WARR data.

The RF section image (Figure 9 c), which refers to the 1 D migrated section of radial stacking, presents an overall view of the nature of traces along the profile. It's possible to check the variation of quality of the traces in function of the tectonic site. The Amazonian Craton, Tocantins and Borborema Provinces show good signal/noise ratio and a less stratified crust, whilst the Parnaíba Basin, specifically Grajaú Block, shows a more stratified crust (reddish/positive peaks), passive of intense reverberation that disturbs de seismic energy, producing high background noises and giving a "ringing" aspect to the traces in that region. This issue is probably related to Cenozoic deposits and intense magmatism that occur in that region, quite notable from offset 200 km to 600 km and in WARR data (Soares *et al.*, 2018).

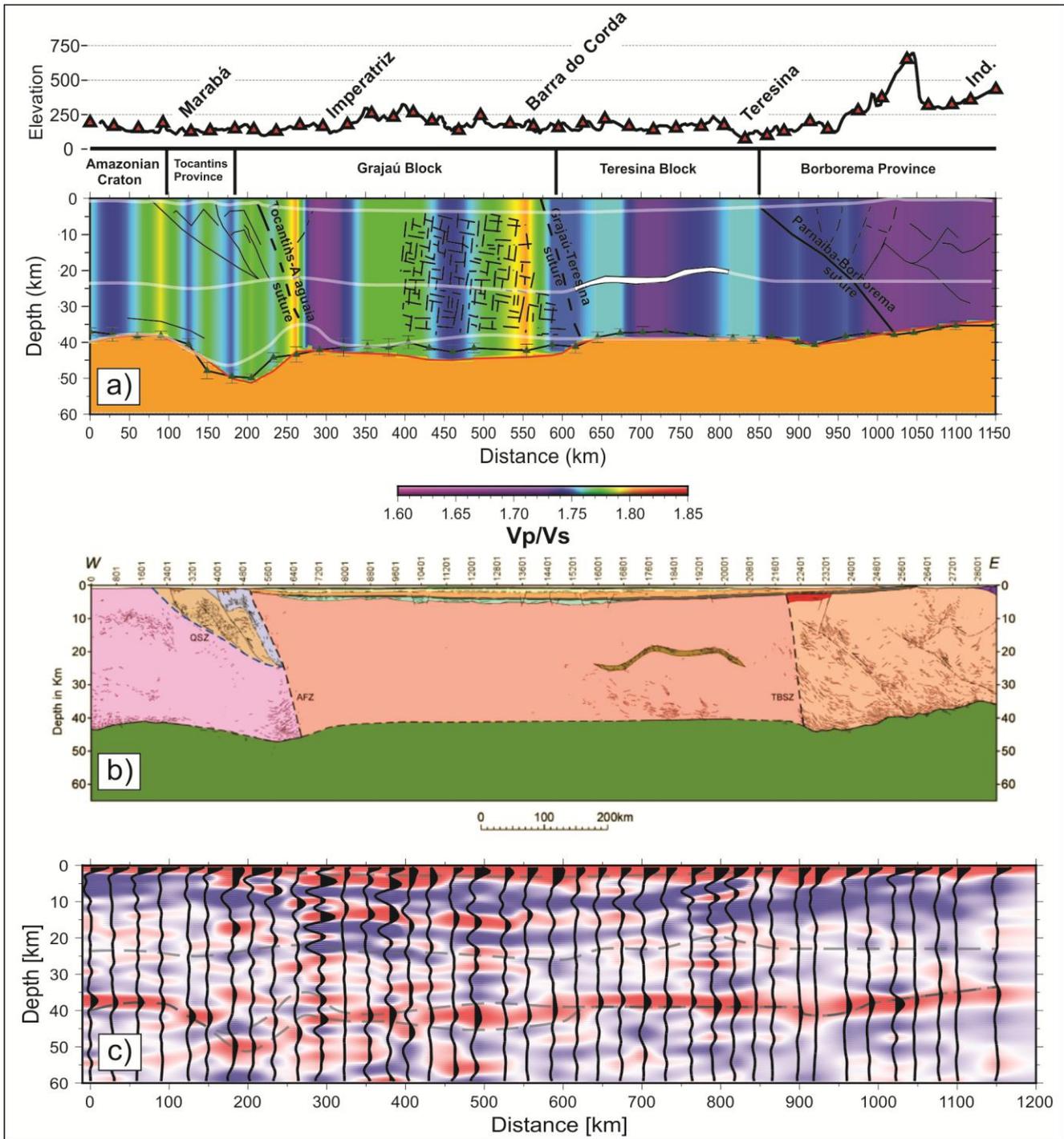


Figure 9: Comparison and integration of geophysical surveys performed along the Parnaíba Basin. The data were adjusted to same horizontal and vertical scales, showing in a) Vp/Vs model integrated with P WARR model, WARR's Moho and Receiver Function thickness; b) DSR profile performed by Daly *et al.*, (2014); and c) Section of migrated Receiver Function radial stacking integrated to P WARR model.

Some local geological features were also checked by the RF image. In the shallow portion, the RF identified important geological structures related to the basin's outline. Multiple phases, observed from offsets of 190 km to 850 km (reddish/positive peaks), at depth of approximately 15 km (Figure 9 c) denote the sub-basins' contour, expressed in deep, coincident to the superficial basin limits. Another important feature

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recognized is the Jaibaras Through, apparently controlled by the Transbrasiliiano Lineament, which represent the scar of the Neoproterozoic convergence that led to formation of Gondwana (Shobbenhaus Filho, 1978). The rift is observed between offsets of 850 km and 950 km (reddish/ positive peaks), indicated by multiples phases occurring at 6 km deep (Figure 9 c).

The RF deep portion reflects the Amazonian Suture Front scenario, indicated by Ps arrivals, composing a dipping layer toward metasediments of Araguaia Belt, confirming the SLAB proposed Soares *et al.*, (2018), observable from offsets 0 and 200 km. The underplating, considered to be related to the basin's depocenter shift (Soares *et al.*, 2018) in Cretaceous is very well constrained, proving its existence and extents, as observed in figures 9 a) and c). The Moho interface is well matched by DSR, WARR and FR results, which presents positive correlation and very close limits. The Grajaú Block show the thicker crust along the Parnaíba Basin, reaching 42 - 43 km deep, contrasting with the Teresina Block, which denotes a Moho uplift with flat interface geometry (Figure 9 c).

The qualitative analysis (Figure 9 a), provided from hk-stacking results confirms the statements appointed by Nunes, (1992), who first determined different geotectonic provinces in the Parnaíba Basin, including a subdivision of the basin in "eastern" (Teresina) and "western" (Grajaú) provinces, besides others. Castro *et al.*, (2014) refined the compartmentalization, proposing the existence of 3 major basin basement compartmentalization (North Parnaíba, South Parnaíba and Teresina) plus surrounding folded belts and cratonic fragments.

The RF data show that Parnaíba Basin basement indeed comprises these different principal domains appointed by sharp Vp/Vs changes along the profile. The interpretation performed by Soares *et al.*, (2018), principally those related to tectonic limits, also fits the Vp/Vs profile estimative (Figure 9 a). Moreover, the 1 D migration, performed using Vp grid from WARR model expresses the reliability of the proposed interpretation, since the principal limits and structures of the image fits with WARR and DSR data (Figure 9 c).

FINAL REMARKS

The Parnaíba Basin, developed primordially during the transition of

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Neoproterozoic to Eopaleozoic, represent an important geological site that accommodated compressive and extensive efforts suffered due tectonic evolution, culminating in a complex terrane with intricate geological diversification.

Deep regional geophysical surveys have been used to constrain the principal framework and physical properties of the Parnaíba Basin and its Pre-Cambrian complex basement. The execution of several geophysical methods have shown primordial for the comprehension and understanding of the key features related to the geological evolution.

We have deployed 40 short period three-component stations, evenly spaced through the Parnaíba Basin and its surrounding geological units. The receiver function results could corroborate previous geophysical knowledge, like regional suture characteristics and tectonic limits, improving the basin's compartmentalization, formerly constrained essentially by potential methods.

The geophysical models are consistent with geological and geochronological evidence of a typical collisional margin (Pimentel and Fuck, 1992), where the Araguaia Fold Belt overlapped the eastern boundary of the subducted Amazonian Craton (D'el-Rey Silva et al., 2011). The RF Moho geometry confirms WARR data, and the Vp/Vs changes, fitted with WARR and DSR interpretation endorse the existence of different blocks along the Parnaíba Basin basement, amalgamated during the consolidation of West Gondwana.

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CAPÍTULO 4

4. ONDAS S

Este capítulo apresenta os dados da modelagem obtidos com a análise das ondas cisalhantes S (ou ondas secundárias), originadas com o experimento de refração sísmica ao longo da Bacia do Parnaíba.

O entendimento do campo de velocidade das ondas S é muito importante para estudos relacionados a evolução litosférica. A modelagem dos dados do campo de velocidade de ondas P combinado com ondas S possibilita a composição dos valores de V_p e V_s das camadas, para verificação do comportamento da V_p/V_s ao longo do perfil. A razão ressalta mudanças de padrões composicionais do meio, que não são sensíveis ao campo de velocidades P ou S separadamente (Musacchio *et al.*, 1997; Zandt & Ammon, 1995).

A V_p/V_s é uma medida adimensional, que além da sensibilidade ao conteúdo de sílica, mostra também resposta à anisotropia ou pressão de poro/fluido. A determinação dos padrões de V_p/V_s podem refletir a anisotropia do meio, traduzidos por mudanças na velocidade S em função da trajetória do raio sísmico e ângulo de incidência com estrutura anisotrópica (*i.e.* foliação mineral) ou mudanças composicionais em profundidade.

Na determinação de fluidos ou influência de pressão de poro, as ondas S apresentam atenuação maior que as ondas P, o que resulta em maiores valores de V_p/V_s , considerando-se baixa V_p (Christensen, 1996; Musacchio *et al.*, 1997). Holbrook *et al.*, (1992) determinaram os padrões de V_p/V_s quanto à classificação composicional, obtendo valores médios de 1.71 para rochas félsicas e 1.84 para rochas máficas.

A seguir é descrito o banco de dados de ondas S, os sismogramas utilizados, os critérios e procedimentos adotados para modelagem e obtenção dos valores de V_p/V_s .

4.1- Banco de Dados

O banco de dados, oriundo do projeto PABIP, foi adquirido com 600 estações verticais compostas pelo registrador RefTek Texan 125_A e o sensor Sercel L4A-3D, de 2 Hz (0,5 s). O

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registrador funcionou em modo contínuo, com taxa de amostragem de 100 SPS (*samples per second*). Devido à qualidade dos sismogramas, dos 24 tiros, apenas os tiros 3, 5, 8 e 23 não foram apresentados. O tiro 22 apresenta apenas dados nas fases profundas, por contas de questões operacionais de campo.

Os sismogramas apresentam diferença na qualidade, com relação à razão sinal/ruído, em função do sítio tectônico. Os tiros fora da bacia apresentam menores incertezas na etapa de *picking* e menores padrões de erro RMS, tendo em vista menos fatores atenuantes da energia da onda sísmica. No interior da bacia, os tiros sofrem influência das camadas sedimentares e do magmatismo, os quais perturbam o retorno das ondas sísmicas aos sensores e comprometem a identificação das fases das formas de onda.

A identificação das fases apresentam de forma geral alinhamentos claros, exceto em regiões intensamente afetadas pelo magmatismo do Bloco Grajaú (*e.g.* tiros 10 e 11; Fig. 1), onde é difícil a identificação de alinhamentos significativos.

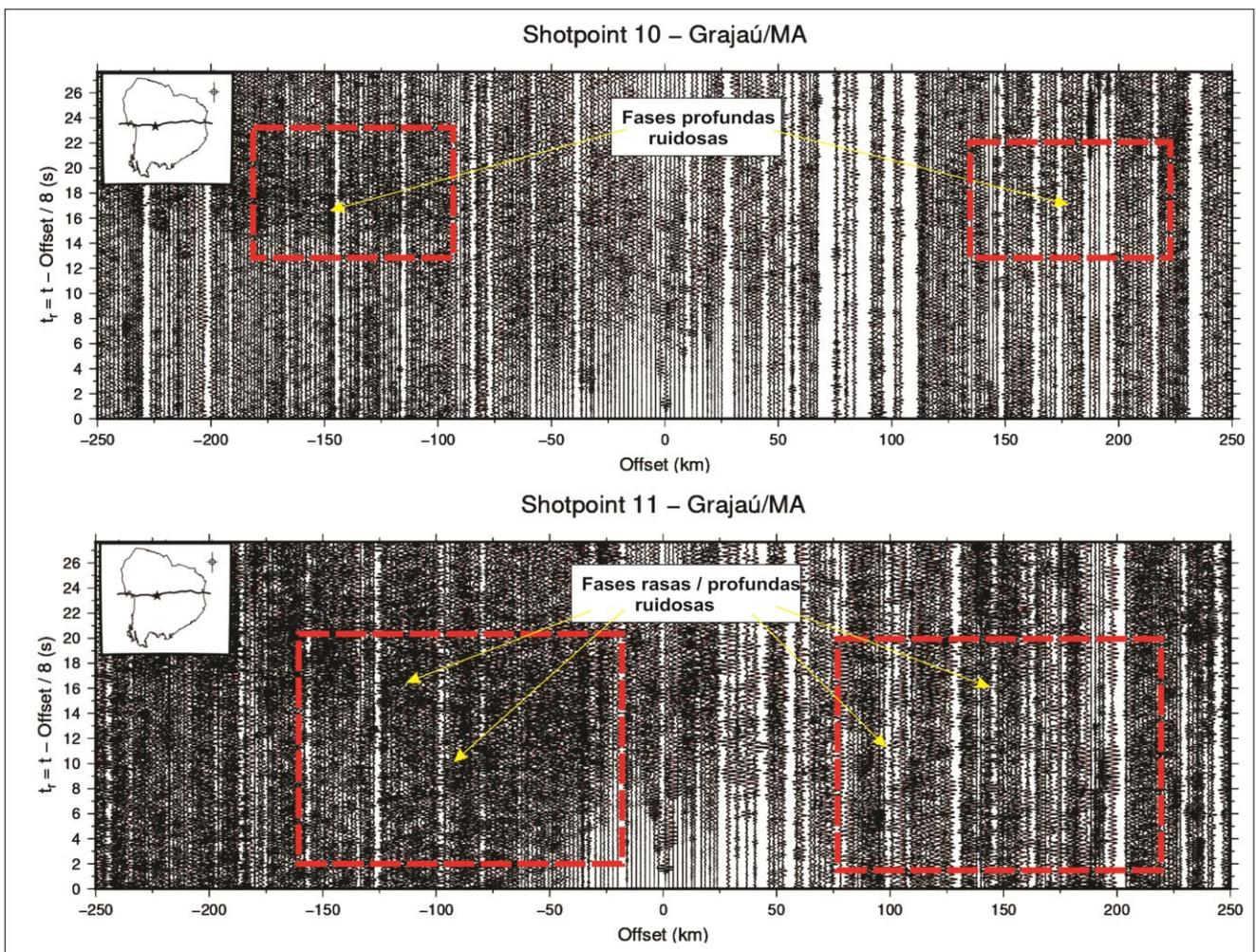


Figura 1: Sismogramas ruidosos obtidos com o experimento da Bacia do Parnaíba. Notar difícil reconhecimento de fases, tendo em vista a presença de intenso magmatismo recorrente no Bloco Grajaú. No sismograma 10, percebe-se que a ausência de fases alinhadas é intrínseca às fases profundas, uma vez que no tiro 11 é difícil o reconhecimento de fases tanto em regiões rasa quanto profundas.

4.2- Processamento dos Dados

O processamento dos dados foi realizado com a mesma rotina utilizada nas ondas P (Capítulo 1, item 1.4.1.3). Para melhor visualização e auxílio na identificação das fases, foram gerados os 20 sismogramas de ondas S com velocidade de redução de 4.62 km/s e janela de tempo de 27.68 s, considerando-se razão V_p/V_s de 1.73. Para etapa de filtragem, foram aplicados filtros de banda de 2 - 6 Hz.

Uma vez obtidas as seções dos sismogramas e reconhecidos os principais alinhamentos de fases, procedeu-se com a leitura (*picking*; Fig. 2) para inversão dos dados no programa TOMO-2D e posterior modelagem de ondas S. As principais fases utilizadas foram as refrações da bacia (*Ssed*), quando existentes, refrações da crosta superior (*Sg*), crosta inferior (*Si*) e reflexões da interface crosta inferior / manto (*SmS*). As figuras 3, 4, 5, 6 e 7 mostram os sismogramas de ondas S dos 20 tiros utilizados.

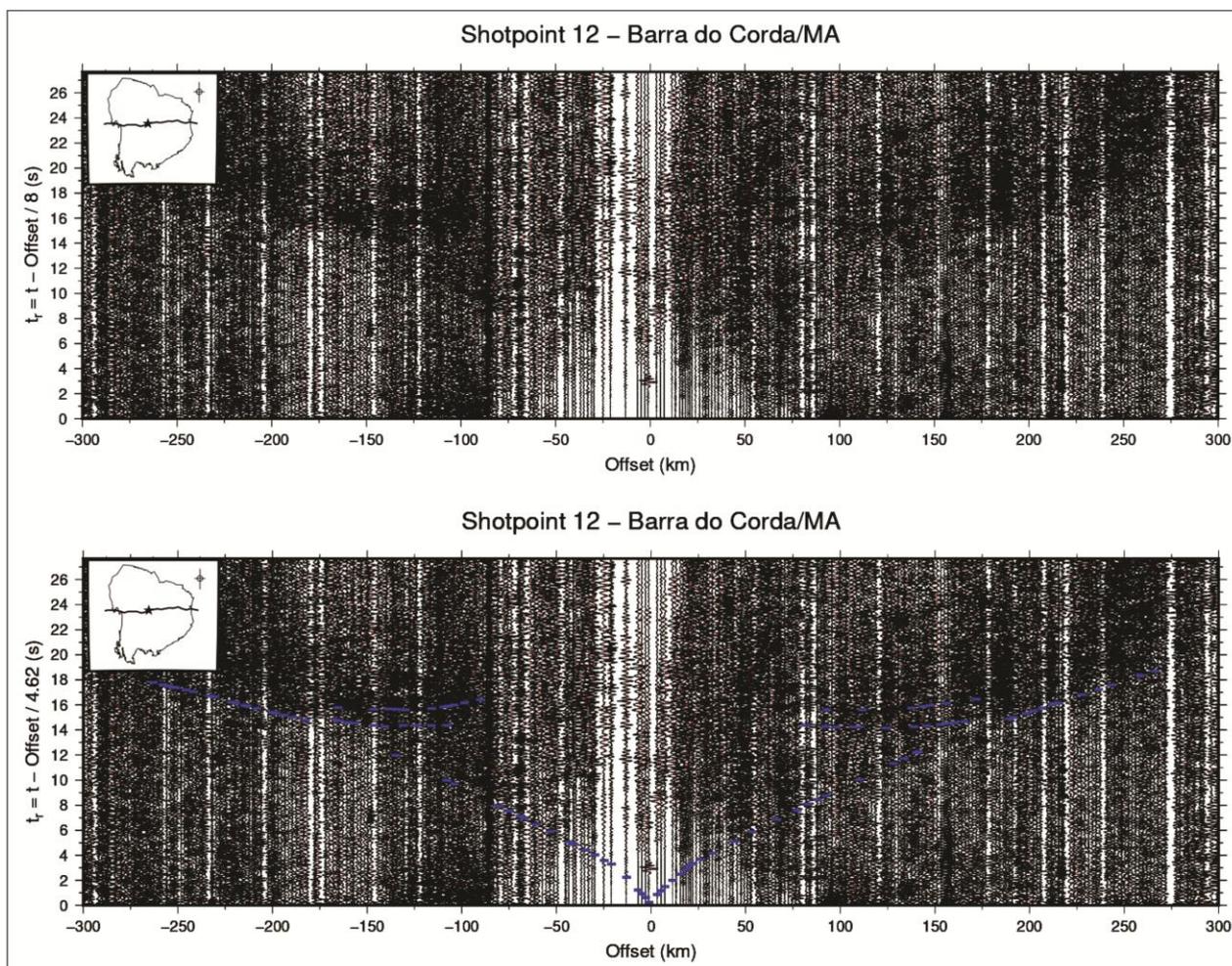


Figura 2: Exemplo de sismograma utilizado para realizar a leitura as fases. As fases de refração (*Ssed*, *Sg* e *Si*) e reflexão (*SmS*) são expressas no painel inferior, com pontilhados de cor azul. A leitura das fases S permite a inversão dos dados no programa TOMO-2D, para obtenção da primeira aproximação dos campos de velocidade de ondas S.

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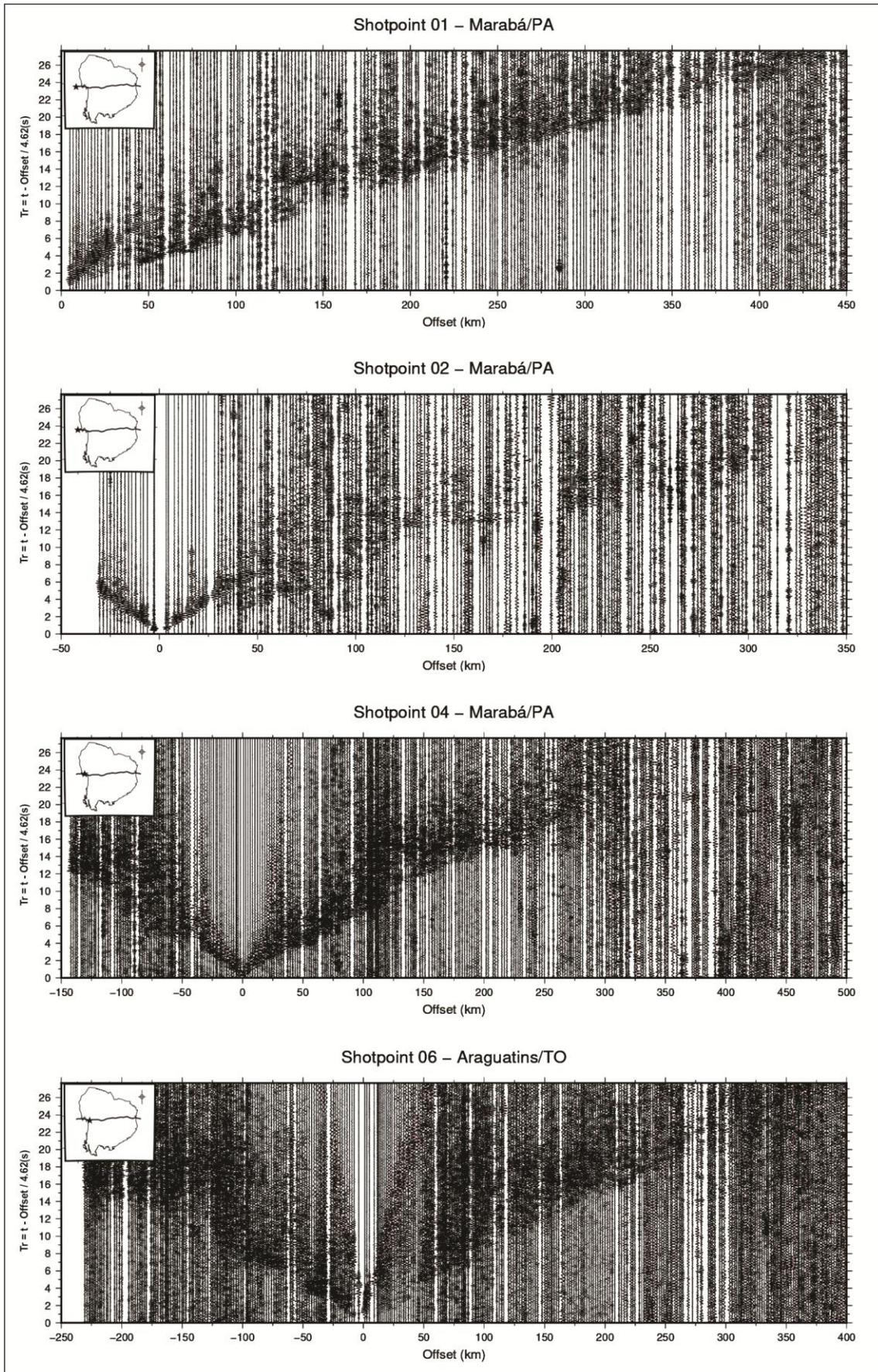


Figura 3: Sismogramas de ondas S dos tiros 1, 2, 4 e 6.

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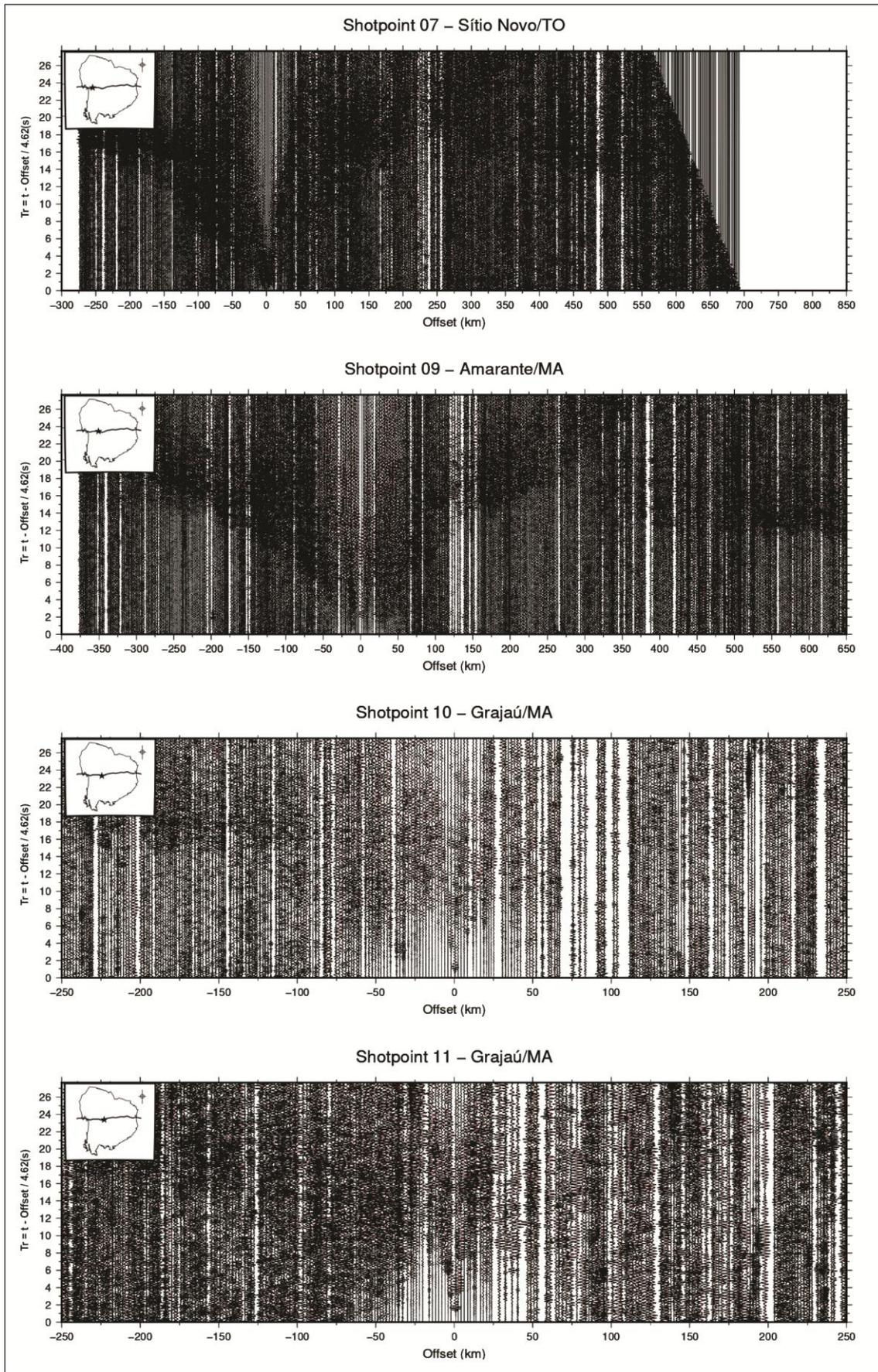


Figura 4: Sismogramas de ondas S dos tiros 7, 9, 10 e 11.

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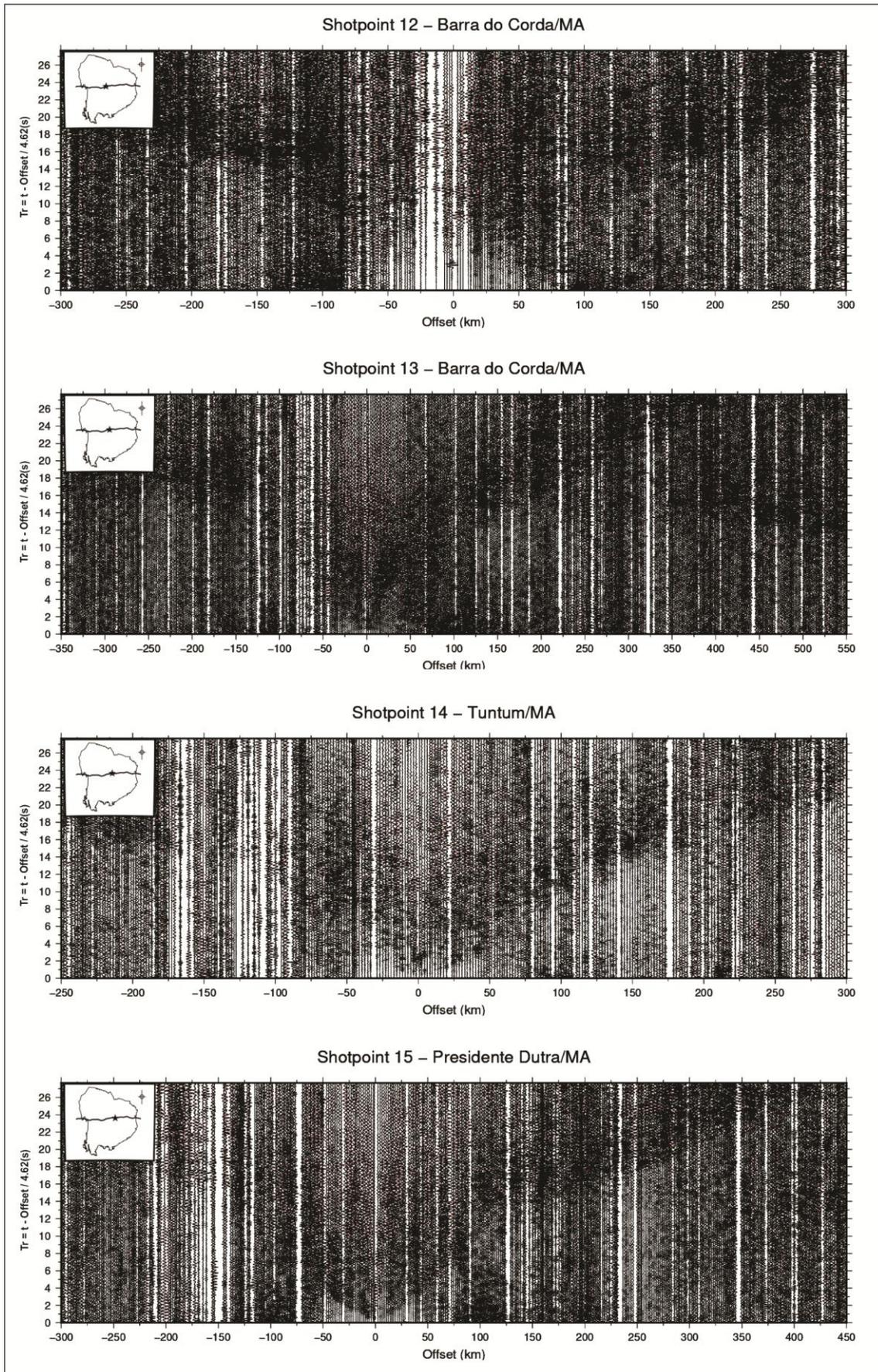


Figura 5: Sismogramas de ondas S dos tiros 12, 13, 14 e 15.

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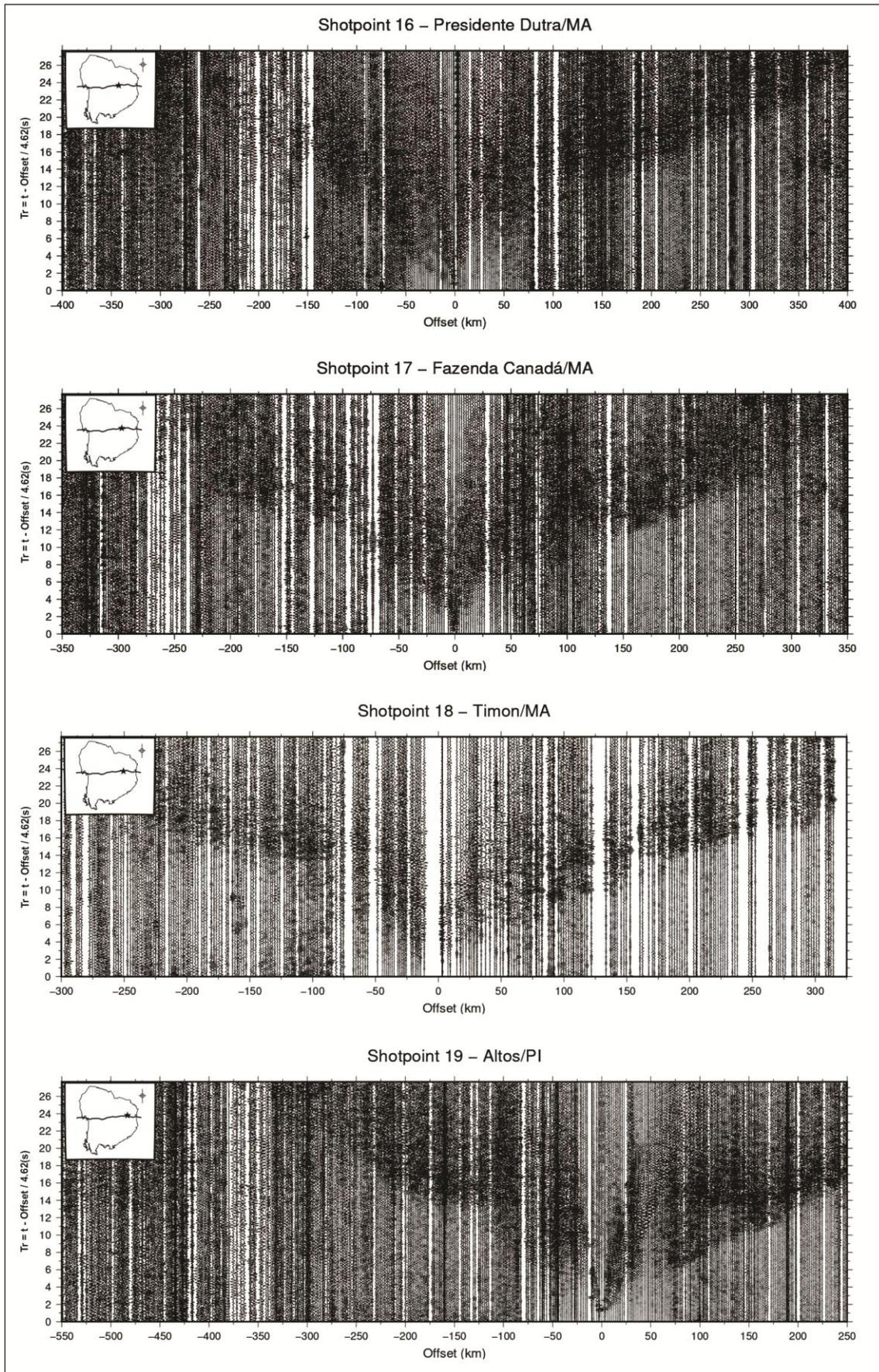


Figura 6: Sismogramas de ondas S dos tiros 16, 17, 18 e 19.

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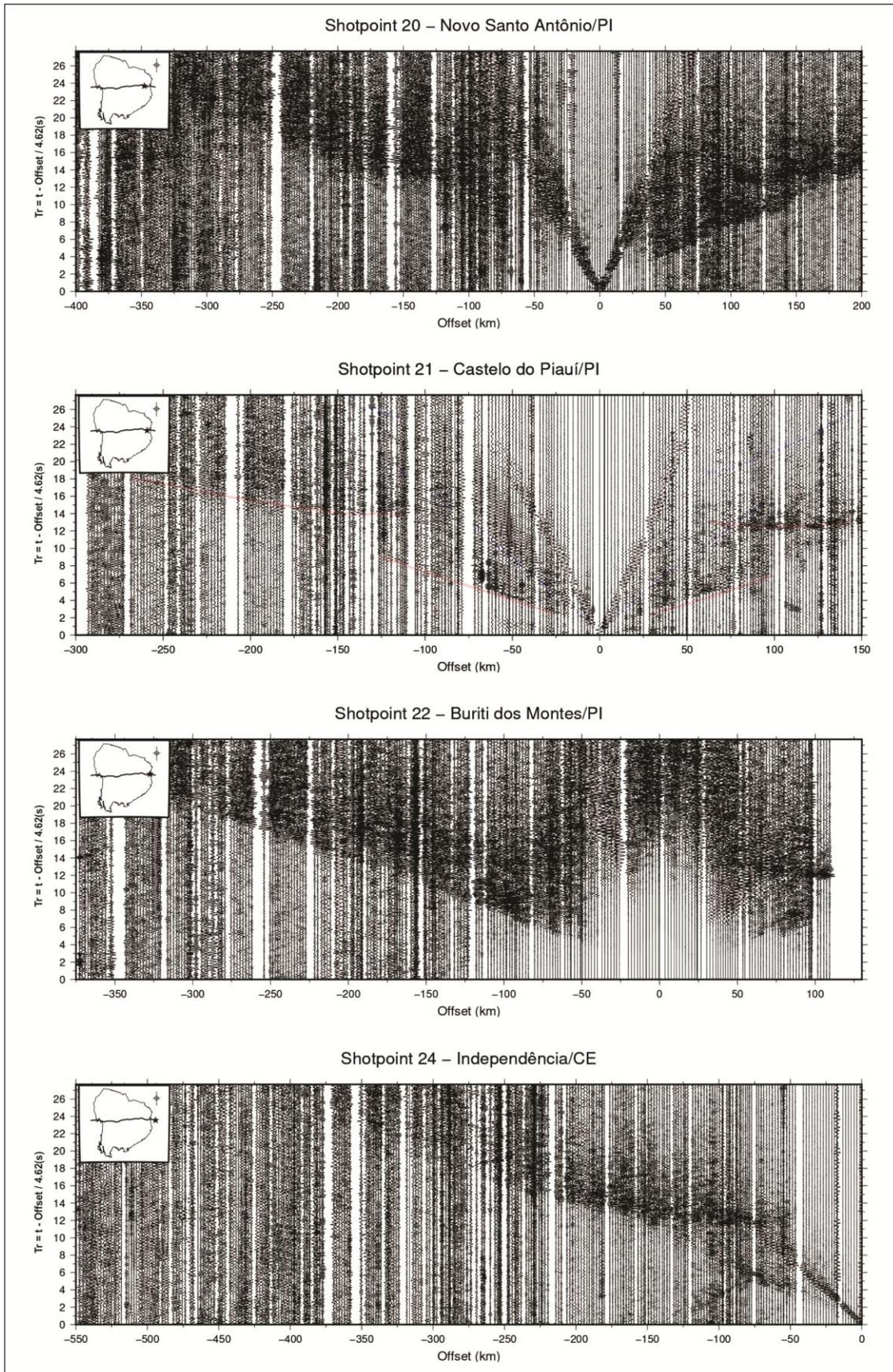


Figura 7: Sismogramas de ondas S dos tiros 20, 21, 22 e 24.

4.3- Tomografia 2D

A inversão dos dados por tomografia 2D foi realizada para obtenção da primeira aproximação do modelo de velocidade, por meio das primeiras quebras (*first breakes*) e reflexões do manto (SmS). Foi utilizado o programa TOMO-2D (Korenaga *et al.*, 2000), que utiliza um modelo inicial pré definido e informações do tempo de trânsito das fases refratadas e refletidas. O algoritmo realiza inversão para obtenção do modelo de velocidade e profundidade, amarrado a um refletor flutuante.

O modelo foi parametrizado por meio do modelo de refração em formato ASCII (*v.in*), utilizando-se uma malha com espaçamento variável entre a horizontal e a vertical (*i.e.* 0 - 500 m horizontal / 0 - 100 m vertical), valendo-se das leituras de fases refratadas e refletidas obtidas dos sismogramas (*tx.in*). Para rodar o programa, foi definido peso 1 e 5 iterações (Figura 8).

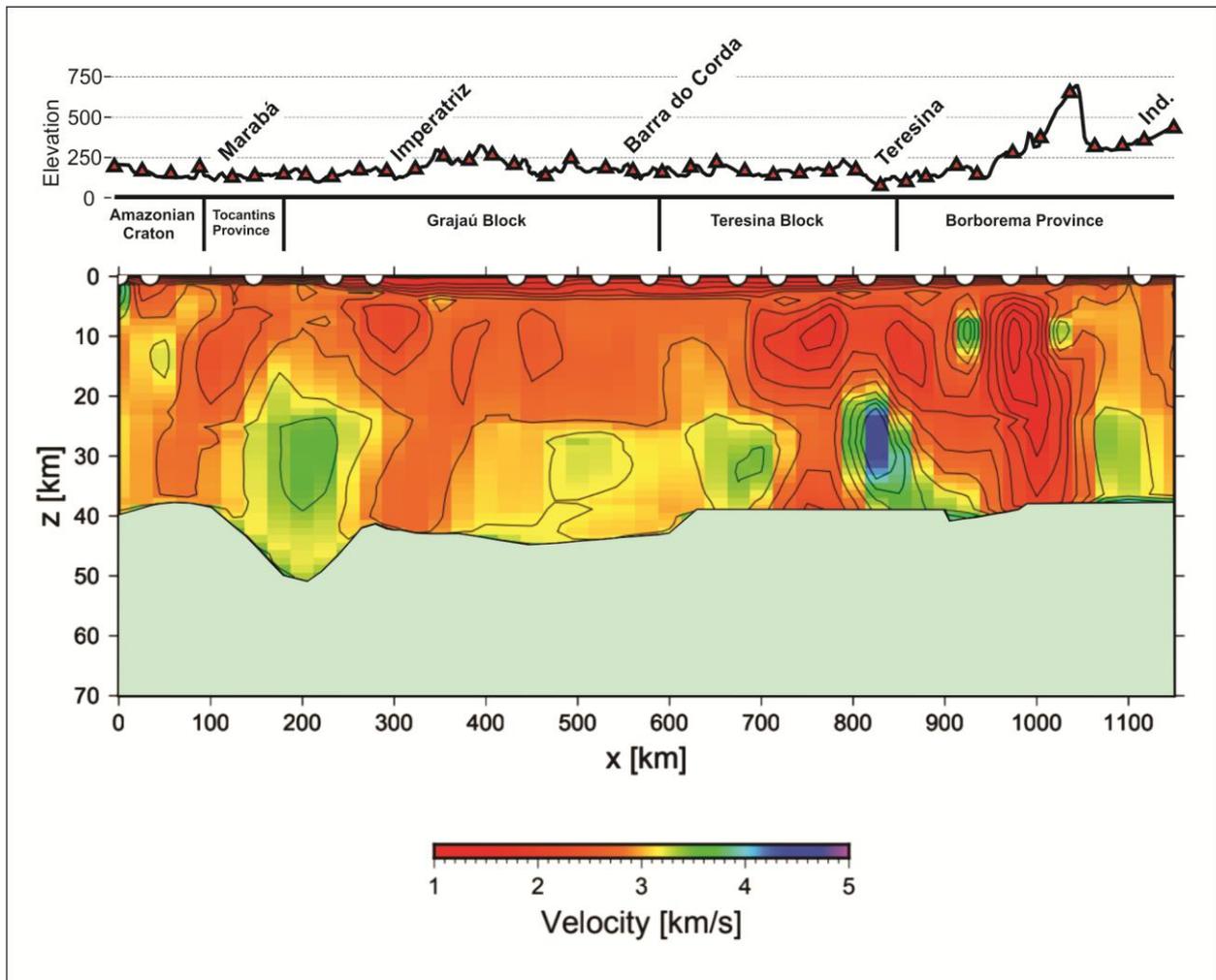


Figura 8: Tomografia 2D obtida para as ondas S do experimento sísmico na Bacia do Parnaíba. A região da crosta superior e inferior apresentam contrastes claros, diferenciados por mudanças na velocidade das ondas.

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Os dados da tomografia 2D mostram diferentes padrões de velocidade conforme as camadas do modelo. Na porção rasa, relacionada à bacia, pode-se visualizar o modelo com velocidade média de 2.1 km/s.

A crosta superior apresenta heterogeneidades ao longo de todas as províncias geológicas. Na Frente de Sutura Amazônica, os dados mostram anomalia de baixa velocidade de direção NE-SW, com velocidade média de 2.50 km/s ao longo de toda a crosta. O Bloco Grajaú apresenta-se homogêneo em sua extensão, com velocidade média de 2.65 km/s, exceto entre os offsets de 250 km e 350 km e 10 km de profundidade, que mostra velocidade média de 2.1 km/s.

Ainda com relação à crosta superior, o Bloco Teresina apresenta menor velocidade média comparado ao Bloco Grajaú, com aproximadamente 2.0 km/s, exceto na região de contato com o Bloco Grajaú, onde observa-se anomalia de velocidade com aproximadamente 3.1 km/s (offset ~ 620 km - 660 km). A Província Borborema apresenta importante feição na altura do Lineamento Transbrasileiro, evidenciado por isolinhas verticalizadas, abrangendo uma faixa de aproximadamente 100 km entre os offsets de 950 km e 1050 km. A partir daí, até seu limite leste, o modelo apresenta velocidade média de 3.0 km/s e representa a região de maior velocidade de ondas S da crosta superior.

A crosta inferior apresenta anomalias de velocidade na Frente de Sutura Amazônica, com velocidade média de 3.6 km/s, contrastante com o início do perfil, que mostra velocidade em torno de 2.4 km/s. O Bloco Grajaú apresenta em geral velocidade média de 3.25 km/s, ao passo que o Bloco Teresina evidencia duas anomalias de velocidade, entre os offsets de 600 km e 700 km; e 800 km e 900 km, com velocidades de 3.6 km/s e 3.9 km/s, respectivamente. A Província Borborema, exceto pela região que seria afetada pelo Transbrasileiro, mostra velocidade média de 3.4 km/s.

4.4- Modelagem de ondas S

A modelagem de ondas S foi desenvolvida com o algoritmo que calcula o método do traçado do raio (Červený *et al.*, 1977; Červený, 2001). O método simplifica o cálculo do caminho que uma onda percorre em um meio heterogêneo, com variações de velocidade ao longo das camadas. Cada onda é modelada como um conjunto de feixes (raios) que viajam no interior do meio até seu retorno ao receptor.

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Para modelagem dos dados de onda S, foi utilizada a tomografia 2D obtida como base para a parametrização do modelo, uma vez que a geometria do modelo já é amarrada ao modelo de ondas P. Foi considerada a estratégia *strip layer approach* ou "remoção de camada" (Zelt, & Smith, 1992; Zelt, 1999), a qual consiste numa aproximação do tipo "através e para baixo", para otimização do processo da modelagem direta.

O algoritmo utilizado para o cálculo do traçado de raios em um meio bidimensional parametrizado foi inicialmente desenvolvido por (Zelt & Ellis, 1988), posteriormente aperfeiçoado e integrado ao pacote de programas RAYINVR (Zelt & Smith, 1992) que promove o cálculo do traçado de raios e verificação dos tempos de trânsito das ondas em relação às fases observadas. A figuras 9 a seguir mostra o modelo preliminar obtido com a modelagem de ondas S, as figuras 10 - 13 mostram o resultado da modelagem obtida para alguns tiros em diferentes offsets ao longo da transecta e a figura 14 apresenta o estado da arte da modelagem dos dados.

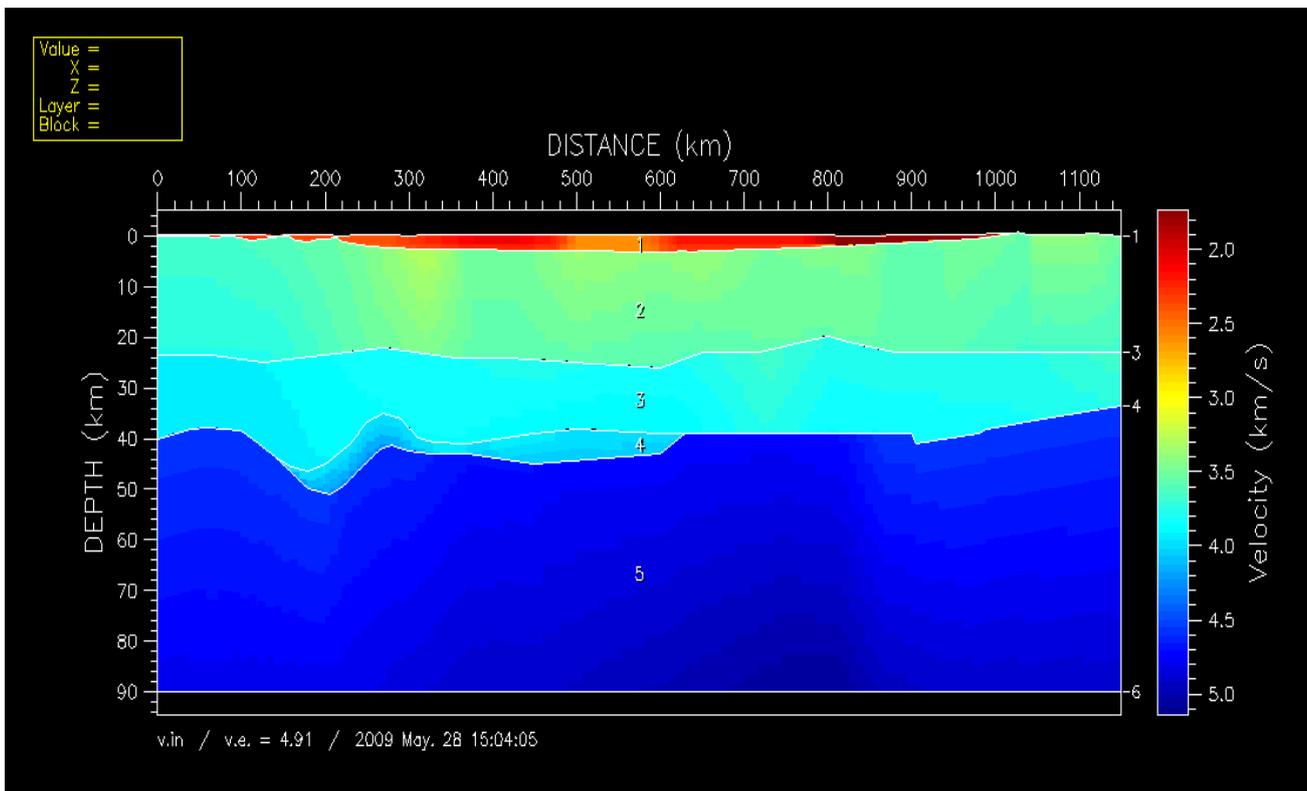


Figura 9: Modelo de ondas S obtidos no programa VMED. O modelo utilizado é composto da mesma geometria de camadas utilizada para modelagem de ondas P, com mudanças apenas os dados dos nós de velocidade dos campos de onda S, conforme distribuição das camadas em profundidade.

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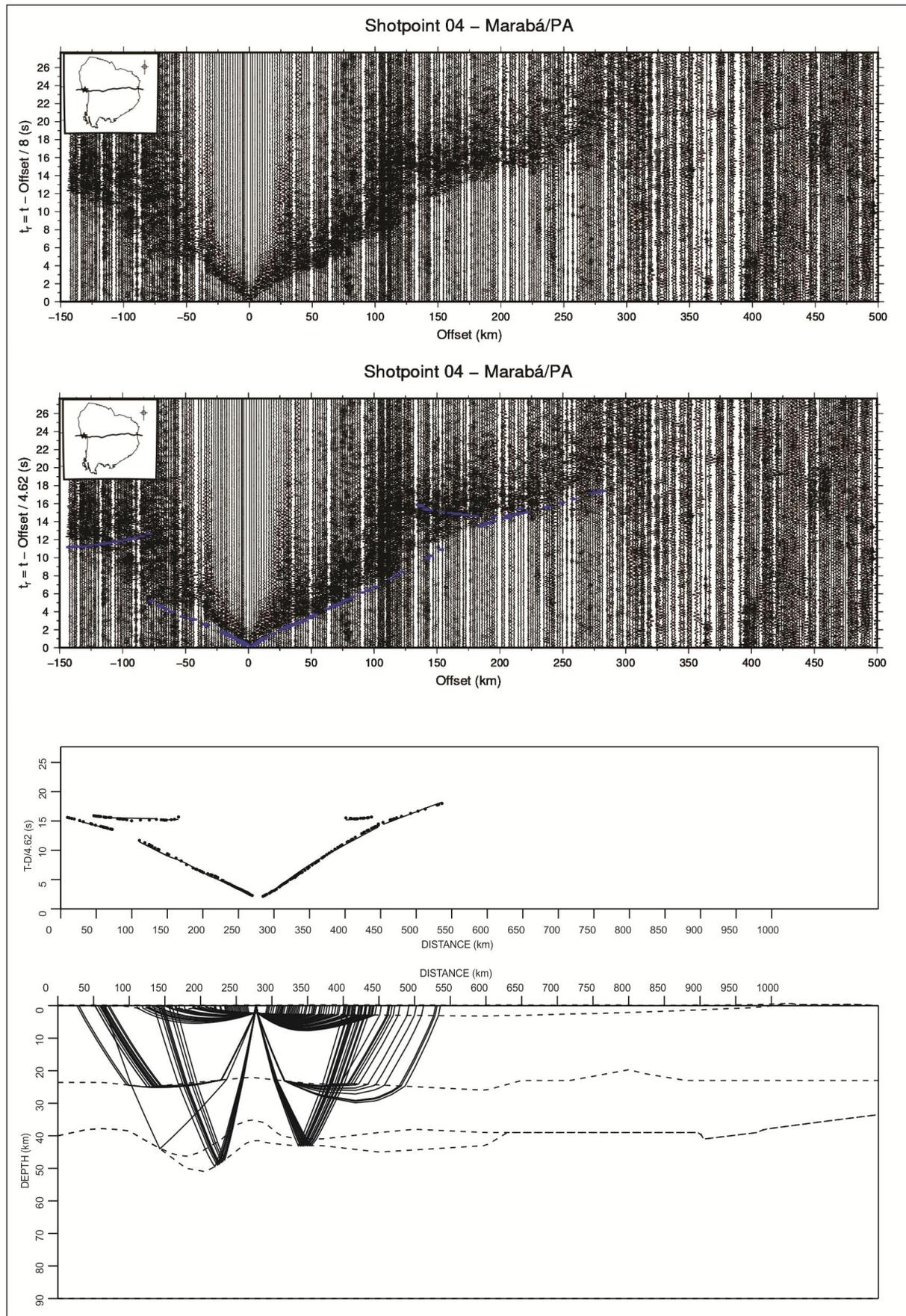


Figura 10: Modelagem do tiro 4 - Marabá/PA

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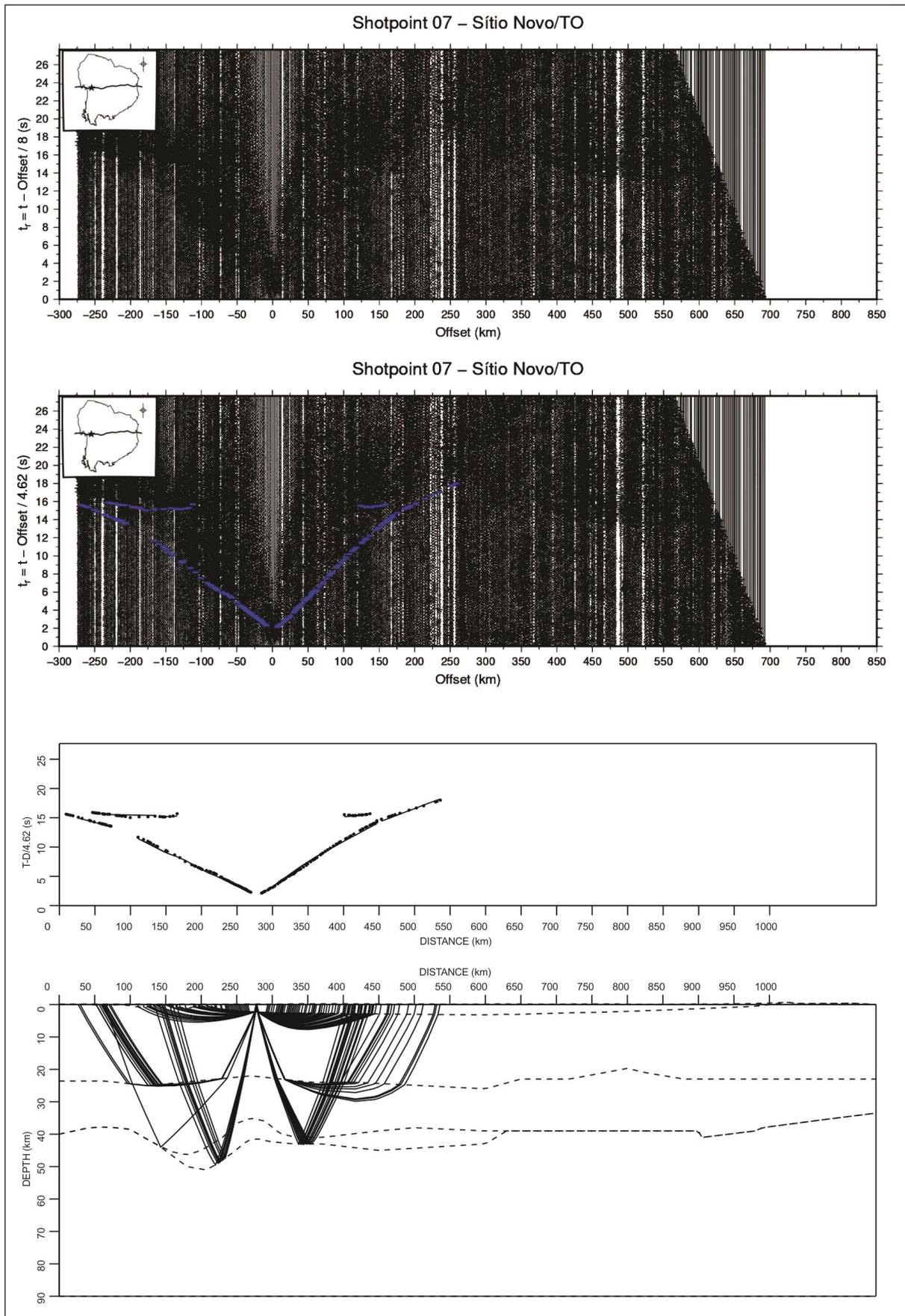


Figura 11: Modelagem do tiro 7 - Sítio Novo/TO.

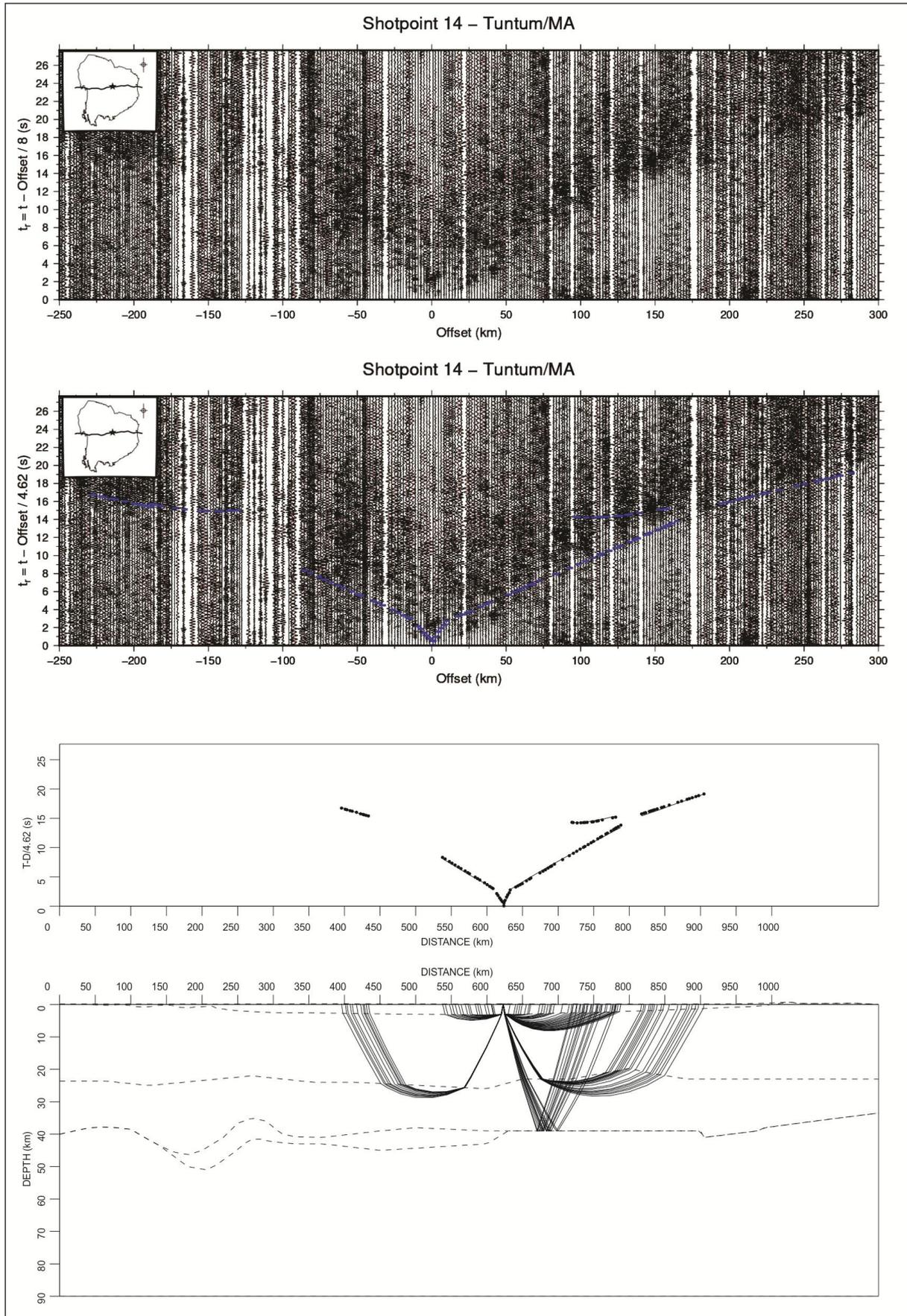


Figura 12: Modelagem do tiro 14 - Tntum/MA.

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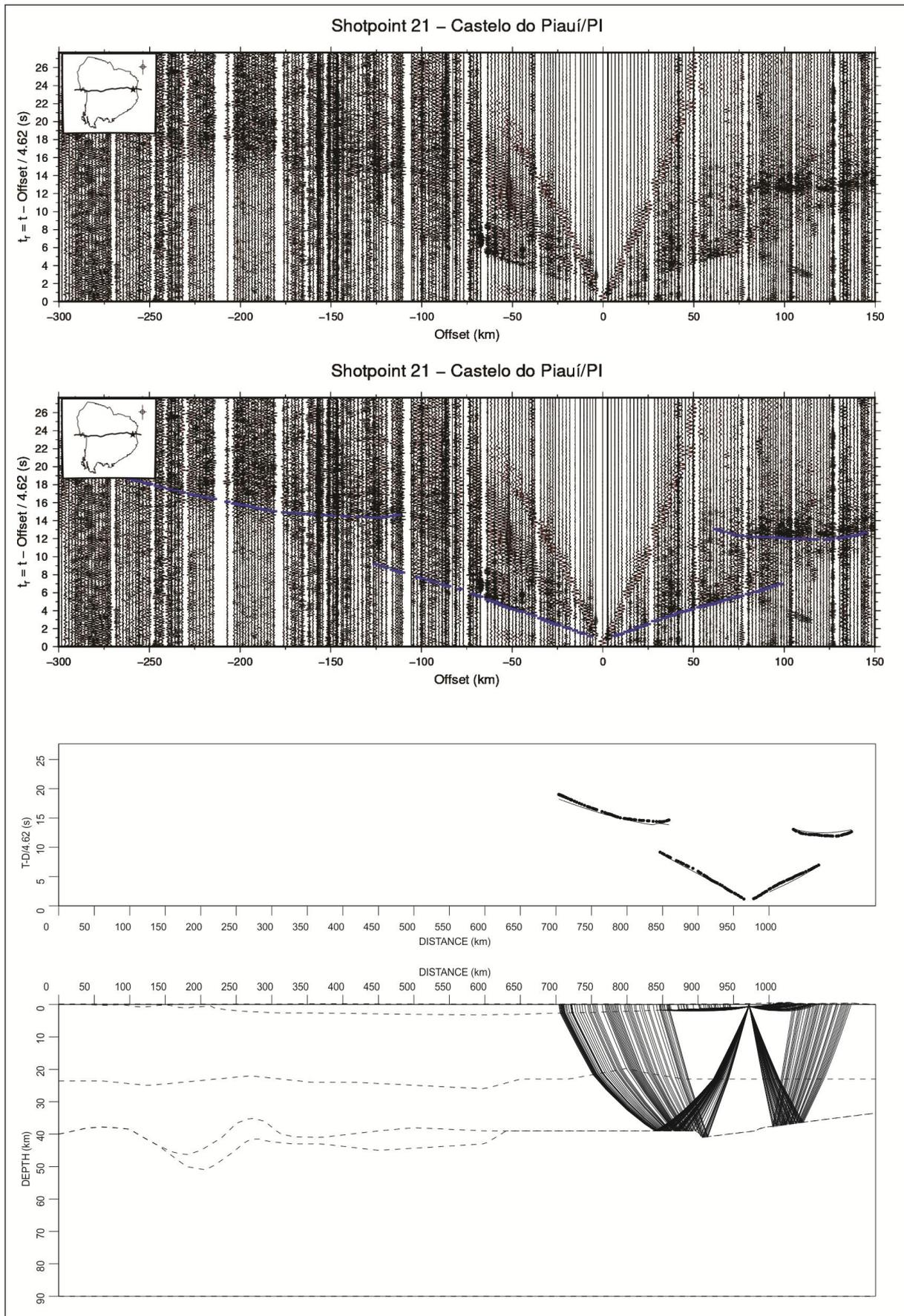


Figura 13: Modelagem do tiro 21 - Castelo do Piauí/PI.

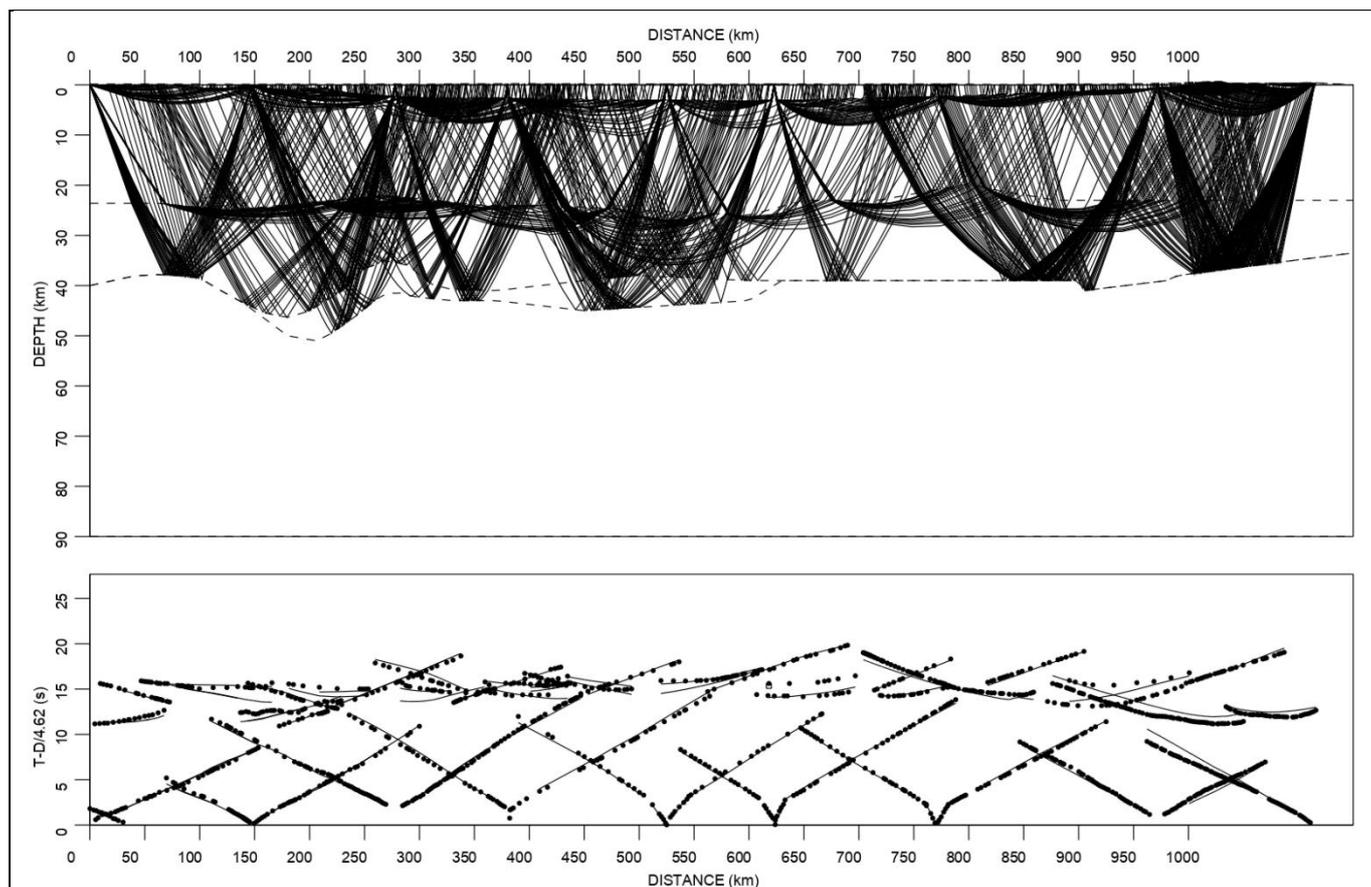


Figura 14: Estado da arte da modelagem de ondas S. Praticamente todas as fases foram modeladas, com bom ajuste, exceto algumas reflexões profundas (offset entre 900 km e 1100 km) e fase Sg do tiro extremo leste.

A modelagem atual dos dados permite apresentar uma proposta de modelo para o campo de velocidade de ondas S. Alguns últimos refinamentos precisam ser feitos, em descontinuidades profundas da Moho na porção leste do perfil (Fig. 15) e alguns gradientes de velocidade de S granítica que podem ser reajustados para melhor representar o modelo.

O principal objetivo de modelagem das ondas S em combinação com as ondas P é montar o *grid* de ambos campos de velocidade (V_p/V_s), conforme descrito no item 4. A razão V_p/V_s trará nova abordagem à interpretação da evolução da litosfera na região abaixo do perfil da Bacia do Parnaíba, obtendo-se mais detalhes da variação de V_p/V_s por camadas, diferentemente da função do receptor que calcula um valor médio.

Uma vez finalizada a etapa de modelagem, será montada a discussão sobre os valores de V_p/V_s ao longo do perfil, comparando-os aos dados de Função do Receptor já obtidos. A integração dos dados promoverá novos detalhes ao estudo da composição da crosta e sua discussão servirá de base para a elaboração do quarto manuscrito

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intitulado *S Wave characteristics and Vp/Vs Ratio of Parnaíba Basin - Brazil: insights from receiver function and deep seismic refraction.*

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CAPÍTULO 5

5. CONCLUSÕES

Os resultados do experimento de refração sísmica profunda em conjunto com os resultados de função do receptor permitiram imagear e determinar as descontinuidades marcantes da litosfera sob a Bacia do Parnaíba, com destaque para a presença de uma camada de alta velocidade na base da crosta do bloco Grajaú interpretada como *underplating*.

Os dados de refração de ondas P mostram a geometria assimétrica da Bacia do Parnaíba, com profundidade de 3,2 km em seu depocentro, e resolvem estruturas relativamente complexas para o método de refração, como os grabens da Faixa Araguaia e a (paleo) sutura entre o Cráton Amazônico e o embasamento da Bacia do Parnaíba. Destacam-se ainda na porção profunda da bacia no domínio do Bloco Teresina ondas P com alto valor de velocidade, que possivelmente são relacionadas ao magmatismo crustal dos domínios do Bloco Teresina.

A crosta apresenta espessura significativa, com trechos maiores que 40 km de profundidade e variações do campo de velocidade que traduzem as heterogeneidades dos sítios tectônicos. Os dados mostram ainda que a razão de espessura crosta superior/crosta inferior nos domínios da bacia é próximo a 1, o que descartaria deformações extensionais significativas durante o Paleozóico.

A descontinuidade de Moho foi mapeada com significativa acurácia e mostra geometria heterogênea ao longo da transecta, com profundidade estimada entre 33 km e 53 km. Os contatos tectônicos são evidenciados por oscilações de ordem quilométrica na descontinuidade de Moho, que por sua vez apresenta afinamento crustal na medida que se aproxima da Província Borborema.

Os dados de função do receptor mostram correlação positiva com os resultados de refração, de tal forma que a descontinuidade de Moho apresenta ajustes bem próximos ao obtido pelo modelo de ondas P.

Os dados de função do receptor imagearam importantes feições geológicas, como os limites do rifte do Jaibaras, o *underplating* máfico nos domínios do Bloco Grajaú (Soares *et al.*, 2018) e confirmam a zona de sutura do Cráton Amazônico com o embasamento da bacia. As fases múltiplas rasas da bacia delinearam seu contorno e definiram limites coincidentes com os limites geográficos superficiais.

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Os resultados de Vp/Vs indicaram a composição média em cada domínio crustal, com valores variados ao longo do perfil. Os dados sugerem a existência de dois diferentes domínios crustais no embasamento da Bacia do Parnaíba, corroborando a diferença entre a natureza dos blocos Grajaú e Teresina, que teriam sido amalgamados na transição do Proterozóico pro Cambriano, conforme proposto por Nunes *et al.*, (1993); Castro *et al.*, (2014) e Solon *et al.*, (2018), suportados por dados potenciais e magneto-telúrico.

A verificação de características estruturais e propriedades físicas da Bacia do Parnaíba, conforme vislumbrado nos últimos anos, tem possibilitado a proposição de modelos evolutivos mais robustos, tendo em vista a multidisciplinaridade dos dados. As principais implicações são relacionadas à composição da crosta, determinante para o entendimento da gênese e evolução tectônica da bacia.

A modelagem de um *underplating* máfico de grandes dimensões, corroborado pela modelagem gravimétrica obtida por Tozer *et al.*, (2017) e sugerido por Castro *et al.*, (2014), deve ter desempenhado importante papel na evolução tectônica da bacia (Soares *et al.*, 2018). A concepção de origem da bacia a partir de rifte central e subsidência termal sob grande área (Klein, 1995; Goes & Feijó, 1994), não comporta os modelos geofísicos obtidos por dados sísmicos (Daly *et al.*, 2014; Tozer *et al.*, 2017; Soares *et al.*, 2018; Coelho *et al.*, 2018) e gravimétricos (Castro *et al.*, 2014; Tozer *et al.*, 2017).

As principais argumentações advêm de constatações como poucas evidências de deformações extensionais ao longo da bacia, ausência de um *graben* central com falhas normais comuns em regimes de tectônica rúptil e curvas de *backstripping* flexural não compatíveis com modelos de rifte (Tozer *et al.*, 2017).

Por outro lado, os indícios da presença de intenso magmatismo disseminado na crosta (Soares *et al.*, 2018) sugere que a carga destes materiais intrudidos (combinados com resfriamento e mudanças de fase) contribuíram para a subsidência inicial da bacia, puxando a litosfera para baixo e flexionando a crosta sobreposta.

No Cretáceo, durante a abertura do Oceano Atlântico, a crosta inferior na porção leste pode ter sido estirada, resultando em *rebound* e exposição de sedimentos mais antigos das rochas da bacia e do embasamento, dando origem à topografia recente e definindo o limite erosivo leste da bacia. A magnitude e a distribuição da deformação intraplaca seria controlada pela reologia da litosfera e, possivelmente, o domínio do Bloco Grajaú foi preservado de significativa deformação Cretácea, haja vista a constatação de uma placa fóssil subductada preservada, camadas crustais com

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espessuras significativas e a relação crosta superior / crosta inferior destoante de modelos de rifte, que sugerem afinamento crustal e *uplift* litosférico.

Apêndice A

APÊNDICE A

Tabela A.1: Resumo de dados das estações sismográficas utilizadas na pesquisa da Bacia do Parnaíba.

Station	Latitude	Longitude	Elevation (m)	Distance (km)	Moho Ps (s)	Number of RF a = 4
BP 000	-5,51903	-50,20351	260	0,0	4,749	42
BP 010	-5,42512	-49,94781	200	028,570	4,669	111
BP 020	-5,44005	-49,67061	159	060,056	4,789	54
BP 030	-5,44102	-49,39870	160	090,090	4,898	13
BP 040	-5,42786	-49,07796	139	125,232	5,253	100
BP 050	-5,47653	-48,86055	146	148,660	5,430	93
BP 060	-5,53693	-48,57927	144	180,162	6,143	70
BP 070	-5,69813	-48,36077	175	205,068	5,817	92
BP 080	-5,73157	-48,10600	124	232,900	5,592	103
BP 090	-5,65297	-47,84593	229	262,211	6,258	13
BP 100	-5,55614	-47,58424	176	291,541	5,060	23
BP 110	-5,56494	-47,30866	173	322,309	5,237	21
BP 120	-5,59780	-47,03419	239	352,336	5,522	38
BP 130	-5,58506	-46,78689	237	379,443	5,474	52
BP 140	-5,68900	-46,47201	175	404,385	6,012	06
BP 141	-5,70043	-46,33450	159	430,761	5,842	06
BP 150	-5,75632	-46,04532	211	460,789	5,335	05
BP 160	-5,64585	-45,80336	238	487,546	5,502	37
BP 170	-5,45905	-45,46329	190	525,987	5,730	11
BP 171	-5,41478	-45,20704	177	554,550	5,820	31
BP 172	-5,36994	-44,91978	103	586,775	5,278	09
BP 173	-5,32479	-44,64743	121	616,812	5,350	21
BP 180	-5,29963	-44,39504	125	644,653	4,945	47
BP 190	-5,36015	-44,13615	182	673,337	4,867	42
BP 200	-5,27655	-44,13615	142	702,116	4,695	31
BP 210	-5,23745	-43,61212	157	730,889	4,734	48
BP 220	-5,19278	-43,33032	155	762,737	4,785	65
BP 230	-5,10947	-43,06687	198	791,133	4,972	04
BP 240	-5,15004	-42,83722	082	816,460	5,036	49
BP 250	-5,05624	-42,59166	153	842,938	4,755	25
BP 260	-5,12597	-42,39786	143	865,579	4,915	19
BP 270	-5,26398	-42,09840	225	898,963	5,218	25
BP 280	-5,29237	-41,89689	147	920,070	5,170	42
BP 290	-5,32641	-41,54291	249	959,208	4,923	55
BP 300	-5,33823	-41,28563	329	987,988	4,651	52
BP 310	-5,27260	-40,99248	602	1021,320	4,557	88
BP 320	-5,17623	-40,99248	298	1046,304	4,517	86
BP 330	-5,29115	-40,49734	325	1076,877	4,214	24
BP 340	-5,43164	-40,27947	338	1099,755	4,509	14
BP 350	-5,43617	-40,00283	548	1150,000	4,211	33

Apêndice B

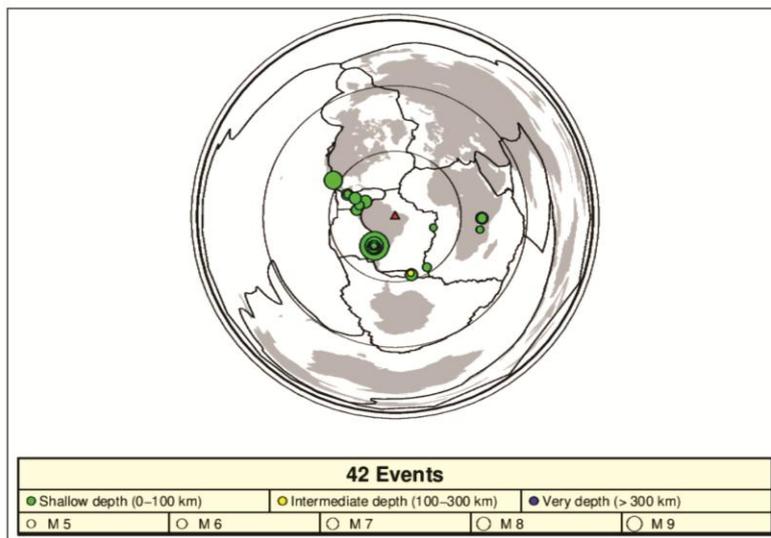
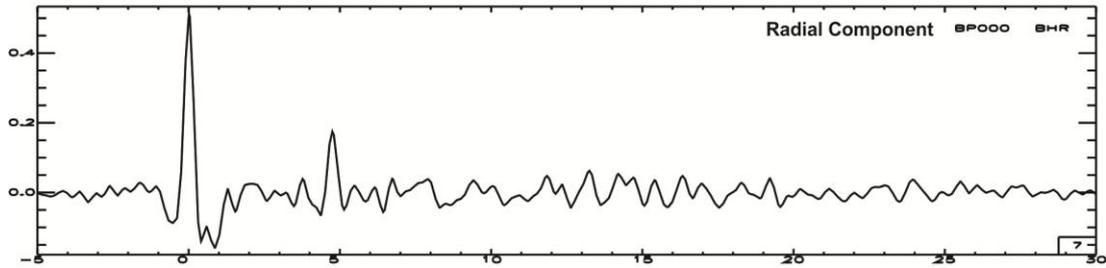
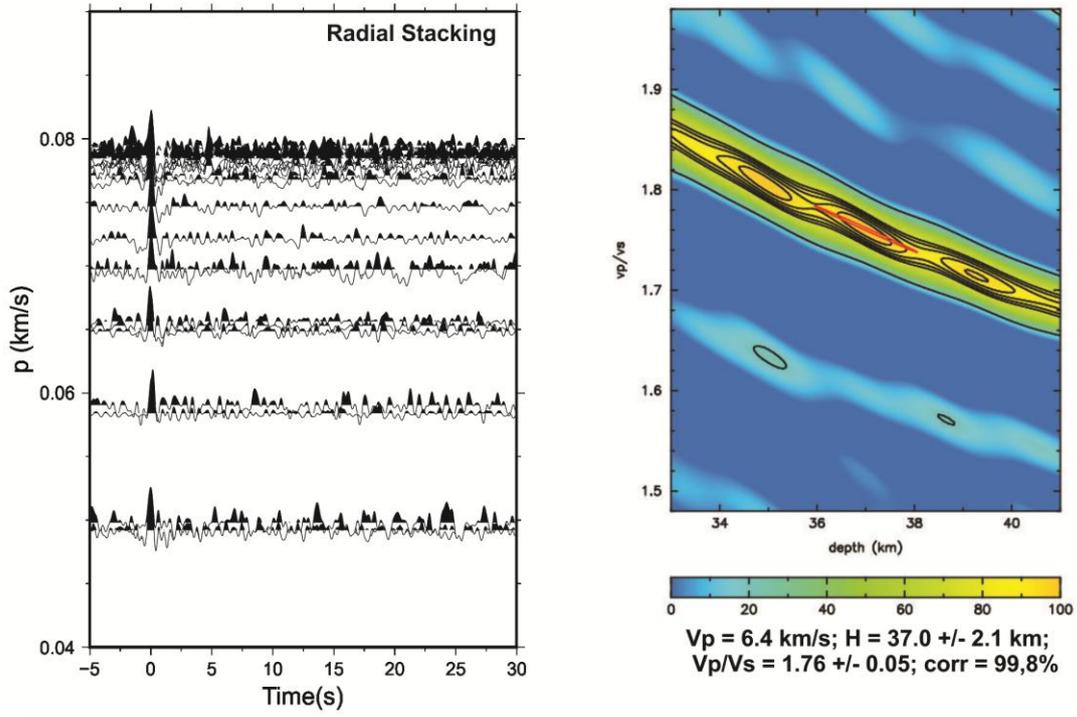
APÊNDICE B

Esta seção apresenta o material suplementar utilizado para obter os resultados do artigo nº 2 (*Crustal structure and Vp/Vs ratio of Parnaíba Basin - Brazil: Evidences of Neoproterozoic amalgamation in West Gondwana*). As imagens mostram a solução HK_Stacking, o diagrama do empilhamento radial por parâmetro de raio, o traço representativo da componente radial e o diagrama de distribuição dos eventos utilizados durante a amostragem da estação.

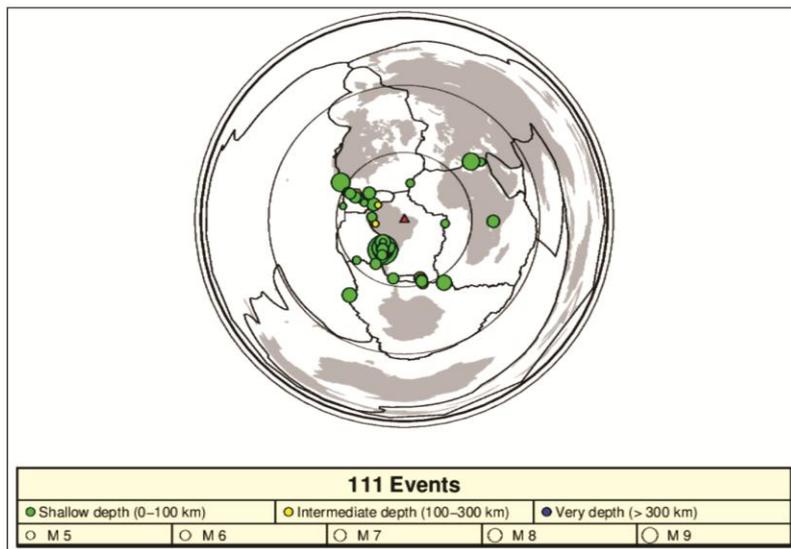
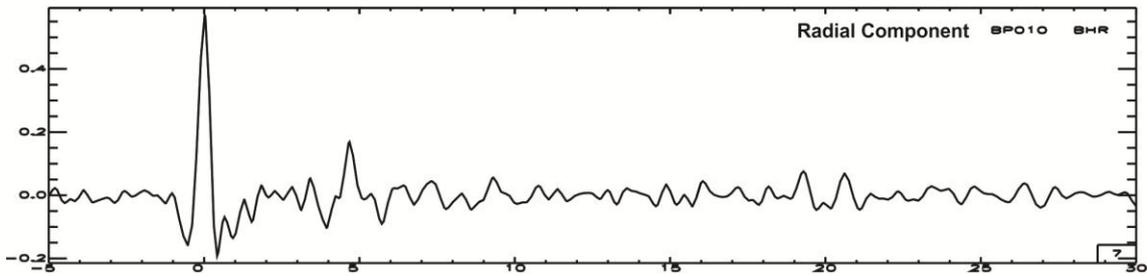
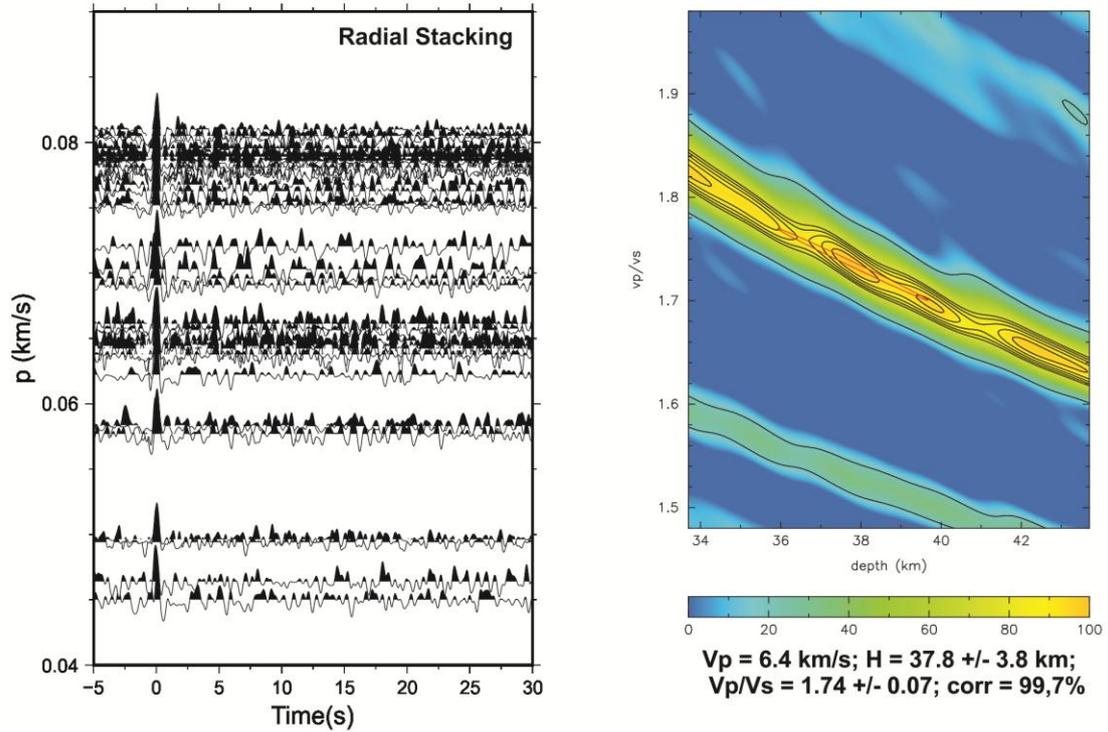
Os resultados foram calculados com o método do *bootstrap* (Efron & Tibshirani, 1991), para a maioria das estações. As estações que não utilizaram as estatísticas do método do *bootstrap* são atribuídas, em geral, ao domínio do Bloco Grajaú. O principal motivo é relacionado às intrusões magmáticas presentes na crosta naquela região, as quais promovem reverberações que dificultam o reconhecimento das fases múltiplas, utilizadas para os cálculos estatísticos do programa.

Apêndice B

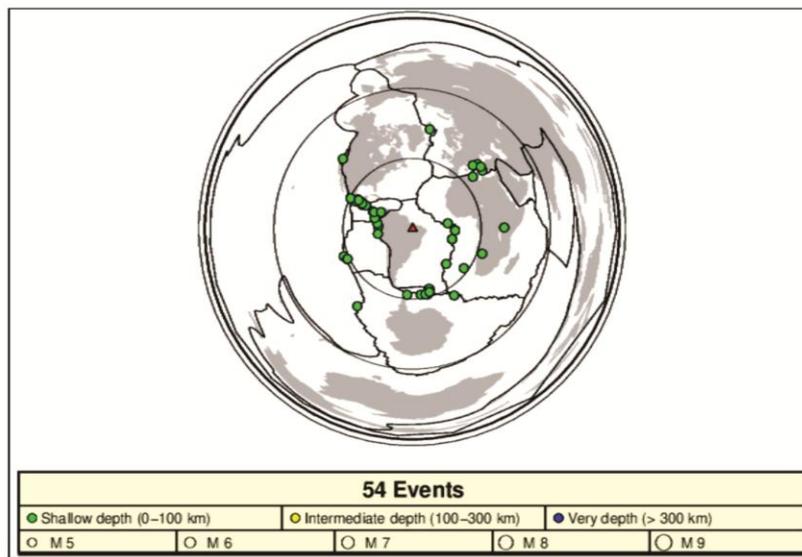
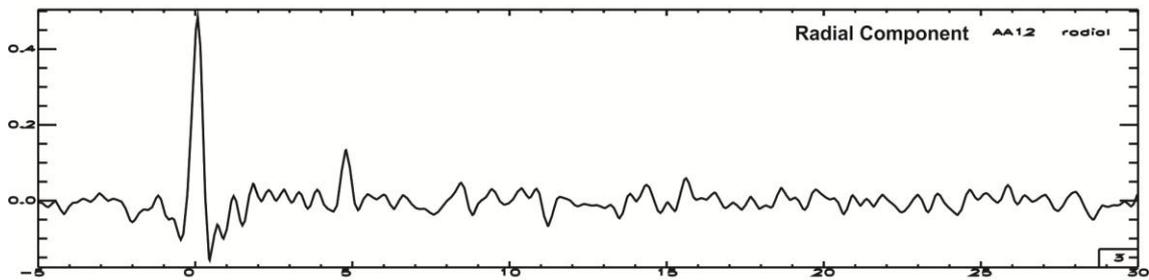
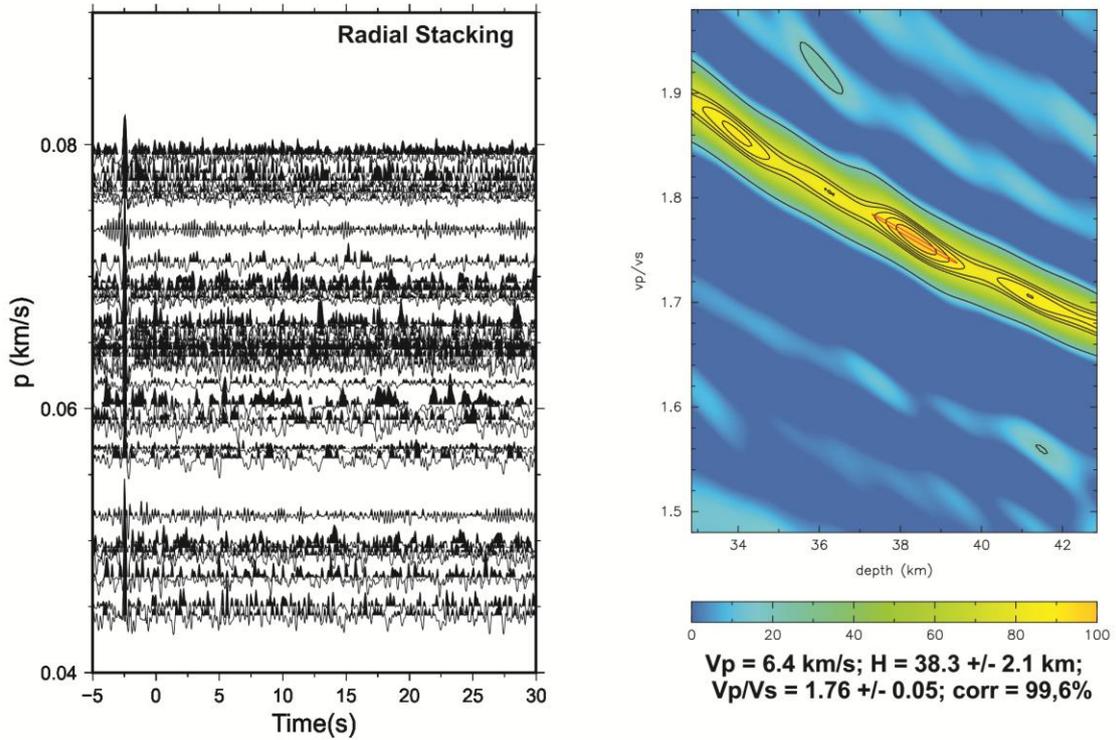
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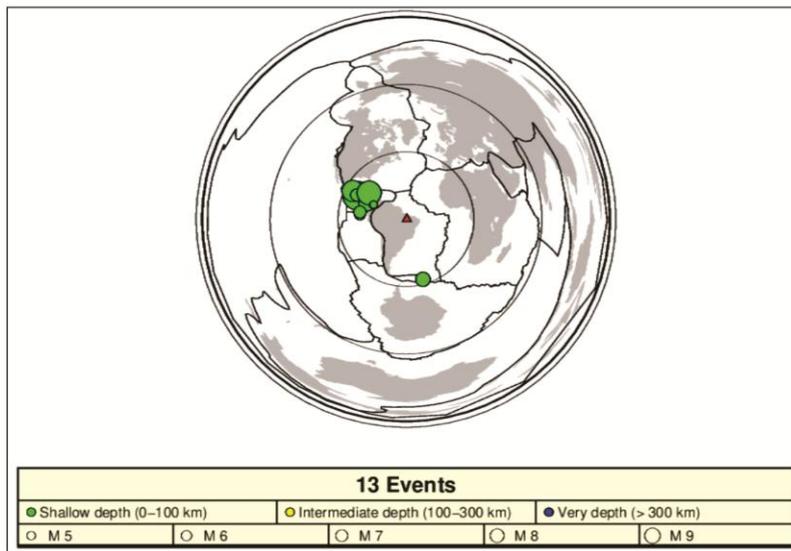
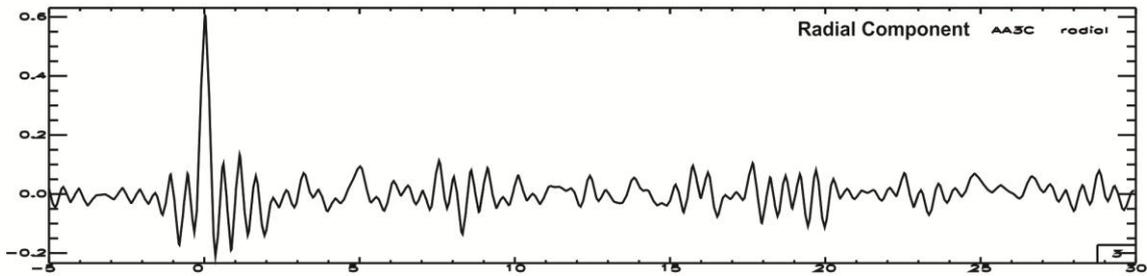
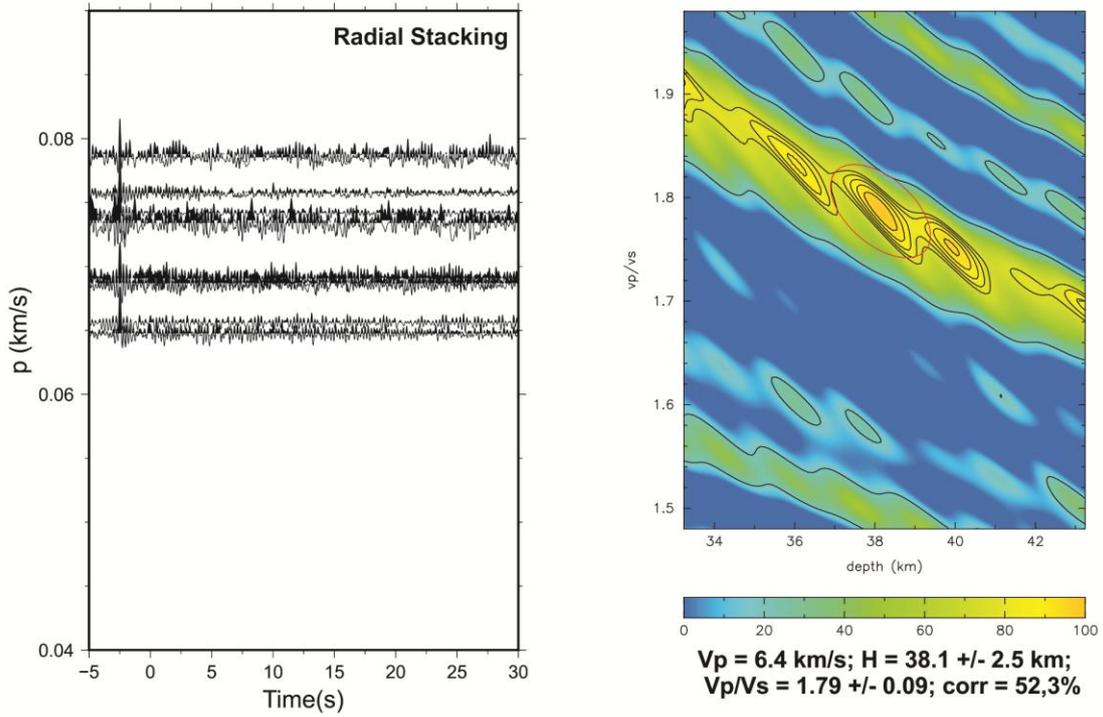
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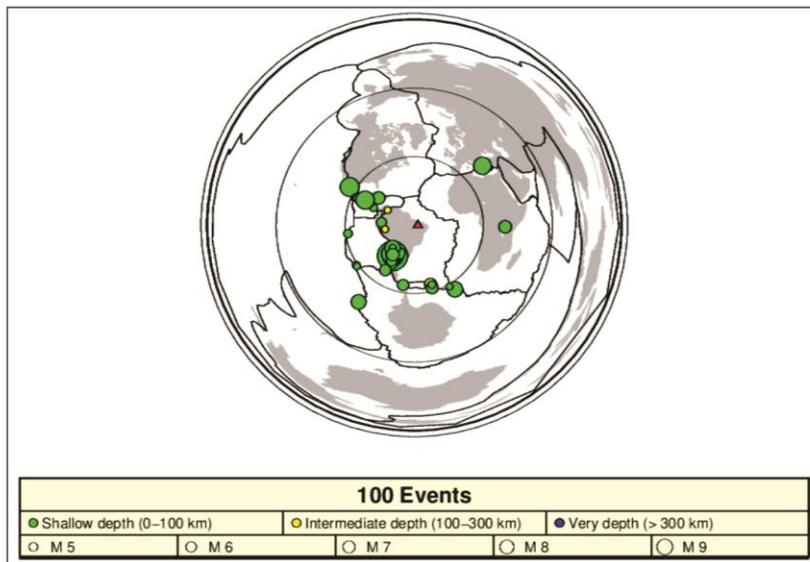
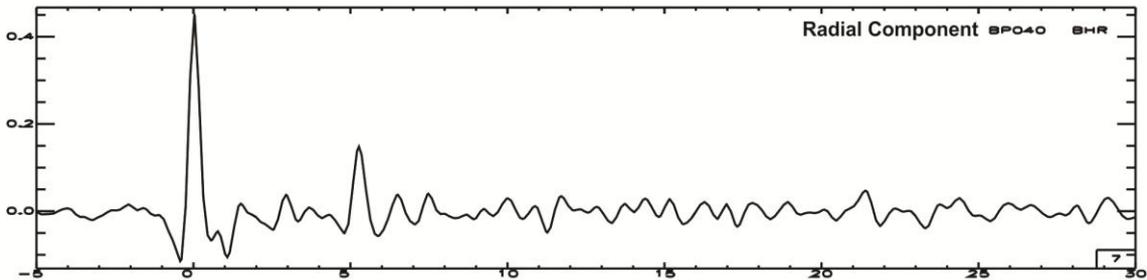
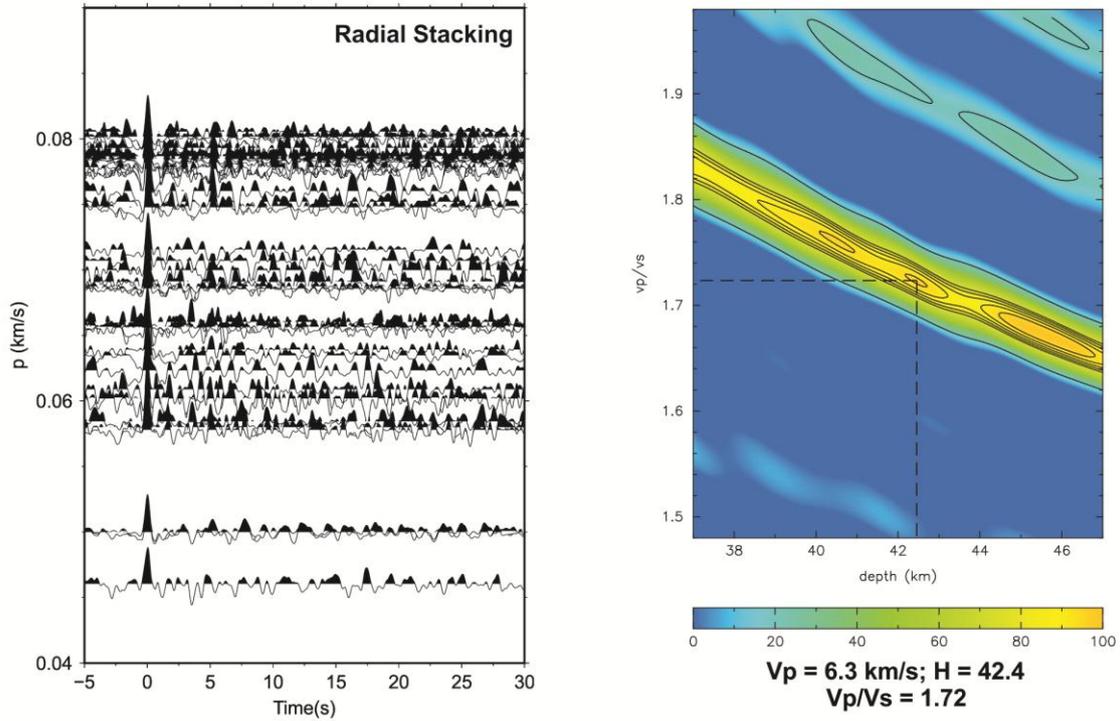
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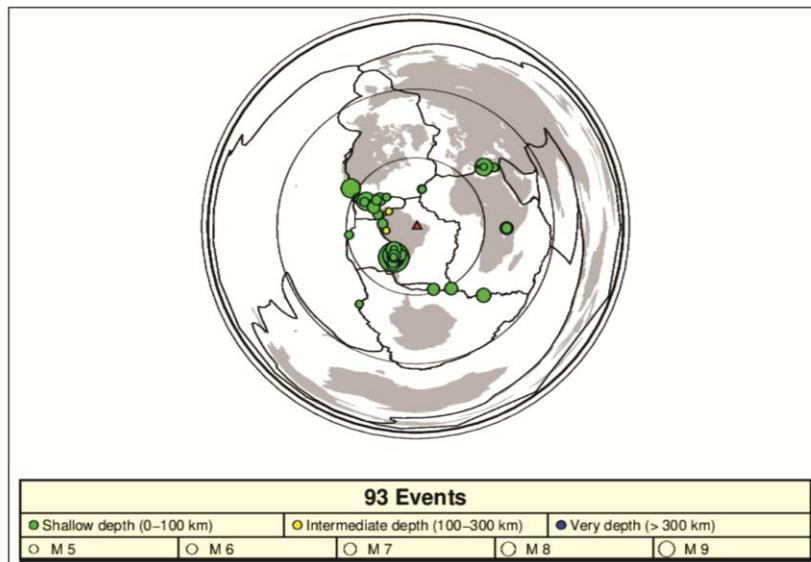
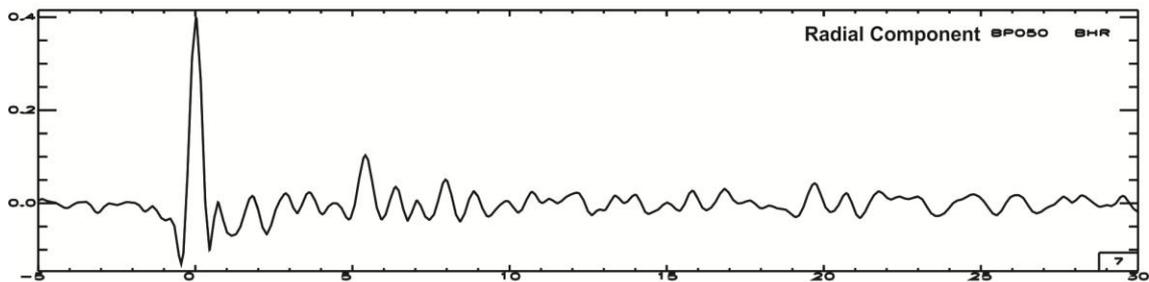
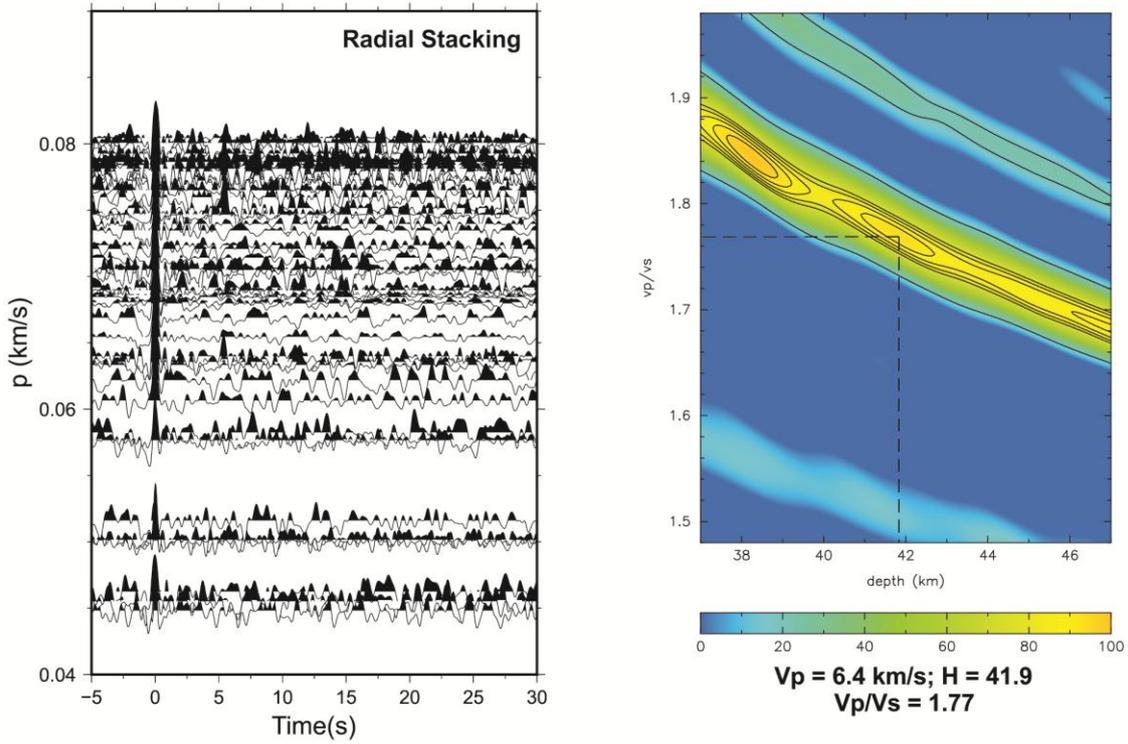
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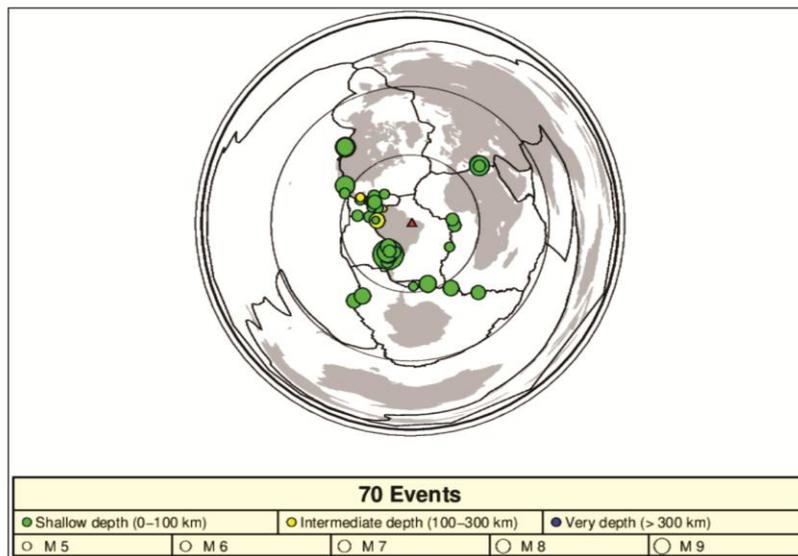
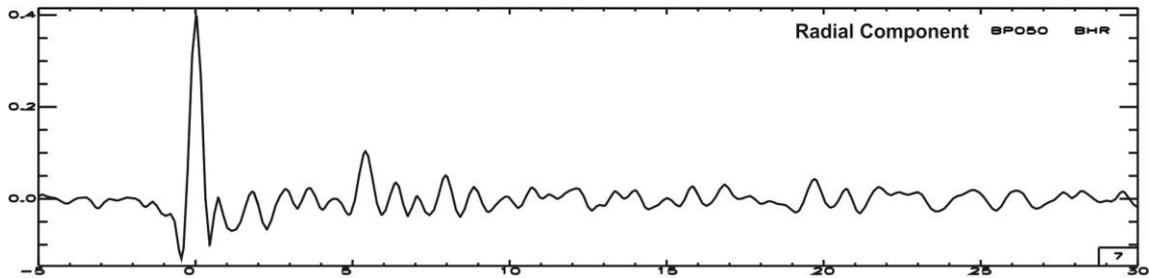
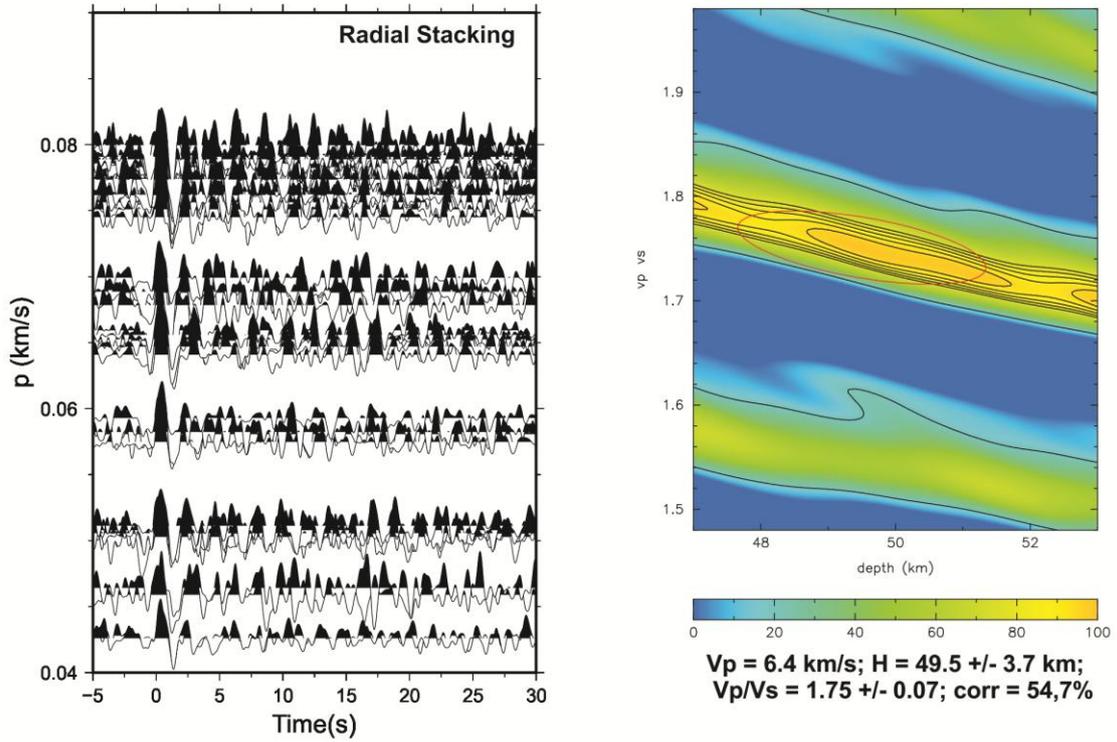
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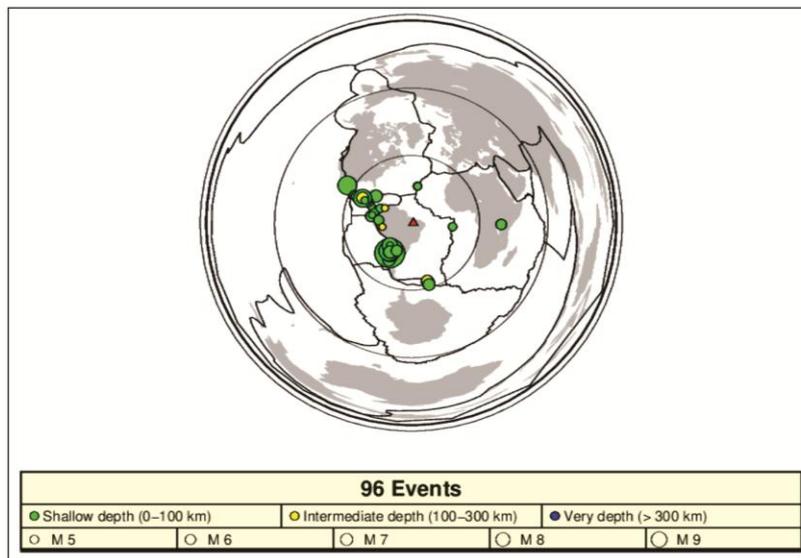
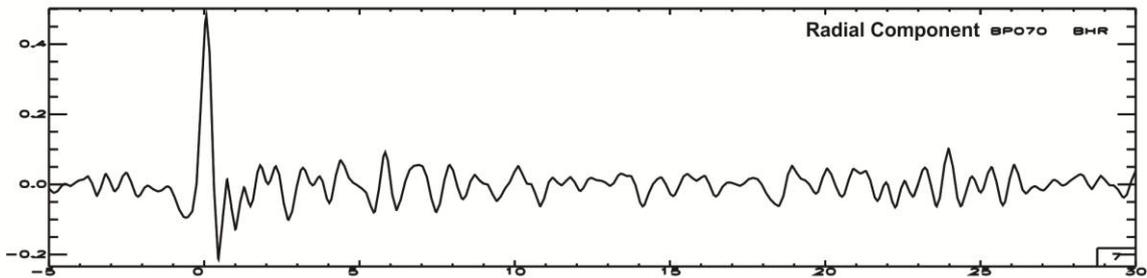
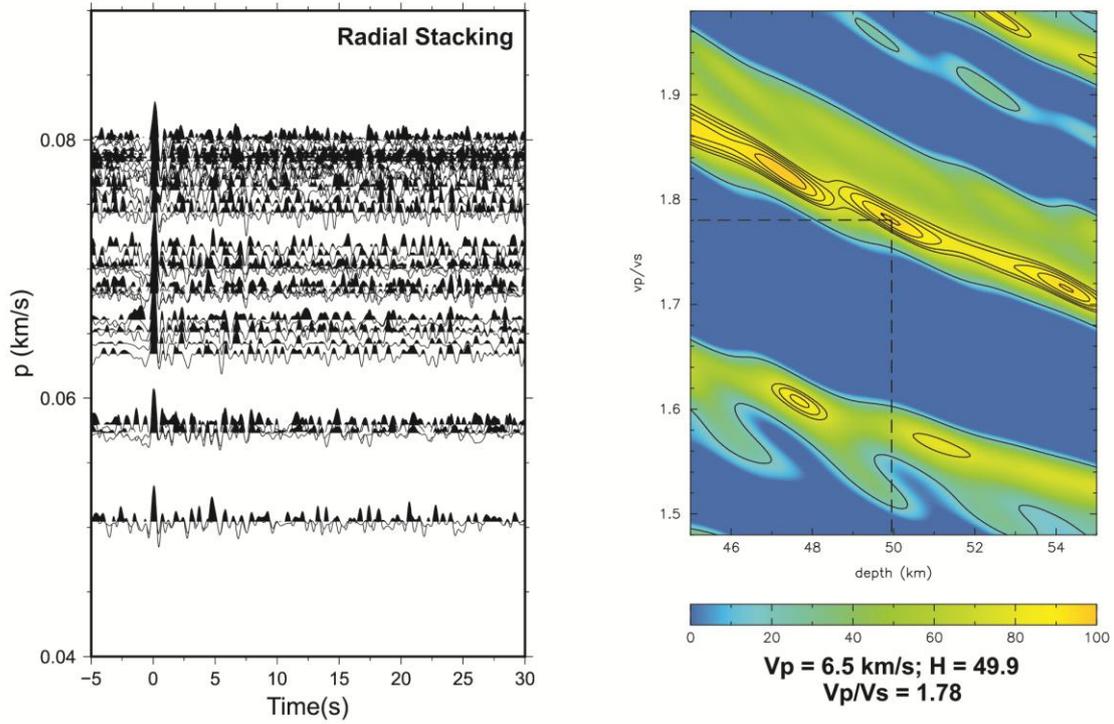
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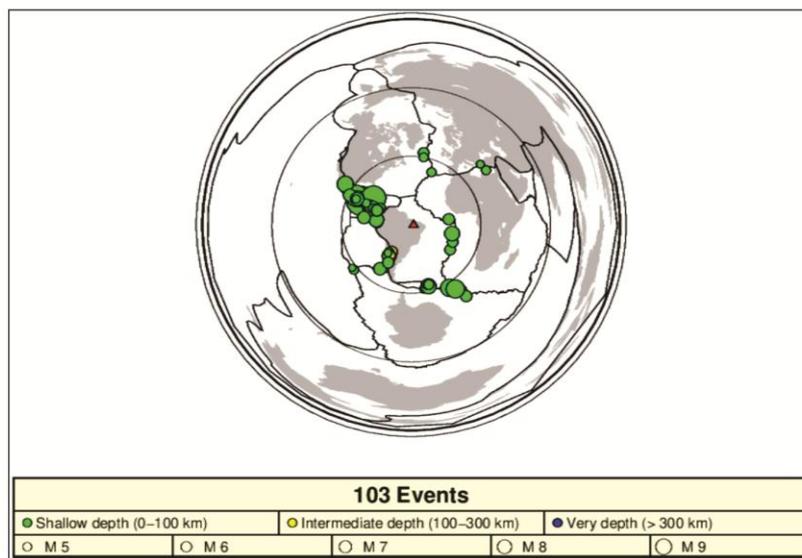
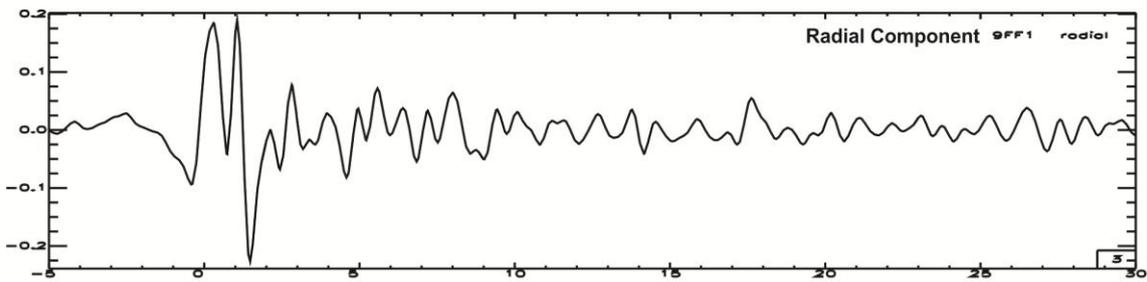
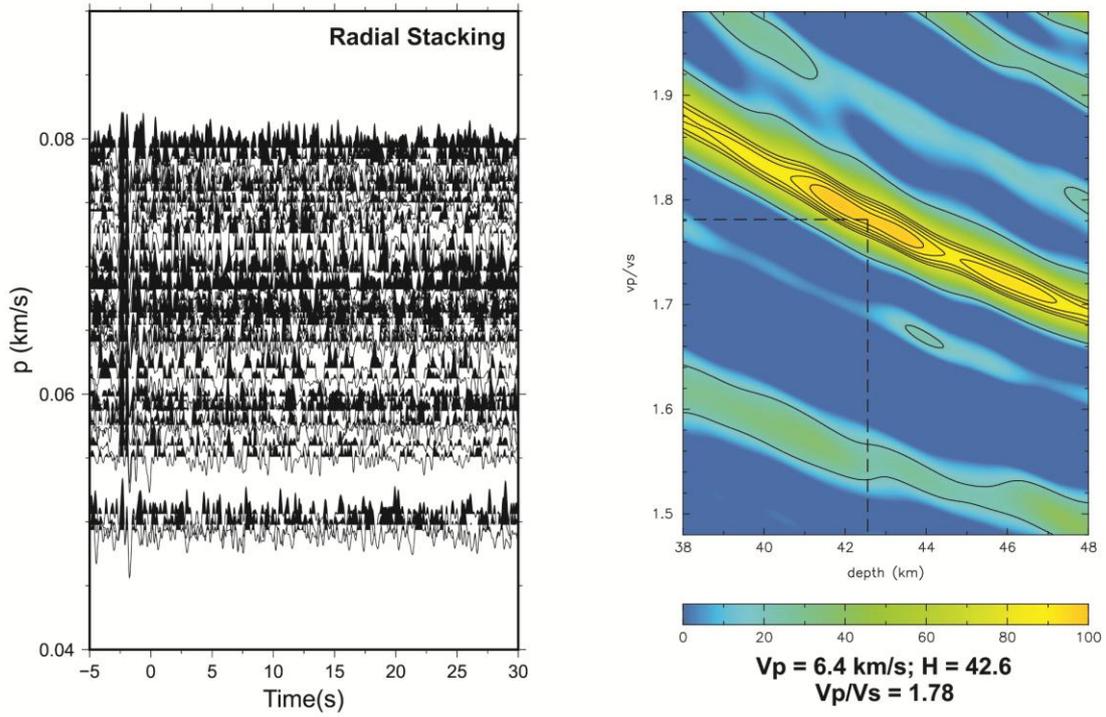
BP_060



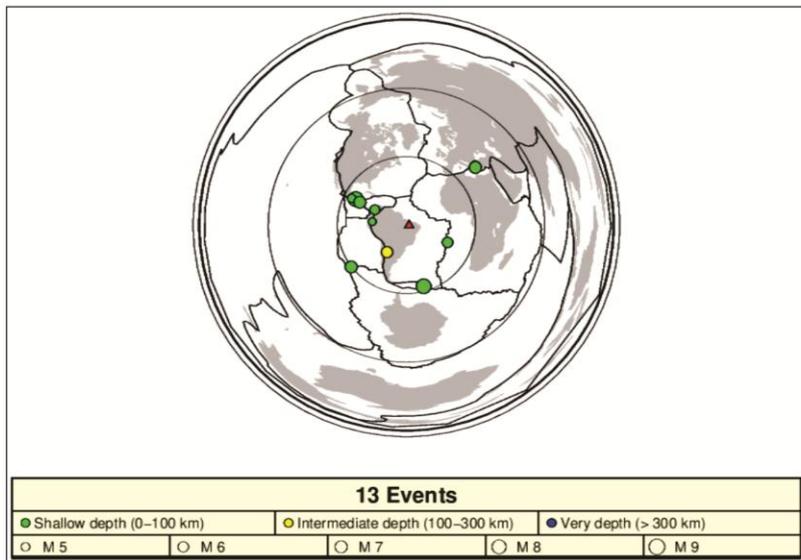
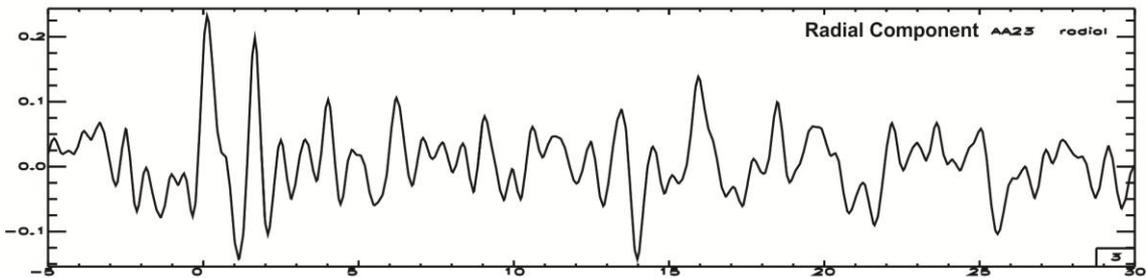
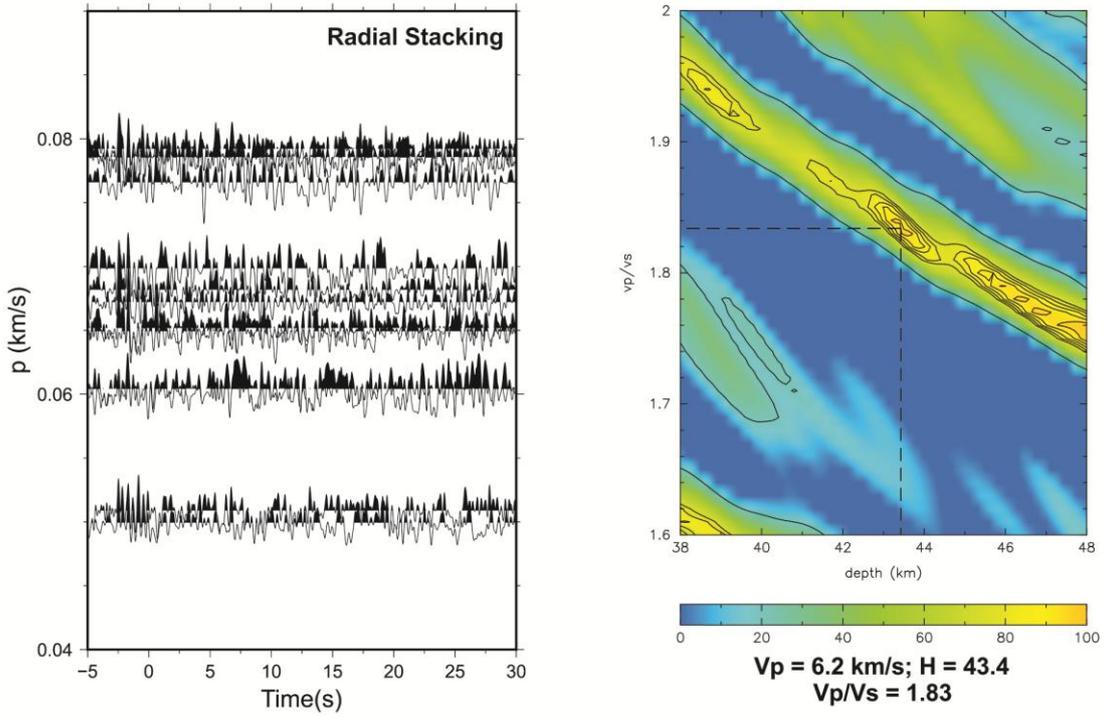
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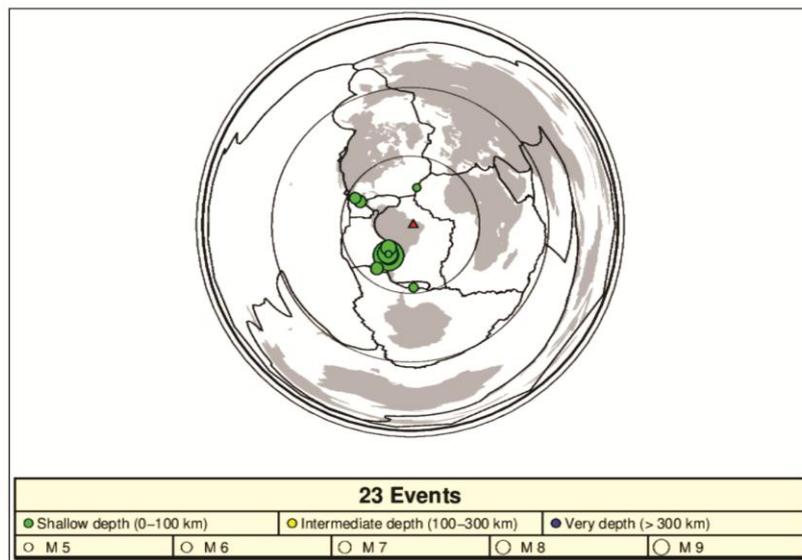
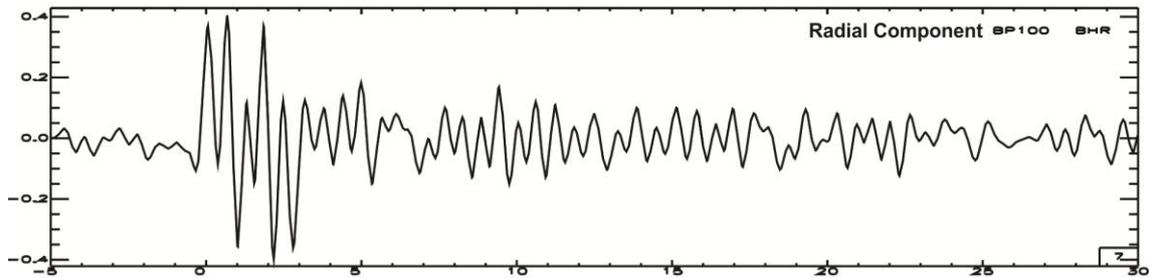
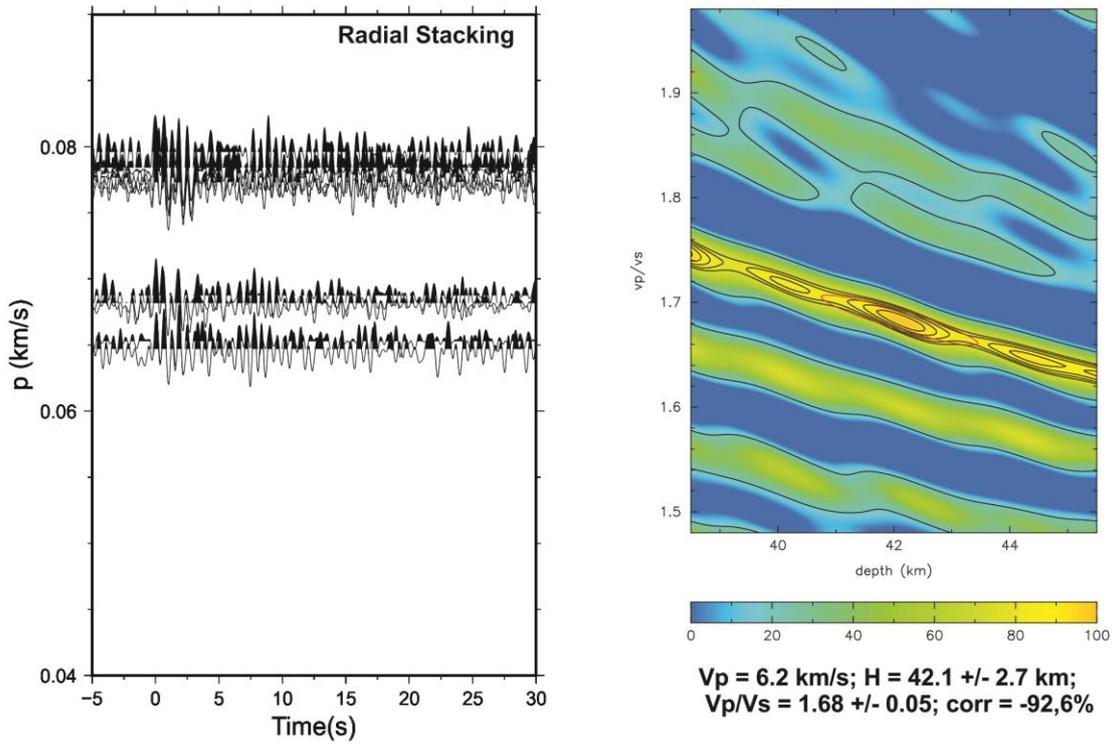
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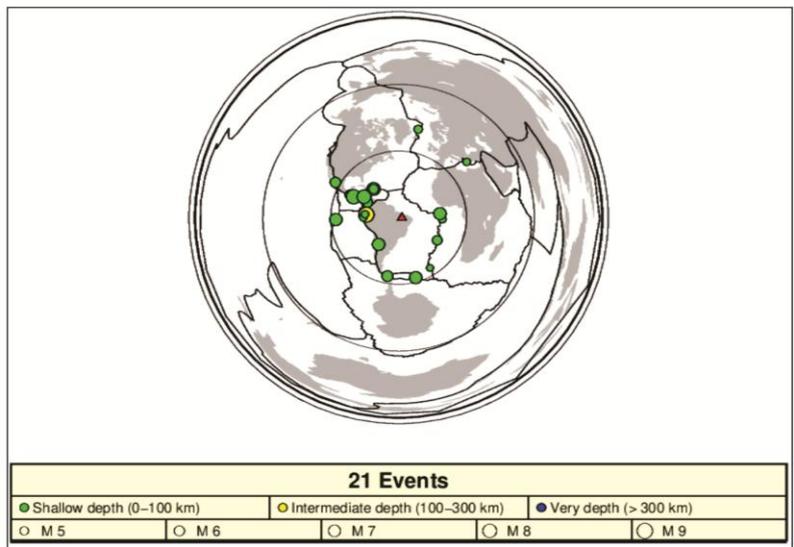
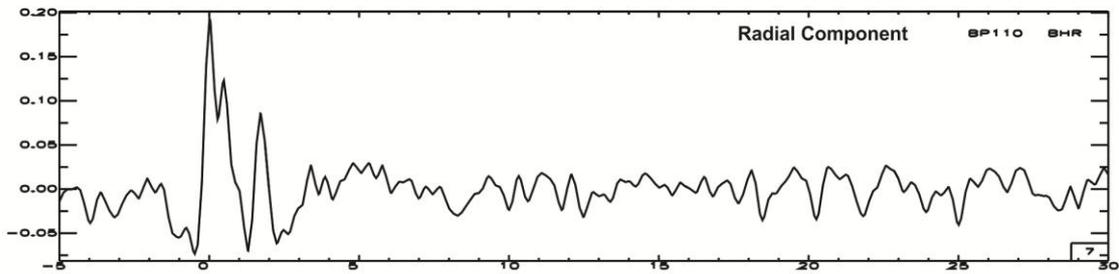
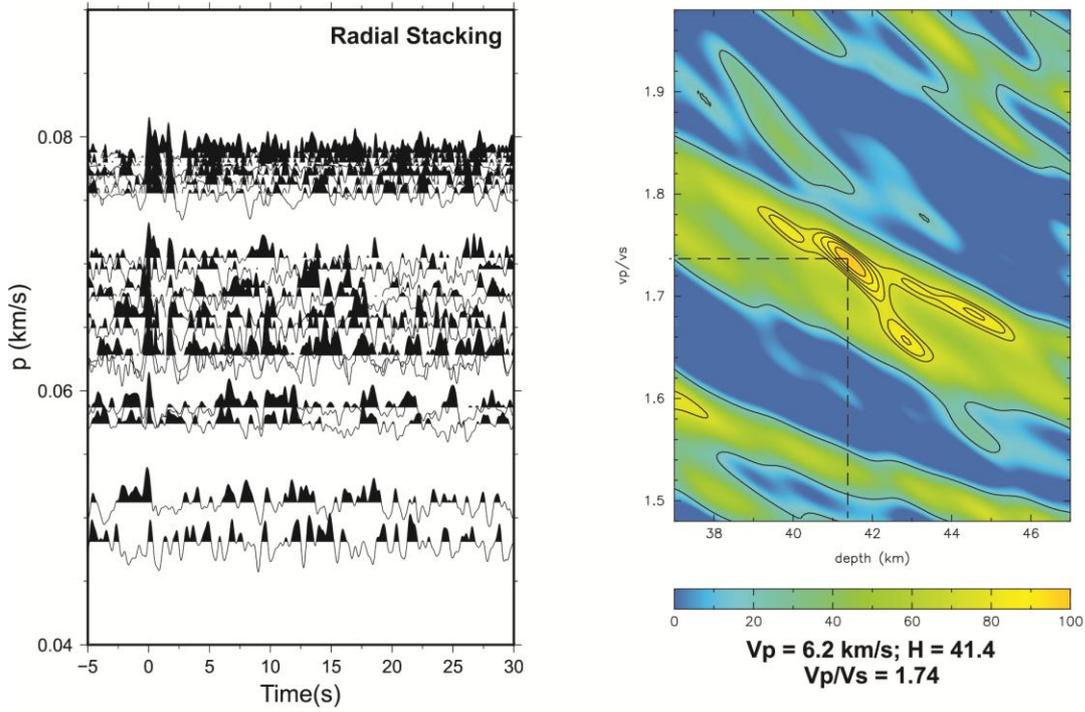
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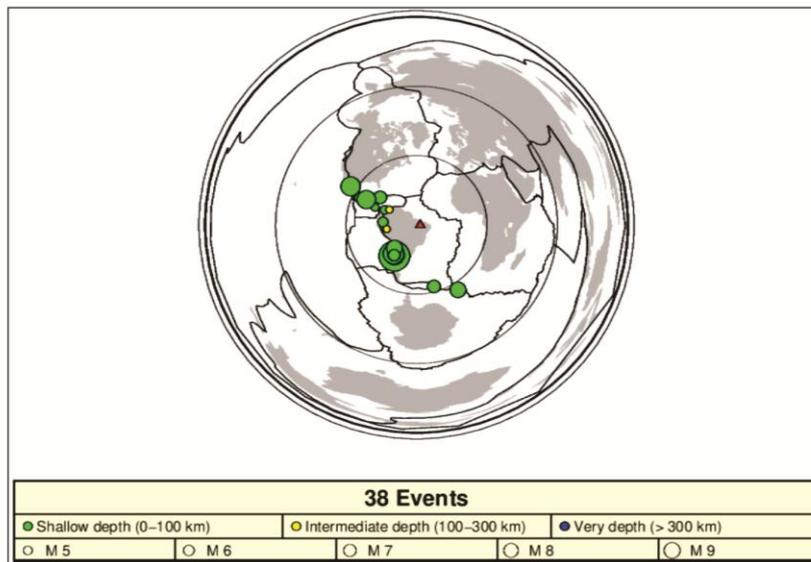
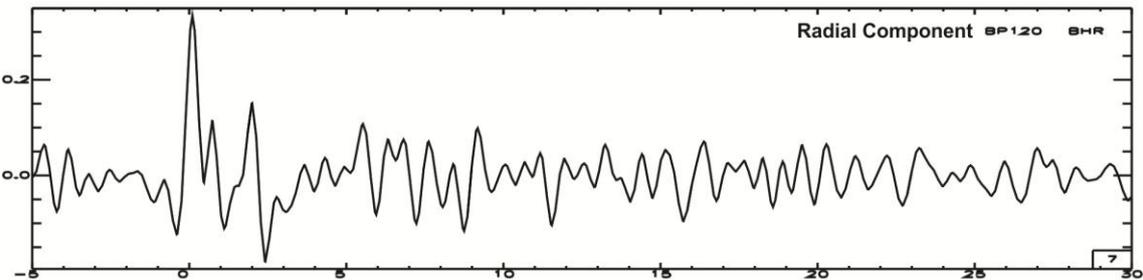
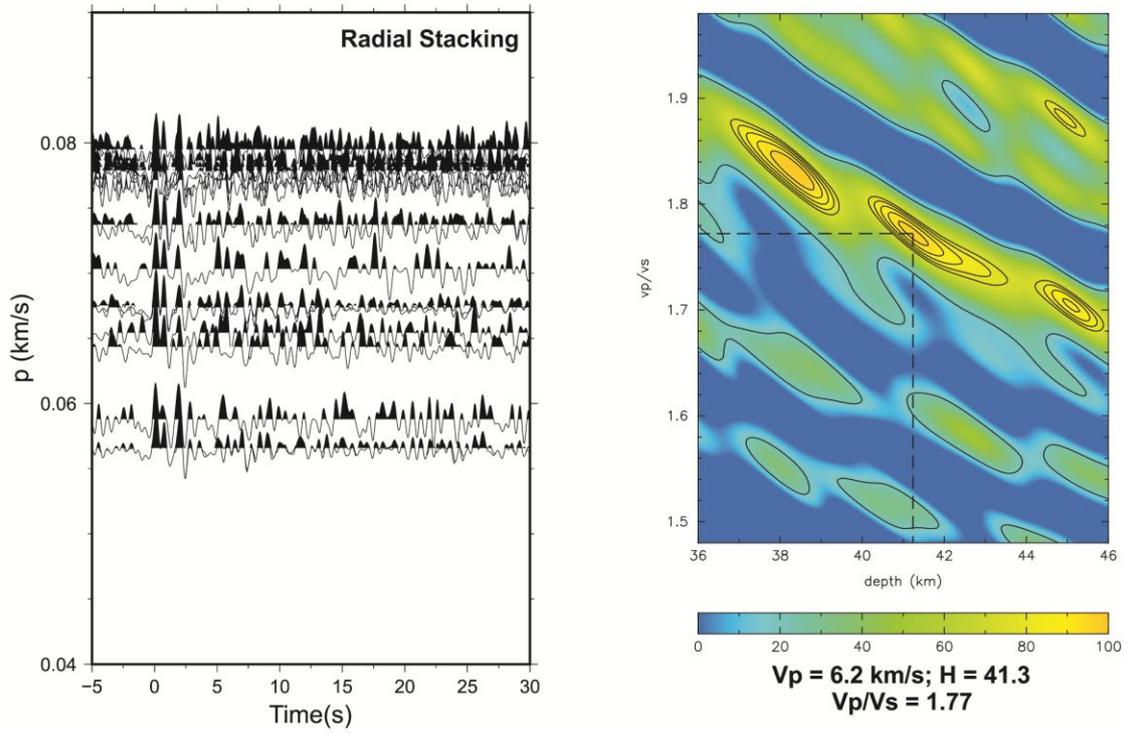
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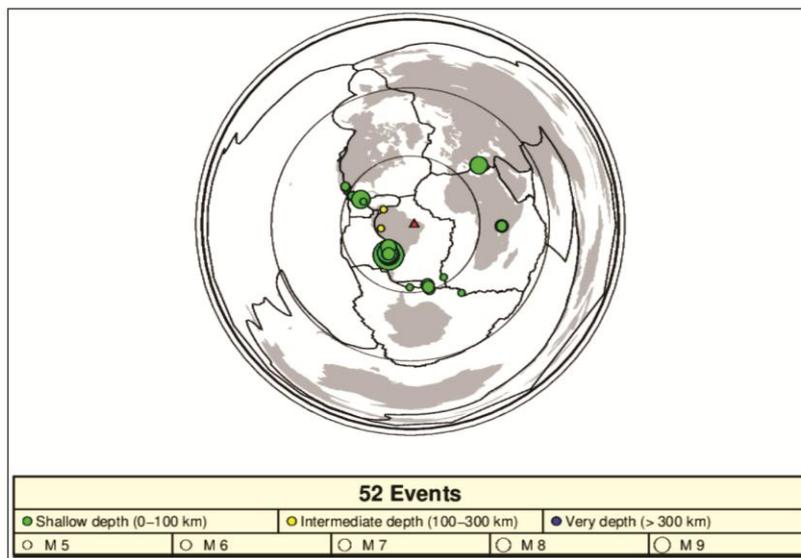
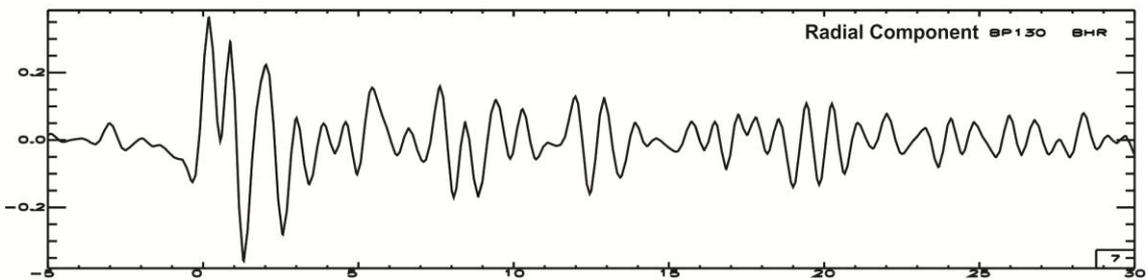
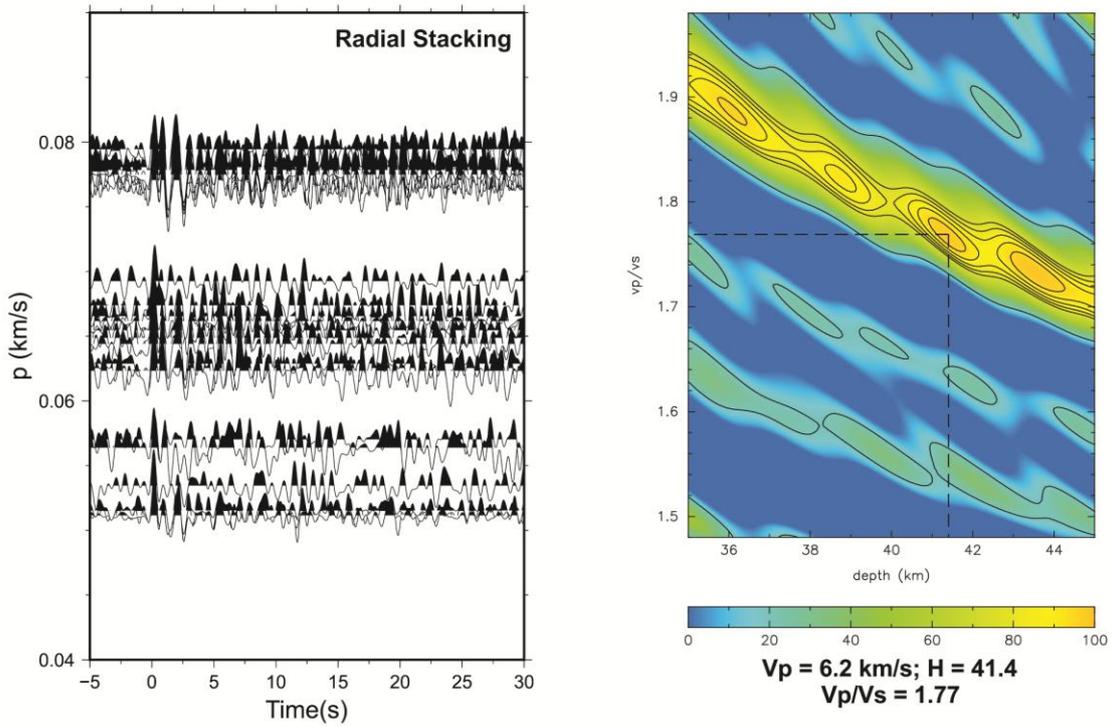
BP_110



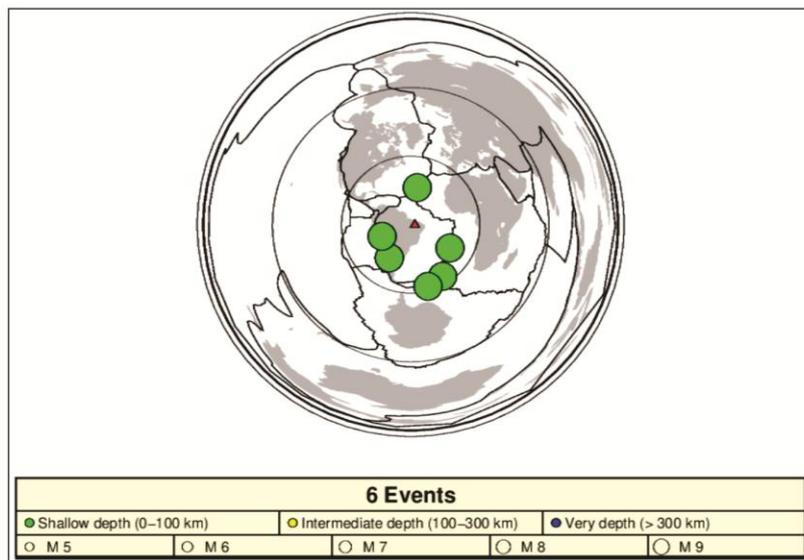
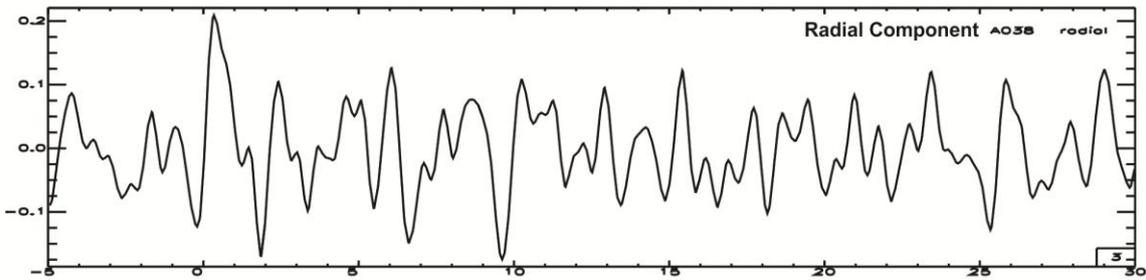
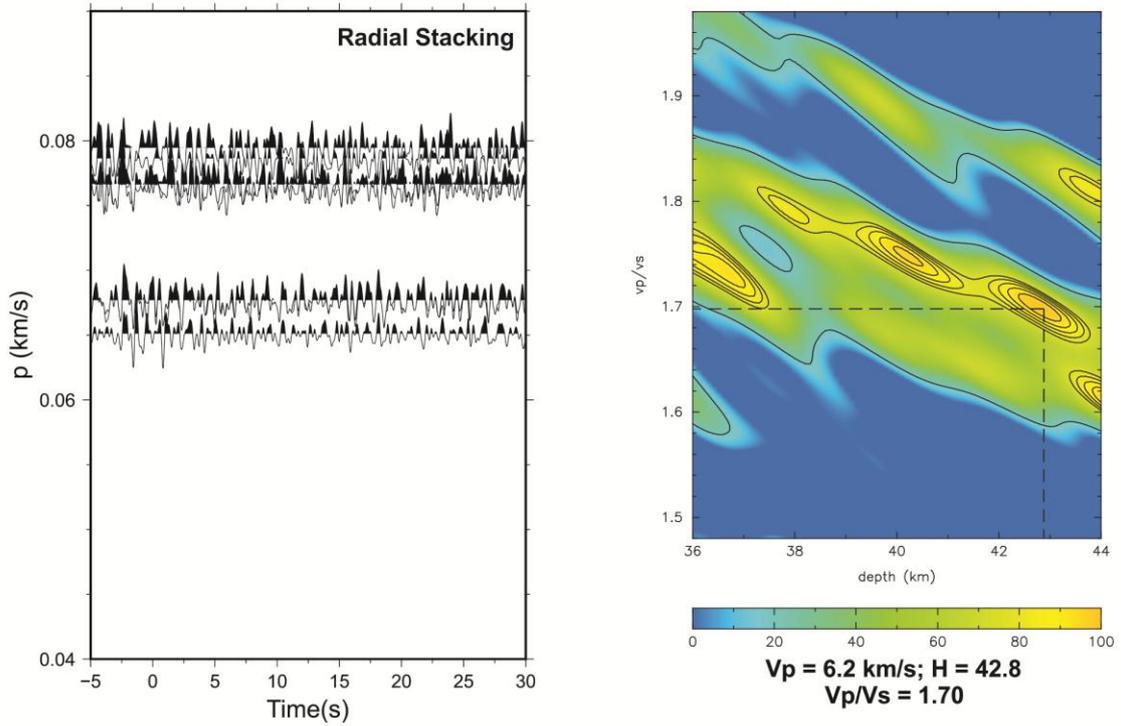
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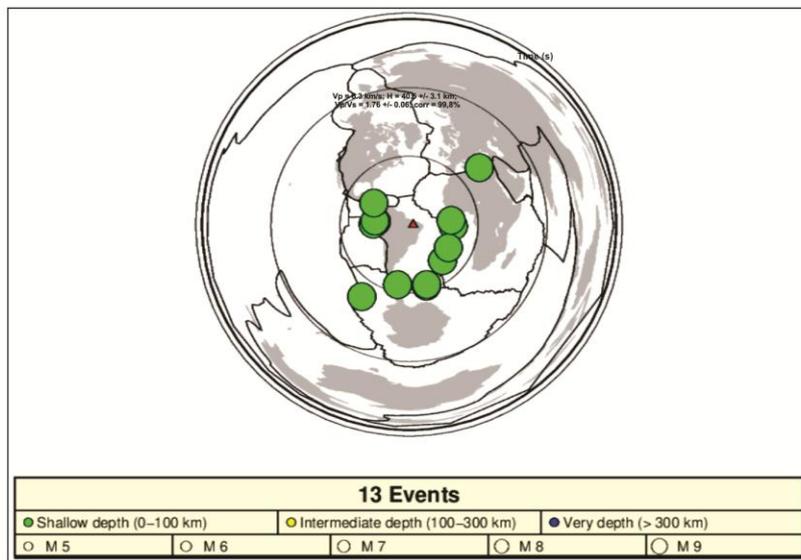
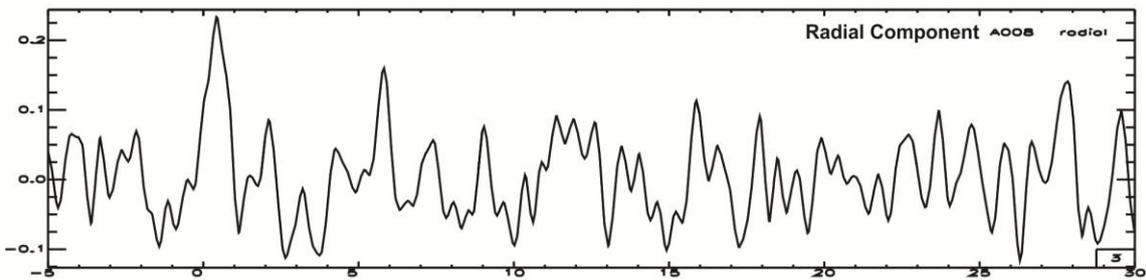
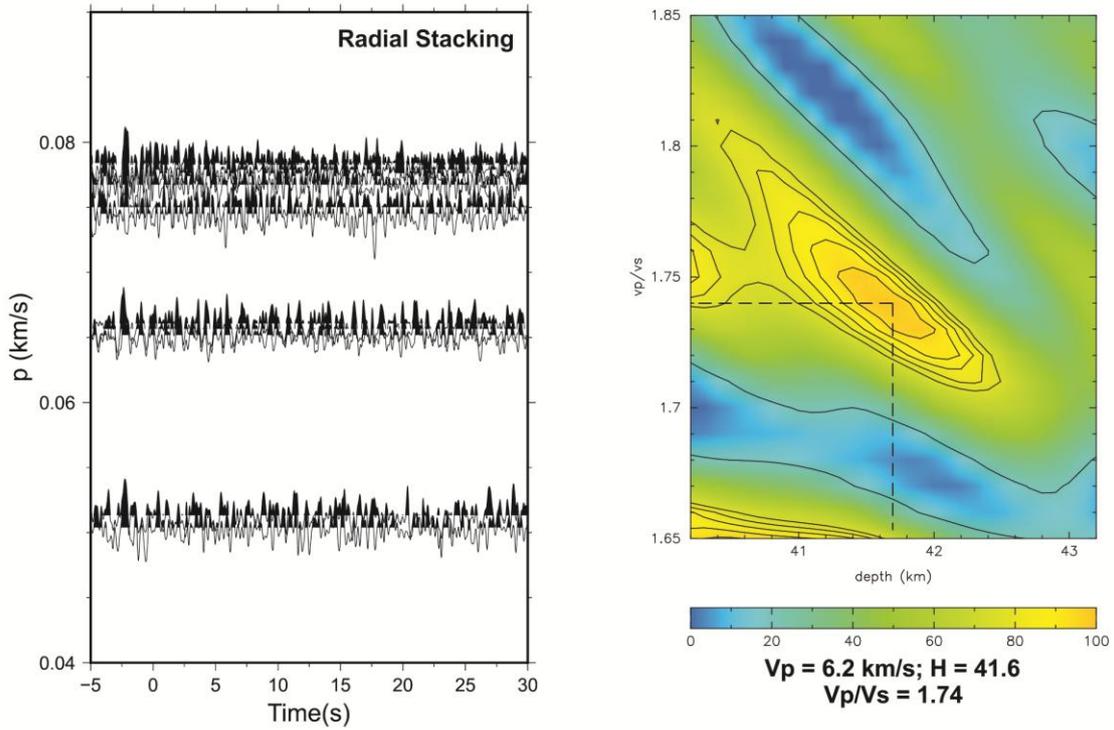
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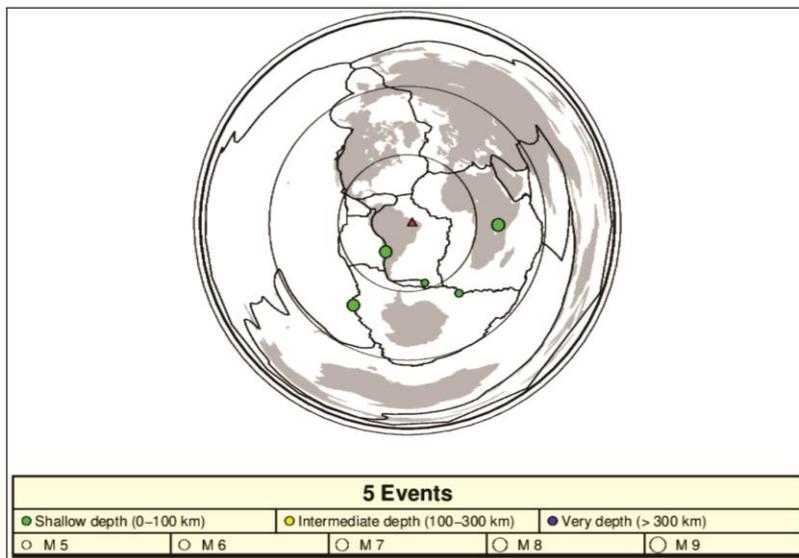
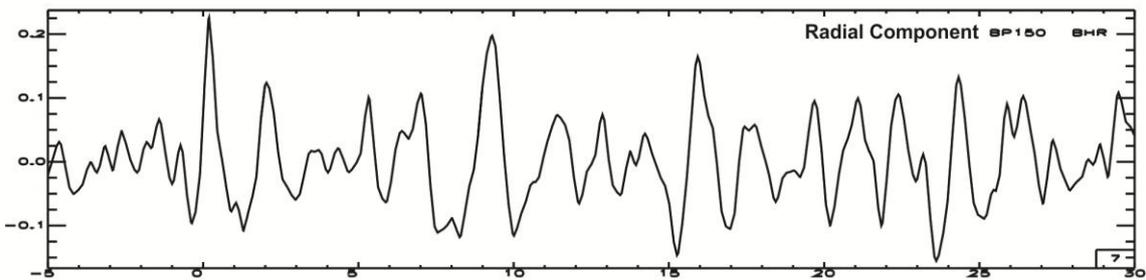
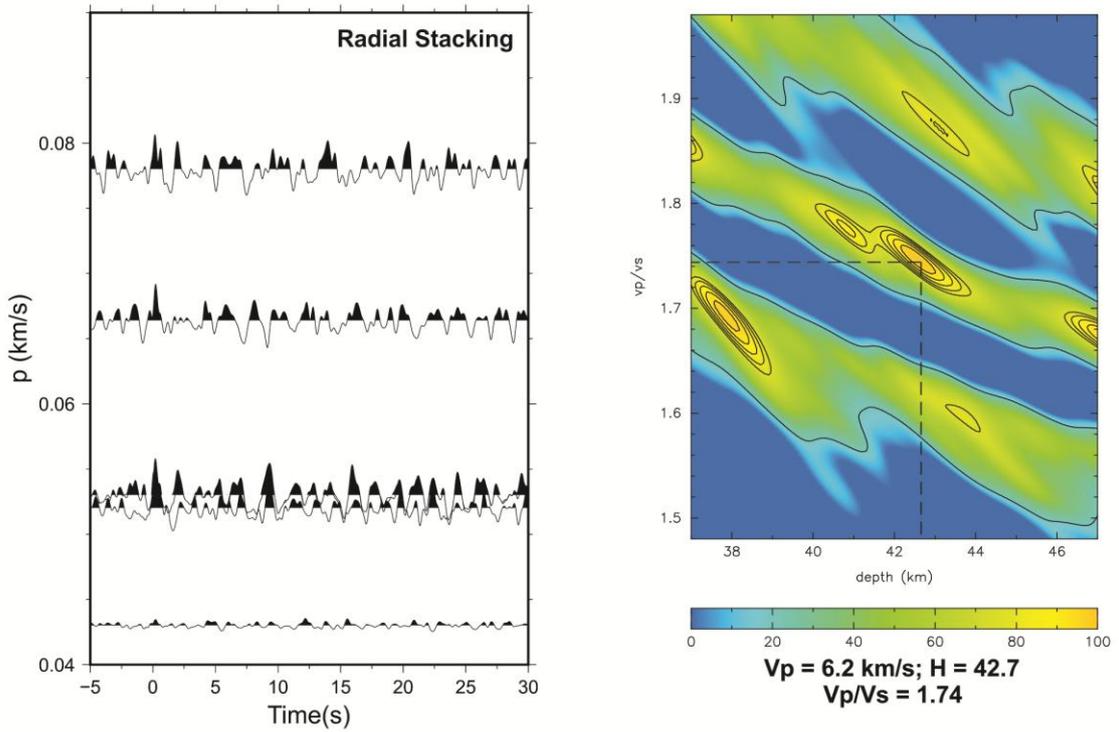
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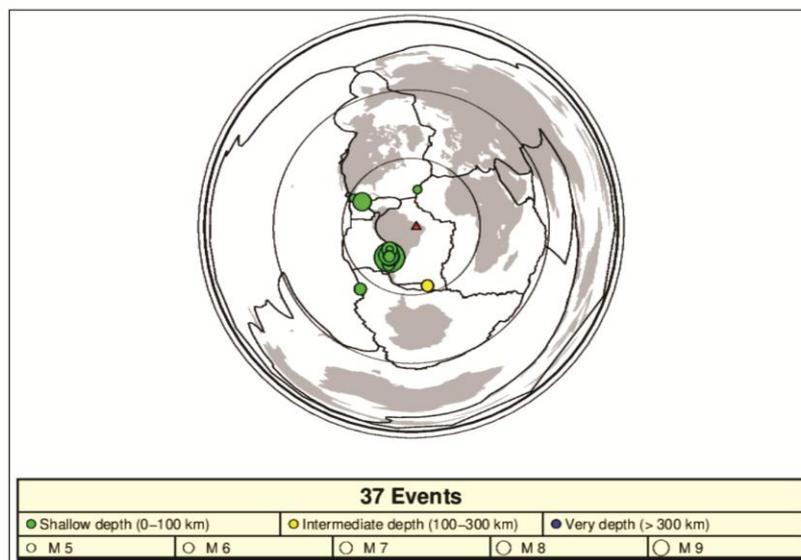
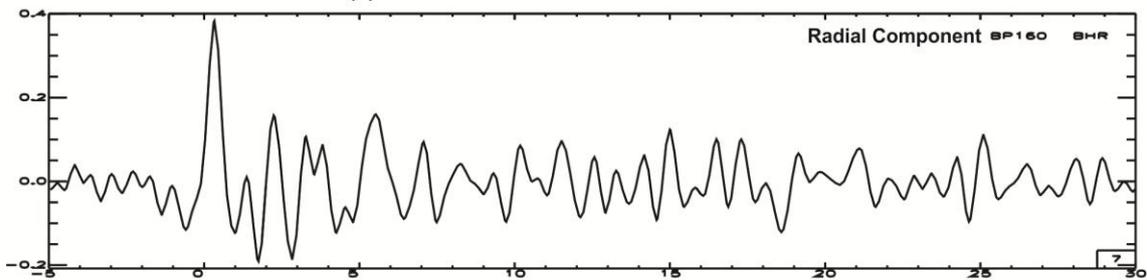
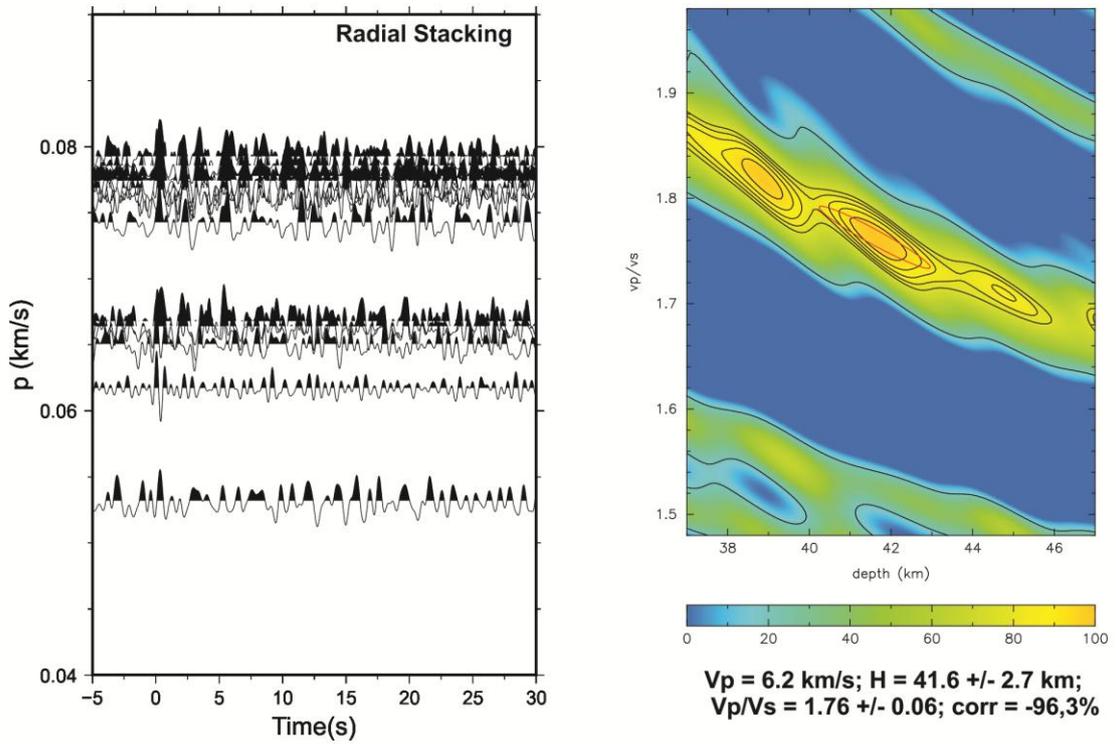
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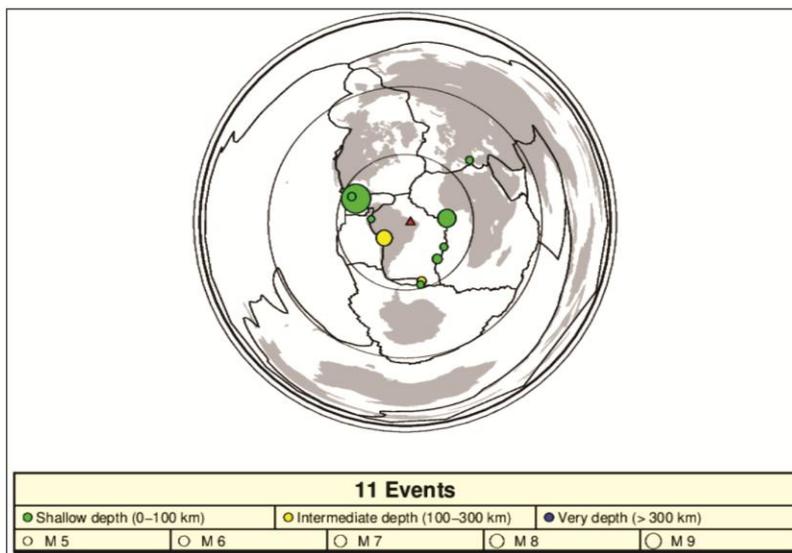
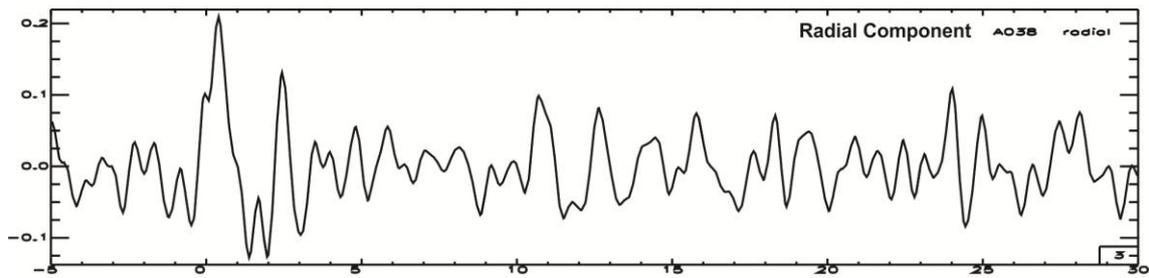
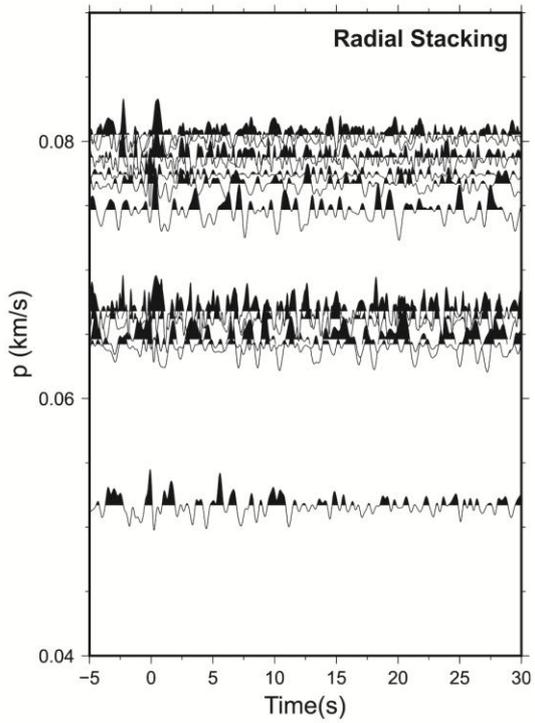
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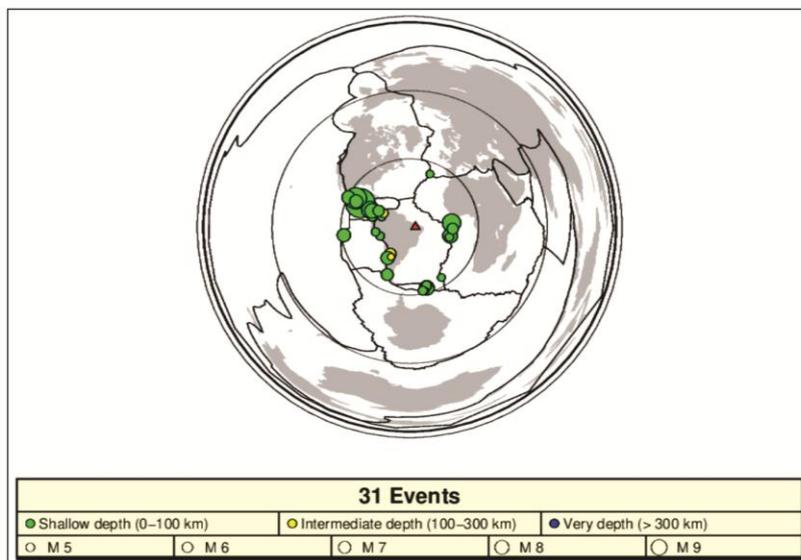
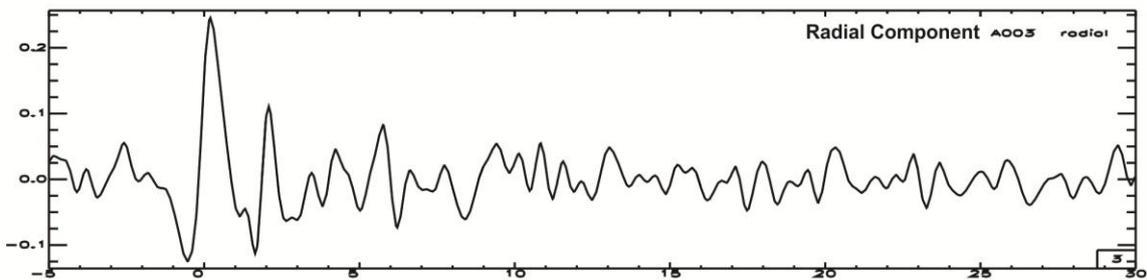
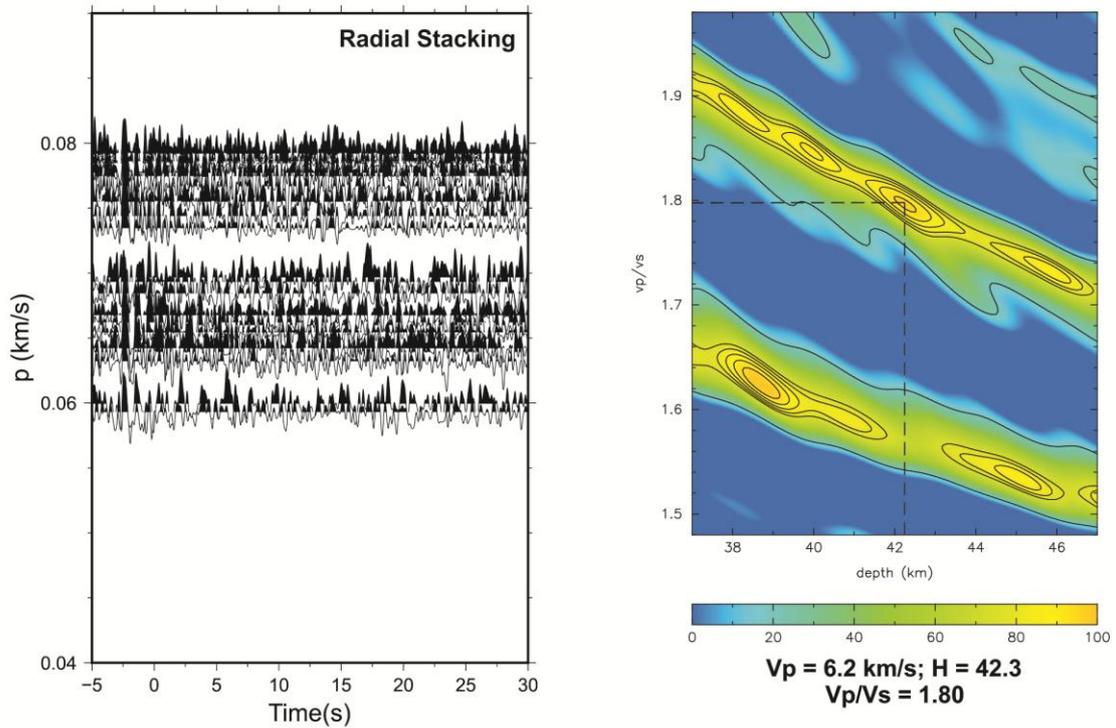
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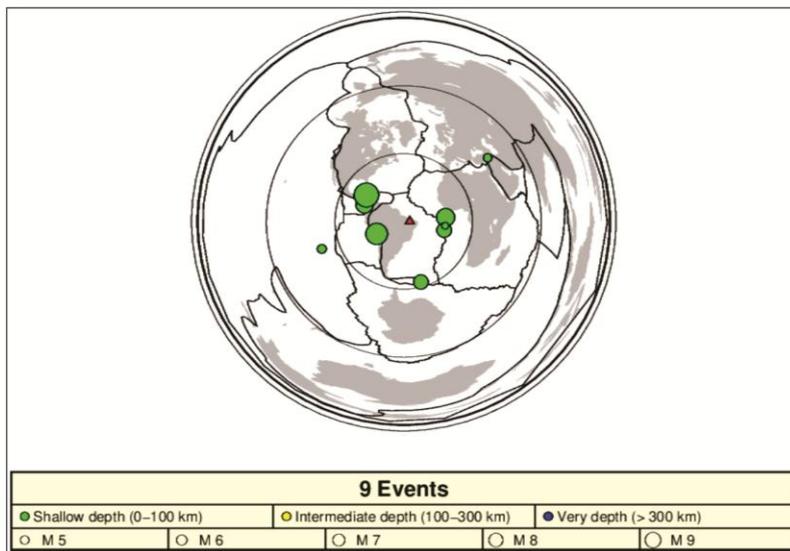
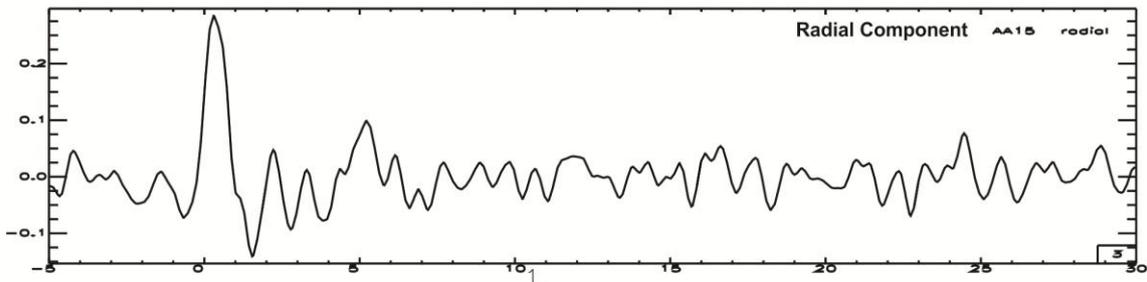
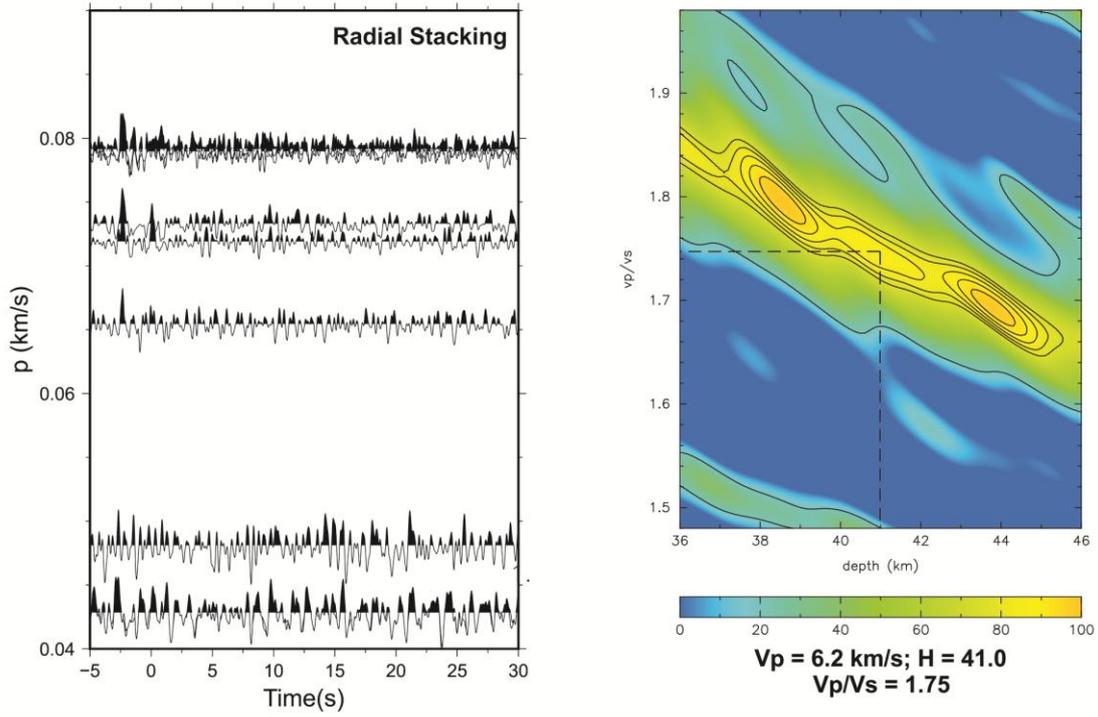
BP_170



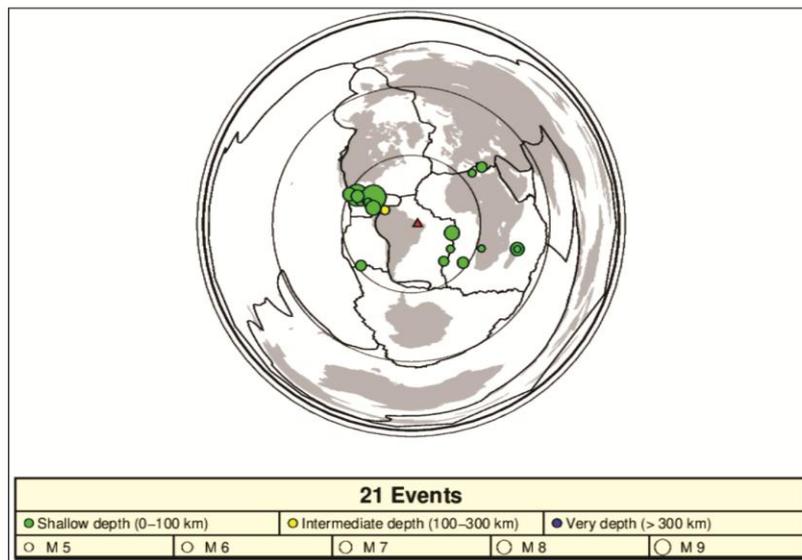
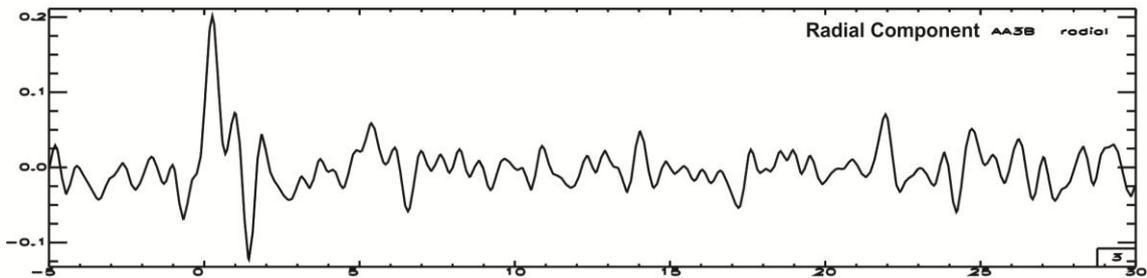
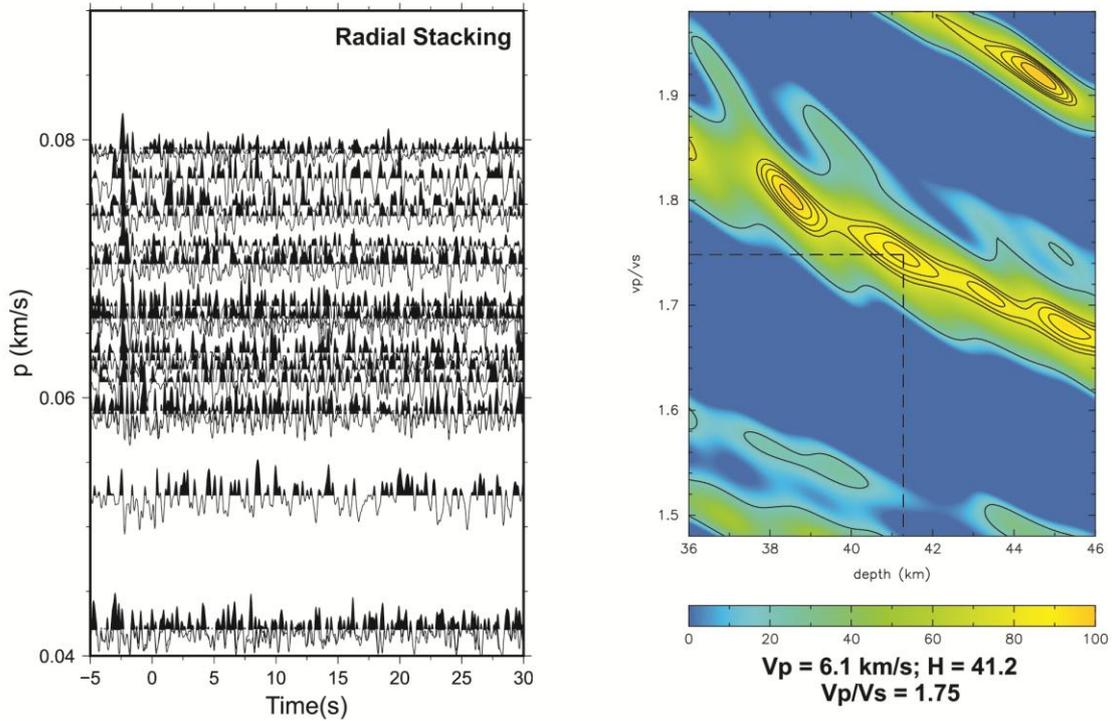
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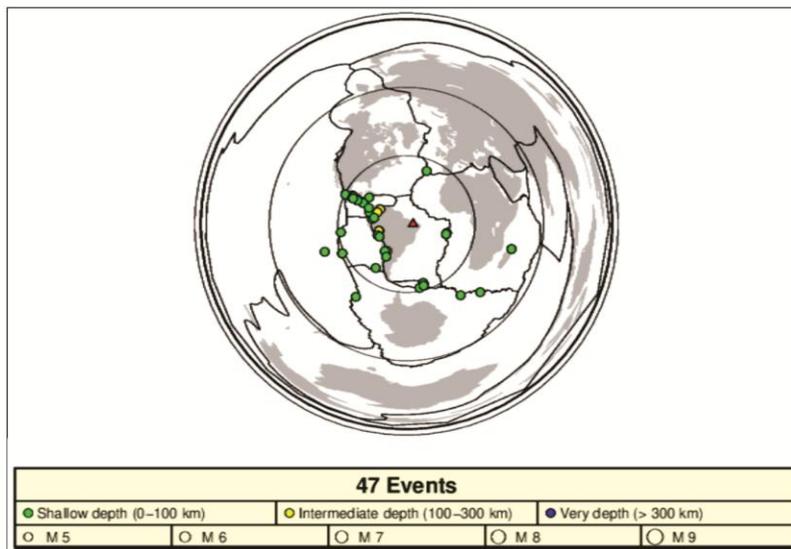
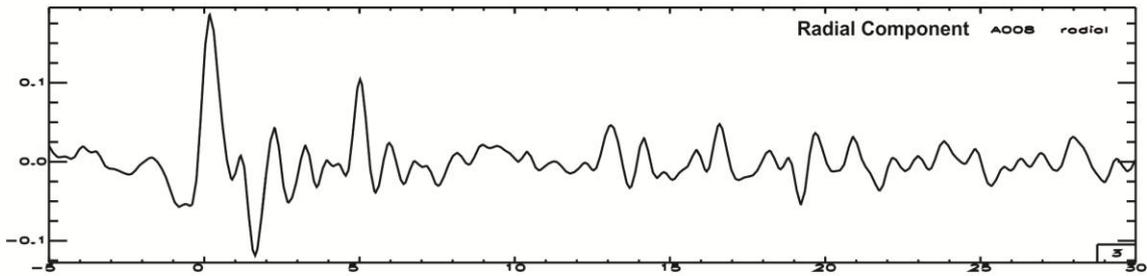
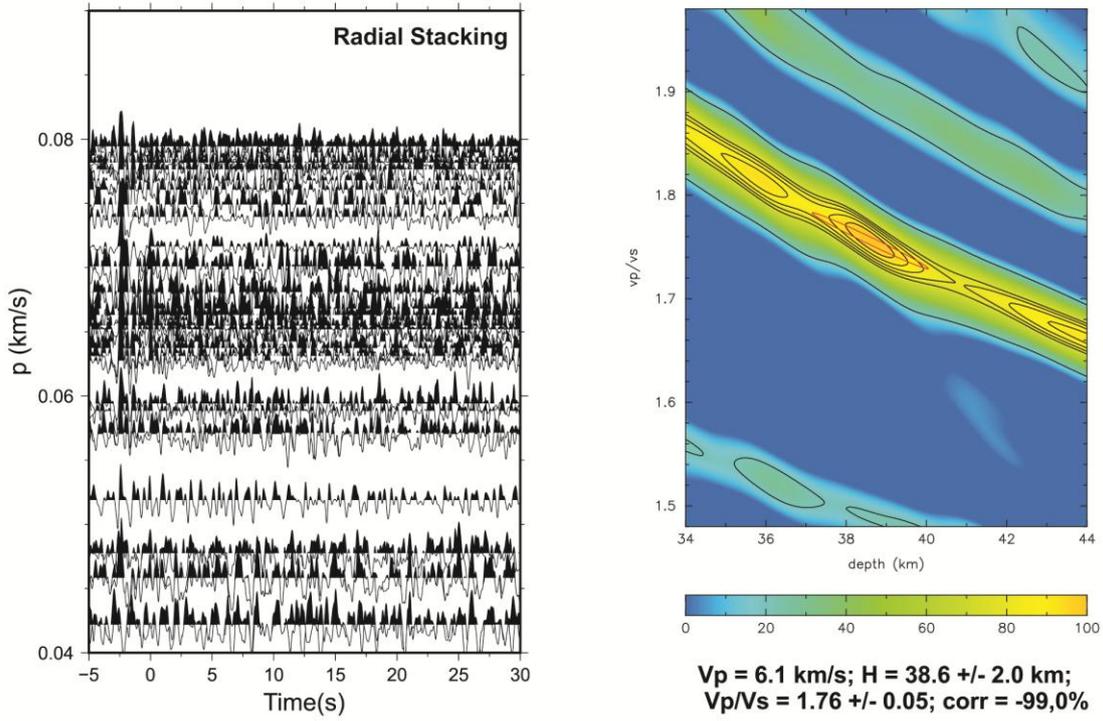
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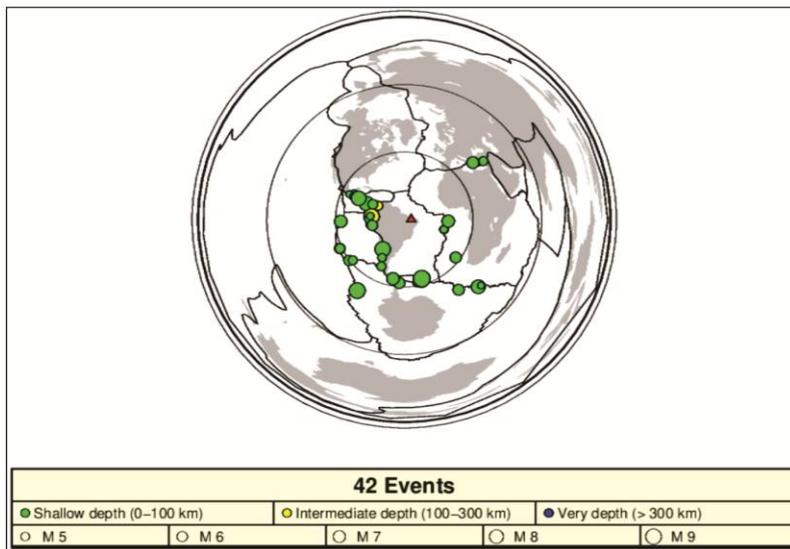
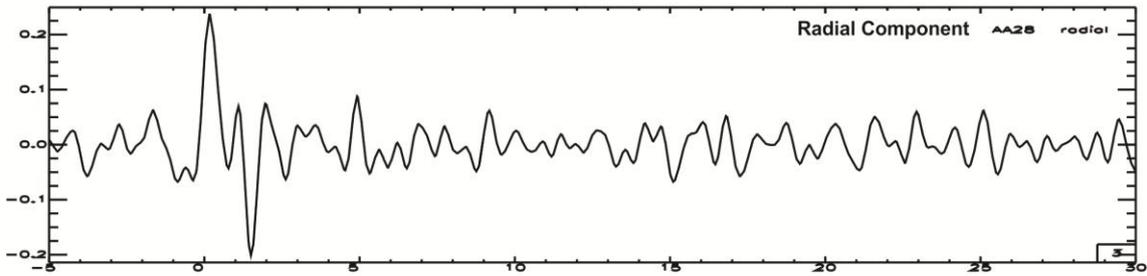
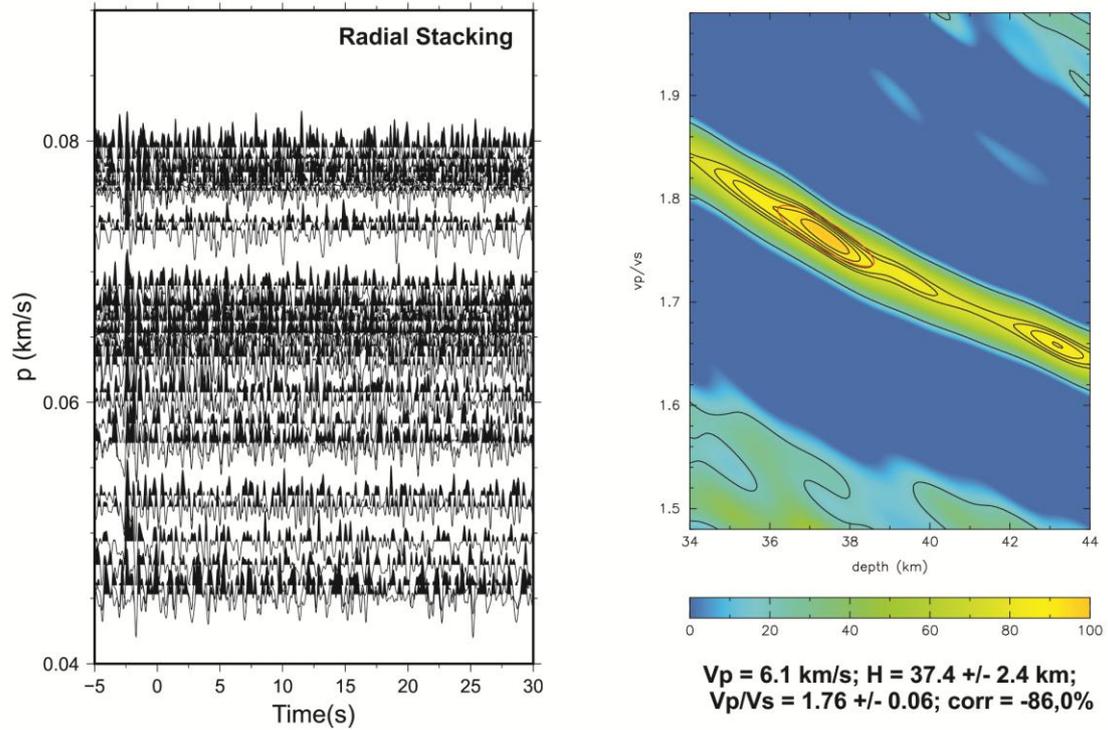
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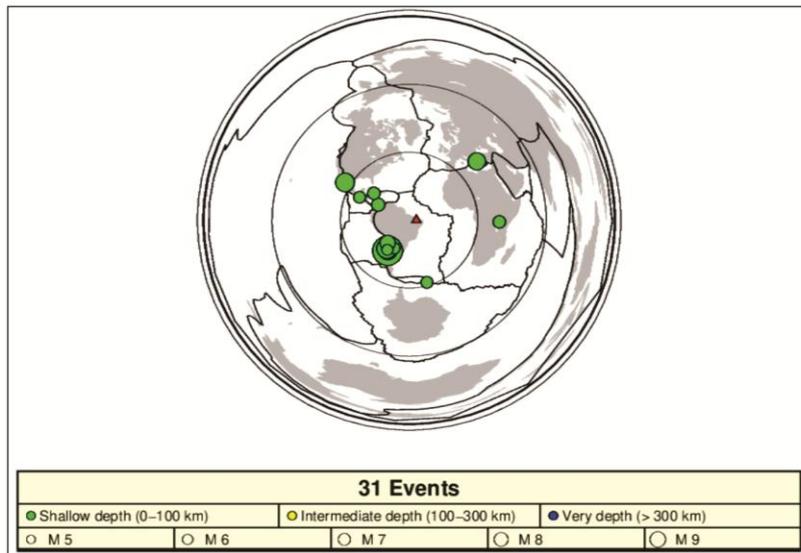
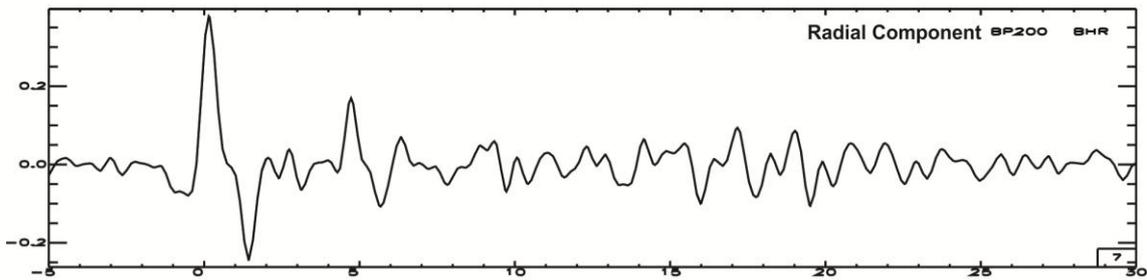
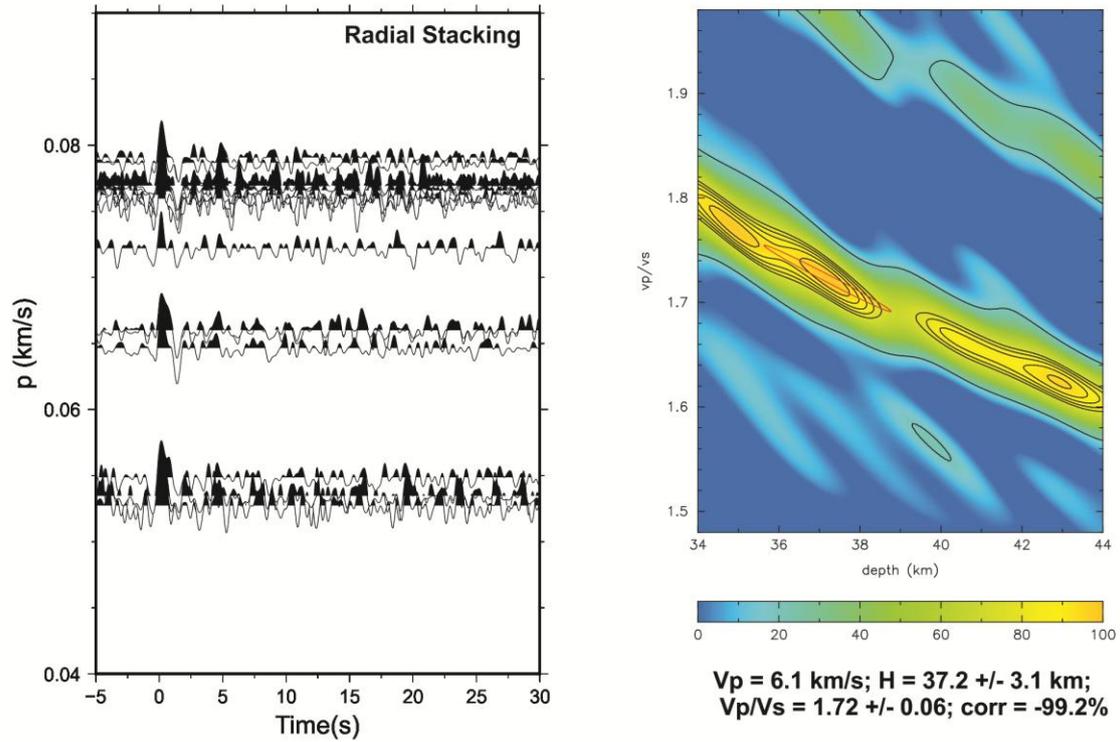
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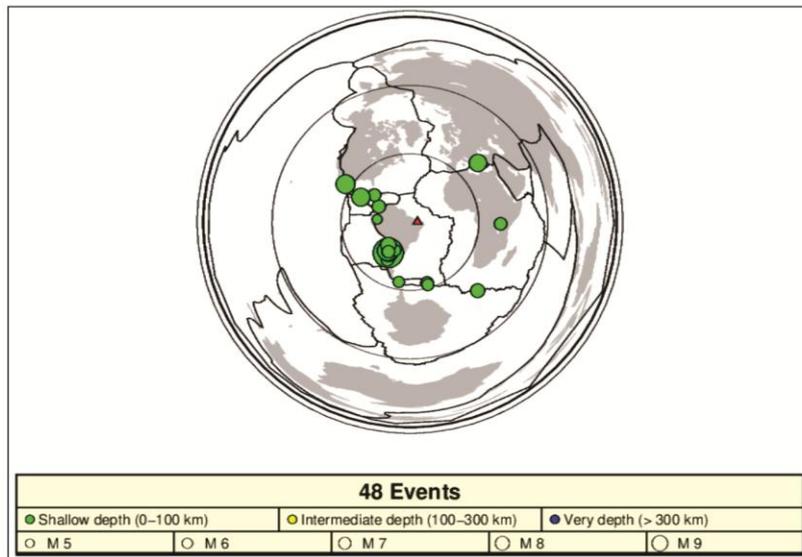
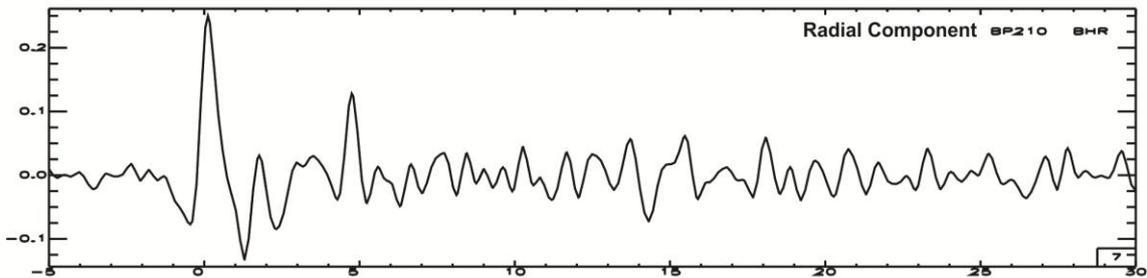
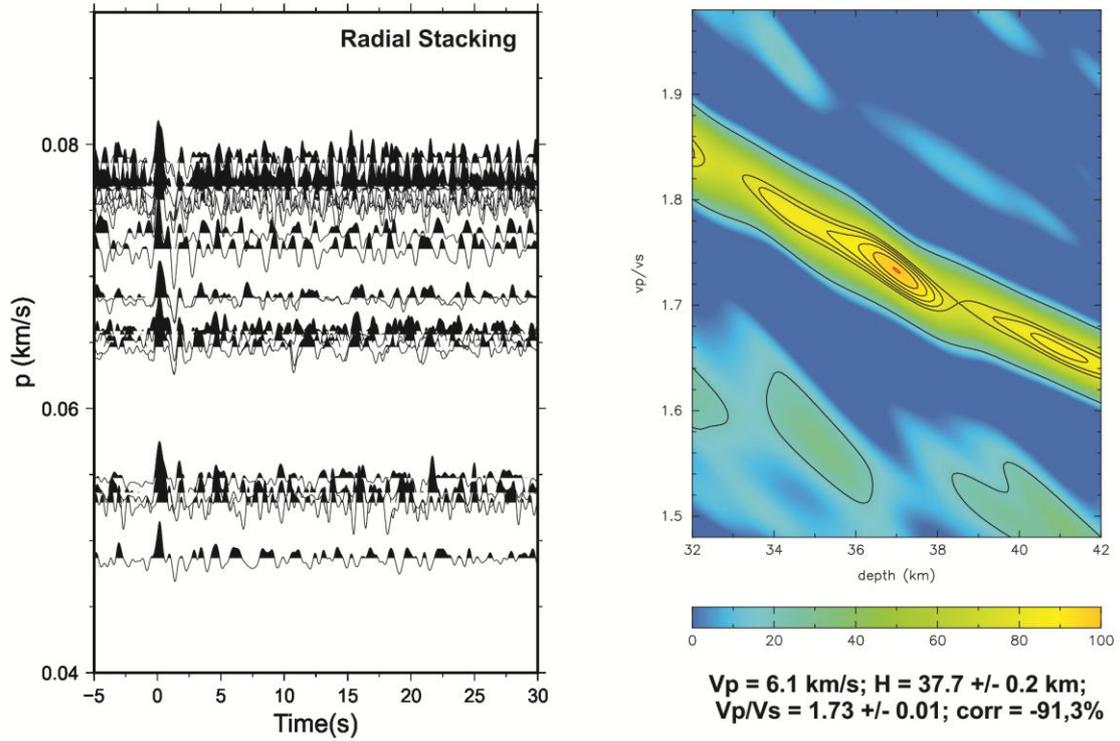
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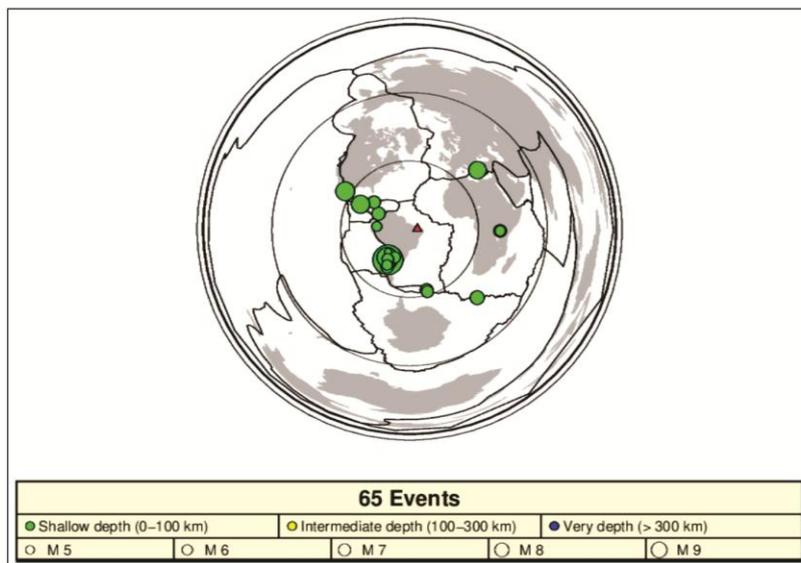
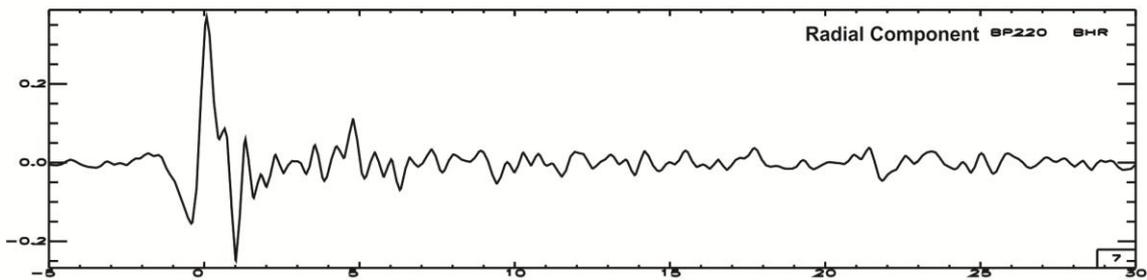
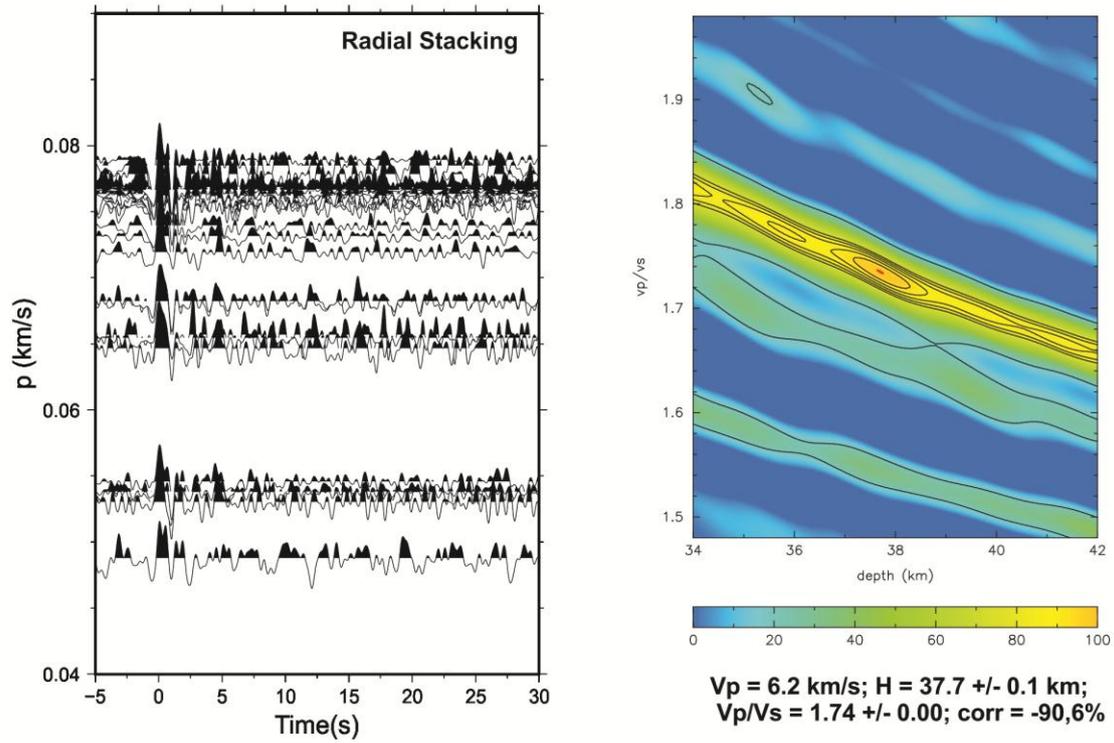
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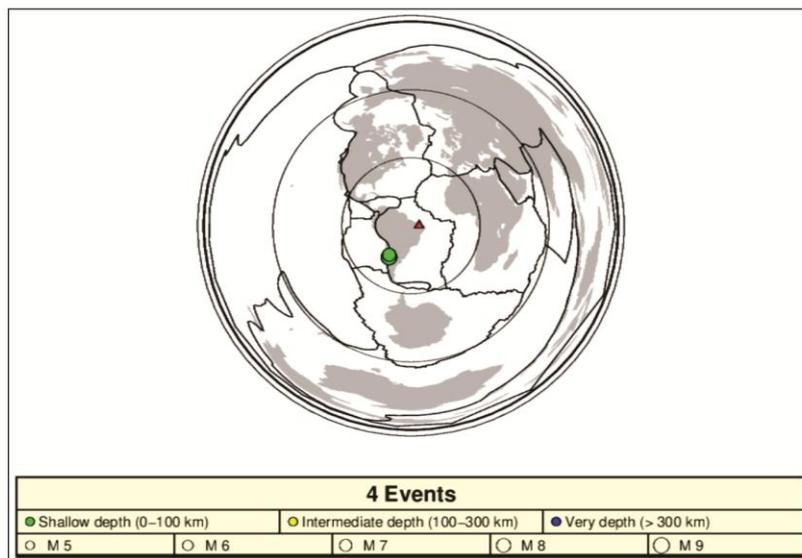
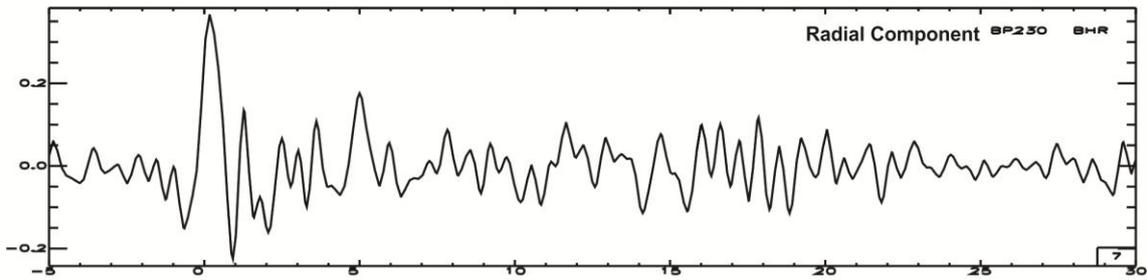
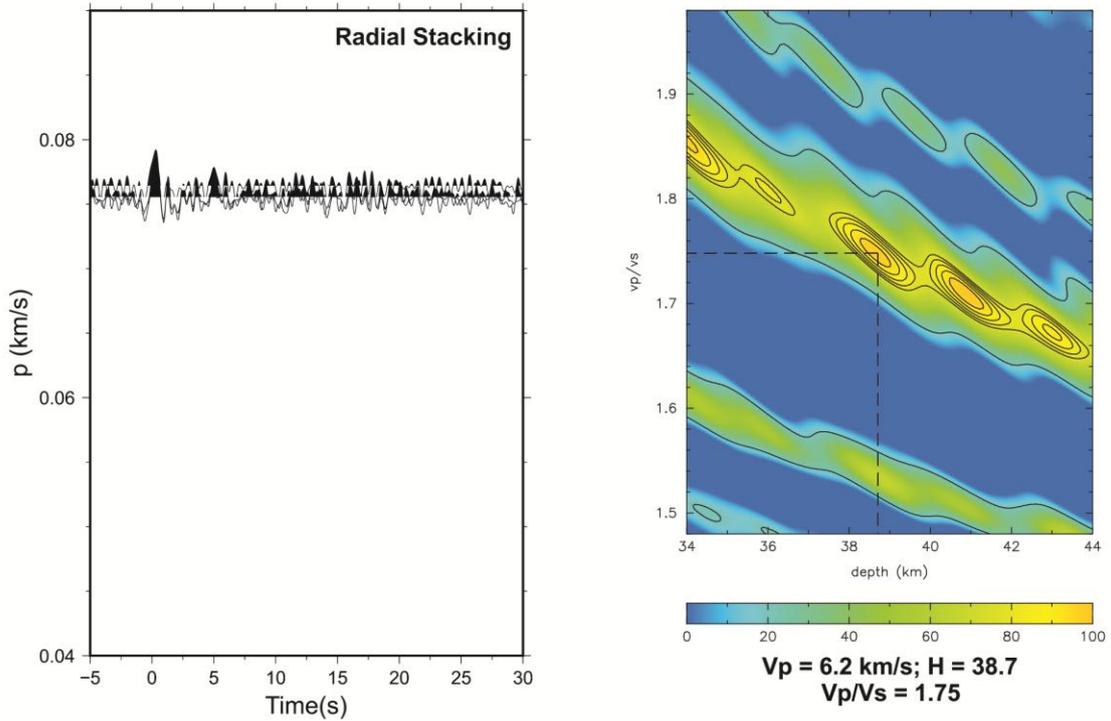
BP_210



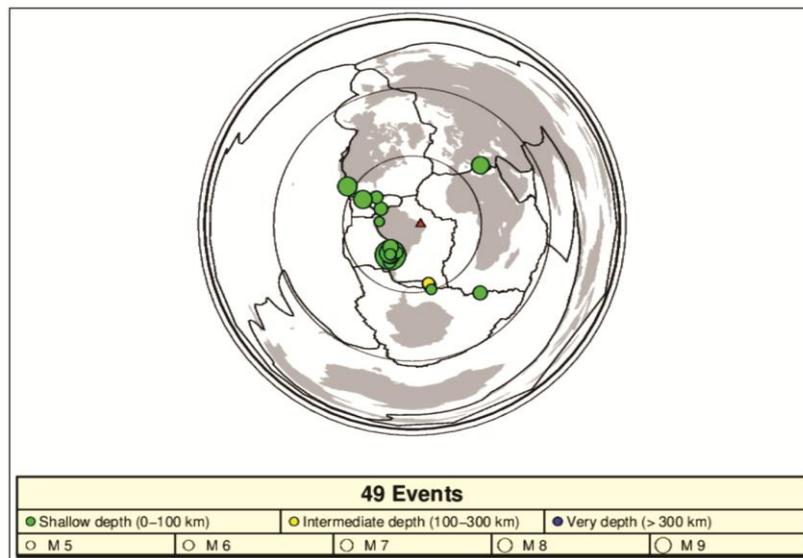
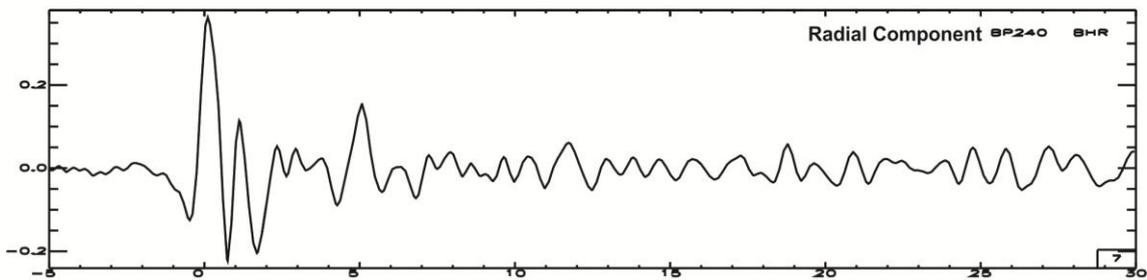
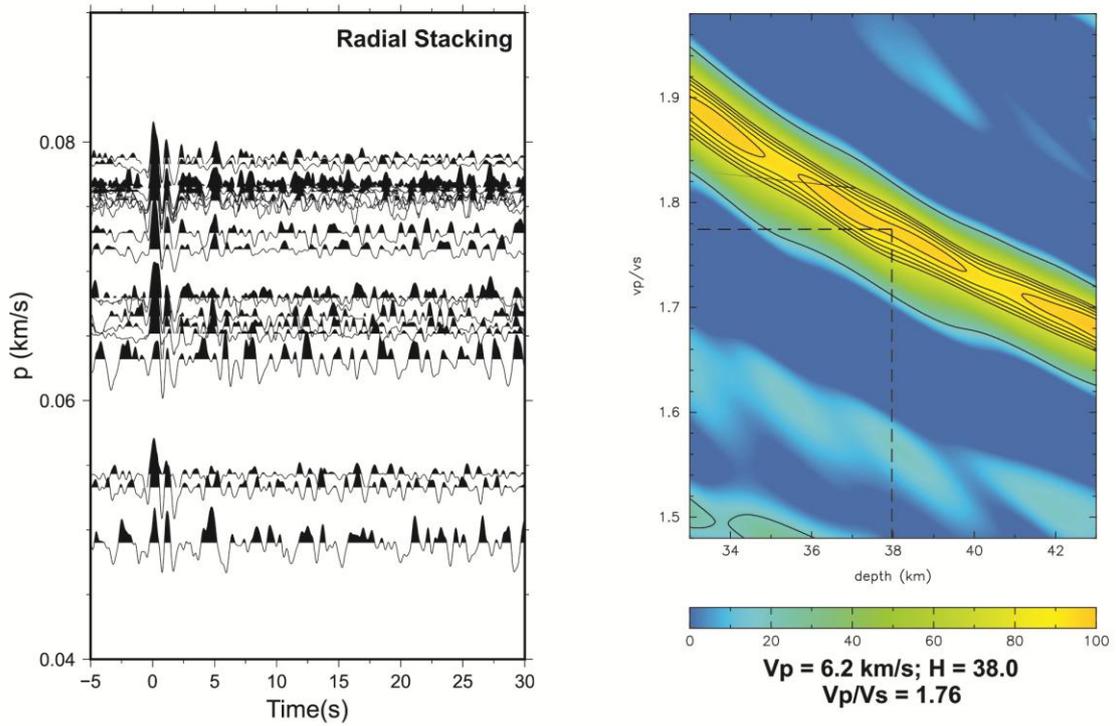
BP_220



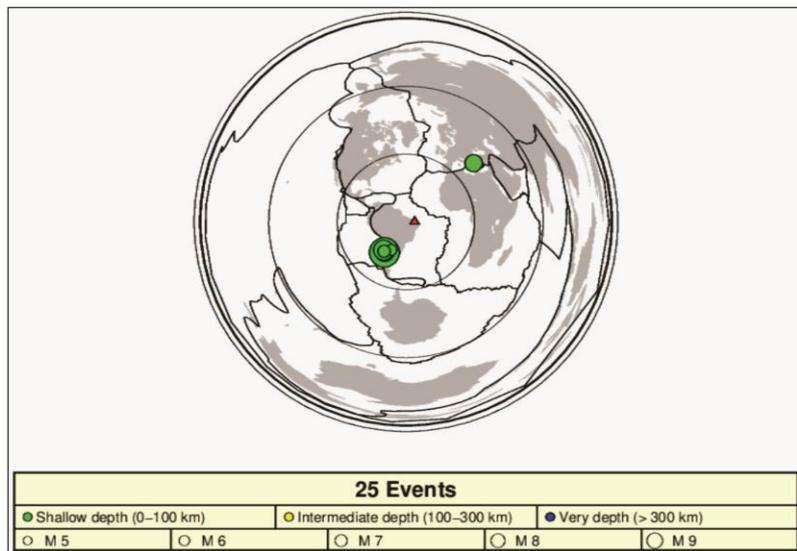
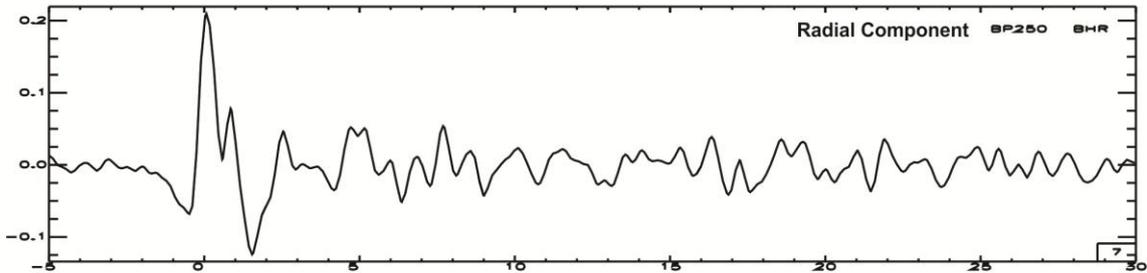
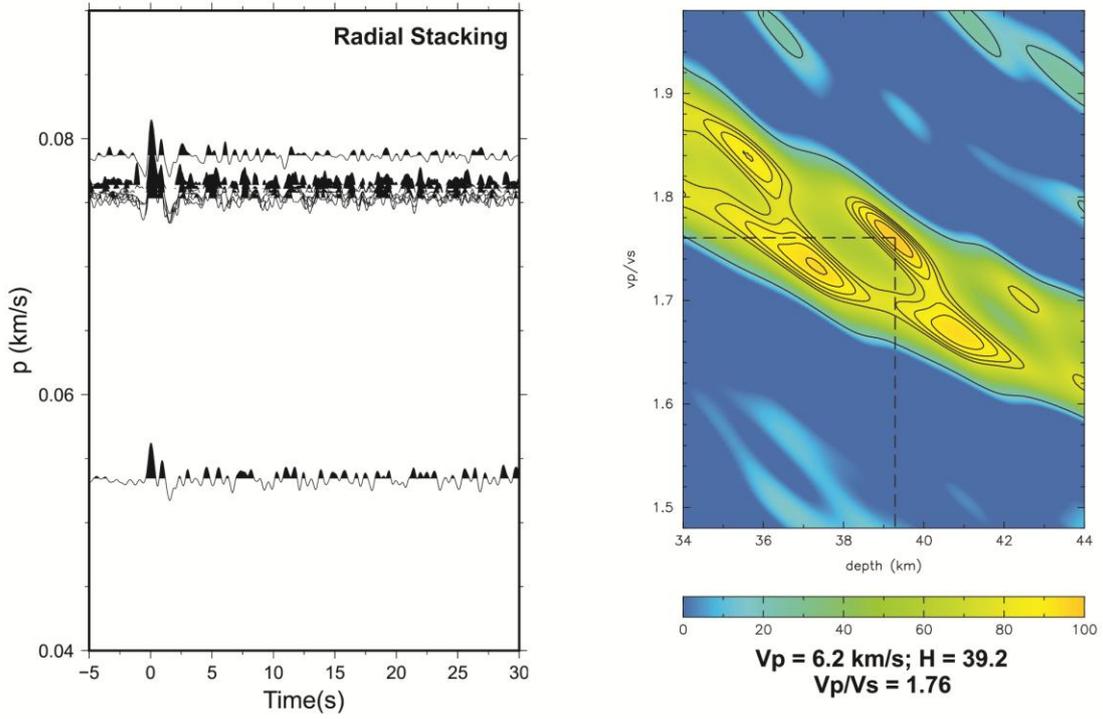
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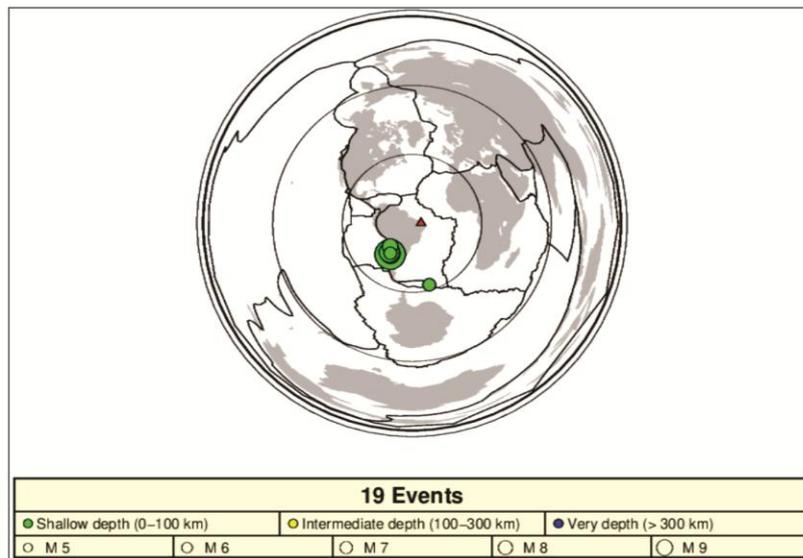
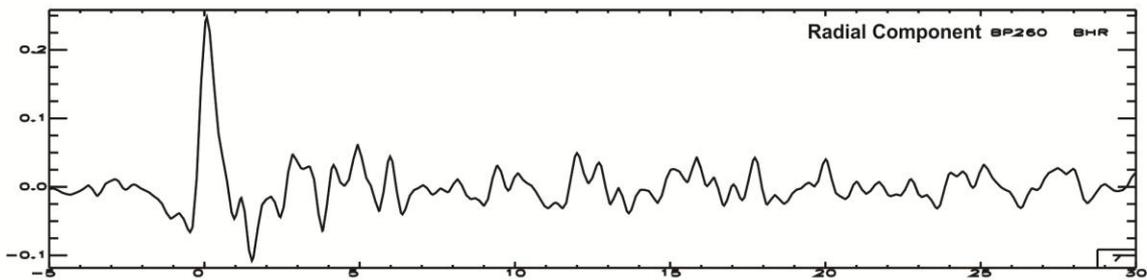
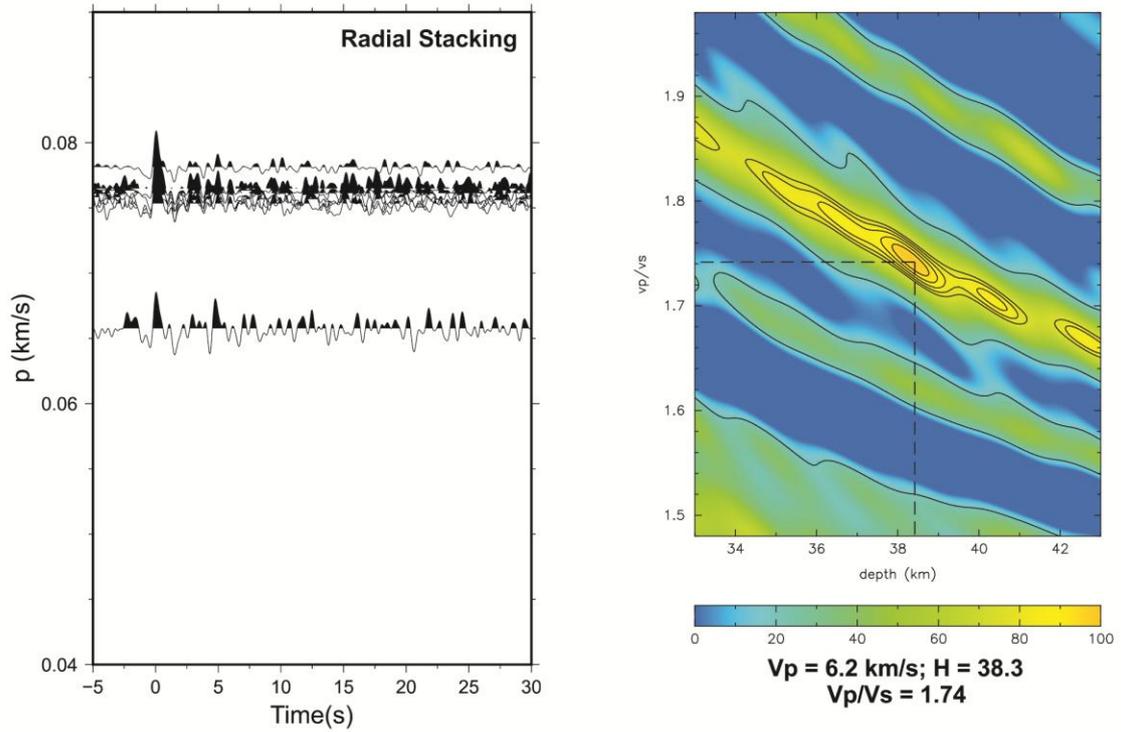
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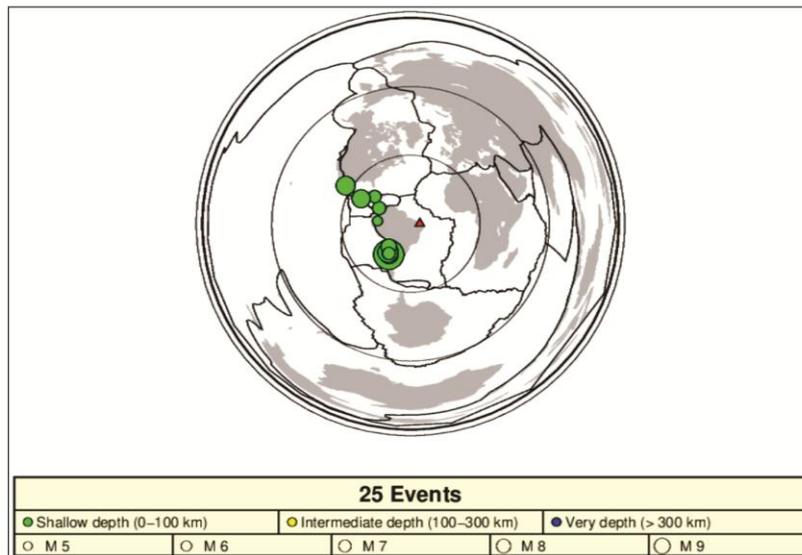
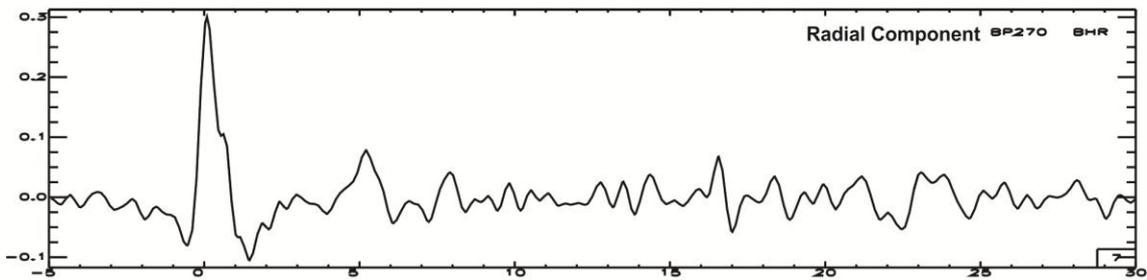
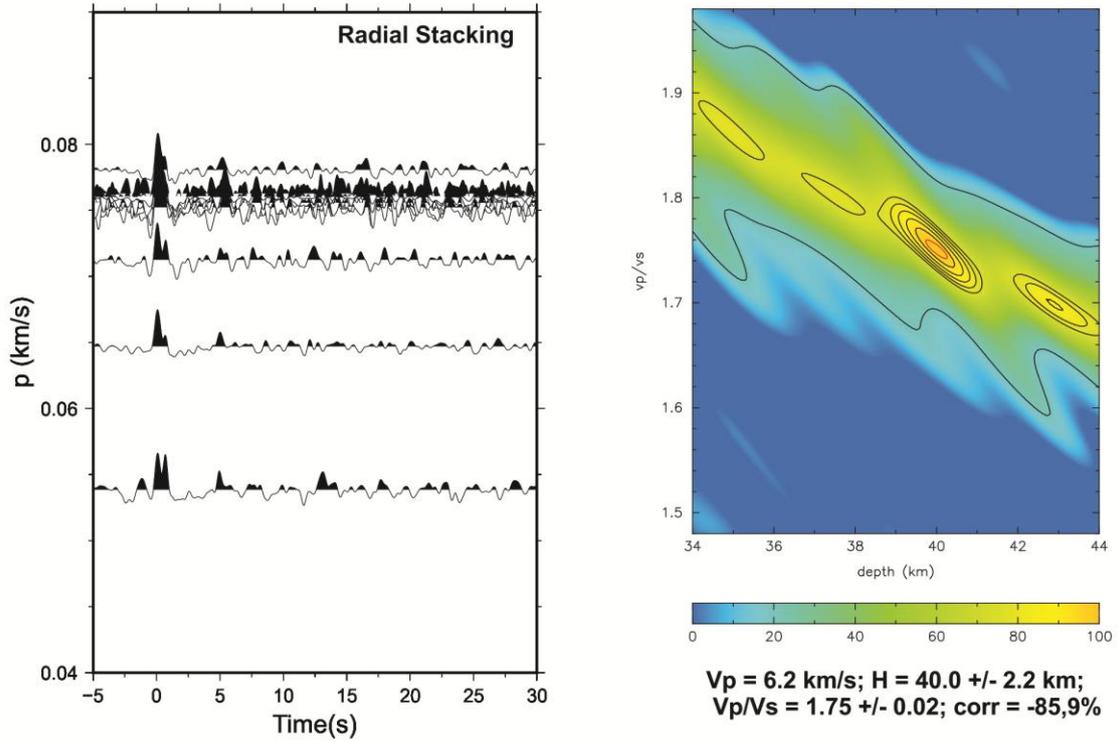
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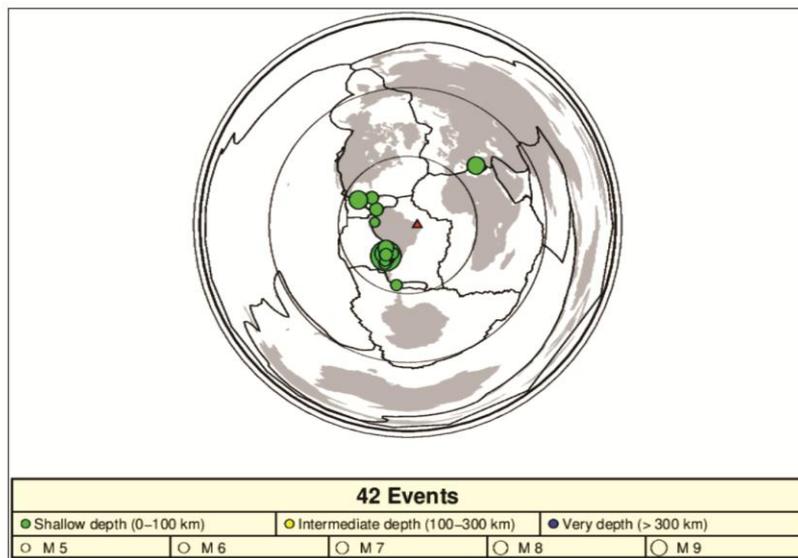
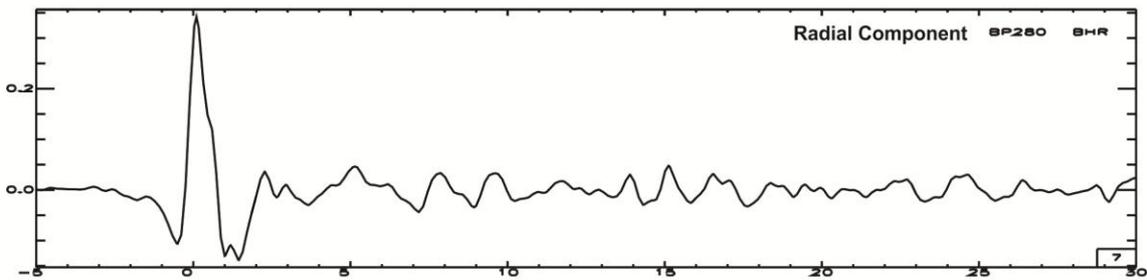
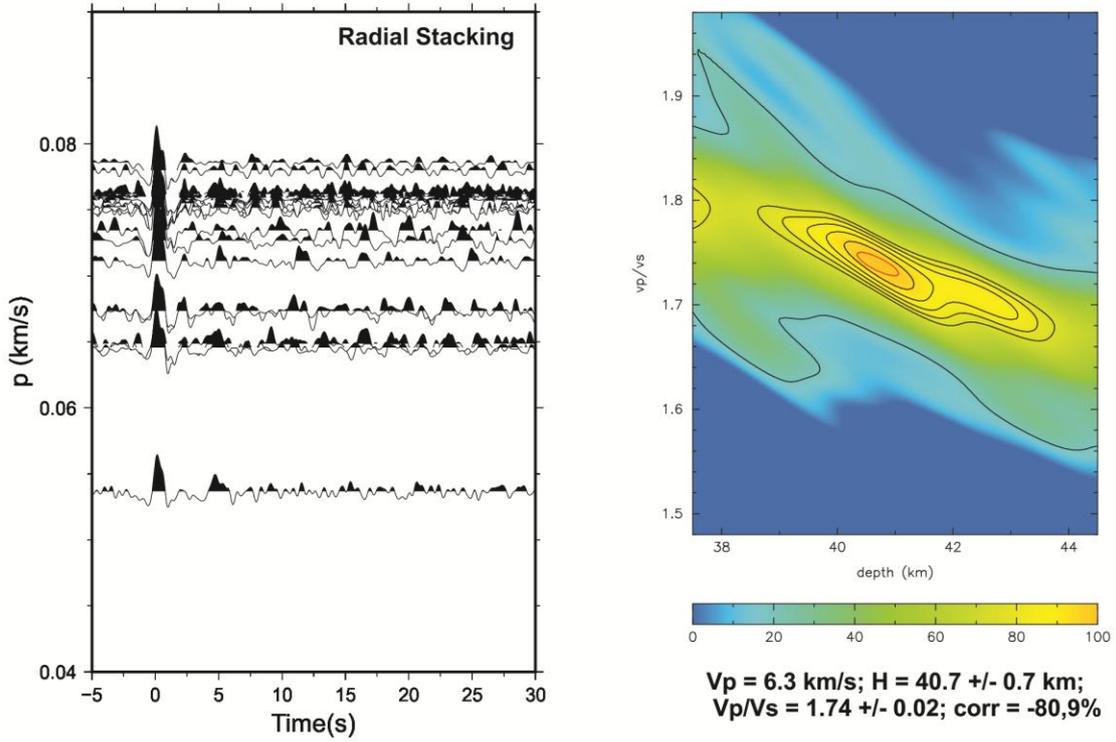
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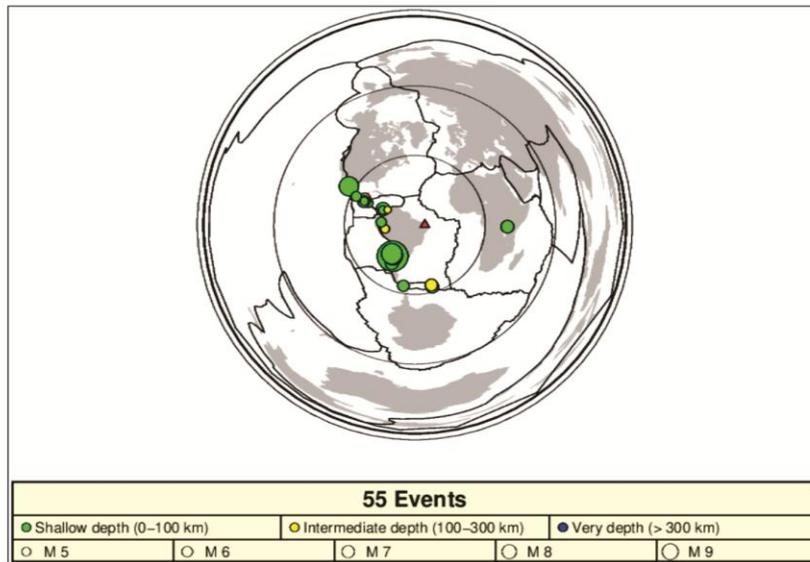
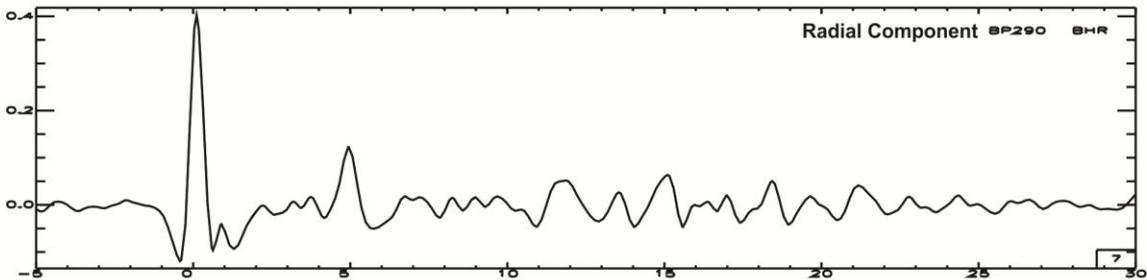
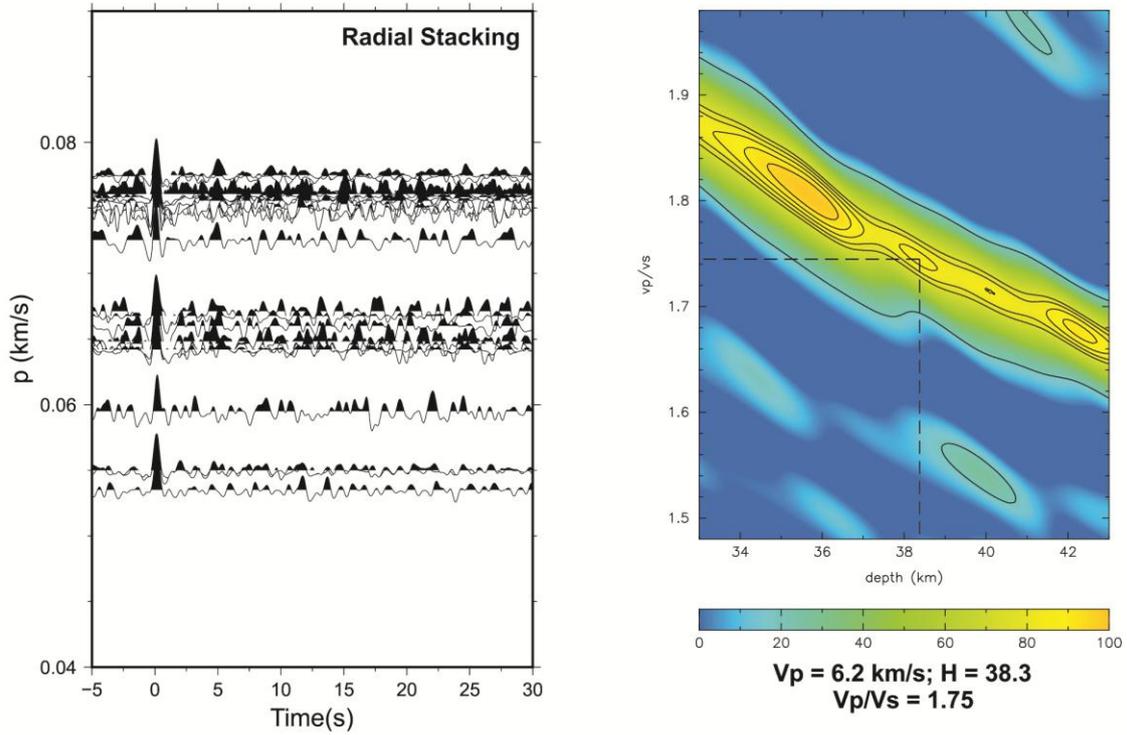
BP_270



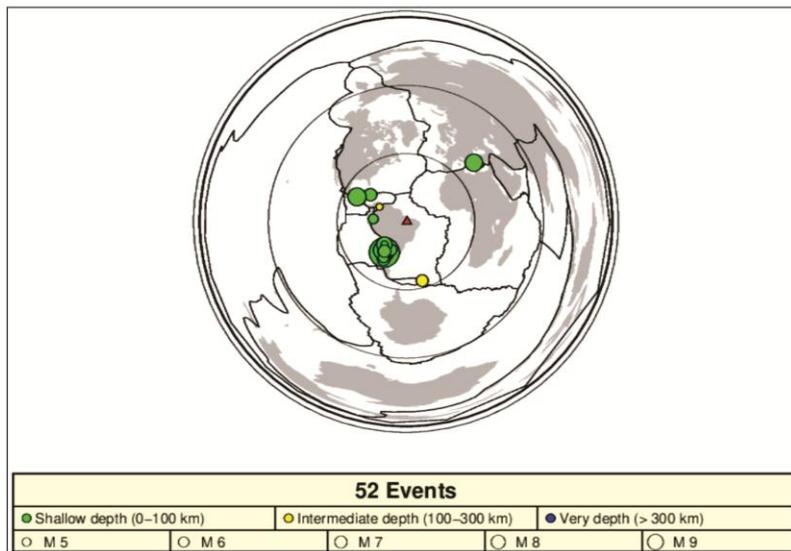
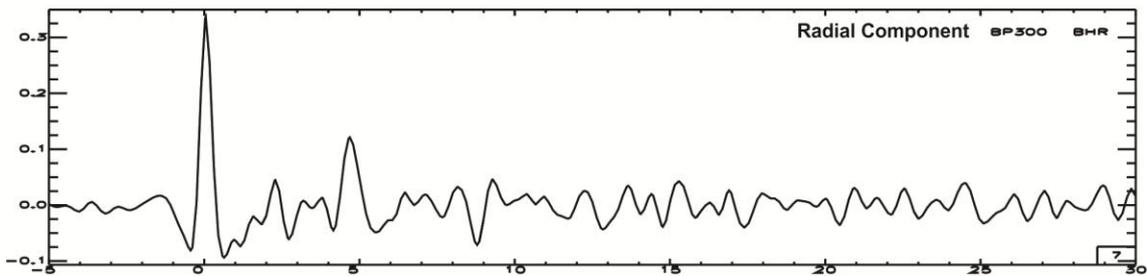
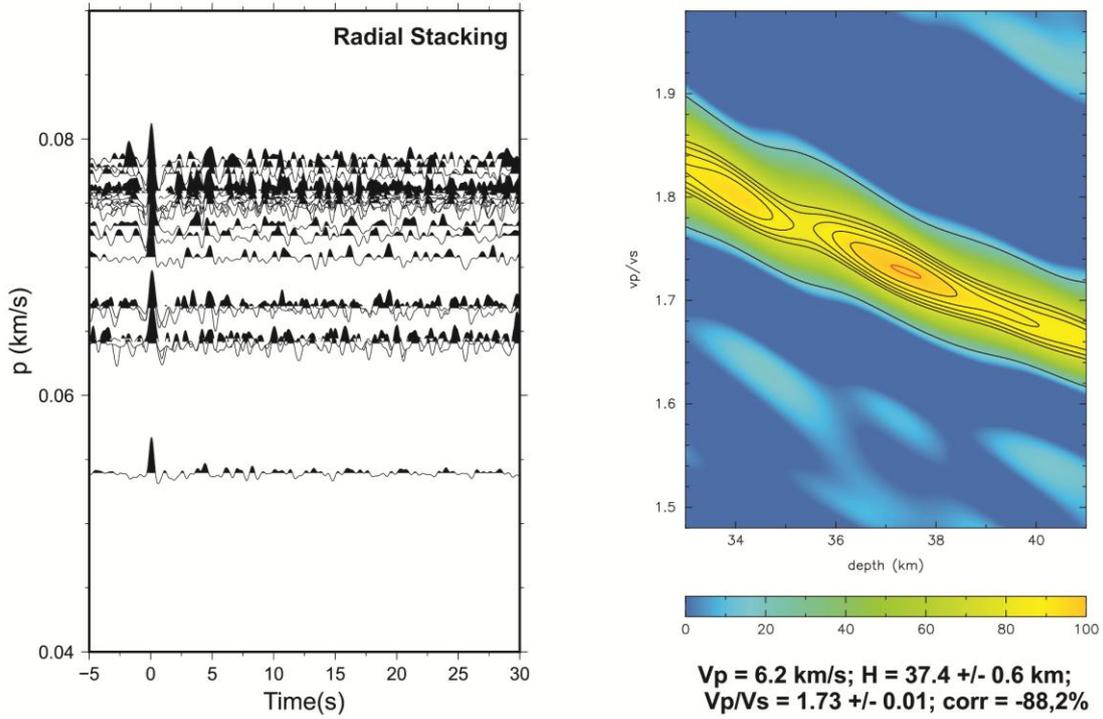
BP_280



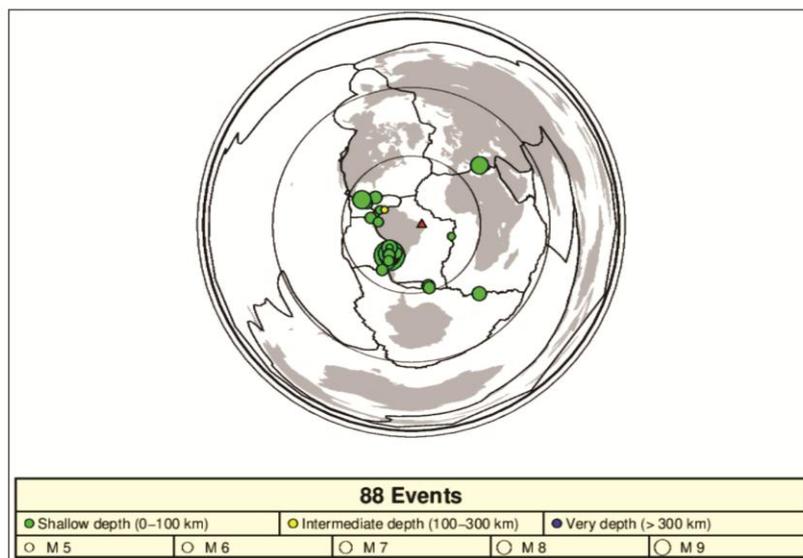
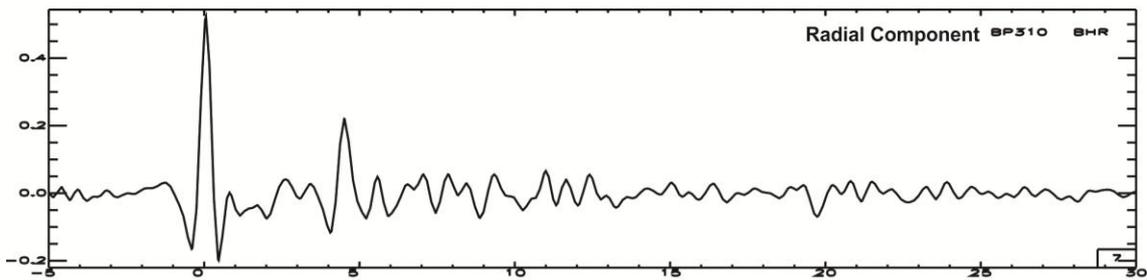
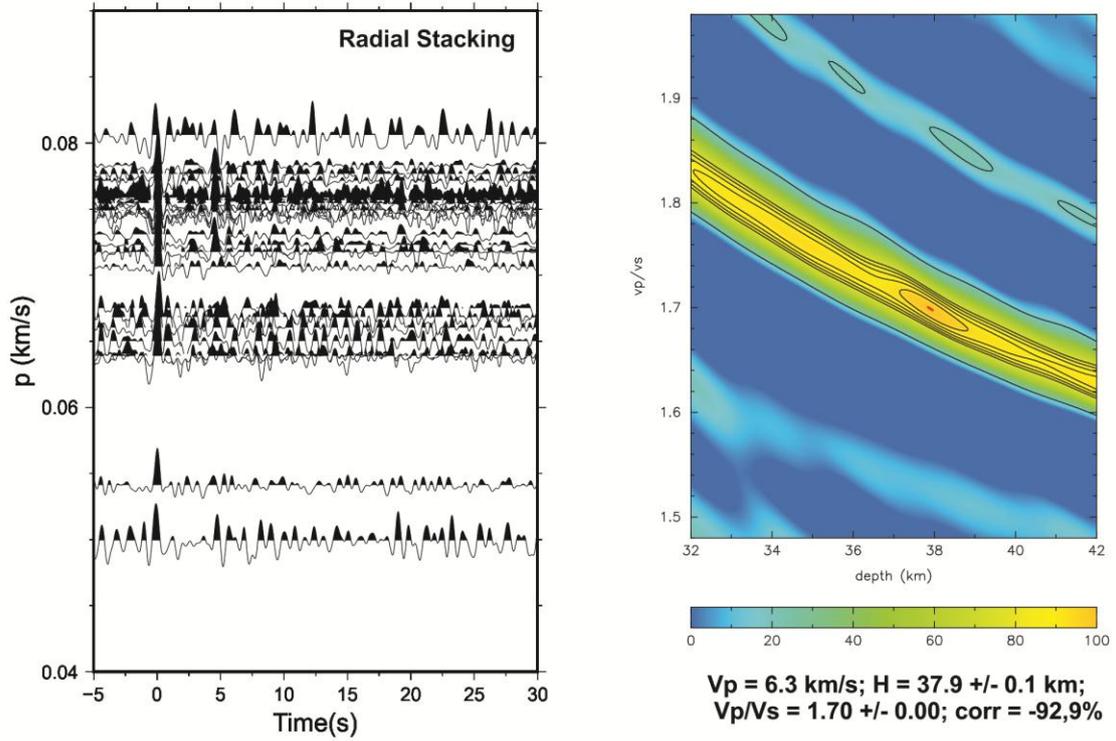
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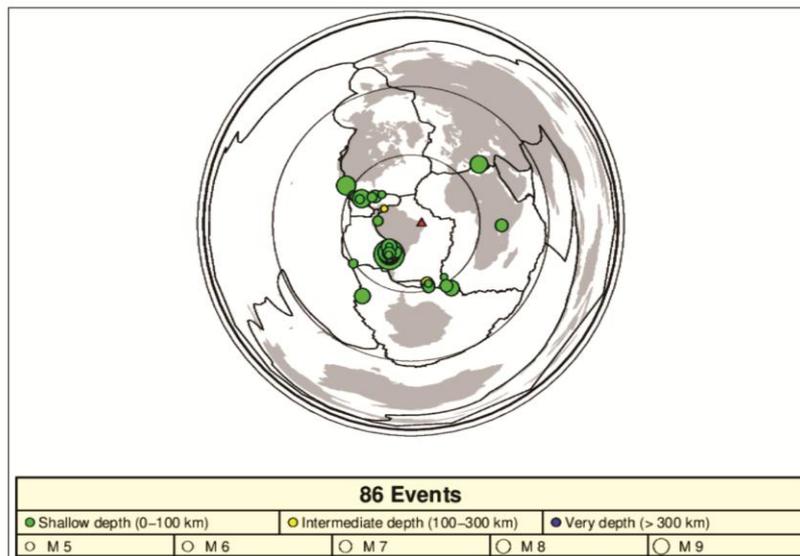
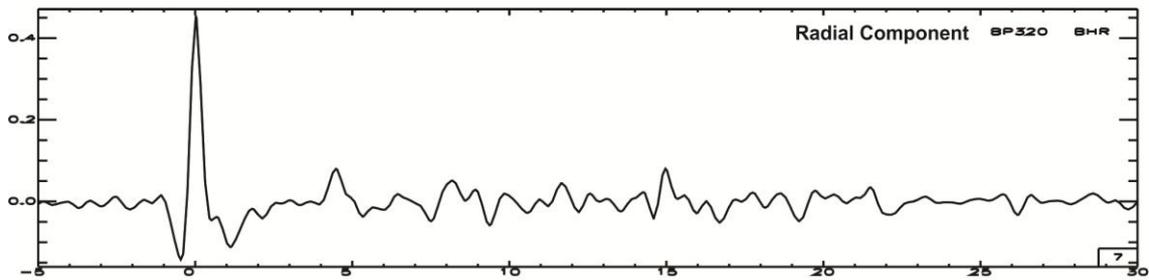
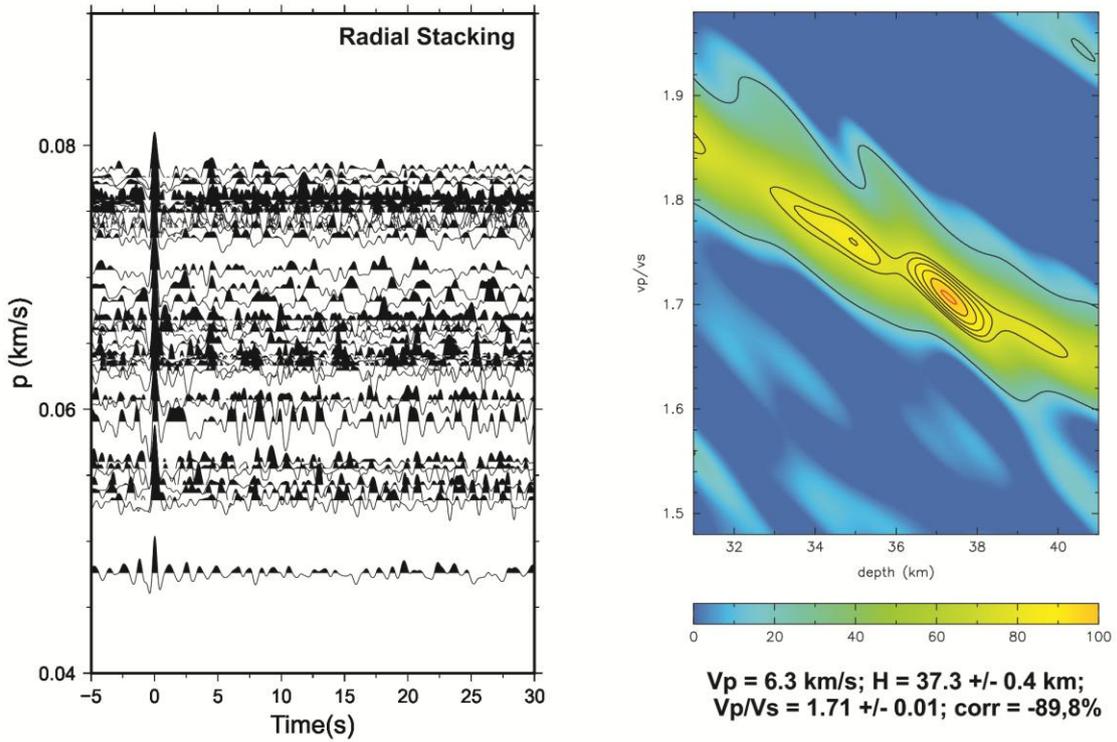
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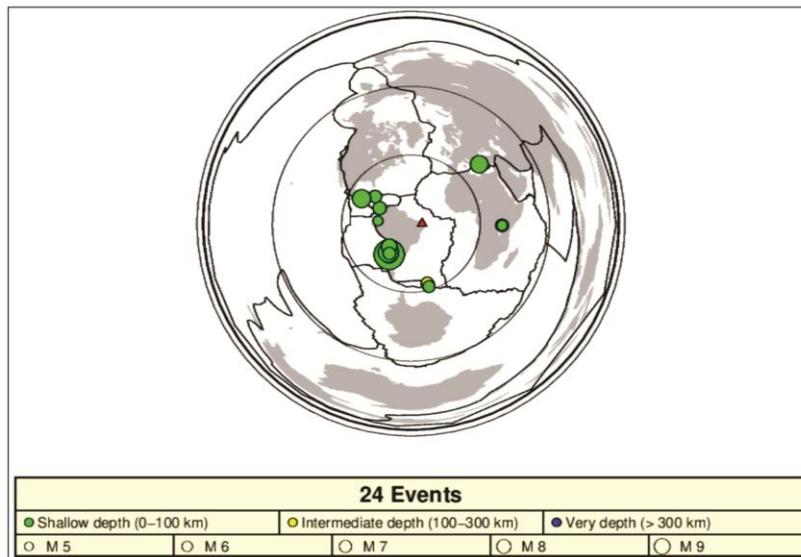
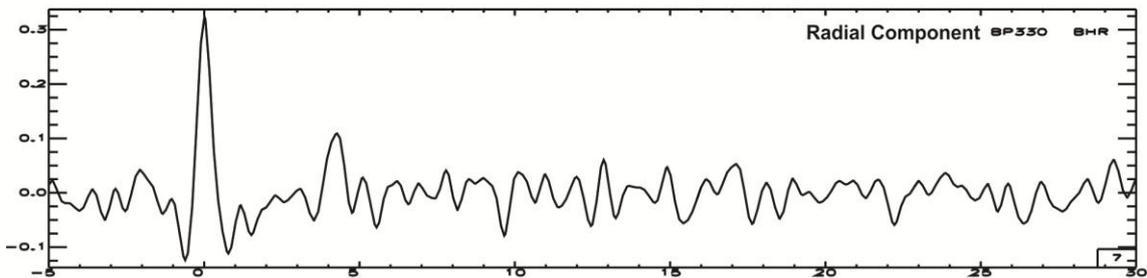
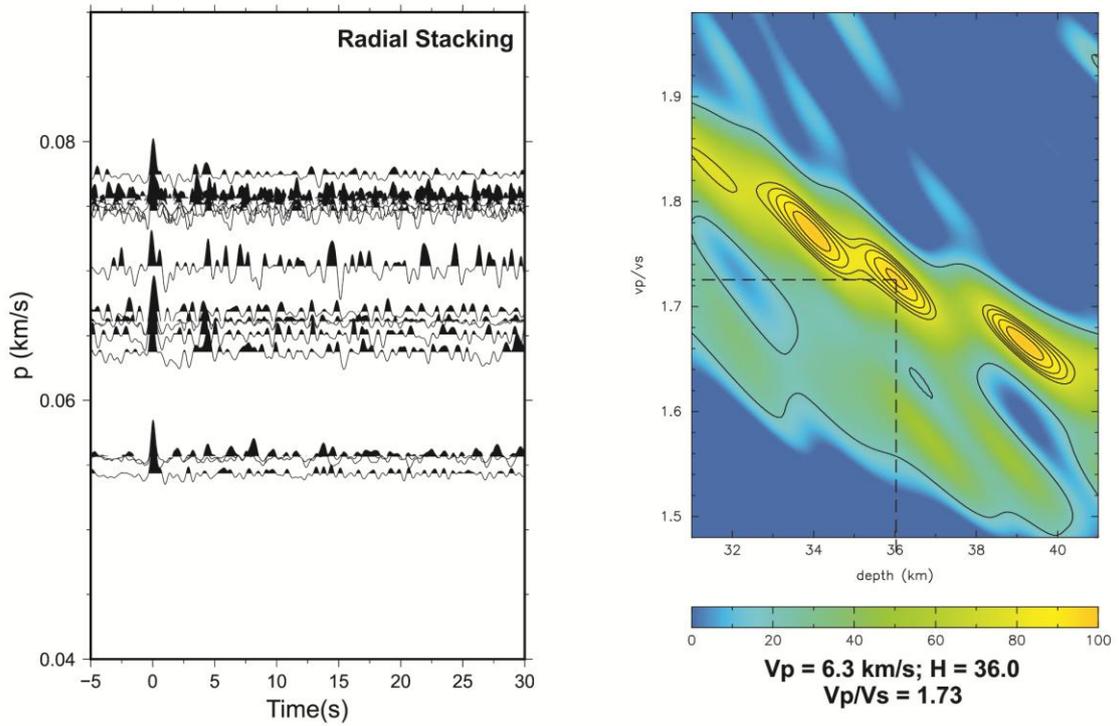
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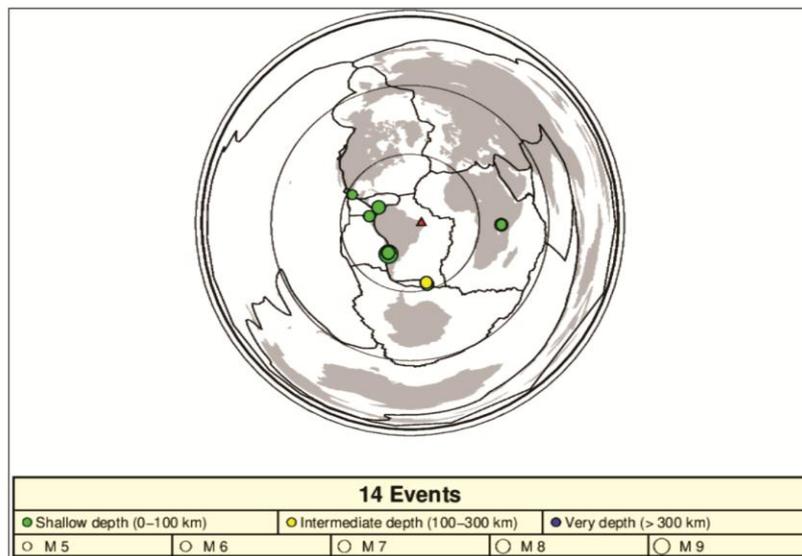
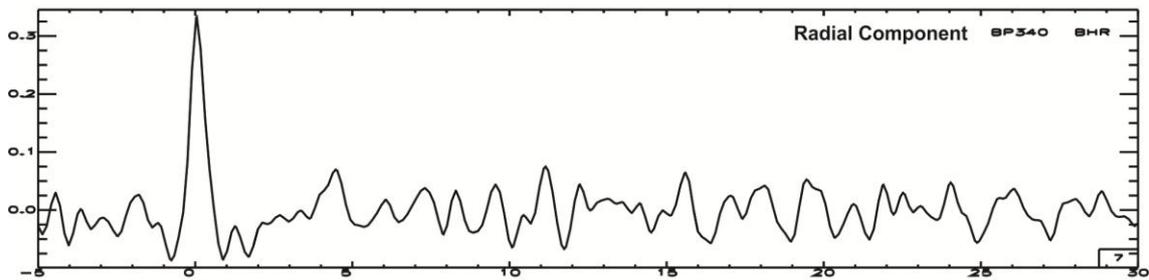
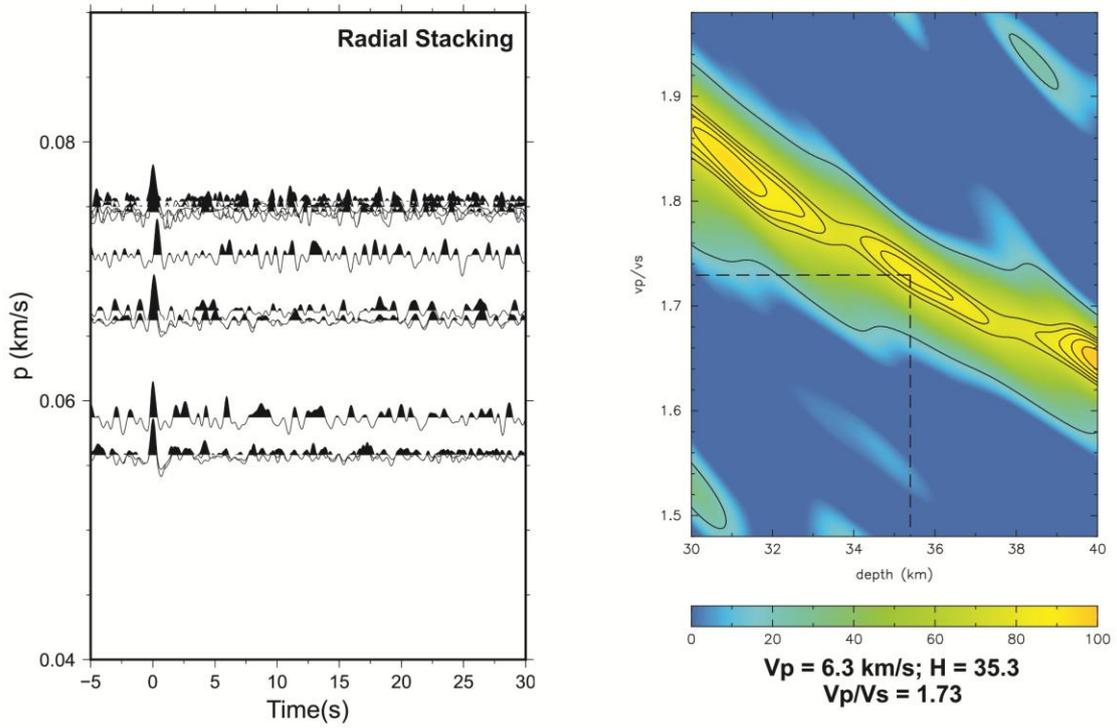
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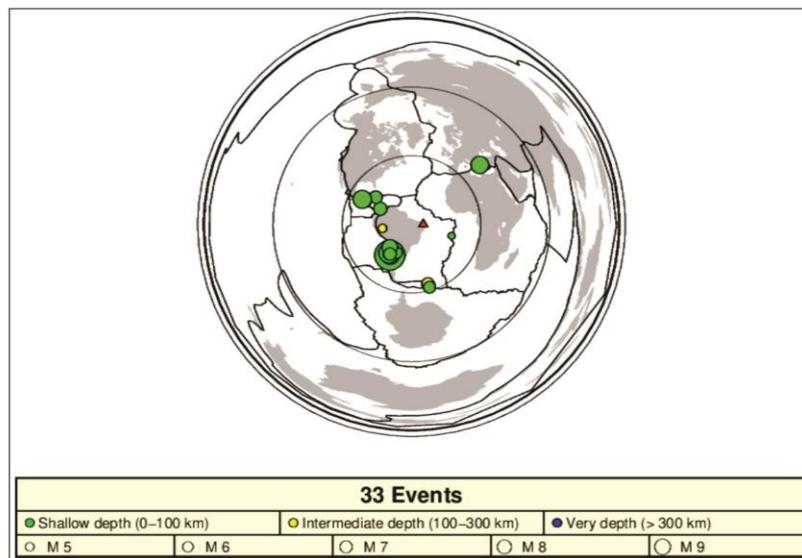
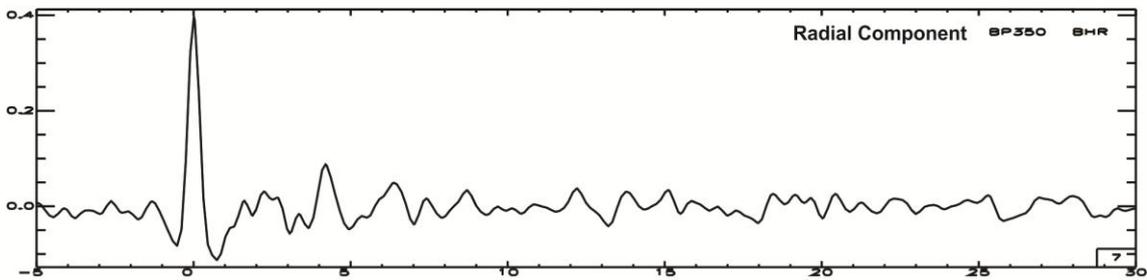
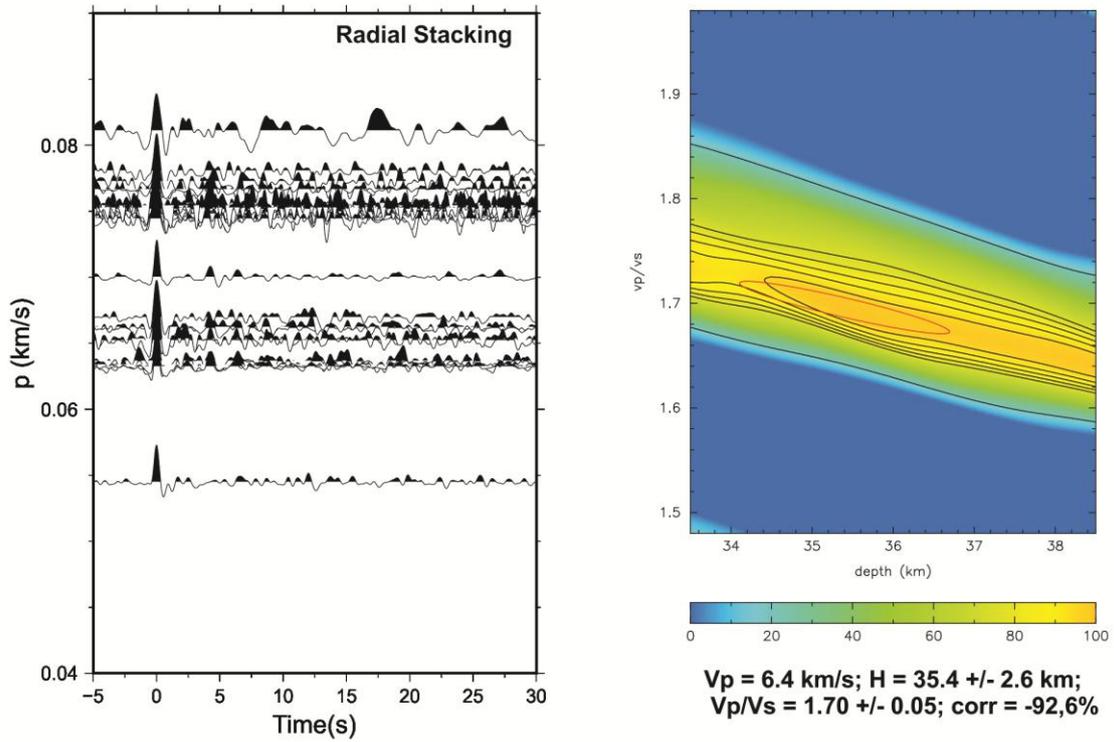
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Characterization of crustal structure by comparing reflectivity patterns of wide-angle and near vertical seismic data from the Parnaíba Basin, Brazil

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SUMMARY

Recently an ambitious experiment combining deep seismic surveys from near-vertical and wide-angle acquisition methods was carried out in Brazil. The seismic lines are essentially coincident and crossed the Parnaíba Basin from west to east near latitude 5°S. Here, the wide-angle reflection and refraction (WARR) and deep seismic reflection (DSR) results, which were previously interpreted independently, are compared by directly correlating WARR interfaces converted to TWTT with the major reflective horizons identified in the zero-offset image and by considering coincident reflectivity patterns displayed in both data sets. This integrated WARR and DSR analysis allowed a spatial association of the apparently acoustically featureless crust imaged in the DSR profile to the high reflectivity observed in the WARR data. Numerical tests and elastic modelling show that variations of the elastic properties of the crust, particularly as they are characterized by low V_p and V_s contrasts with a possible increase of the V_p/V_s ratio, can only weakly explain the observed reflectivity patterns but that fine-scale lithological heterogeneity within the crust is capable of replicating the observed contrasting seismic responses. The segment of the Parnaíba Basin crust that is characterized by fine-scale lithological heterogeneity lies directly above a mafic crustal underplate defined by the WARR model and was named as the Grajaú domain on the basis of WARR-derived velocity model. The applied methodologies allow added value to be taken from the independent seismic data sets and provide new information about crustal structure that may have important implications for overlying intracontinental basin evolution.

Key words: Composition and structure of the continental crust; South America; Controlled source seismology; Crustal imaging; Crustal structure.

1 INTRODUCTION

The imaging of the lithosphere by seismic methods through near-vertical deep reflection (DSR) and wide-angle reflection/refraction (WARR) data have revealed deep features of the crust and upper mantle critical for establishing constraints concerning the evolution of the continental crust and continental lithosphere as a whole. DSR data tend to highlight structural heterogeneity and structural relationships while WARR data provide direct velocity information and, hence, inferences about mechanical properties and composition.

Legacy examples of such results are described in numerous papers and many were obtained along transects acquired as part of extensive exploration programs such as COCORP (USA; Barazangi

& Brown 1986a,b) BIRPS (UK; Matthews 1986), DEKORP (Germany; Meissner 1991) and LITHOPROBE (Canada; Clowes *et al.* 1999). Of these, only the last (LITHOPROBE) aimed explicitly at coincident DSR and WARR profiling.

In South America, and in Brazil in particular, the study of crustal structure and upper mantle using deep seismic reflection imaging has been conducted only in recent years. Daly *et al.* (2014) presented a pioneer 1400-km-long DSR profile (two-way traveltime [TWTT] 20 s) crossing the intracontinental Parnaíba Basin in northwestern Brazil and Soares *et al.* (2018) presented a coincident WARR P -wave velocity model.

Although spatially coincident, the data sets differ in terms of their seismic responses, given differences in their wavefield frequency bandwidths, spatial coverage and source–receiver aperture. However, if properly combined, the information contained in these distinct seismic data sets, not just their interpretations, is complementary and should be capable of providing added value and new insights about the nature of the structures and features present in the crust and uppermost mantle and the processes that have formed them.

There are different ways of composing or correlating the results of near-vertical incidence and wide-angle reflection–refraction seismic data (Mooney & Brocher 1987). Holbrook *et al.* (1991) used two 1-D velocity models derived from refraction data to identify the depth of origin of the reflections in order to associate the reflectivity patterns observed on the PASSCAL/COCORP reflection shot-gathers with geological characteristics of the crust of the Basin and Range province of the southwestern USA. A simple and direct approach is to calculate the two-way traveltimes of the crustal velocity model derived from WARR data and then to plot the predicted traveltimes onto the post-stack reflection image (e.g. Stephenson *et al.* 2006).

In this work we use the PBAP (Parnaíba Basin Analysis Project) DSR and WARR data sets, the acquisition of which was funded by BP Energy do Brasil. The integrated database comprises the post-stack time migration seismic reflection profile (Daly *et al.* 2014) and a 2-D ray tracing model of the crust and upper mantle with its respective WARR data set consisting of 20 wide-angle shot-gathers (Soares *et al.* 2018). Our aim was to go beyond classical ideas that the continental crust can be typically characterized by a seismically transparent upper crust and a reflective lower crust (BIRPS reference/typical BIRP). Rather, we test the idea that there may be intrinsic links between contrasting reflectivity patterns in coincident WARR and DSR data sets and that recognizing these and what they mean may be evidence of crustal attributes indicative of genetic tectonic processes.

In order to carry out a systematic (shot by shot) analysis of the reflectivity patterns observed in the respective Parnaíba data sets, we convert the depths of the WARR interfaces to TWT aiming to place the reflections in the layers of the crust and thus to associate the reflectivity patterns present in the shot-gathers of the refraction data with the respective reflectors recorded in the illuminated region of the DSR image. Despite the resolution and lower spatial coverage of the WARR data, wide-angle reflections are the most prominent signals in the deep seismic refraction sections that exhibit significant reflectivity. Accordingly, we proceed to explore the physical properties of the crustal structure based on a joint analysis of the reflectivity patterns from both coincident data sets. In particular, we focus on the coincidence of ‘transparent’ crust in DSP imaging with highly reflective crust in WARR imaging observed on the PBAP profile.

2 STUDY AREA AND TECTONIC SETTING

The study area is located in northeastern Brazil, encompassing the Phanerozoic Parnaíba Basin, which is bounded by the Precambrian Amazonian, São Luís and São Francisco cratons and Borborema and Tocantins geological provinces (Fig. 1).

The Parnaíba Basin is a large Phanerozoic intracontinental basin with a subcircular surface geometry of total area of ca. 600 000 km². The basin has a long history of subsidence and sediment deposition

that spans the time from the Silurian to the late Cretaceous (Góes & Feijó 1994).

The tectonostratigraphic evolution of the Parnaíba Basin is recorded by five sedimentary supersequences separated by regional unconformities: Silurian, Devonian–Carboniferous, Carboniferous–Triassic, Jurassic and Cretaceous. The last two are marked by two magmatic events represented by the Mosquito and Sardinha formations. The sedimentary infill as a whole is characterized by a shallow marine environment, but also presents fluvio-deltaic and continental arid environments, and consists of a sedimentary package up to 3500 m of thickness that is roughly saucer-shaped (Góes & Feijó 1994; Vaz *et al.* 2007).

The basin architecture and seismostratigraphic sequences are imaged in detail by reflection seismic sections and well-logs made available by the ANP (Brazilian Petroleum Agency). These reveal some graben-like structures beneath the sag sequences that have been interpreted as remnant basins containing pre-Silurian strata (de Castro *et al.* 2016; Porto *et al.* 2018), probably genetically linked to regional shear zones such as the Transbrasiliano Lineament (Fig. 1).

The basement of the Parnaíba Basin is formed of Precambrian crust accreted and stabilized during the Neoproterozoic Brasileiro Orogeny (Brito Neves *et al.* 1984). However, only recently has special attention been given to the characterization of the basement concealed beneath the basin, mainly from new data sets provided by deep geophysical soundings. A laterally heterogeneous nature of the crust has been established with the recognition of distinct crustal blocks constrained by geophysical modelling and inferred differences in physical properties.

Castro *et al.* (2014) interpreted airborne potential field data and identified gravity and magnetic signatures that could be associated with the main structural trends and crustal segments underlying the basin, allowing to differentiate the basement in Parnaíba and Teresina domains. Regional Bouguer gravity and magnetic anomaly profiles along the WARR line extracted from WGM2012 global anomaly maps (Bonvalot *et al.* 2012) and global Earth Magnetic Anomaly Grid (Maus *et al.* 2009) [EMAG2] are shown in Fig. 2(a).

Daly *et al.* (2014) interpreted from DSR profiling that the crust underneath the Parnaíba Basin consists of three distinct tectonic blocks that they called the Amazonian Craton/Araguaia Belt, the Parnaíba block (underlying the central part of the Parnaíba Basin) and Borborema Province. However, Daly *et al.* (2014) were not able to characterize much about the crust of the Parnaíba block because of a lack of systematic reflectivity in this part of the profile. Although not exposed, the lateral limits between these blocks are well marked by abrupt changes in the reflectivity patterns, as indicated in Fig. 2(c), where the border with the western Amazonian–Araguaia block is labelled as TAS (Tocantins–Araguaia Suture).

In turn, from the analysis of average 1-D *P*-velocity curves extracted from the 2-D WARR profile, Soares *et al.* (2018) proposed the presence of four main crustal domains, recognizing that the Parnaíba block can be subdivided into the Grajaú and Teresina domains. In particular, the Grajaú domain is marked by a seismic high-velocity layer at the base of the lower crust, interpreted as being a crustal underplate.

Solon *et al.* (2018) presented an electrical conductivity model obtained from inversion of magnetotelluric data that were acquired by MT broadband stations along the same path as the DSR profile. They also subdivided the profile into three major blocks bounded by electrical discontinuities of lithospheric scale that can be related to the suture zones defined by the interpreted seismic model of Soares *et al.* (2018). In addition, pronounced variations in resistivity

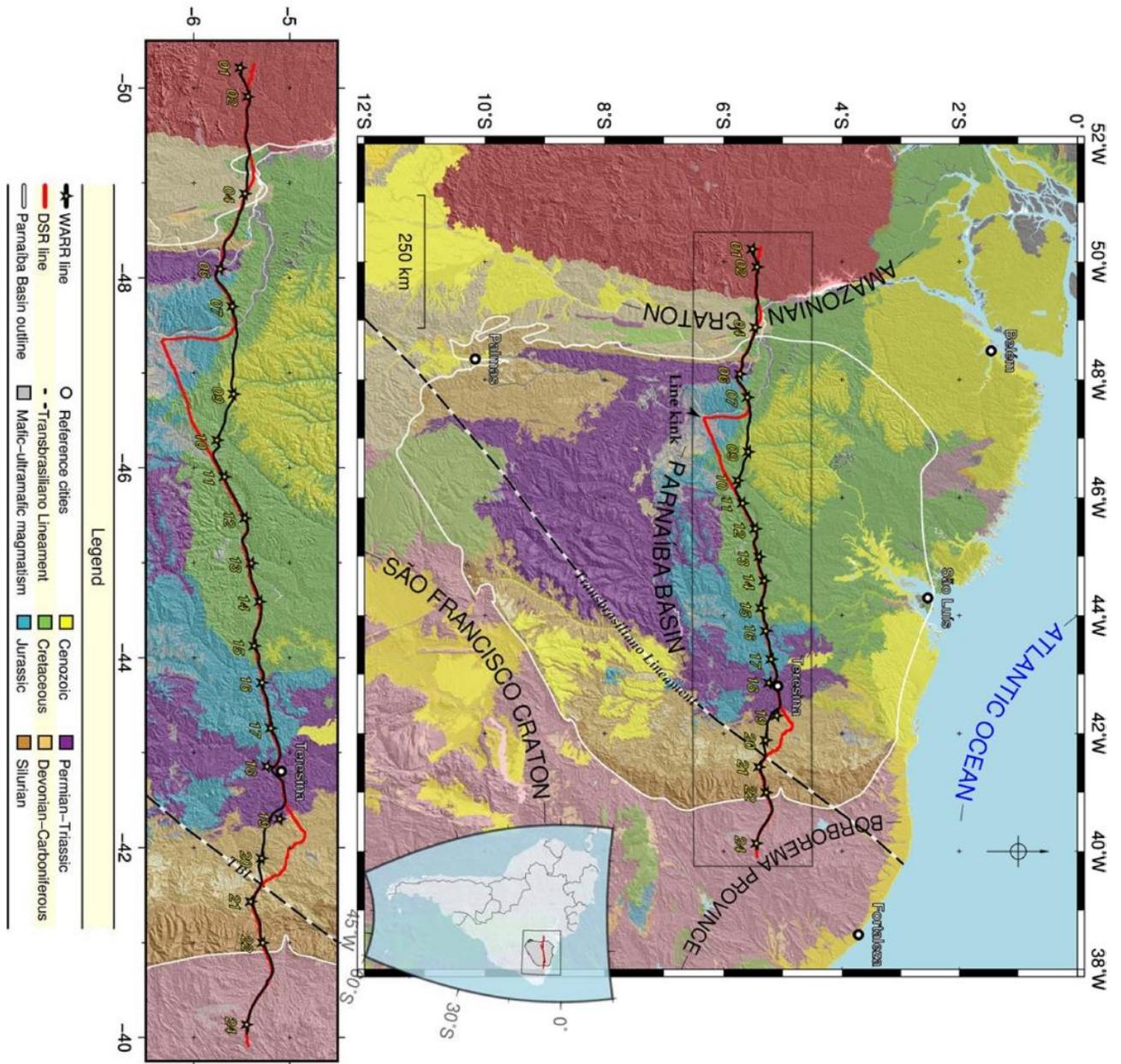


Figure 1. Overview geological map of the study area with tectonic provinces indicated by names highlighting the limit of the Parnaíba Basin and its stratigraphic sequences, showing the locations of approximately coincident seismic profiles. Stars indicate the locations of the WARR profile shot-points and the dashed line is the inferred location of the Transbrasiliano Lineament (CPRM 2004). The line kink is indicated where the deviations between the seismic profiles were corrected by orthogonal projection of the CDPs to the WARR more linear profile. The inset map shows the Parnaíba Basin in the context of the South America continent and enlarged map showing in detail WARR and DSR seismic lines.

related to the presence of anomalous conductivity zones in the crustal basement were observed beneath the basin.

3 WARR AND DSR DATA SETS

The WARR model (Fig. 2b) is composed of a sequence of five layers: a sedimentary layer (sag basin and half-grabens), upper and lower crust, a crustal ‘underplate’ and upper mantle. The boundaries and velocity distributions seen in Fig. 2(b) were obtained from forward modelling of refraction and wide-angle reflection *P*-wave

data. The seismic data set consists of 19 out of 20 acquired shot-gather seismic sections (see the supplementary material presented in Soares *et al.* 2018). The processing of the recorded sections involved trace normalization by maximum value, application of a bandpass filter of 2–8 Hz and reducing velocity on the vertical (time) axis of 8.0 km s^{-1} .

The Parnaíba deep seismic reflection (DSR) profile is a 1430-km-long E–W seismic line that crosses the Parnaíba Basin and neighbouring blocks near latitude 5° S (Fig. 1). The original seismic image has a high trace density, with CDP spacing of 12.5 m and

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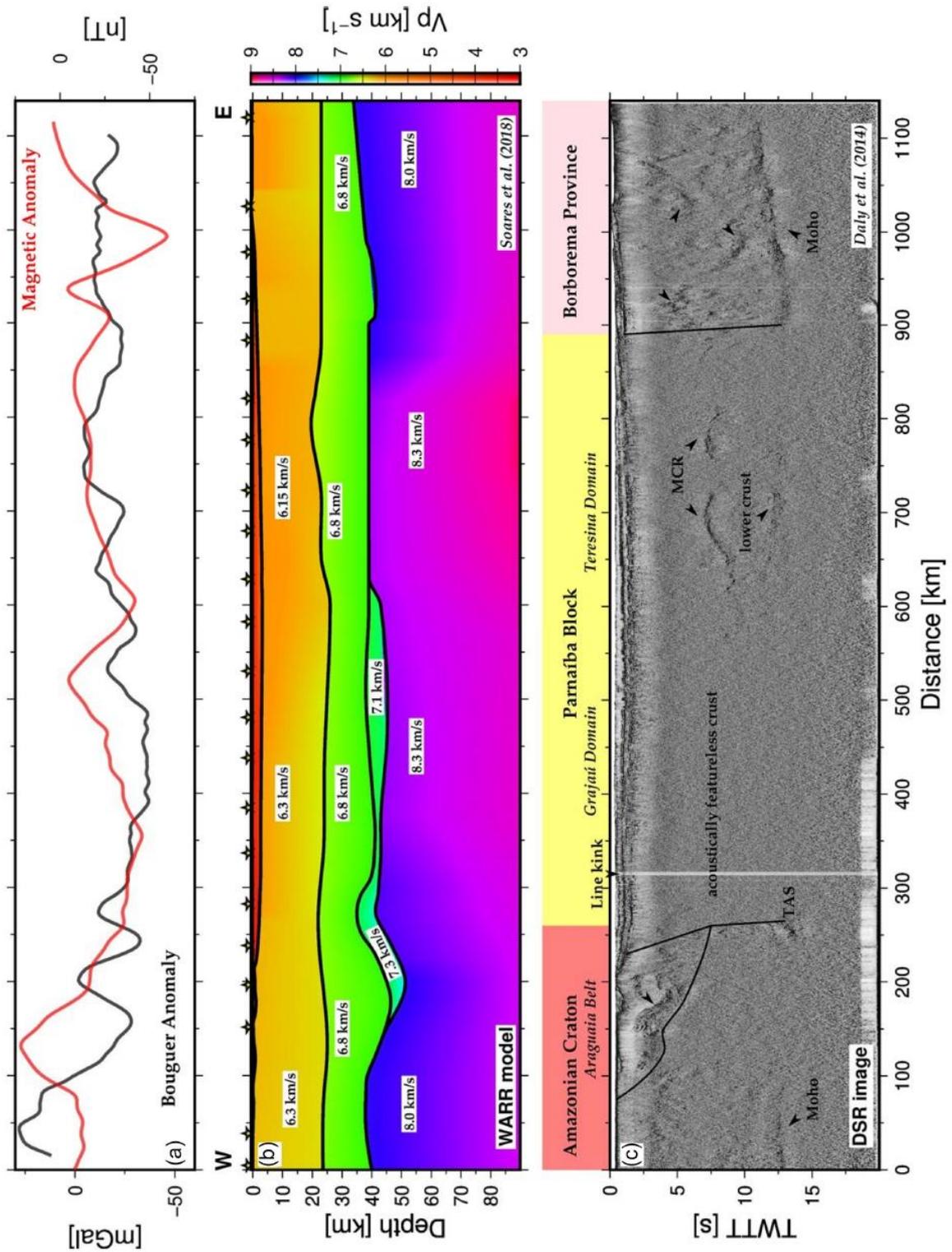


Figure 2. (a) Regional Bouguer gravity and magnetic anomaly profiles along the WARR line extracted from WGM2012 global anomaly maps (Bonvalot *et al.* 2012) and global Earth Magnetic Anomaly Grid (Maus *et al.* 2009) [EMAG2], both with 2-arcmin resolution; (b) 2-D velocity model of the crust and upper mantle obtained from the WARR experiment. *P*-wave velocities are indicated by the colour bar; (c) post-stack time migrated image of the Parnaíba deep seismic reflection profile with the main features indicated by arrows; solid lines represent the boundaries between the blocks that from left to right correspond to the Amazonian Craton, Araguaia Belt (TAS—Tocantins-Araguaia Suture), Parnaíba block and Borborema province; CDP traces where there is line kink have been removed as indicated in the projected DSR profile.

a TWTT time window of 20 s (Fig. 2c). With the exception of the continuous and well-defined behaviour of the stratigraphic features of the sedimentary package, the DSR image presents a highly heterogeneous and complex reflectivity pattern, which can be directly related to the three main tectonic ‘blocks’ crossed by the profile: Amazonian Craton, Parnaíba block and Borborema Province, which are marked by steep contacts between them (Fig. 2c).

The Amazonian Craton has an intermittently reflective crust, alternating reflective zones with transparent ones. The most pronounced seismic events correspond to the ‘worm-shaped reflectors’ (Daly *et al.* 2014; p. 7) defined by the folded package of metasedimentary rocks of the Araguaia Belt (located between positions 70 and 200 km and 2–5 s of the profile in Fig. 2c) and by the Moho reflection that dips eastward until it abruptly disappears in contact with the Parnaíba block and marks the position of the Tocantins–Araguaia suture.

The Parnaíba block occupies the central portion of the line and it comprises two units. The western unit is characterized by acoustically featureless crust, totally transparent, with no visible Moho reflection events. This singular and controversial crustal character of acoustically featureless crust has not yet been properly explained and inferences about its causes and nature are speculative. The eastern section of the Parnaíba block has a transparent upper crust and is characterized by a subhorizontal, high amplitude, mid-crustal structure (MCR). The lower crust is weakly reflective below this mid-crustal zone, whose base should define the Moho.

The Borborema Province contrasts with the Parnaíba block due to its strong reflective style, showing a highly structured seismic character of the upper and lower crust.

Analysis of the WARR data set in this work is restricted to traces found at source–receiver distances less than 200 km, which corresponds to the expected range for primary crustal reflections.

4 DATA ANALYSIS AND METHODS

Three different approaches were used in order to evaluate the correspondence between the DSP and WARR models (i.e. to compare the reflectivity patterns seen in each and to test numerically possible factors that could characterize the reflectivity behaviour observed in the real data). However, prior to doing this, the positions of the CDPs of the DSR line were projected along the WARR seismic profile in order to obtain an accurate spatial correlation between the refraction and reflection data, because the profiles were not perfectly aligned and only approximately coincident. The linear profile is the great circle from a least-squares fit of all station locations from the WARR survey. After projection, the DSP CDP traces were resampled at a regular spacing of 25 m.

4.1 Depth–TWTT conversion

The time–depth relationship is the basis of the velocity concept, so that the conversion of depth to TWTT and vice versa is obtained directly using the velocity model and considering the vertical path of the seismic ray travelling through the layer and reflecting on each of the interfaces as described by the eq. (1):

$$twt_i = 2 \sum_i z_i / v_i, \quad (1)$$

where the two-way traveltime twt_i is the elapsed time for a normal-incidence seismic wave travel with velocity v_i from its source to i th reflector through i layers with thickness z_i and return to a receiver

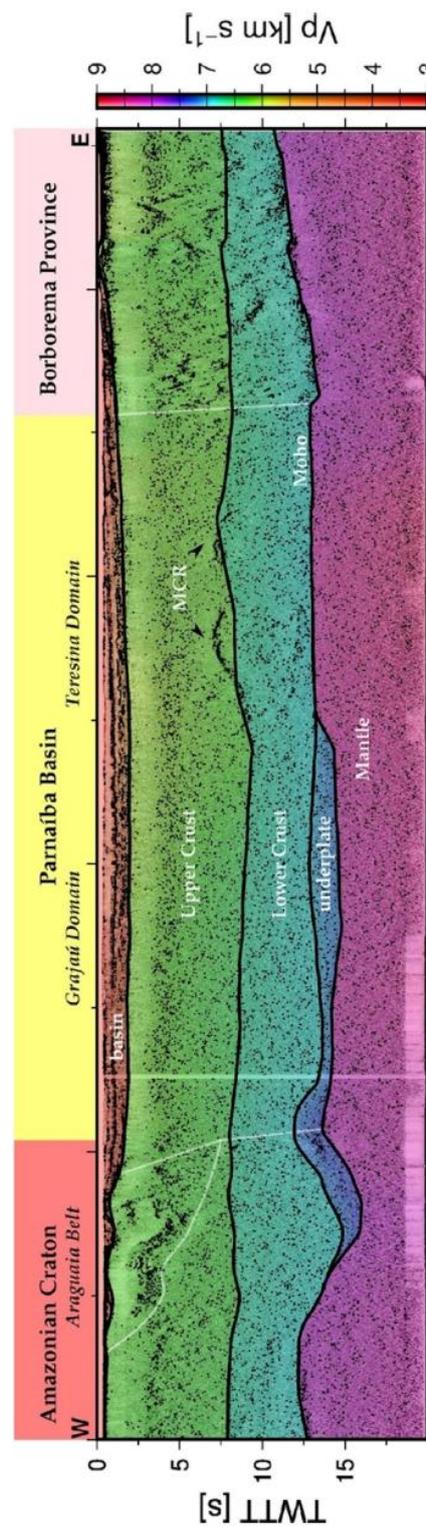


Figure 3. Image of post-stack time migrated of the reflection profile superimposed by the 2-D velocity field converted to TWTT. WARR P -wave velocities are indicated by the colour bar.

located in the zero-offset at the Earth's surface. Computation of the two-way traveltimes of refraction model boundaries was performed from the VMODEL program of the RayInvr package (Zelt & Smith 1992).

In addition, it was possible to convert the whole velocity field described in terms of depth $V(x,z)$ to a velocity model as a function of time $V(x,t)$ using the Seismic Unix software (Stockwell Jr 1999; Cohen & Stockwell Jr 2015).

4.2 Comparison of WARR and DSR reflectivity

In order to evaluate the information regarding the behaviour of the reflected waveforms, the procedure illustrated in Fig. 4 was used. The reflectivity patterns were evaluated qualitatively by visual inspection of the strength and coherence of the events observed in the seismograms. Although the approach is interpretative, the technique is based on the remarkable character of the post-critical reflections amplitudes even considering the differences in acquisition/processing methodology and frequency bandwidth of the WARR data.

Therefore, the reflectivity is indicated and classified according to its crustal depth, position relative to the source and intensity of the amplitude. For example, the reflectivity identified in the upper crust on the branch to the right of the shot-point was labelled R_u . The indices u and l indicate upper crust and lower crust, respectively, and the indices r and l define the branches of the reflections on the right and left of the shot-point, respectively. In addition, interpreted patterns with high reflectivity are labelled as HR . The corresponding illuminated portion of crust in the CDP reflection image is determined from the minimum and maximum take-off angles for reflected ray groups at the upper-lower crust interface (P^*P) and the Moho (PmP) obtained by the ray trace modelling of the WARR data.

The complete set of these analyses is presented in the Supporting Information.

4.3 Calculation of reflection coefficient curves

It is known that reflectivity at wide angles (post-critical) is influenced by the S -wave velocity (V_s) contrast at the reflecting boundary as well as the P -wave velocity (V_p) contrast (Pullan & Hunter 1985). In order to investigate the influence of the V_s contrast we simulate the reflectivity response described by the Zoeppritz equations (e.g. Lay & Wallace 1995; Aki & Richards 2002) for the reflection coefficient of the P wave reflected from an incident P wave.

The reflection (and transmission) coefficients given by the Zoeppritz equations provide the analytical solutions to the elastic wave equation that result from a plane wave incident on a horizontal plane interface as a function of the incidence angle. Therefore, variations in reflection amplitude and phase (waveform shape) can be determined exactly by varying the rock properties involved (e.g. density, P - and S -wave velocities).

4.4 Full waveform modelling

In order to evaluate how seismic wavefields are affected by variations of the V_p/V_s ratio and the presence of fine-scale heterogeneities in the crustal models based on the WARR acquisition geometry, synthetic seismograms were generated using SOFI2D software ('Seismic mODEling with FInite differences in 2 Dimensions' developed

by the GPIAG working group in Applied Geophysics at the Geophysical Institute of the Karlsruhe Institute of Technology). SOFI2D performs full waveform seismic modelling in 2-D elastic and viscoelastic media using the finite difference method.

The parametrization of the model was defined in order to avoid numerical artefacts and instabilities during the wavefield simulation, satisfying the spatial and temporal sampling criteria. The Ricker wavelet with a central frequency of 5 Hz was used to represent an explosive source. The dimensions of the model grid was 200 km x 50 km with a spatial grid interval of 50 m. The modelling covers a time span of 41 s with the time step size of 0.010 s.

5 RESULTS AND DISCUSSION

5.1 Depth-TWTT conversion

The TWTT responses of the WARR velocity model were generated for five layer interfaces: sedimentary layer-basement, upper-lower crust, lower crust-crustal underplate and lower crust- or crustal underplate-uppermost mantle (Moho). The TWTT boundaries were then plotted on the reflection section, in order to compare the reflectivity to the respective crustal layers (Fig. 3).

Fig. 3 shows that there is a good agreement between the TWTT contours computed from the WARR refraction model with the main reflective zones recorded on the DSR image (Fig. 3). For example, the WARR sediment-basement times closely correspond to the limit interpreted for the Lower Palaeozoic sedimentary package in the DSR image.

Assessing the correlation between the reflection and refraction Moho, the refraction Moho occurs around the top of the reflective zone in the lower crust. In this case, the lack of a perfect match is most likely due to the difference in the interpretation of the origin of the PmP phases. The approach used in the forward modelling of the WARR data was to define the Moho based on the initial instant in which the PmP phases arrive at the recording stations. On the other hand, the near-vertical method interprets Moho at the base of the high reflectivity of the lower crust; that is, the depth of the Moho is picked at the base of a reflector sequence. However, the difference of resolution and frequency content of the data sets may influence the determination of those reflective zones that characterize Moho and, therefore, can cause small variability in the depths estimated by both methods. Even so, although largely coincident, the comparison between the 'reflection Moho' and the 'refraction (WARR) Moho' is still an object of discussion, as well as Mohorovicic's original definition itself as a first order discontinuity (Mjelde et al. 2013; Prodehl et al. 2013).

The cause of the mid-crustal reflectivity (MCR), interpreted as being an igneous intrusive body by Daly et al. (2014), suggests that it can be placed on the upper-lower crust boundary. If so, this feature should correspond to the structural geometry of the top of the lower crust in the refraction velocity model. Variations between the predicted times of the lower crust and the MCR may be related to the limitations intrinsic to the refraction method. Nevertheless, Tozer et al. (2017) showed from box wave-gathers recorded during the PBAP DSR survey that it is possible to correlate the refraction arrivals from the top of the lower crust (P^* phase) with phases reflected in the mid-crustal zone from the top of a high velocity layer ~ 3 km thick, the position of which is consistent with that of the MCR. Therefore, the discrepancy between the results of WARR and DSR in this regard can be largely explained by the seismic

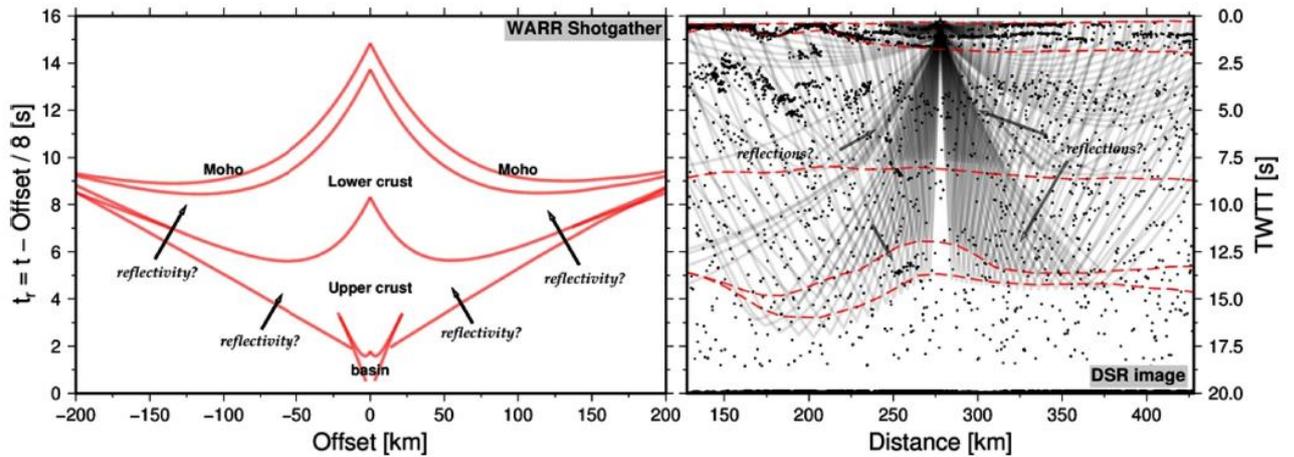


Figure 4. Schematic diagram of the analysis method of the reflectivity patterns in WARR (left-hand panel) and DSR (right-hand panel) data. Time-reduced shot-gather on the left is plotted with red lines indicating modelled traveltime curves representing the main crustal structures. Ray tracing diagram on the right for phases modelled on the left showing the zone illuminated by the shot-point through the seismic image; red dashed lines indicate the TWT boundaries and the locations with the highest absolute values of amplitude have been highlighted by black dots in order to enhance the main reflective zones.

nature of the MCR feature itself rather than by errors of analysis or methodology.

5.2 Comparison of WARR and DSR reflectivity

The analysis of the reflectivity patterns was performed for each WARR shot-gather by associating the reflectivity observed in the seismograms of the shot-gathers with possible reflectors (or reflectivity) identified in the DSR section as shown in Fig. 4.

The reflectivity patterns displayed in the WARR data are quite heterogeneous (e.g. shot-gathers 2, 14, 18 and 20 in Fig. 5). In some cases, it is difficult to distinguish isolated events and associate them with the corresponding event in the reflection image. However, in general the practical result is that most of the reflections observed in the DSR profile can be identified in the WARR data, obviously taking into account the acquisition geometry, resolution and the frequency content of the signals recorded in the WARR data.

On the other hand, there is no reciprocity; that is, patterns of high reflectivity in the WARR shot-gather are not necessarily observed in the reflection image. This feature is most evident in regions marked by a high amplitude pattern (HR) that are spatially associated with the reflectively ‘quiet’ zone in the DSR image, as clearly demonstrated in Fig. 6 for shots 7, 9, 12 and 13. In this case, the high amplitudes in WARR data cannot be attributed to the natural reverberations caused by the sedimentary package of the basin or by the variation of energy released by the different shot-points because these characteristics are observed for the same shot (e.g. shot 12) recorded at sensors arranged completely over the basin. Therefore, this ambiguity in the reflectivity patterns is spatially correlated and characterizes the crustal seismic response of the region corresponding to the Grajaú domain as argued by Soares *et al.* (2018).

5.3 Reflection coefficient curves

Given that the one essential difference between the character of the DSR data and the WARR data are the angle of incidence of the reflected wave (i.e. near vertical versus wide-angle aperture), we calculated the reflection coefficient curves for different seismic

media in order to investigate the influence of the parameters in the amplitude variation with offset.

Three theoretical scenarios were investigated: (1) varying the V_p contrast across a reflector while maintaining a constant V_s contrast; (2) varying the V_s contrast across while maintaining a constant V_p contrast and (3) varying the V_p contrast in the absence of any contrast in V_s across the boundary. For all scenarios, the same densities were used. The curves for each of the scenarios are presented in Fig. 7, with the absolute value of the reflection coefficient plotted as a function of the angle of incidence. They have been shifted relative to the critical angle in order to allow an easier comparison.

Scenario 1 (Fig. 7a) demonstrates the influence of V_p contrast variation on the reflectivity across the range of offsets. As expected, when the contrast increases, there is an increase in the energy reflected at angles below the critical angle; above the critical angle this behaviour is the inverse. However, regardless of the intensity of the V_p contrast, the reflection coefficient always reaches the maximum at the critical angle (total reflection). This could explain the observation of reflection events in the WARR data even in regions with low acoustic impedance contrasts.

Scenario 2 (Fig. 7b) demonstrates how the V_s contrast contributes to the reflectivity at angles close to the critical angle. As the contrast increases, the energy of the reflected P wave decreases for subcritical and post-critical angles, and for low angles the V_s contrast has no influence.

From the previous scenarios we isolated and analysed the effect obtained in scenario 3 (Fig. 7c), in which it can be seen that sub- and post-critical reflectivity depends only on the V_s contrast, and the V_p contrast variation only affects the pre-critical reflectivity. In fact, for short offsets (i.e. near-vertical as in DSR profiling) the reflection coefficient depends only on the acoustic impedance contrast and not on elastic impedance. In addition, the reflectivity will be total when there is no V_s contrast, that is, all incident energy will be reflected in P wave because there will be no energy converted to S -wave reflection. Alternatively, the relative decrease of V_s contrast can be interpreted as a gradual increase of the V_p/V_s ratio.

In this context, the effect produced by a homogeneous crust in terms of V_s on the reflectivity patterns displayed in shot-gathers could be evaluated from the variations of amplitude observed in full waveform modelled seismic traces. Synthetic seismograms were

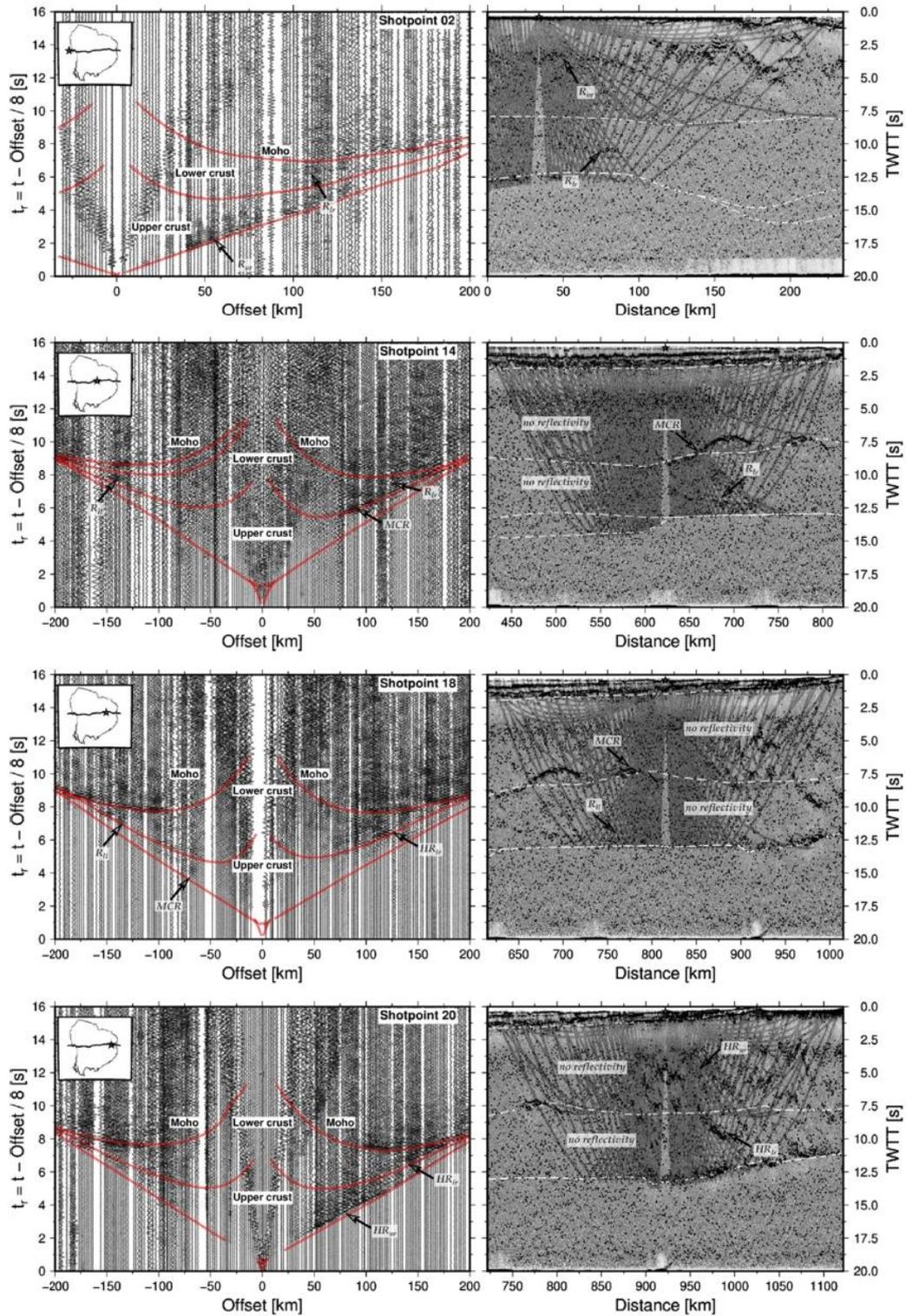


Figure 5. Comparison between reflectivity patterns for WARR shot-gathers 2, 14, 18 and 20 to the relevant segment of the DSR profile showing corresponding wide-angle ray paths. The continuous red lines are theoretical traveltimes computed from the velocity model for the main crustal phases restricting and constraining the areas of the seismograms to the corresponding crustal layers as indicated by the labels on the WARR shot-gathers to: upper crust, lower crust and Moho.

generated from the simulation of a survey with the same parameters of acquisition of the actual WARR data survey. The 1-D V_p curve

from the Grajaú domain (Soares *et al.* 2018) was used to construct the models considering two situations: varying the V_s considering

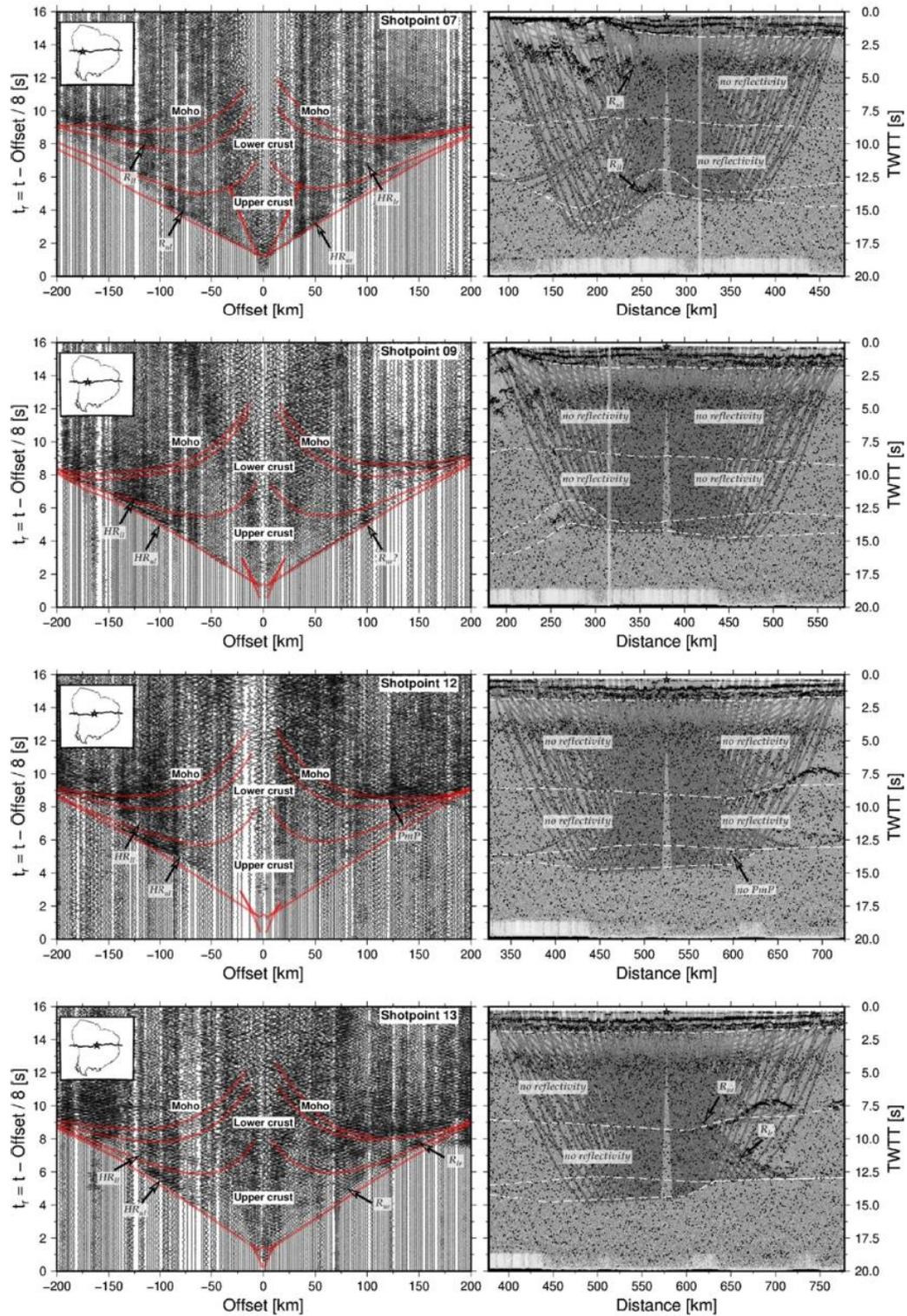


Figure 6. Comparison between reflectivity patterns for shot-gathers 7, 9, 12 and 13 to the relevant segment of the DSR profile showing corresponding wide-angle ray paths. The continuous red lines are theoretical travel-times computed from the velocity model for the main crustal phases restricting and constraining the areas of the seismograms to the corresponding crustal layers as indicated by the labels on the WARR shot-gathers to: upper crust, lower crust and Moho.

a constant V_p/V_s ratio of 1.73 and absence of any contrast in V_s across the crust (Fig. 8a).

The difference between the amplitudes is evidenced by the overlapping of both synthetic seismograms as shown in Fig. 8(b). The

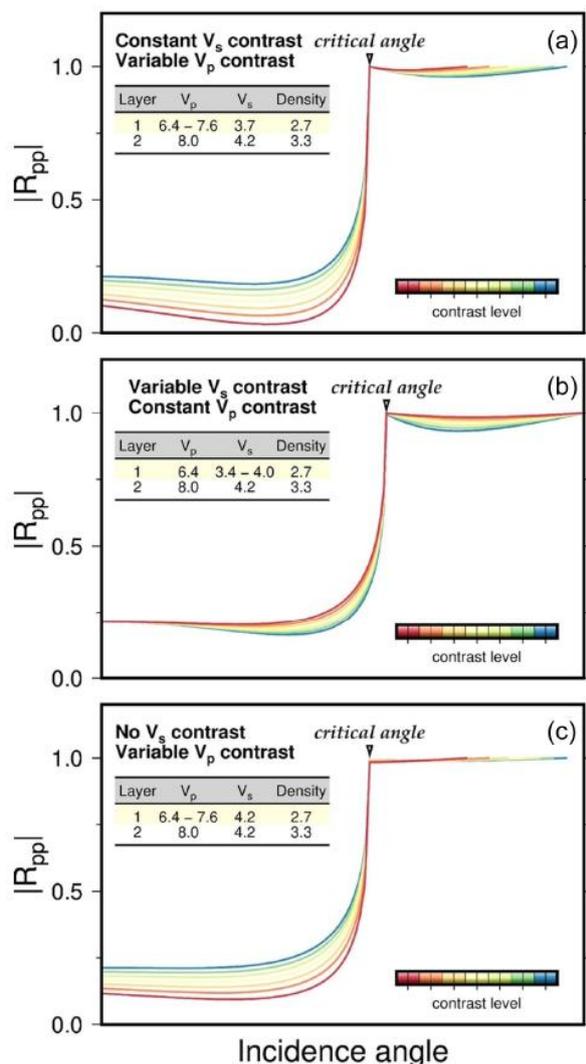


Figure 7. Curves of the coefficient of reflection based on Zoeppritz’s equations for the three proposed scenarios (hot colours representing smaller contrasts). Velocity values are given in km s and density in kg m⁻³.

black wiggle traces represent the seismogram for the crustal model with variable V_s (black curve in Fig. 8a) and the traces with wiggle in red refer to the model of crust with constant V_s (red curve in Fig. 8a). Fig. 8(c) is a zoom in to the area highlighted by the rectangle in Fig. 8(b), in order to better visualize the degree of these variations.

Although subtle, the absence of crustal contrast in V_s generated an increase in the reflectivity in WARR data as expected and predicted by the Zoeppritz’s equations. However, this increase in reflectivity is still lower than that observed in the seismic sections, particularly in the shot-gathers recorded on the Grajaú domain (see shots 7 and 9), indicating that variations in the S model only will not generate pronounced reflectivity changes in the WARR data, so that the high reflectivity cannot be attributed solely to V_s heterogeneities (or V_p/V_s anomalies).

5.4 Synthetic seismograms from random heterogeneity models

Since the elastic modelling of an increase in the V_p/V_s ratio is not

able to reproduce satisfactorily the response recorded in seismograms in terms of reflectivity patterns the observed seismic response may be related to fine-scale heterogeneities, connected to the effects of parameters intrinsically controlling scattering of seismic energy.

Levander *et al.* (1994) showed from stochastic modelling that a ‘salt and pepper’ pattern, similar to that observed in the PBAP-DSR image, can be indicative of heterogeneity with short characteristic scales (200 m vertical and 50 m horizontal). They suggested that the geological environment compatible with this crustal model could be represented, for example, by an upper crust of amphibolite facies gneiss intruded by mafic dykes overlying a more mafic amphibolite to granulite facies lower crust. The reference geological terrain used by Levander *et al.* (1994) to represent this crustal type was the Archaean Lewisian gneiss complex in northwest Scotland. However, this does not necessarily imply establishing any tectonic affinity with the terrains from the Parnaíba Basin.

Here, we have modelled the seismic response for three crustal models (top of Fig. 9) incorporating the presence of heterogeneities and characterized by V_p of 6.75 km s⁻¹ and V_p/V_s ratio of 1.8. The V_p/V_s ratio chosen is compatible with laboratory measurements in rock samples for mafic crustal lithologies and is consistent with previously established assumptions about the increase of reflectivity due to V_p/V_s anomalies. The reference parameters for the dimension, proportion and distribution of these bodies have been chosen according to Levander *et al.* (1994).

The calculated shot-gathers (bottom of the Fig. 9) clearly support the observations of high reflectivity in WARR data and, as demonstrated by Levander *et al.* (1994), could represent the poorly reflective crust in DSR image, as well.

In addition, as the proportion of heterogeneity increases, the average crustal velocity also increases, as estimated by the WARR model (6.3 km s⁻¹ in the upper crust in the Grajaú domain as opposed to the Teresina domain with 6.15 km s⁻¹). Further, an increase in the vertical scale of the heterogeneities, simulating greater connectivity between them, (Fig. 9c) tends to increase the reflectivity. The heterogeneities also tend to ‘homogenise’ the crust as a whole, reducing property contrasts at interfaces and reducing the difference between the mean velocities of the layers.

This region of the Parnaíba block is spatially coincident with what was interpreted as a crustal underplate in the WARR model (Soares *et al.* 2018). This aspect, added to the features that describe and differentiate the seismic and compositional nature of the crust based on the reflectivity patterns, tends to reinforce the interpretation that the Parnaíba block is composed of two different domains: Grajaú and Teresina, the Grajaú domain being defined by an apparently homogeneous crust (low velocity contrasts) and of more mafic composition than the Teresina domain (with higher V_p/V_s ratio) resulting from a crust highly intruded by small-scale mafic bodies. The differences recognized between the Grajaú and Teresina domains may be inherited from independent lithospheric blocks amalgamated during the Neoproterozoic Brasiliano Orogeny (Soares *et al.* 2018) or may be wholly or in part related to Jurassic and Cretaceous-aged magmatic rocks (Mosquito and Sardinha formations) found within the Parnaíba Basin (e.g. Klöcking *et al.* 2018).

6 CONCLUSIONS

The correlation of coincident DSR and WARR data sets across the intracontinental Parnaíba Basin in northeastern Brazil has revealed additional information about the crust underlying the basin with

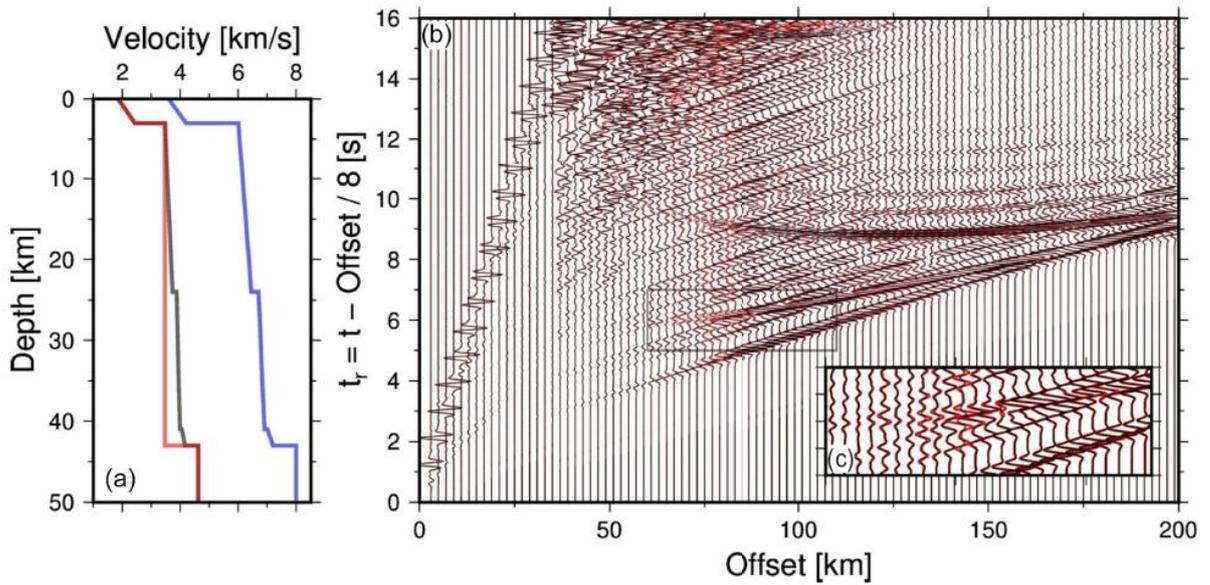


Figure 8. (a) 1-D curves of seismic velocities: V_p (blue line) and V_s (black line corresponding to V_p/V_s of 1.73 and red line corresponding to constant V_s) used for the calculation of the synthetic seismograms; (b) synthetic seismograms generated for each of the models considering only the variation of the V_s between them; (c) Zoom in to area highlighted by the rectangle in (b).

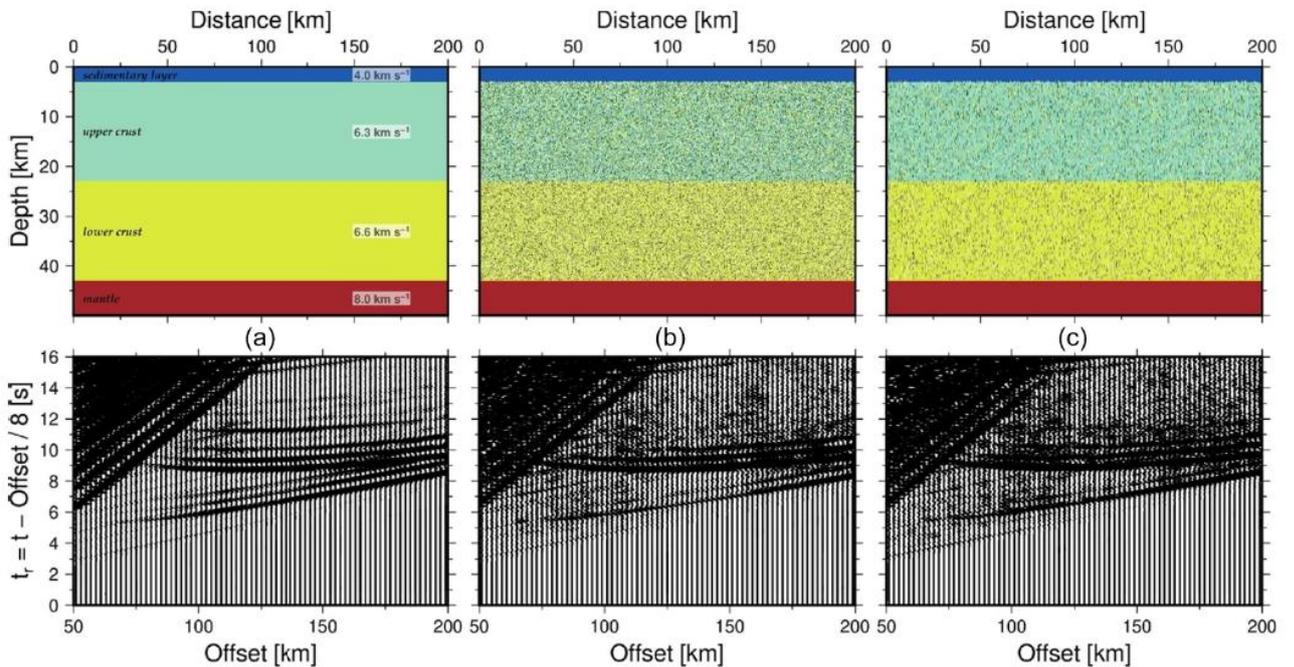


Figure 9. Seismic crustal models proposed in order to illustrate of the presence of heterogeneities on the crust (top panel) and to investigate the influence from the respective synthetic seismograms (bottom panel) obtained from the seismic modelling: (a) crustal model composed of three homogeneous layers (sedimentary layer, upper and lower crust); (b) crystalline basement intruded by mafic bodies (V_p of 6.75 km s⁻¹ and V_p/V_s ratio of 1.8) distributed randomly by the crust in a proportion of 23 per cent with dimensions of 50 and 200 m for horizontal and vertical scale, respectively; (c) same situation as the previous model, but reducing the proportion to 15 per cent and increasing the size to 100 and 500 m.

implications for the basin's present preserved architecture. The main conclusions are as follows.

(1) Direct comparison of the DSR and WARR data in TWTT shows that there is very good agreement of the WARR model velocity interfaces and the main reflective zones of the DSR image.

(2) Joint analysis of reflectivity patterns observed in both data sets allowed inferences to be made about the origin and nature of reflectivity by associating them with variations in V_p and V_s contrast (hence, elastic parameters) as a function of source-receiver aperture.

(3) The acoustically featureless DSR image of the Parnaíba block crustal segment is incompatible with WARR shot-gathers showing high reflectivity. These diametrically opposed patterns are explained by the random distribution of small-scale heterogeneities, represented by the intrusion of mafic bodies with dimensions in the range 50–200 m.

(4) The analysis has highlighted differences in the physical properties of the Precambrian Grajaú and Teresina domains (comprising together the Parnaíba crustal block underlying the Parnaíba Basin), which may have significance for understanding the Phanerozoic evolution of the Parnaíba Basin.

(5) The study has demonstrated the complementarity between information from different seismic data sets, reiterating the added value of acquiring coincident DSR and WARR seismic profiles for characterizing the continental crystalline crust.

SUPPORTING INFORMATION

Supplementary data are available at *GJI* online.
supplementary_material_LR1.zip.

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Apêndice C

Comparing reflectivity patterns of WARR and DSR 13

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