UNIVERSIDADE DE SÃO PAULO
INSTITUTO DE GEOCIÊNCIAS

**SEDIMENTOLOGIA E CRONOLOGIA POR LUMINESCÊNCIA
DA ILHA DE SÃO FRANCISCO DO SUL (SC):
CONSIDERAÇÕES SOBRE A EVOLUÇÃO HOLOCÊNICA DE
BARREIRAS ARENOSAS DA COSTA SUL E SUDESTE DO
BRASIL**

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DISSERTAÇÃO DE MESTRADO

Programa de Pós-Graduação em Geoquímica e Geotectônica

São Paulo

2011

Ficha catalográfica preparada pelo Serviço de Biblioteca e Documentação
do Instituto de Geociências da Universidade de São Paulo

Zular, André

Sedimentologia e cronologia por luminescência da
Ilha de São Francisco do Sul (SC): considerações
sobre a evolução holocênica de barreiras arenosas
da costa sul e sudeste do Brasil / André Zular. -
São Paulo, 2011.

95 p.

Dissertação (Mestrado) : IGc/USP
Orient.: Sawakuchi, André Oliveira

1. São Francisco do Sul (SC): Quaternário 2.
São Francisco do Sul (SC): Sedimentologia 3. São
Francisco do Sul (SC): Paleoclimatologia 4.
Luminescência opticamente estimulada I. Título

Scientists have found that moving into middle age for most is a journey into a happier time. In particularly hard or stressful moments it may not seem likely, but around middle age, we start growing happier, and the cause may be aging itself. The positive wins out over the negative in how we see the world, in part because we start to use our brains differently.

Barbara Strauch (2010)

Agradecimentos

Ao Prof. Dr. Paulo César Boggiani. Sem o seu incentivo, a idéia de voltar a estudar não teria vingado.

Ao grupo “eólico-quaternário” da Geo, Prof. Dr. André Oliveira Sawakuchi, Prof. Dr. Paulo César Fonseca Giannini, Carlos Guedes, Vinícius Ribau, Daniel Nascimento, Ana Paula Tanaka e Milene Fornari, que me receberam de braços abertos.

Aos colegas de pós Carlos Guedes, Vinícius Ribau e Daniel Nascimento que tiveram paciência e tempo para auxiliar no aprendizado e por seu entusiasmo e motivação.

A Profa. Dra. Ana Góes, pelo incentivo e elogios ao bolo de milho.

A todo o pessoal do Lab Sed. Isaac, Jordana, Elaine, Taís e Vítor.

Aos meus colegas de sala, Gabriella, Emiliano, Gisela e Alexandra.

Finalmente, um agradecimento especial a toda a minha família, Paulo, Myriam, Jayme, Fernanda e Bia (in memoriam).

Apresentação

Essa dissertação é apresentada na forma de 2 artigos. O artigo *Late Holocene dune development and provenance changes in São Francisco do Sul barrier: coastal dynamics shift forced by cold fronts intensification in Southern Brazil* foi submetido a *Marine Geology*. Esse artigo trata da evolução da barreira holocênica da Ilha de São Francisco do Sul através de dados de luminescência opticamente estimulada, análise geomorfológica, granulométrica e de minerais pesados e a sua correlação com eventos climáticos no Holoceno médio e tardio. Ele engloba o tema principal desta dissertação de mestrado.

O artigo *Geomorphological analysis of coastal landforms in SE Brazil aided by Google Earth coupled with the integration of chronological and sedimentological data by means of a Fusion Table* foi submetido a *Geological Society of America* para o *Special Paper: Google Earth and Virtual Visualizations in Geoscience Education and Research*. Este artigo abrange aspectos geomorfológicos da Ilha de São Francisco do Sul e do sul e sudeste do Brasil, métodos de análise e funcionalidade de imagens do Google Earth e a introdução do conceito de Fusion Tables para a consolidação de dados de sistemas deposicionais costeiros.

Em ambos os artigos, André Zular é o primeiro autor. Assim sendo, nesse volume são apresentados somente dados adicionais que complementam os artigos apresentados e a tabela de minerais pesados.

Os dois artigos constam desse volume como anexos. A formatação de cada um deles está de acordo com a publicação indicada, exceto no caso das tabulações e figuras e tabelas que foram inseridas no corpo do texto para fácil acesso.

RESUMO

A ilha de São Francisco do Sul (ISFS) está localizada no litoral norte de Santa Catarina. Abrange uma área de cerca de 265 km² com uma extensão de costa oceânica de aproximadamente 40 km. A ISFS foi formada por sistemas deposicionais costeiros ativos durante as variações do nível do mar dos últimos 120 mil anos. A progradação costeira da barreira regressiva localizada a leste da lagoa de Icaraí da ISFS estaria associada à desaceleração da ascensão do nível relativo do mar do Holoceno médio combinada com um aporte alto de sedimentos.

Características geomorfológicas da SFSI foram analisadas principalmente com o auxílio do Google Earth e com levantamentos de campo que indicaram a prevalência de sobreposição de dunas vegetadas formadas pela influência dos ventos S-SE na parte central e norte da barreira holocênica. Ao longo da costa, predomina uma estreita faixa de 5 a 10 m de dunas frontais associadas com *swales*. Em direção ao interior, as dunas frontais são gradualmente substituídas por *blowouts* e/ou dunas parabólicas de 10 a 20 m de altura ou por dunas com formatos irregulares seguidos por alinhamentos de cordões litorâneos.

Foram feitas datações de 11 amostras de sedimentos através de luminescência opticamente estimulada (LOE); cinco de cordões litorâneos, cinco de dunas parabólicas e uma de *blowout* numa área total de 7 km². As datações demonstraram que a construção da barreira mediante progradação de cordões litorâneos sem atividade eólica significativa ocorreu no período entre 4900 a pelo menos 3100 anos atrás. A partir de 1900 anos atrás, a progradação da barreira passou a ocorrer com o desenvolvimento de dunas parabólicas, cuja estabilização teria ocorrido até cerca de 1200 anos atrás. A sensibilidade LOE do quartzo foi estimada nas alíquotas analisadas para avaliar o retrabalhamento dos sedimentos nas diferentes unidades geomorfológicas. As amostras mais antigas dos cordões litorâneos mostraram valores elevados de sensibilidade LOE que indicam sedimentos muito retrabalhados, possivelmente submetidos a vários ciclos de deposição e de erosão.

Análise granulométrica e de minerais pesados foram realizadas em 45 amostras. Os cordões litorâneos foram caracterizados por areias finas e por uma assembléia metamórfica de minerais pesados em contraste com as dunas parabólicas, *blowouts* e areias da praia atual onde predominam sedimentos de granulometria média e uma maior contribuição de proveniência de rochas plutônicas ácidas.

A progradação holocênica da barreira da ISFS teve uma mudança acentuada na morfodinâmica há cerca de 1900 a 1800 anos atrás, caracterizada pelo desenvolvimento episódico das dunas parabólicas migrando para o NW sobrepostas aos cordões litorâneos e a uma mudança acentuada na proveniência dos sedimentos. Essa mudança morfodinâmica é associada a um aumento na força dos ventos de sul e a maior intensidade da deriva litorânea rumo ao norte. Esses fatores indicam o fortalecimento das frentes frias a partir de 1900 a 1800 anos atrás. A maior atividade das frentes frias no sul do Brasil pode estar relacionada com a expansão para o norte da faixa de ação dos ventos de oeste (*Westerlies*) e intensificação do *El Niño*/Oscilação Sul (ENOS). As alterações geomorfológicas e de proveniência detectadas na ISFS demonstram que as barreiras holocênicas do sul e sudeste do Brasil são sensíveis às mudanças climáticas do Holoceno Tardio. Assim, a geocronologia e sedimentologia de fácies geomorfológicas, como demonstradas em uma pequena área de SFSI, podem atuar como um indicador válido de eventos climáticos do passado.

ABSTRACT

São Francisco do Sul Island (SFSI) is located on the northern coast of Santa Catarina State, Brazil. It covers an area of about 265 km² with an approximate length of oceanic coastline of 40 km. The island was formed by coastal depositional systems active during the relative sea-level changes of the last 120,000 years. The following relative sea-level fall after the Mid-Holocene maximum highstand combined with high sediment input have contributed to coastal progradation of the regressive barrier located east of Icaraí lagoon. Geomorphological features of SFSI were analyzed primarily with the aid of Google Earth and field surveys and indicated the prevalence of superimposed vegetated dunes formed under the influence of the S-SE winds on the central and northern part of the Holocene barrier. Along the coastline, a narrow belt of 5-10 m high foredune ridges associated with swales occurs. The foredunes are gradually replaced inland by blowouts and/or 10-20 m high parabolic or irregular dune forms followed by beach ridges.

Optically Stimulated Luminescence (OSL) dating of 11 samples using the single-aliquot regenerative-dose (SAR) protocol of the beach ridges (5 samples), parabolic dunes (5 samples) and blowouts (1 sample) over an area of 7 km² showed two distinct periods of stabilization. Beach ridges stabilized at the 4.9-3.1 ka period and parabolic dunes at the 1.9-1.2 period. Quartz OSL sensitivity was measured in the dating aliquots to evaluate the sedimentary reworking of sands from the studied geomorphological units. Elevated OSL-sensitivity values associated with the oldest beach ridge samples indicate highly reworked sediments, possibly submitted to many cycles of barrier construction and erosion. Grain-size and heavy minerals analyses were performed in 45 samples. Beach ridges were characterized by fine sands and a metamorphic heavy minerals assemblage in contrast to the parabolic dunes, blowouts and present beach sands of medium grain-size and a higher contribution of an acid plutonic rocks provenance.

The Holocene progradation of the SFSI barrier had a pronounced morphodynamic shift around 1.9-1.8 ka, which is characterized by the episodic development of the parabolic dunes migrating to NW over beach ridges and a marked change in sediment provenance. This

morphodynamic shift derived from an increase in the strength of winds from south and northward alongshore drift, implied strengthening of cold fronts activity since 1.9-1.8 ka. Higher cold fronts activity in Southern Brazil can be linked with the northward expansion of the south westerly wind belt (Westerlies) and intensification of El Niño Southern Oscillation (ENSO). Thus, the luminescence chronology and sedimentology of different geomorphological facies in barrier systems as shown in a small area of SFSI may act as a valid proxy for past climate events.

Índice

1.Sedimentologia e cronologia por luminescência da ilha de São Francisco do Sul (SC): considerações sobre a evolução holocênica de barreiras arenosas da costa sul e sudeste do Brasil.....	1
1.1. Introdução	2
1.2.Síntese Bibliográfica.....	4
1.2.1. Aspectos geológicos e geomorfológicos da área de estudo	4
1.2.2. Estudos anteriores.....	6
1.2.3. Clima	9
1.2.4. Marés e Ondas	13
1.3. Discussão	14
1.4. Conclusão	15
Referências bibliográficas	16
Anexo	20
 2. Late Holocene dune development and provenance changes in São Francisco do Sul barrier: coastal dynamics shift forced by cold fronts intensification in Southern Brazil	 21
2.1. Introduction.....	23
2.2. Study setting.....	24
2.2.1. Geological aspects	24
2.2.2. Climate	29
2.2.3. Paleoclimate.....	31
2.3. Methods	32
2.3.1. Surveying and sampling	32
2.3.2. Grain-size analyses	35
2.3.3. Heavy-Minerals analysis	35
2.3.4. OSL dating and sensitivity analyses	36

2.4. Results	37
2.4.1. Geomorphology	37
2.4.2. Grain Size	40
2.4.3. Heavy Minerals.....	42
2.4.4. OSL ages and sensitivity.....	46
2.5. Discussion	52
2.5.1. Holocene barrier progradation and dune building in São Francisco do Sul Island.....	52
2.5.2. Changes in sediment provenance and reworking.....	54
2.5.3. Coastal morphodynamics shift induced by cold fronts intensification in the Late Holocene.....	57
2.6. Conclusion	59
References.....	60

3. Geomorphological analysis of coastal depositional systems in SE Brazil aided by Google Earth coupled with the integration of chronological and sedimentological data by means of a Fusion Table

3.1. Introduction.....	72
3.2. Regional Settings	76
3.3. Google Earth	77
3.3.1. Modeling.....	77
3.3.2. São Francisco do Sul – Santa Catarina State.....	77
3.3.3. Ilha Comprida – São Paulo State	81
3.3.4. Campos Verdes and Ji – Santa Catarina State	83
3.3.5. Tubarão River Delta – Santa Catarina State	84
3.3.6. Ibiraguera Beach – Imbituba-Laguna Region – Santa Catarina State	85
3.4. Google Fusion Tables	86
3.5. Conclusion	90
References.....	92
Supplementary KML code	95

Índice de Figuras

1. Sedimentologia e cronologia por luminescência da ilha de São Francisco do Sul (SC): considerações sobre a evolução holocênica de barreiras arenosas da costa sul e sudeste do Brasil

Fig. 1. Imagem obtida através do satélite LANDSAT 5 da Ilha de São Francisco do Sul.	3
Fig. 2. Padrão retangular da rede de drenagem que dissecou os terraços do Pleistoceno Superior durante o período com nível do mar mais baixo que o atual (entre 120.000 e 7.000 AP), na planície costeira a oeste do Rio Sai-Mirim. (1) terraços pleistocênicos (2) planície paleoestuarina holocênica (3) cursos fluviais (Angulo <i>et al.</i> , 2004).	5
Fig. 3. Imagens Google Earth com zoom progressivo da esquerda para a direita na parte noroeste oceânica da Ilha.	6
Fig. 4. Mapa CPRM (2004) da Ilha de São Francisco do Sul com legendas adaptadas. Escala 1:1.000.000. Folha SG 22 – Curitiba.	7
Fig. 5. Representação gráfica de avanço de uma frente fria no sul do Brasil. Os eixos x e y indicam E e N, respectivamente (Stech <i>et al.</i> , 1992).	10
Fig. 6. Direção do vento e intensidade durante o avanço de frente fria no sul do Brasil (Gallucci & Netto, 2004). ...	11
Fig. 7. Distribuição da frequência do vento em função de sua intensidade e direção (Truccollo, 1998).	12

2. Late Holocene dune development and provenance changes in São Francisco do Sul barrier: coastal dynamics shift forced by cold fronts intensification in Southern Brazil

Fig. 1. Landsat ETM +7 image (2002) of São Francisco do Sul Island.	26
Fig. 2. Geological map of the eastern portion of the state of Santa Catarina, Brazil, showing SFSI and the exposed region of the Florianópolis batholiths (modified from Guadagnin <i>et al.</i> , 2010).	27
Fig. 3. Mid-Holocene sea-level curve based on vermetid samples dated along the eastern Brazilian coast with their error bars. Dashed line indicates values in the southern part of Santa Catarina State. Solid line indicates values obtained from the remaining states. It was assumed that sea-level values for the island of SFSI were in between the two lines (Angulo <i>et al.</i> , 2006).	29
Fig. 4. Present-day South America: physical characteristics of the continent with the location of the major atmospheric features of the climatic system (ITCZ, SASM, SACZ, Westerlies and Polar advections). Modified from Sylvestre (2009).	32
Fig. 5. Georeferenced Google Earth image of SFSI (2009, by GeoEye). Dots indicate sample collection sites on the central and northern portion of SFSI. OSL collection sites are shown with red text.	34
Fig. 6. Google Earth image (imagery date: 7/3/2009 by GeoEye). White solid line displays the boundary between beach ridges (left) and parabolic dunes (right). Placemarks SFS-9-L and SFS-12-L indicate sample collection sites. The distance from the actual shore face is 140 and 400m, respectively.	37
Fig. 7. Sample SFS-19-L site. Beach face, foredunes and blowouts are common features in the northeastern segment of SFSI.	38
Fig. 8. Sample site SFS-8-L1 (beach ridge) shows horizontal and slightly seaward-inclined parallel-stratified sands, suggesting deposition in the foreshore zone. Bioturbation was found in many sites.	39
Fig. 9. Sample site SFS-25-L (beach ridge). Erosional surfaces separating sets of plan-parallel stratification marked by lamina with high concentration of heavy minerals. Heavy minerals concentration may be evidence of storm activity.	39
Fig. 10. Frequency distribution of grain size for each geomorphological unit (mean values). Grain size data in phi units.	42
Fig. 11. Heavy minerals assemblages from different geomorphological units.	44
Fig. 12. (A) Typical zircon grain from sample SFS-12-L (paleodune) with length to width ratio of 257:87 μm (B) Typical reworked zircon grain from sample SFS-13-L (beach ridge) with length to width ratio of 77:63 μm	45
Fig. 13. Boxplots of RZi and TZi values. Beach ridges show higher and more varied values of RZi and TZi compared to all other units.	46

Fig. 14. Plot of sensitivity corrected OSL signal versus radiation dose for single-aliquot from sample SFS-8-L.3 The horizontal line shows the natural OSL signal. The dose is given in time of irradiation (dose rate of 95.95 ± 4.1 mGy/s).....	49
Fig. 15. Equivalent doses estimated for the aliquots of samples SFS-9-L and SFS-12-L. N = number of aliquots.....	49
Fig. 16. Histogram of recycling ratio distribution of 252 dating aliquots.....	50
Fig. 17. Comparison among beach ridges, blowouts and paleodunes ages.....	50
Fig. 18. Mean size distribution in different geomorphological units.....	50
Fig. 19. Digitized Google Earth image of SFSI (2009, by GeoEye). Coastal progradation on the central- northernmost part of the SFSI where OSL ages were obtained. Section "A" denotes the period from from 5 to approximately 3.1 ka (beach ridge progradation period only). The following section "B" denotes deposition that starts at 3.1ka to the present date. Dashed line indicates the boundary with superimposed dunes.....	51
Fig. 20. Sample collection site SFS-18-L, a blowout close to the shore with OSL age of 87 ± 8 years. Sands with cross-bedding dipping from 16° to 34° to WNW are common in the blowout facies in SFSI.....	52

3.Geomorphological analysis of coastal depositional systems in SE Brazil aided by Google Earth coupled with the integration of chronological and sedimentological data by means of a Fusion Table

Fig. 1. Google Earth images of Brazil's SE coast. A) Ilha Comprida, B) São Francisco do Sul, C) Ibiraquera Beach – Imbituba-Laguna Region, D) Tubarão River Delta, E) Campos Verdes and Ji.	74
Fig. 2. Google Earth image of a partial view of the oceanic coast of São Francisco do Sul Island. Blowouts are outlined in red and paleodunes boundaries in white.....	75
Fig. 3. Georeferenced Google Earth image of São Francisco do Sul Island processed with the help of ArcGis software.....	78
Fig. 4. Google Earth image showing the boundary between beach ridges and paleodunes terrains in the São Francisco do Sul Island. Despite the cover of intense vegetation, well-preserved paleodune morphology is conspicuous. NW parabolic dune orientation attests to strong SE winds in the past. Paleodunes overimpose older beach ridges. Recently obtained OSL ages for beach ridges are higher than 3.1 ka and lower than 1.9 ka for paleodunes.	79
Fig. 5. Comparison between aerial photographs, Landsat 7 image and by SIO, NOAA, US Navy, NGA, and GEBCO images available on Google Earth from São Francisco do Sul. (a,b,c) aerial photographs from 1938, 1957 and 1978 surveys, respectively.(d) Landsat 5 image.	80
Fig. 6. Placemarks on the Google Earth image were used to georeference the image in the ArcGis program. The raster obtained from Google Earth was also helpful in georeferencing photographs from 1938, 1956 and 1978 in São Francisco do Sul.	80
Fig. 7. 2009 Google Earth image. Blowout evolution on the northern part of São Francisco do Sul Island. Solid line depicts blowout boundary obtained from the 1938 aerial photography survey.	81
Fig. 8. Google Earth historical images were utilized to elucidate sediment dynamics linking erosion and deposition in Ilha Comprida from 2001 to 2010. The barrier has experienced extensive erosion on its oceanic NE side followed by progradation on its on its northernmost point in this period. An area of 0.69 km^2 was eroded from 2001 to 2010. Conversely, a progradation of 0.74 km^2 occurred at the same period at the northernmost point of the island.	83
Fig. 9. Comparison of 1956 photograph with Google Earth image. Circled areas show previous ridges on the photograph no longer visible on the Google Earth image. They were replaced by shrimp tanks.....	84
Fig. 10. The red arrow on the Google Earth image shows the distance from the paleo channel to its current position at Carniça River.	85
Fig. 11. Outlining differentiated generations of eolian depositional system with the aid of Google Earth.	86
Fig. 12. From an Excel spreadsheet to placemarks on the Google Earth Image. Customized pop-up window with links, sample site pictures and sedimentological and heavy minerals data displayed as graphs and charts.....	89

Índice de Tabelas

1.Sedimentologia e cronologia por luminescência da ilha de São Francisco do Sul (SC): considerações sobre a evolução holocênica de barreiras arenosas da costa sul e sudeste do Brasil

Tabela 1. Contagem de minerais pesados separados por unidades geomorfológicas. As quantidades dos minerais individuais estão em %. No caso das contagens dedicadas para índices, as quantidades são em valores absolutos.	20
--	----

2. Late Holocene dune development and provenance changes in São Francisco do Sul barrier: coastal dynamics shift forced by cold fronts intensification in Southern Brazil

Table 1. Grain size distribution of the sediments from the SFSI geomorphological units.	40
Table 2. Descriptive statistics of the grain size for samples grouped by geomorphological units. Q1 = first quartile, Q3 = third quartile.	41
Table 3. Differences in the heavy minerals content on the very fine sand fraction from different geomorphological units. In all cases there is a wide dispersion of values as indicated by standard deviation values. N = number of samples, Q1 = first quartile, Q3 = third quartile.	43
Table 4. Relative abundance (mean values) of heavy minerals by geomorphological units. N= number of samples, Zi= Zircon, Tu= Tourmaline, Ru= Rutile, Hn= Hornblende, Ep= Epidote, Sl= Sillimanite, Ky= Kyanite. St= Staurolite, Mz= Monazite, Hy= Hyperstene, Di= Diaspore, Gr= Garnet, Ap= Apatite, Cl= Clinozoisite, Ac= Actinolite, Tr= Tremolite, An= Andalusite, En= Enstatite.	44
Table 5. Zircon percentage in the different SFSI geomorphological units. Q1 = first quartile, Q3 = third quartile. ...	45
Table 6. RZi and TZi. Striking differences in RZi and TZi among the SFSI geomorphological units. Q1 = first quartile, Q3 = third quartile.	46
Table 7. OSL dating results in SFSI	48

3.Geomorphological analysis of coastal depositional systems in SE Brazil aided by Google Earth coupled with the integration of chronological and sedimentological data by means of a Fusion Table

Table 1. List of fields used in the Brazilian Coastal Landforms Fusion Table.....	88
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1.Sedimentologia e cronologia por luminescência da ilha de São Francisco do Sul (SC): considerações sobre a evolução holocênica de barreiras arenosas da costa sul e sudeste do Brasil

1.1. Introdução

As planícies costeiras constituem importante elemento geomorfológico da costa brasileira, tendo sido formadas em fases transgressivas e regressivas do Quaternário, com destaque para as fases de mar alto do Pleistoceno tardio (aproximadamente 120.000 anos AP) e do Holoceno médio (5.500 anos AP; Van Andel *et al.*, 1964; Suguio *et al.*, 1985; Martin *et al.*, 1988; Angulo *et al.*, 2006). Estas planícies são produto da evolução quaternária de sistemas deposicionais costeiros, os quais incluem elementos fisiográficos diversos, tais como deltas, estuários, lagunas, praias e dunas. A evolução destas planícies costeiras é registrada pelo desenvolvimento de elementos geomorfológicos de origem diversa como alinhamentos de cordões litorâneos, canais de maré, leques de sobrelavagem, dunas frontais, cavas de deflação, dunas parabólicas e campos de dunas transgressivos. A distribuição espacial destes elementos é variável, porém, diversas barreiras holocênicas do litoral norte catarinense, paranaense e sul paulista destacam-se pela concentração de formas deposicionais eólicas nas porções mais oceânicas sugerindo mudanças na dinâmica do sistema costeiro no Holoceno Tardio (Amin Jr. *et al.*, 2006; Giannini *et al.*, 2007; Sawakuchi *et al.*, 2008; Guedes *et al.* 2011). Estas mudanças seriam representadas por ventos mais intensos e constantes, combinados com aporte sedimentar costeiro elevado. Deste modo, os sedimentos acumulados nestas planícies costeiras representam, por meio da geomorfologia, aspectos ligados ao clima das áreas costeiras.

A Ilha de São Francisco do Sul faz parte da planície costeira do litoral norte do Estado de Santa Catarina. Esta ilha possui 12 praias arenosas, algumas estuarinas, banhadas pelas águas da baía de Babitonga, que conta com um arquipélago formado por 24 pequenas ilhas (Fig. 1).

Fig. 1. Imagem obtida através do satélite LANDSAT 5 da Ilha de São Francisco do Sul.

As praias do Ervino e Grande formam a porção leste oceânica da Ilha. A planície costeira adjacente a estas praias compreende alinhamentos de cordões litorâneos, canais de maré e dunas eólicas vegetadas. Grande parte desta região possui ecossistema de restinga ainda bem preservado e destaca-se pela presença de faixa externa com dunas frontais, cavas de deflação (*blowouts*) e dunas parabólicas (Angulo *et al.*, 2009).

Essa dissertação teve como objetivos principais a caracterização sedimentológica e a definição da cronologia dos elementos geomorfológicos que constituem a planície costeira da Ilha de São Francisco do Sul, com ênfase nas formas deposicionais eólicas e cordões praias. Os sedimentos costeiros arenosos foram datados pelo método da luminescência opticamente estimulada (LOE), protocolo de alíquota única (*SAR - Single Aliquot Regeneration*). Este método permite a determinação de idades de deposição de sedimentos em intervalo de poucas dezenas de anos a centenas de milhares de anos e sua utilidade para datação de sedimentos

costeiros tem sido demonstrada por diversos estudos (Murray-Wallace *et al.*, 2002; Nielsen *et al.*, 2006; Lopez *et al.*, 2007; Brooke *et al.*, 2008; Guedes *et al.*, 2011). Dados sedimentológicos obtidos a partir de análise granulométrica e análise de minerais pesados associados a interpretação de imagens de fotos aéreas e satélite e pesquisas de campo forneceram, junto com as datações obtidas, informações suficientes para que se pudesse elaborar um modelo evolutivo da barreira holocênica da Ilha de São Francisco do Sul nos últimos 5.000 anos e a sua relação com as alterações climáticas prevalentes durante esse período.

1.2.Síntese Bibliográfica

1.2.1. Aspectos geológicos e geomorfológicos da área de estudo

A Ilha de São Francisco do Sul está localizada no litoral norte do Estado de Santa Catarina entre as latitudes sul de 26°09'42" e 26°27'05" e as longitudes oeste de 48°29'38" e 48°42'59". Compreende uma área de cerca de 280 km² com comprimento aproximado de linha de costa oceânica de 40 km. Seu substrato é composto por rochas pré-cambrianas graníticas e gnáissicas do Cinturão Granitóide Costeiro (Basei *et al.*, 1992) , concentradas principalmente na extremidade centro-oeste e por depósitos de barreira localizados a leste da Ilha . O substrato rochoso faz parte de um complexo ígneo-metamórfico polifásico, que inclui grande variedade de rochas graníticas/metamórficas distribuídas desde a Ilha de São Francisco do Sul até o sul da cidade de Itatins, no Estado de São Paulo (Siga Jr. *et al.*, 1993). A cobertura sedimentar da ilha foi formada por sistemas deposicionais costeiros ativos durante os eventos transgressivos e regressivos ocorridos durante o Pleistoceno Tardio e Holoceno e por sedimentos costeiros quaternários provenientes da plataforma interna ou trazidos pela corrente de deriva litorânea, distribuídos por toda a ilha. Em alguns locais as rochas do embasamento alcançam a costa formando promontórios e pequenas ilhas.

Embora ainda não se tenha as idades absolutas de sedimentos na parte a oeste da Lagoa do Icaraí, considera-se que se constituem de depósitos de barreira pleistocênicos (Horn Filho *et al.*, 2008). que se estendem até os afloramentos do embasamento, a oeste. Esses

sedimentos são arenosos e apresentam em planta contornos sinuosos, sugerindo cordões litorâneos e feições erosivas atribuídas à dissecação por ação de antigas redes de drenagem de padrão retangular. De acordo com Angulo *et al.* (2004) uma das características regionais morfológicas mais destacadas desses terraços é a evidência de terem sido recortados por sistemas fluviais com nível de base inferior ao atual, com padrão de drenagem retangular e com vales paralelos e transversais aos alinhamentos dos antigos cordões litorâneos (Fig. 2).

Fig. 2. Padrão retangular da rede de drenagem que dissecou os terraços do Pleistoceno Superior durante o período com nível do mar mais baixo que o atual (entre 120.000 e 7.000 AP), na planície costeira a oeste do Rio Sai-Mirim. (1) terraços pleistocênicos (2) planície paleoestuarina holocênica (3) cursos fluviais (Angulo *et al.*, 2004).

A leste da Lagoa do Icarai estão os depósitos de barreira holocênicos, que compõem uma faixa NE de aproximadamente 2,5 km de largura média. Esses depósitos são arenosos e apresentam relevo plano ou suavemente ondulado devido a presença de cordões litorâneos. Sobre tais depósitos, na sua porção norte e central, ocorrem os depósitos eólicos holocênicos. Esses depósitos apresentam-se como faixas de dunas parabólicas com frentes de avanço voltadas para SE, com alturas de até 17 m na parte norte da praia Grande (Fig. 3) e progressivamente menores até ficarem inexistentes rumo ao sul. Os depósitos praias atuais, constituídos por areias, estão localizados na costa leste, no extremo norte e no extremo sul da ilha, voltadas para o oceano. Nos depósitos praias destacam-se feições como bermas, dunas

frontais, *swales* e *nebkhas*. Os depósitos eólicos apresentam-se como dunas ativas ou vegetadas ou dunas estabilizadas, onde predominam areias médias quartzosas e arredondadas. Em toda costa oceânica, observa-se um ou mais dunas frontais separadas por *swales* seguidos no sentido ilha adentro por rupturas de deflação e dunas parabólicas vegetadas. Os sedimentos holocênicos teriam sido depositados em contexto de nível relativo do mar (NRM) descendente, após o máximo transgressivo holocênico.

Fig. 3. Imagens Google Earth com zoom progressivo da esquerda para a direita na parte noroeste oceânica da Ilha.

1.2.2. Estudos anteriores

Martin *et al.* (1975, 1976) realizaram amplos estudos sobre a influência das variações do NRM (nível relativo do mar) quaternário na distribuição de unidades sedimentares da costa brasileira. Estes autores aventaram a possibilidade de existência de terraços marinhos construtivos distintos, correlacionados com dois níveis do mar pós-glaciais ocorridos no Pleistoceno Tardio e no Holoceno. Estes mesmos autores, em trabalho posterior (Suguio *et al.*, 1978), elaboraram modelo de evolução quaternária e de variação do NRM nos últimos 7.000 anos e sugeriram critérios de distinção entre areias regressivas do Pleistoceno e do Holoceno. Estes critérios incluíam a altitude, a nitidez dos “alinhamentos superficiais de cristas praiais” e

o grau de impregnação epigenética dos grãos. Em costas arenosas de baixa declividade, o abaixamento do NRM provoca intenso aporte de areia da plataforma interna para a praia. Em setores onde o transporte por deriva litorânea é fraco ou nulo, ocorre então progradação dos sistemas deposicionais costeiros. Através de estudos realizados em vários locais do litoral brasileiro, Suguio *et al.* (1978) interpretam a ocorrência de areias muito finas a finas bem selecionadas com coloração amarelo-marrom e com presença de tubos fósseis de *Callichirus* SP como as existentes na parte a oeste da Lagoa do Icaraí com características indicativas de terraços ou barreiras pleistocênicas. Esses autores sugerem que no Pleistoceno, o sistema de barreiras seria caracterizado pela presença de depósitos marinhos, lacustres e eólicos.

Em 2004, o Serviço Geológico do Brasil (CPRM) lança a folha Curitiba (SG-22) na escala 1:1.000.000. Não há divisão entre a barreira holocênica e pleistocênica na Ilha de São Francisco do Sul nesse mapa (Fig. 4).

Fig. 4. Mapa CPRM (2004) da Ilha de São Francisco do Sul com legendas adaptadas. Escala 1:1.000.000. Folha SG 22 – Curitiba.

Horn Filho *et al.* (2008) especifica que no caso da Ilha de São Francisco do Sul, os depósitos pleistocênicos de origem marinha e lagunar ocorrem na base (substrato) da parte oeste da ilha e os de origem eólica podem ocorrer acima destes. Estima-se que esses

depósitos alcancem altitudes médias de 12 a 16m, contudo, foi observado no setor central da ilha (de 26°15' S) um terraço de forma circular com 19 Km² de área atingindo 25m de altitude (Horn Filho *et al.*, 2008) . Estes depósitos assemelham-se àqueles de idade holocênica, contudo, a posição mais interiorizada na planície costeira com relação à linha de costa atual e as maiores altitudes são conclusivas para defini-los como de idade pleistocênica (Horn Filho *et al.*, 2008). Esses depósitos teriam sido formados quando o nível do mar atingiu 8 ± 2 m acima do NRM atual na fase regressiva da máxima transgressão/regressão Sangamoniana-Yarmoutiana entre 18 a 120.000 anos AP, período que corresponde a transgressão Cananéia no Estado de São Paulo.

Horn Filho *et al.* (2008) definem 7 estágios paleogeográficos da planície costeira de São Francisco do Sul desde o final do Plioceno até o Holoceno tardio:

I – Estágio 1 – Transgressão máxima do Plioceno

II - Estágio 2 – Regressão máxima do Plioceno

III – Estágio 3 – Transgressões e Regressões do Pleistoceno Inferior e Médio

IV – Estágio 4 – Máxima Transgressão do Pleistoceno Superior

V – Estágio 5 - Máxima Regressão do Pleistoceno Superior

VI – Estágio 6 - Máxima Transgressão do Holoceno

VII – Estágio 7 - Máxima Regressão do Holoceno

Em relação aos depósitos holocênicos, Possamai *et al.* (2010) destaca os depósitos lagunares que constituem uma faixa orientada no sentido SW-NE e possuem até 2km de largura. De acordo com esse autor, os depósitos lagunares possuem morfologia bastante plana, por vezes ondulada quando há ocorrência de sobreposição de depósitos marinhos e são constituídos por sedimentos areno-argilosos, de coloração cinza-escuro e por vezes preta, devido ao enriquecimento por matéria orgânica decomposta. Os sedimentos teriam origem em ambiente estuarino ou lagunar (Possamai *et al.*, 2010).

1.2.3. Clima

A Ilha de São Francisco do Sul insere-se em área de clima regional subtropical, com verões chuvosos e invernos secos e úmidos (Cfa de acordo com a classificação Koeppen). A temperatura média anual oscila entre 16 e 20°C e a precipitação pluviométrica anual varia entre 1000 e 1500 mm. Predominam dois tipos de massas de ar oceânicas. O Anticiclone do Atlântico Sul é um centro de alta pressão ativo formador de uma massa de ar tropical marítima de temperatura e umidade elevadas devido a intensa radiação solar e forte evaporação marítima. Em consequência, o seu predomínio na área de estudo implica, normalmente, em condições de estabilidade do tempo com ocorrência de dias ensolarados. O Anticiclone Móvel Polar, gerado através da interação dos ventos *Westerlies* com massas frias provenientes da Antártica, se desloca no sentido SW-NE, em direção ao território sul-brasileiro (Truccollo, 1998).

A ocorrência de frentes frias de maior intensidade no inverno originadas pelo Anticiclone Móvel Polar em contato com o sistema semi-fixo de alta pressão do Anticiclone do Atlântico Sul gera ventos sobre a região que se propagam a uma velocidade média de 500 km/dia (Stech *et al.*, 1992).

Stech *et al.* (1992) indicam que a passagem de uma frente fria produz variações bruscas da pressão atmosférica e da temperatura do ar, ocasionando também uma modificação na magnitude e direção do vento. Através de dados coletados entre os anos de 1980 a 1985 em estações meteorológicas costeiras no sul e sudeste do Brasil, estima-se que a duração média de uma frente fria é de 2 a 3 dias com intervalo médio de tempo consecutivo entre as frentes de 6,5 dias. Com a aproximação da frente fria, a velocidade média do vento de nordeste é de 5 m/s. Durante a permanência da frente, o vento passa a soprar do quadrante sul com uma velocidade média de 8 m/s no setor frio. A Fig. 5 é uma representação gráfica do modelo proposto pelos autores para a região sul do Brasil.

Fig. 5. Representação gráfica de avanço de uma frente fria no sul do Brasil. Os eixos x e y indicam E e N, respectivamente (Stech et al., 1992).

Através de dados coletados durante a passagem de duas frentes frias em Junho de 2002 no Sul da Ilha de Santa Catarina, Gallucci *et al.* (2004) **demonstram** as variações de direção e intensidade do vento durante esse período (Fig. 6).

Fig. 6. Direção do vento e intensidade durante o avanço de frente fria no sul do Brasil (Gallucci & Netto , 2004).

Nos dois dias que antecederam a passagem da primeira frente fria (dias -2 e -1), os ventos sopravam exclusivamente do N – NW. No dia 0 (zero, início da passagem da frente fria) o vento mudou para S-SE com uma velocidade de 5,6 m/s. Nos dias 1, 2 e 3 caracterizados pela passagem da primeira frente os ventos N voltaram a predominar, exceto no dia 2, quando ocorreram ventos do sul de velocidade média de 3,6 m/s . Os ventos voltaram a ocorrer de S-SE durante os dias 4 e 5, indicando a passagem de uma segunda frente fria de menor intensidade.

Utilizando dados de direção e intensidade de vento, coletados entre os meses de agosto a dezembro de 1996 no norte da Ilha de São Francisco do Sul, Trucollo (1998) indica três regiões de maior concentração do vento durante esse período (Fig. 7). A frequência de frentes frias durante esse período foi de cerca de 6,25 eventos mensais.

Fig. 7. Distribuição da freqüência do vento em função de sua intensidade e direção (Truccollo, 1998).

A região mais expressiva é a de direção norte-nordeste com ventos de intensidade entre 2 a 4 m/s. Essa região corresponde aos ventos predominantes na ilha, gerados através da atuação do Anticiclone do Atlântico Sul. Os ventos de direção oeste e leste com intensidades de aproximadamente 2 m/s correspondem as brisas marinhas e terrestres, ortogonais a linha de costa. Os ventos de sudeste, de maior intensidade, com velocidades de 6 a 8 m/s, são associados as passagens de frentes frias.

Truccollo (1998) comparou os dados obtidos com os valores médios mensais de medições de 29 anos realizadas no Porto de São Francisco do Sul (DHN, 1994). Os dados dessa série são compatíveis aos obtidos no período de cinco meses por Truccollo(1998).

A ação dos centros de alta pressão discutidos acima tem conferido ao vento um papel fundamental na morfogênese regional, tanto atual como pretérita. Além de formar extensos campos de dunas, ondas e correntes geradas por ventos são fatores básicos de controle da hidrodinâmica oceânica e dos corpos lagunares da região. Em resposta à ação desses ventos, as dunas eólicas presentes apresentam orientação SSE-NNW e migram no sentido NNW (Truccollo, 1998). Há indicações, de modelos principalmente, mostrando que o clima no Holoceno no sul do Brasil sofreu variações significativas no que diz respeito a ocorrência de períodos secos e úmidos (Cruz *et al.*, 2009; Chiessi *et al.*, 2010).

1.2.4. Marés e Ondas

A partir de análises estatísticas, Truccollo (1998) propôs uma relação dinâmica entre as forçantes atmosféricas locais e a maré meteorológica em São Francisco do Sul. Além dos dados de direção e intensidade dos ventos e pressão atmosférica, foram coletados dados de séries horárias do nível do mar no píer da PETROBRÁS a 2,74 m de profundidade em relação ao nível zero do IBGE (Truccollo, 1998).

A maré astronômica em São Francisco do Sul pode ser caracterizada por micro-maré, predominantemente semi-diurna com desigualdades de altura para as preamares e baixamarés consecutivas. Truccollo (1998) ressalta, entretanto, a importância da maré meteorológica através da contribuição deste componente nas sobre-elevações do nível do mar, apresentando uma percentagem de ocorrência de 2% quando considerado um valor limite de 80 cm, que é a somatória da componente astronômica e meteorológica. Esse valor representa em um ano, por exemplo, a ocorrência de pelo menos uma semana de marés maiores que 80 cm na região devido somente a componente meteorológica. Na Praia Grande, já se observou valores de 106 cm (Truccollo *et al.*, 1999).

As ondas locais são caracterizadas por períodos curtos de cerca de 4 a 7 s com alturas aproximadas variando de 0,5 a 1 m no caso de ventos de E a NE. Já as ondas associadas a frentes frias, de ventos de S a SE, apresentam períodos de cerca de 9 a 15 s com alturas aproximadas variando de 1 a 2 m (Alves, 1996). Alves *et al.* (2001) efetuaram estudo mais detalhado das frentes de onda identificando quatro tipos de ocorrência:

- Ondas de ENE. Predominam no verão. O seu período varia entre 3 a 8 s. A altura média é de 0,75 m com variações de 0,5 a 1,5 m.
- Ondas de SSE. Ondas geradas por ventos de sistema de baixa pressão de frentes frias. Período de 4 a 8 s com variações de altura de cerca de 1 a 3,5 m.
- Ondas de E-SE. São as dominantes no sistema de ondas local. Período de 6 a 11 s com variações de altura de cerca de 0,5 a 1,5 m.

- Ondas de SE. Associadas a marolas (*swells*). Período de 7 a 16 s com variações de altura de cerca de 0,5 a 2 m.

1.3. Discussão

Controles cronológicos são essenciais para avaliar a associação entre processos geomorfológicos costeiros e mudanças climáticas ou de nível relativo do mar. Na falta de idades absolutas, vários indicadores foram usados como parâmetros espaço-temporais nas barreiras holocênicas e pleistocênicas de São Francisco do Sul (Suguio *et al.*, 1978; Horn Filho *et al.*, 2008; Possamai *et al.*, 2010). Muitos deles têm sido usados de maneira dúbia para isso. Na identificação de terrenos pleistocênicos em várias partes do Brasil e no mundo, areias amarelo-marrom com fósseis *Callichirus sp.* podem ser eventualmente bons indicadores, entretanto, os resultados são na maioria das vezes de uma amplitude temporal muito grande para serem correlacionados a eventos cada vez mais precisos do Quaternário. Outras vezes, interpretações cronológicas baseadas em características topográficas e sedimentológicas de cordões litorâneos são invalidadas uma vez obtidas idades absolutas (Guedes, 2009).

Até o aparecimento da datação por termoluminescência (TL) e luminescência opticamente estimulada (LOE), a cronologia de deposição de sedimentos dunares era limitada devido, muitas vezes, a ausência de material orgânico para datação por ^{14}C . Com a introdução do protocolo SAR (Single-Aliquot Regeneration) da LOE, a datação de sedimentos de diversos sistemas deposicionais tem fornecido cronologias precisas que junto com outros indicadores fornecem valiosas interpretações paleoambientais. A obtenção de idades absolutas da barreira holocênica de São Francisco do Sul associada a análise granulométrica, de minerais pesados e geomorfológica forneceu ferramentas para identificar as diferentes fácies deposicionais, procedência dos sedimentos e situá-las num período de tempo mais preciso.

A identificação de mudanças climáticas ocorridas no Holoceno Tardio, especificamente da alteração de intensidade e deslocamento dos ventos de oeste (Westerlies) associado ao desenvolvimento do ENSO (*El Niño Southern Oscillation*) no Holoceno Médio, forneceram

ferramentas para a integração e interpretação de dados climáticos relacionados a formação de dunas em São Francisco do Sul. Os *Westerlies* são os ventos oceânicos mais fortes da Terra (Russel et al., 2006), devido principalmente, a inexistência de barreiras topográficas (terras emersas) nas latitudes médias do Hemisfério Sul, que reduziriam a velocidade dos ventos. Esses ventos conduzem a Corrente Circumpolar Antártida para leste em torno de continente antártico e através da sua intensidade conseguem carregar águas superficiais antárticas criando zonas de ressurgência. Pesquisas recentes (Russel et al., 2006; Lamy et al., 2010) indicam que a intensidade dos *Westerlies* está aumentado. O resultado desse aumento na zona costeira do sul e sudeste do Brasil será a intensificação de períodos mais úmidos e provavelmente um aumento de aporte sedimentar e ventos de sul trazendo, num período de tempo mais curto, mudanças na geomorfologia costeira de São Francisco do Sul mais intensas que as ocorridas entre 1.900 anos atrás e os dias de hoje.

1.4. Conclusão

Características geomorfológicas da SFSI foram analisadas principalmente com o auxílio do Google Earth e com levantamentos de campo que indicaram a prevalência de sobreposição de dunas vegetadas formadas pela influência dos ventos S-SE na parte central e norte da barreira holocênica. Através da análise de dados, sedimentológicos, de minerais pesados e cronológicos da parte norte ($\sim 7 \text{ km}^2$) da barreira holocênica da Ilha de São Francisco do Sul foi possível esabelecer a sua evolução e associá-la a eventos climáticos importantes desde o Holoceno Médio aos dias de hoje. Estudos interdisciplinares de eventos ocorridos no Holoceno tardio em áreas costeiras podem ajudar na projeção de possíveis cenários futuros causados por mudanças climáticas, podendo eventualmente, minimizar as suas consequências.

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Anexo

Tabela de minerais pesados (Tabela 1)

Tabela 1. Contagem de minerais pesados separados por unidades geomorfológicas. As quantidades dos minerais individuais estão em %. No caso das contagens dedicadas para índices, as quantidades são em valores absolutos.

Amostra		X	Y	Unidade Geomorfológica	% Pesados	% Opacos	Zircão	Turmalina	Rutilo	Hornblenda	Epidoto	Sillimanita	Cianita	Estaurilita	Apatita	Clinozoisita	Tremolita	Andaluzita	Actinolita	Enstatita	Monazita	Hiperstenio	Diopsídio	Granada	Topázio	Alterita	Total contados s/opacos	Zi (Ru + Zi)	Ru (Ru + Zi)	Zi (Zi + Tu)	Tu (Zi + Tu)	Tu (Tu + Hn)	Hn (Tu + Hn)	Ru-Zi	Tu-Hn	Tu-Zr
		Praia																																		
SF-1-P	739468	7074446	95	28	85	1	Tr	2	6	4	Tr	Tr	0	0	0	0	0	0	0	0	Tr	0	0	0	0	0	211	200	1	200	3	22	63	0.50	25.88	1.48
SF-2-P	740764	7078235	85	22	94	0	Tr	1	4	Tr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	208	201	1	201	0	0	2	0.50	-	-	
SF-3-P	742721	7081722	72	50	82	2	1	3	8	Tr	0	1	0	1	0	0	0	0	0	0	0	2	0	Tr	0	0	250	206	3	206	5	24	84	1.44	22.22	2.37
SF-4-P	744037	7085486	83	36	84	0	3	3	3	0	0	1	1	0	0	0	0	0	0	0	4	Tr	0	0	0	221	207	7	207	0	0	7	3.27	-	-	
SF-5-P	745804	7089339	44	33	82	1	1	6	6	1	Tr	0	0	0	0	0	0	0	0	0	0	4	0	0	0	254	208	2	208	2	3	32	0.95	8.57	0.95	
SF-6-P	747628	7092697	28	26	57	0	2	6	11	0	0	4	0	6	0	0	4	0	0	0	0	2	0	9	0	49	31	1	31	0	0	3	3.13	-	-	
SF-7-P	749502	7095831	38	34	61	0	Tr	10	21	Tr	2	2	0	0	0	0	0	0	0	0	Tr	1	0	1	0	201	146	1	146	1	1	29	0.68	3.33	0.68	
SF-1-DF	739455	7074450	63	43	76	1	2	5	14	1	0	Tr	0	0	0	0	0	0	0	0	1	0	0	0	0	214	227	7	227	1	1	10	2.99	9.09	0.44	
SF-2-DF	740720	7078254	62	20	66	2	1	16	9	2	0	Tr	0	1	0	0	1	0	0	0	0	2	0	0	0	219	200	2	200	6	14	87	0.99	13.86	2.91	
SF-3-DF	742702	7081733	48	16	69	1	1	9	12	Tr	0	1	0	0	0	0	0	Tr	0	3	2	0	Tr	0	0	229	205	2	200	4	15	123	0.97	10.87	1.96	
SF-4-DF	744024	7085496	46	25	81	0	1	5	4	2	0	1	0	1	0	0	0	0	0	1	3	0	1	0	0	235	205	3	205	3	11	87	1.44	11.22	1.44	
SF-5-DF	745786	7089346	24	19	59	1	1	10	18	3	1	1	0	0	0	0	0	0	0	1	2	Tr	1	0	0	208	204	3	204	4	6	63	1.45	8.70	1.92	
SF-6-DF	747614	7092703	41	19	90	0	1	2	5	0	0	Tr	0	0	0	0	0	0	0	0	2	0	Tr	0	0	241	218	2	218	0	0	9	0.91	-	-	
SF-7-DF	749437	7095858	24	24	73	4	2	9	4	1	2	3	0	0	0	0	0	0	0	0	Tr	1	0	0	0	211	196	5	196	10	18	61	2.49	22.78	4.85	
SF-5-RD	745728	7089381	58	13	88	1	3	2	3	1	0	Tr	0	0	0	0	0	0	0	0	0	1	0	0	0	208	208	7	208	3	14	34	3.26	29.17	1.42	
SF-6-RD	747536	7092885	46	34	75	1	1	10	7	0	0	1	0	1	0	0	0	1	0	Tr	3	0	0	0	0	231	201	2	201	3	5	43	0.99	10.42	1.47	
SF-17-L	747941	7093473	59	29	80	3	2	3	4	Tr	0	2	0	0	0	0	0	0	0	3	Tr	0	0	0	0	206	200	6	200	7	20	80	2.91	20.00	3.38	
SF-18-L	748801	7095029	53	13	66	1	1	10	13	0	0	1	0	1	0	1	0	1	2	0	0	3	0	Tr	0	234	203	4	203	4	19	158	1.93	10.73	1.93	
SF-19-L	747733	7093041	73	42	76	1	1	6	8	0	1	0	0	0	0	0	0	0	0	0	1	5	0	0	0	207	159	2	159	2	2	14	1.24	12.50	1.24	
SF-10-L	748660	7094776	56	29	67	3	2	14	8	0	0	2	0	1	1	0	0	0	0	0	3	0	Tr	0	0	225	200	5	200	6	10	41	2.44	19.61	2.91	
SF-8-L3	748034	7094844	24	35	60	8	2	10	9	1	0	4	0	0	0	0	Tr	1	0	1	2	0	0	0	0	221	216	7	216	29	29	34	3.14	46.03	11.84	
SF-9-L	748352	7094860	35	36	75	3	1	2	10	2	1	2	0	0	0	0	0	0	0	0	4	0	0	0	0	242	207	4	207	13	84	121	1.90	40.98	5.91	
SF-12-L	746217	7090565	24	22	57	4	4	15	11	1	0	1	0	0	0	0	0	0	1	0	6	0	Tr	0	0	217	203	10	203	13	28	88	4.69	24.14	6.02	
SF-15-L	747367	7093504	37	45	70	2	1	14	8	Tr	0	1	0	0	0	0	0	Tr	0	1	1	0	1	0	0	220	200	2	200	5	18	142	0.99	11.25	2.44	
SF-16-L	747649	7093410	42	32	75	2	2	8	6	1	1	3	0	0	0	2	0	0	0	0	1	0	Tr	0	0	233	195	5	194	6	16	65	2.50	19.75	3.00	
SF-26-L	747583	7094223	46	4	95	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	226	215	10	215	0	0	0	4.44	-	-	
SF-11-L	745770	7090759	30	46	80	4	6	0	4	0	1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	275	220	17	220	11	11	0	7.17	-	4.76	
SF-14-L	744968	7088705	14	23	73	8	5	Tr	7	Tr	0	5	0	0	0	0	0	0	0	Tr	0	Tr	0	0	0	220	200	11	200	16	70	18	5.21	79.55	7.41	
SF-13-L	746392	7092520	9	48	52	18	8	Tr	11	3	4	2	0	0	0	0	0	0	0	0	0	Tr	0	0	0	249	170	29	170	30	166	38	14.57	81.37	15.00	
SF-22-L	742059	7087639	1	45	72	2	8	0	0	6	10	0	0	0	0	0	0	0	0	0	0	0	0	1	0	201	184	17	200	4	4	0	8.46	-	1.96	
SF-23-L	743035	7087595	1	42	38	18	11	3	15	2	7	1	0	0	0	1	4	0	0	0	0	0	0	0	0	179	161	46	125	75	167	35	22.22	82.67	37.50	
SF-24-L	744174	7086910	23	32	79	6	6	0	0	4	3	2	0	0	0	0	0	0	0	0	Tr	0	0	0	0	207	189	12	189	13	13	0	5.97	-	6.44	
SF-27-L	740120	7085801	0	32	61	1	23	0	0	5	9	0	0	0	0	0	1	0	0	0	0	0	0	0	0	179	157	46	201	3	3	0	22.66	-	1.47	
SF-28-L	738236	7090064	5	20	88	0	5	0	1	1	4	0	0	0	0	1	0	0	0	0	0	0	0	1	214	190	10	190	0	0	0	5.00	-	-		
SF-29	739922	7089294	5	50	54	18	12	0	0	4	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0	163	146	63	150	50	50	0	30.14	-	25.00	
SF-30	743188	7083844	5	29	62	21	10	0	0	4	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	183	179	34	154	51	51	0	15.96	-	24.88	
SF-31	742702	7082331	1	13	85	5	6	0	Tr	1	1	Tr	0	0	0	0	0	0	0	0	0	0	0	0	Tr	201	192	12	192	11			5.88	-	5.42	
SF-32	741781	7080914	7	21	83	0	11	0	0	1	4	Tr	0	0	0	0	0	0	0	0	0	1	0	0	0	223	184	24	199	1	1	0	11.54	-	0.50	
SF-33	740766	7079726	1	46	42	29	15	0	0	2	7	5	0	0	0	0	0	0	0	0	0	0	0	1	0	167	161	50	129	80	80	0	23.70	-	38.28	
SF-34-L	739810	7078026	1	50	55	4	22	0	0	5	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	167	150	56	186	19	19	0	27.18	-	9.27	
SF-8-L1	748014	7094824	0	39	11	16	3	26	30	4	3	5	0	0	0	0	0	0	0	0	Tr	1	0	0	0	216	75	31	75	100	100	140	29.25	41.67	57.14	
SF-8-L2	748024	7094834	1	36	13	22	2	24	23	2	6	3	0	Tr	0	0	0	0	0	0	2	0	0	0	0	252	116	31	116	125	125	75	21.09	62.50	51.87	
SF-25-L1	747539	7094593	2	51	30	3	22	0	2	14	21	0	0	6	0	1	0	0	0	0	0	0	0	0	1	153	135	75	189	12	12	0	35.71	-	5.97	
SF-25-L2A	747540	7094592	9																																	

2. Late Holocene dune development and provenance changes in São Francisco do Sul barrier: coastal dynamics shift forced by cold fronts intensification in Southern Brazil

**Late Holocene dune development and provenance changes in São Francisco do Sul barrier:
coastal dynamics shift forced by cold fronts intensification in Southern Brazil**

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ABSTRACT

The provenance and luminescence chronology of beach ridges sands and superimposed dunes sands is investigated in São Francisco do Sul Island (SFSI), a regressive Holocene barrier in Southern Brazil. The Holocene progradation of the SFSI barrier had a pronounced morphodynamic shift around 1.9-1.8 ka, which is characterized by episodic development of parabolic dunes migrating to NW over beach ridges and a marked change in sediment provenance. This morphodynamic shift derived from an increase in the strength of winds from south and northward alongshore drift, implying strengthening of cold fronts activity since 1.9-1.8 ka. Higher cold fronts activity in Southern Brazil can be linked with the northward expansion of the south westerly wind belt and an intensification of El Niño Southern Oscillation ENSO events since the Middle Holocene. Optically Stimulated Luminescence dating coupled with grain size, heavy minerals, quartz OSL sensitivity and geomorphological analyses helped evaluating the impacts of Holocene climate changes on the evolution of SFSI in a centennial to millennial timescale.

2.1. Introduction

Beach ridges with superimposed dunes are a significant feature of coastal progradational barriers formed by regression following the Mid-Holocene relative sea level highstand throughout the world (Clemmensen et al., 1996; Lancaster et al., 2002; Orford et al., 2003; Cooper and Navas, 2004). A great number of coastal barriers on the SE-S coast of Brazil prograded during Mid to Late Holocene with superimposed dunes forming at a later stage of the barrier development (Giannini and Santos, 1994; Giannini et al., 2007, 2009; Martinho et al., 2006; Sawakuchi et al., 2008, 2009; Guedes et al., 2011a, 2011b). However, the processes generating these superimposed dunes during the later evolution stages of S-SE Brazilian barriers and eventual decoupling of sediments from their beach ridges and dunes have not been completely understood. The dynamics of barrier depositional systems is under the influence of climate and sea-level forcings (Cowell et al., 1994). Late Holocene climate changes in South America have been documented by several authors under different proxies (Rodbell et al., 1999; Lamy et al., 2001, 2010; Haug et al., 2001; Markgraf, 2003; Gilli et al., 2005; Wanner et al., 2008; Sawakuchi et al., 2008; Cruz et al., 2009; Vimeux et al., 2009; Fletcher and Moreno, 2011). Changes in the intensity and displacement of the Westerlies and the onset of the El Niño Southern Oscillation (ENSO) at about 5 ka ago triggered shifts that persist to the present day (Markgraf, 1998; Moreno, 2004; Gilli et al., 2005). The Westerlies activity generates the development of cold fronts in southern South America (Stutt and Lamy, 2004; Gilli et al., 2005; Lamy et al., 2010). The northward advance of cold fronts stimulates S-SE winds as well as a northward sediment transport along the Brazilian coast. In this context, the São Francisco do Sul Island (SFSI) stands out as prograded barrier in the southern Brazilian coast presenting well developed parabolic dunes generated by S-SE winds. Thus, temporal changes in the Westerlies activity can play an important role on sediment transport and deposition throughout the southern Brazilian coast during the Holocene.

The aim of this study was to evaluate the relation between changes in the Westerlies and the generation of aeolian dunes during the late stages of development of SFSI. Possible sediment decoupling between beach ridges sands and superimposed dunes sands is also investigated in this island. Sediment decoupling under different aeolian and beach environments have been reported by several authors (Shulmeister and Kirk, 1993; Orford et al., 2003; Bauer, 2005; Anthony et al. 2010) and have been associated to adjustment of sand supply by relative sea level change, fluctuations in the availability of sand, change of sediment source and by wind or climatic conditions. Hitherto one hindrance in solving the mechanisms responsible for shifts in barrier geomorphology and sediment decoupling was the lack of absolute ages. First absolute ages obtained by Optically Stimulated Luminescence (OSL) with the application of the single-aliquot regenerative-dose (SAR) protocol for beach ridges and dunes in SFSI were attained. Beach ridges with superimposed dunes occur only at a small fraction ($\sim 7 \text{ km}^2$) of the SFSI barrier seaward portion. Thus, OSL ages provided a detailed chronological record that coupled with grain size, heavy minerals, quartz OSL sensitivity and geomorphological analyses helped evaluating the forcing variables controlling the centennial to millennium evolution of the island during the Holocene.

2.2. Study setting

2.2.1. Geological aspects

The southeast Brazilian coast rests against crystalline massifs that forms the Serra do Mar coastal range, stretching from the southern State of Espírito Santo ($\sim 20^\circ \text{ S}$) to the southern State of Santa Catarina ($\sim 28^\circ \text{ S}$, Angulo et al., 2009). Its most prominent geomorphologic characteristic is the scarped coastal range that, when intersecting the coastline, creates coastal embayments where strandplains, and less frequently estuarine systems, are found (Angulo et al., 2009). SFSI is located in southern Brazil, on the northern coast of Santa Catarina State in Babitonga bay estuary vicinity (Fig. 1). It covers an area of about 280 km^2 with an approximate length of oceanic coastline of 40 km. The facing inner shelf is identified by a low-gradient slope

(~0.01%) with the –50 m contour 45–75 km away from the shore (Angulo et al., 2009). The Precambrian substrate is composed of granite-gneissic rocks of the Coastal Granitoid Belt (Basei et al., 1992; Siga Jr. et al., 1993).

Fig.1. Landsat ETM +7 image (2002) of São Francisco do Sul Island.

On the northernmost part of the island, these rocks reach the shore forming headlands and small islands. Also, they outcrop in the western part and in scattered hills throughout the island. Despite the occurrence of granites, low to high grade metamorphic rocks represented by schists, gneisses and migmatites (CPRM, 2004) prevail over the landward regions (Fig.2).

Fig. 2. Geological map of the eastern portion of the state of Santa Catarina, Brazil, showing SFSI and the exposed region of the Florianópolis batholiths (modified from Guadagnin et al., 2010).

Limited coastal progradation occurred in the first 1000 years after sea level maximum (around 5 ka, Angulo et al., 2006), when the estuaries were flood-dominant and sequestered sand from the coastal system (Angulo et al., 2009). Coastal progradation was accelerated first

with the halt of flood dominance in the estuaries, that eventually became ebb-dominant (Angulo et al., 2009), and later by a scheme of abundant sediment supply that coupled with the effects of swell waves from the south and sea-level fall construed the conditions for the evolution of a progradational barrier system on SFSI.

The SFSI barrier may be segmented in western and eastern sectors in relation to Icaraí lagoon, which could represent two different barriers. The western sector is up to 6 km wide and is considered by many authors (Martin and Suguio, 1975; Horn Filho and Simó, 2008; Lessa et al., 2000; Possamai et al., 2010; Angulo, 2009) to be a Pleistocene age barrier due to sedimentological, paleontological and geomorphologic features although no chronological analysis has been undertaken yet. Its formation is associated with the last Pleistocene relative sea-level highstand at about 120 ka, when relative sea level stood 8 ± 2 m above the present level. The Pleistocene barrier is wider than the Holocene barrier reaching up to 10 km in width (E-W). The eastern barrier is supposed to be Holocene in age and is the focus of this study. It covers an area of approximately 65 km² and comprises a succession of beach ridges, parabolic dunes, blowouts and established foredunes with same orientation as the present coastline.

The passive Brazilian continental margin likely experienced relative tectonic stability throughout the Quaternary (Riccomini and Assumpção, 1999). Thus, it appears unlikely that tectonics have contributed to development of Brazilian Holocene barriers. Rather, sea-level variations, periods of abundant sediment supply and episodic climatic events have contributed to the progradation of the coastal systems and the formation of dunes (Sawakuchi et al., 2008; Giannini et al., 2009; Guedes et al., 2011b). Holocene relative sea-levels in southern Brazil have been established through a variety of indicators such as vermetid tubes, mollusk shells, wood fragments, shell-midden deposits, shoreline displacement and archaeological remains (Van Andel and Laborel, 1964; Bigarella, 1971; Martin and Suguio, 1975; Angulo et al., 1997; Angulo et al., 2005). In a period of 40 years, more than 1000 samples all over Brazil have been radiocarbon dated for this purpose (Angulo et al., 2006). Paleo-sea-level investigations in the Santa Catarina State show a Mid-Holocene maximum highstand of 2.5 ± 1.0 m above present mean sea-level at approximately 5,000 cal yr BP (Fig. 3; Milne et al., 2005; Angulo et al., 2006). The following relative sea-level fall combined with high sediment input have contributed to

coastal progradation and formation of sandy barriers (Carter and Woodroffe, 1997). An overview of sea-level changes on the Brazilian coast is given by Angulo et al. (2006).

Fig.3. Mid-Holocene sea-level curve based on vermetid samples dated along the eastern Brazilian coast with their error bars. Dashed line indicates values in the southern part of Santa Catarina State. Solid line indicates values obtained from the remaining states. It was assumed that sea-level values for the island of SFSI were in between the two lines (Angulo et al., 2006).

2.2.2. Climate

The SFSI climate is subtropical (Cfa, according to Köppen's classification) with humid summers and moderately dry winters. The annual rainfall varies between 1000 and 1500 mm and the mean average temperature is 18° C. The interaction among three large air masses formed by the Atlantic, Polar anticyclones and the wind-driven Antarctic Circumpolar Current control the climate and the atmospheric circulation in southern Brazil (Nobre et al., 1986). These interactions are made through high pressure systems originated from low latitudes, tropical anticyclones migrating towards the continent or the South American coastline or through extratropical cyclones associated with the passage of cold fronts and precipitation during the winter (Nobre et al., 1986). The extratropical circulation regime is responsible for a significant fraction of the regional precipitation during the winter and early spring (May to September) as a result of migratory cyclones along the subtropical Atlantic coast interacting with southern Westerlies that transport moisture from the Pacific Ocean to the South American

continent. This wind system is driven by the strong Antarctic Circumpolar wind current (Heil, 2006). The position and intensity of the Westerlies varies seasonally as a consequence of changes in sea surface temperature in eastern South Pacific Ocean and during austral winter the belt expands northward conveying wet conditions in subtropical South America (Heil, 2006; Lamy et al, 2010). In contrast, the warm-season precipitation (Atlantic anticyclone) from late September to April is associated with the activity of the South American Summer Monsoon (SASM; Cruz et al., 2006). An important feature of the SASM is the South American Convergence Zone (SACZ), a NW–SE elongated band of enhanced convective activity emanating from the Amazon basin and extending into subtropical latitudes and over the Atlantic Coast (Cruz et al. 2006).

Usually, cold fronts may be preceded by disturbed weather and rapid changes in wind direction. Data collected from 1980 to 1985 indicate an average duration of a cold front from 2 to 3 days in the South Brazil Bight with a mean time interval between successive fronts of 6.5 days (Stech and Lorenzetti, 1992). An approaching cold front brings 5 m/s NE winds which may turn up to 8 m/s SSE winds the following day. In addition, the Santa Catarina coast shows distinct interannual variations in precipitation with either high rainfall or dry periods. This seems to be a consequence of the effect of the ENSO cycle as well as of the La Niña Southern Oscillation (LNSO) on the global climate (Nobre *et al.*, 1986).

The direction of more energetic and predominant incident swells is SSE with a period of 7 to 16 s (Truccollo, 1998). Significant wave heights varying between 1 and 2 m are connected to local winds (Alves, 1996). The local tide is microtidal, mainly semidiurnal with small inequalities, with a mean range of around 0.8 m and a maximum tide of 1.2 m (Truccollo, 1998). The meteorological influence on sea level is conspicuous. Storm surges can raise sea level up to 1 m above the astronomical tide, though the elevation may be higher when superimposed on a spring tide (Truccollo, 1998). The coastal system is wave-dominated. The shore may be classified as intermediate with an exposed beach (Klein and Menezes, 2001).

2.2.3. Paleoclimate

Climatic variations that have occurred throughout the Mid-to Late-Holocene illustrate the frequency and magnitude of natural change within a climatic system that is similar to the present one (Milne et al., 2005). According to Cruz et al. (2006), the subtropical Atlantic coast in Brazil is an excellent location for investigating past changes in the atmospheric circulation because it is a region where tropical and extratropical air masses have interacted intensely during the Quaternary. Displacement of the SACZ occurred frequently during the Quaternary, usually associated with Northern Hemisphere glacial boundary conditions during Heinrich events in the Pleistocene (Cruz et al., 2007), sea surface temperature (SST) changes or Inter Tropical Convergence Zone (ITCZ) displacements associated with ENSO or LNSO. When ITCZ was displaced southward it caused an increase in precipitation in northern Brazil (Cruz et al., 2009) and may also have increased the prevalence of ENSO, driving a positive feedback loop dislocating the ITCZ even further south in Brazil in the Late Holocene (Haug et al., 2001). Independent evidence from northern Australia also suggests that ENSO became active only after 5 ka (Rodbell et al., 1999) synchronous with the Mid-Holocene sea level highstand in Santa Catarina State. In addition, through the analyses of sedimentological and pollen records to reconstruct rainfall patterns over the past 12,500 yr from sites along the windward side of the Andes, Lamy et al. (2010) also characterized the ENSO as more active during Late Holocene due to a northbound displacement of the Westerlies during this period. Fig. 4 shows the major air masses and winds in South America today.

Fig. 4. Present-day South America: physical characteristics of the continent with the location of the major atmospheric features of the climatic system (ITCZ, SASM, SACZ, Westerlies and Polar advections). Modified from Sylvestre (2009).

2.3. Methods

2.3.1. Surveying and sampling

A topographic map (1:50.000), Landsat 7 and Google Earth images were used to generate a geomorphological map (1:6000) of the studied area with the help of ArcGis 10 software. This enabled the identification of different depositional features and allowed planning and guidance for field surveys.

Forty five sediment samples were taken from the present beach, foredunes, blowouts, parabolic dunes and beach ridges mostly from the eastern part of the barrier. Sample locations are shown in Fig. 5. These locations were chosen as they were expected to represent the geomorphological and sedimentological variability of the SFSI. Fourteen of these samples were collected in beach-foredune transects. These samples were taken along transects perpendicular to the shoreline surveying around 30 km of the coast. Sandy samples were taken from the swash zone at approximately 0.5m depth and foredune samples were taken from the dune's crest below the vegetation line. Eleven samples from blowouts, parabolic dunes and beach ridges were taken for OSL dating. These samples were singled out to investigate potential aeolian and beach sediment spatial variability emplacement in the study area. OSL-prone samples were collected in opaque plastic tubes hammered into the sediment after cleaning the wall in outcrops or pits at a minimum of 0.5 m depth. These tubes were sealed to protect the samples from light exposure. Additional material of approximately 0.5 kg was taken for radionuclides estimation through gamma spectrometry and water content measurements. The remainder of the samples was taken at randomly selected locations on field trips.

All forty five samples were analyzed for grain-size and heavy minerals. Samples were divided in two major groups according to sedimentary processes of wind-deposited opposed to wave-deposited sediments. In addition, wind-deposited sediments were subdivided into three categories which indicate different aeolian facies: 1) foredunes (active and stabilized), 2) paleodunes (stabilized parabolic dunes), 3) blowouts. Wave-deposited sediments were subdivided into present beach sediments and beach ridges.

Fig.5. Georeferenced Google Earth image of SFSI (2009, by GeoEye). Dots indicate sample collection sites on the central and northern portion of SFSI. OSL collection sites are shown with red text.

2.3.2. Grain-size analyses

Grain-size analyses were carried out in the Sedimentology Laboratory at the Universidade de São Paulo, Brazil. Measurements of particle-size distribution were achieved by laser diffraction method utilizing the Malvern Mastersizer granulometer with the Hydro 2000MU module. Data was tabulated in 0.125 ϕ intervals. Statistical parameters such as the mean, sorting and skewness were obtained directly from the grain-size data. Standard deviation values classified by Folk and Ward (1957) were converted to corresponding descriptive terms.

2.3.3. Heavy-Minerals analysis

Another batch of sediment samples was used for heavy minerals analysis. Pelitic materials were separated through elutriation and the 3.75–3.25 ϕ (very fine sand) fraction was separated by sieving. Heavy minerals were parted from the samples by gravity-settling in bromoform (CHBr_3 , density of 2,83 to 2,89g/cm³). Magnetic minerals were separated using a Frantz separator. The non-magnetic heavy mineral residues were mounted onto a glass slide using Canada balsam for optical study under the polarizing microscope. Two hundred non-micaceous transparent heavy mineral grains plus opaque grains were counted using the ribbon method (Galehouse, 1971), with the content of each mineral type presented as percentage of grains within the heavy-mineral assemblage. Heavy minerals indexes were established through a dedicated count of at least 200 grains per mineral pair, when obtainable. In some instances, this total number was reduced due to absence of grains. These indexes were reckoned to elucidate provenance studies as suggested by Morton and Hallsworth (1994). The indexes chosen were RZi (rutile/zircon+rutile), TZi (tourmaline/zircon+tourmaline).

2.3.4. OSL dating and sensitivity analyses

The samples for OSL measurements were prepared under red light in the laboratory. For the OSL analyses, grains of quartz of 3.00-2.75 ϕ or 2.75-2.50 ϕ in diameter were extracted from each sample using wet sieving followed by chemical treatment with H₂O₂ 27%, HCl 3.75%, HF 48-51% for 40 minutes, in order to remove organic carbon, CaCO₃, feldspars and outer rinds of grains damaged by alpha particles, respectively (Aitken, 1998). Heavy minerals and remaining feldspar grains were separated through a lithium polytungstate solution (at densities of 2.75 g/cm³ and 2.62 g/cm³). OSL measurements were conducted on a Risø DA-15 TL/OSL systems, in the Radiation Dosimetry Laboratory at Oklahoma State University (8 samples) and on a Risø DA-20 TL/OSL systems at the Dosimetry Laboratory at Universidade de São Paulo (3 samples) using a Sr⁹⁰/Y⁹⁰ beta source for irradiation and blue LED (470 nm) for OSL stimulation. Equivalent dose (*D*%) measurements used the SAR dose protocol (Murray and Wintle, 2000; Wintle and Murray, 2006). A high-purity germanium gamma-ray detector was utilized for ⁴⁰K, uranium and thorium estimation and determination of radiation dose-rates. Beta and gamma dose rates were calculated using conversion factors outlined by Adamiec and Aitken (1998). Evaluation of the cosmic ray dose rate was appraised as a function of latitude, longitude, altitude and depth below ground level as described by Prescott and Stephan (1982). Water content for each sample was obtained from the additional sunlight-exposed material (0.5 kg) collected at each site as a result of differences between the fresh weight and dry weight after drying the sample in an oven (48h at 110 °C). Error treatment for age calculations follows Aitken (1998). The equivalent dose was determined by linear fitting of the dose–response data. Additionally, OSL sensitivity was measured in the dating aliquots to evaluate the sedimentary reworking of sediments from the studied geomorphological units. According to Pietsch et al. (2008) and Sawakuchi et al. (2011), OSL sensitivity increases with cycles of burial and erosion, being a proxy of sedimentary reworking.

2.4. Results

2.4.1. Geomorphology

The SFSI coastline orientation is N27°. The shore exhibits occasionally berms, beach cusps and a swash zone composed of medium sand and gentle nearshore slope. It encompasses a 30-70m wide subaerial beach, including a foreshore zone. The foreshore width increases towards north, indicating that a northward longshore sediment transport has prevailed in its development. A 5-10 m narrow belt of foredune ridges associated with swales occurs along the coastline. Dune distribution was outlined through the analyses of satellite images and aerial photographs (Fig. 6).

Fig.6. Google Earth image (imagery date: 7/3/2009 by GeoEye). White solid line displays the boundary between beach ridges (left) and parabolic dunes (right). Placemarks SFS-9-L and SFS-12-L indicate sample collection sites. The distance from the actual shore face is 140 and 400m, respectively.

Landward, the foredunes are gradually replaced by a series of complex aeolian forms and blowouts (Fig. 7) that may have been originated by an increment in the wind intensity or a change in vegetation cover (Hesp, 2002).

Fig. 7. Sample SFS-19-L site. Beach face, foredunes and blowouts are common features in the northeastern segment of SFSI.

Superimposed vegetated parabolic dunes are assembled in the central and northern part of the Holocene barrier in SFSI ($\sim 26.31^{\circ}$ S to $\sim 26.24^{\circ}$ S) encompassing an area of $\sim 7 \text{ km}^2$. Many of the parabolic dunes can be classified as elongated, with length to width ratio greater than 3 (Pye, 1982). Although covered by extensive vegetation, the trailing arms are discernable and encase a central deflation corridor. Parabolic dunes in SFSI can reach a height of up to 17m and up to 1km in length. They migrate to NNW in response to the action of SSE winds. Flat lying beach ridge terrains are exposed landward from the parabolic dunes and are characterized by fine laminated sand with low angle seaward dipping plan-parallel stratified beds (Figs. 8, 9)

Fig. 8. Sample site SFS-8-L1 (beach ridge) shows horizontal and slightly seaward-inclined parallel-stratified sands, suggesting deposition in the foreshore zone. Bioturbation was found in many sites.

Fig.9. Sample site SFS-25-L (beach ridge). Erosional surfaces separating sets of plan-parallel stratification marked by lamina with high concentration of heavy minerals. Heavy minerals concentration may be evidence of storm activity.

2.4.2. Grain Size

Grain size statistical data was assembled by groups related to geomorphological units (Tables 1, 2).

Table 1. Grain size distribution of the sediments from the SFSI geomorphological units.

ϕ	Number of samples										
		$\phi = 4.0 - 3.5$	$\phi = 3.5 - 3.0$	$\phi = 3.0 - 2.5$	$\phi = 2.5 - 2.0$	$\phi = 2.0 - 1.5$	$\phi = 1.5 - 1.0$	$\phi = 1.0 - 0.5$	$\phi = 0.5 - 0.0$	$\phi = 0.0 - -0.5$	$\phi = -0.5 - -1.0$
Depositional System		Very fine sand	Fine sand	Medium sand	Coarse sand	Very Coarse sand					
Beach	7	0.00	0.01	0.93	7.09	19.71	28.95	25.21	13.35	4.47	0.28
Foredune	7	0.09	0.01	2.10	12.11	26.60	31.15	20.55	6.80	0.57	0.00
Blowout	6	0.14	0.00	1.19	11.04	27.04	33.24	21.77	5.58	0.00	0.00
Paleodune	6	0.00	0.37	6.71	23.25	34.55	25.70	8.78	0.64	0.00	0.00
Beach Ridge	19	1.03	7.64	27.48	36.66	20.98	5.63	0.57	0.00	0.00	0.00

Medium sand predominates in all categories, except on the beach ridges where fine sand prevails. Very fine sand is practically absent (<0.1%) on the present beach, foredunes and blowout sands notwithstanding it represents almost 8% of the beach ridges total sand content. Conversely, coarse sand is absent from beach ridges but it appears in considerable amounts on the other units. Very coarse sand is meaningful only on the present beach. There is a conspicuous sand coarsening from the older units to the newer ones (Table 1; Fig. 10). Within the aeolian samples, paleodune samples were on average approximately 0.35 ϕ finer than foredune sands. Beach ridge sands were a 0.60-1.20 ϕ finer than all other geomorphological units.

Table 2. Descriptive statistics of the grain size for samples grouped by geomorphological units. Q1 = first quartile, Q3 = third quartile.

	Present beach	Foredunes	Blowouts	Paleodunes	Beach Ridges
<u>Mean Diam (ϕ)</u>					
Number	7	7	6	6	19
Mean	1.10	1.36	1.32	1.71	2.32
St Dev	0.39	0.23	0.15	0.15	0.27
Minimum	0.61	1.12	1.04	1.51	1.87
Q1	0.83	1.15	1.33	1.60	2.18
Median	1.10	1.27	1.35	1.73	2.30
Q3	1.37	1.58	1.40	1.79	2.48
Maximum	1.62	1.63	1.46	1.92	2.86
<u>Standard Deviation (ϕ)</u>					
Number	7	7	6	6	19
Mean	0.53	0.54	0.48	0.51	0.45
St Dev	0.08	0.05	0.05	0.03	0.06
Minimum	0.45	0.48	0.40	0.47	0.37
Q1	0.48	0.51	0.48	0.48	0.40
Median	0.52	0.53	0.49	0.51	0.45
Q3	0.54	0.59	0.50	0.54	0.47
Maximum	0.68	0.60	0.54	0.55	0.57
<u>Skewness (ϕ)</u>					
Number	7	7	6	6	19
Mean	0.02	0.13	0.05	0.01	0.02
St Dev	0.07	0.15	0.07	0.04	0.05
Minimum	-0.09	0.04	0.00	-0.06	-0.12
Q1	-0.02	0.04	0.01	0.00	0.01
Median	0.04	0.05	0.03	0.02	0.02
Q3	0.06	0.14	0.04	0.04	0.04
Maximum	0.09	0.45	0.20	0.07	0.17

Fig. 10. Frequency distribution of grain size for each geomorphological unit (mean values). Grain size data in phi units.

Sands from the present beach, foredunes and paleodunes are more poorly sorted than those from the beach ridges and blowouts. Sorting classes varied from well sorted (blowouts and beach ridges) to moderately well sorted (beach, foredunes and paleodunes). Overall, beach sands are coarser than foredune sands, though both follow the same sorting class. The grain-size distribution of all geomorphologic units is almost symmetrical as shown by skewness values near zero. Foredune sands are on average more positively skewed than beach sands varying from slightly positive to negatively skewed. This trend is found throughout S-SE Brazil (Amin Jr. et al, 2010; Guedes et al., 2011a). In turn, skewness is not a good indicator to set apart other SFSI units since their values are very similar, in contrast to results found by Guedes et al. (2011a) in Ilha Comprida, a Holocene regressive barrier some 150 km north from SFSI. Pelitic material is found only on the beach ridges (Fig. 10).

2.4.3. Heavy Minerals

The mean heavy mineral accumulation on the very fine sand fraction varied considerably from the beach to the westernmost end beach ridges (Table 3).

Table 3. Differences in the heavy minerals content on the very fine sand fraction from different geomorphological units. In all cases there is a wide dispersion of values as indicated by standard deviation values. N = number of samples, Q1 = first quartile, Q3 = third quartile.

% Heavy Min	Beach	Foredune	Blowouts	Paleodunes	Beach Ridges
Number	7	7	6	6	19
Mean	63.6	43.8	57.6	34.7	6.4
St Dev	26.4	15.8	8.9	9.0	8.1
Minimum	28.2	23.7	46.1	23.8	0.4
Q1	41.0	32.5	53.9	27.1	1.2
Median	71.7	45.5	57.3	36.1	4.5
Q3	83.9	54.9	58.6	40.6	7.8
Maximum	95.4	62.6	73.2	45.8	30.4

There was also a decrease in heavy mineral content from the SW to NE (beach, foredunes and blowout sands) and from younger to older units, albeit some outliers were present on all geomorphological units. Table 4 shows the percentage of heavy minerals identified in the different geomorphological units. Higher concentrations of rutile, kyanite, sillimanite and staurolite point to a metamorphic provenance of the beach ridge sediments (Fig. 11). In turn, all other units show higher contents of zircon and hornblende, suggesting a greater contribution of sediments derived from igneous rocks. Intermixing occurs in both assemblages. Zircon is present in all samples although older deposits showed a reduction in this mineral total content compared to the more recent deposits (Table 5). Fig. 12 shows typical zircon grains from beach ridges and paleodunes.

Table 4. Relative abundance (mean values) of heavy minerals by geomorphological units. N= number of samples, Zi= Zircon, Tu= Tourmaline, Ru= Rutile, Hn= Hornblende, Ep= Epidote, Sl= Sillimanite, Ky= Kyanite. St= Staurolite, Mz= Monazite, Hy= Hyperstene, Di= Diopside, Gr= Garnet, Ap= Apatite, Cl= Clinozoisite, Ac= Actinolite, Tr= Tremolite, An= Andalusite, En= Enstatite.

Unit	Stats	Zi	Tu	Ru	Hn	Ep	Sl	Ky	St	Mz	Hy	Di	Gt	Traces
Beach	Mean (%)	77.8	Tr	1.2	4.4	8.4	Tr	Tr	1.1	Tr	1.3	0.0	1.5	Ap, Cl,
	N= 7 Std Dev	13.5	0.8	1.0	3.0	6.0	1.3	0.9	1.3	1.5	1.3	0.0	3.4	Ac
Foredune	Mean (%)	73.4	1.3	1.4	7.9	9.3	1.3	Tr	1.0	1.0	1.8	Tr	Tr	Cl, Ac
	N= 7 Std Dev	10.1	1.2	0.6	4.7	5.3	1.0	0.9	0.9	1.1	0.9	0.2	0.4	
Blowout	Mean (%)	75.3	1.8	1.7	7.5	7.4	Tr	Tr	1.1	Tr	2.5	0.0	Tr	Cl, Tr,
	N=7 Std Dev	8.3	1.0	0.8	4.5	3.6	0.4	0.6	0.9	1.1	1.7	0.0	0.2	An, Ac
Paleodune	Mean (%)	72.0	3.1	2.3	8.0	7.3	1.0	Tr	1.8	Tr	2.3	0.0	Tr	An, Ac,
	N= 6 Std Dev	13.6	2.8	1.5	6.0	4.0	0.9	0.3	1.5	0.6	2.1	0.0	0.5	En
Beach Ridge	Mean (%)	58.4	9.4	11.7	2.8	4.9	3.2	6.1	1.9	Tr	Tr	0.0	0.0	Cl, An,
	N= 19 Std Dev	22.9	9.1	7.6	7.8	8.7	3.3	5.1	2.0	0.1	0.5	0.0	0.0	Ac, En

Fig.11. Heavy minerals assemblages from different geomorphological units.

Rutile and zircon were present in all samples making the evaluation of RZi possible. Table 6 and figure 13 show the statistics of RZi and TZi on the studied barrier. A conspicuous association between geomorphological units and the RZi (provenance) can be observed. The beach ridges present higher RZi values. The same E-W increase trend observed in the RZi is displayed in the TZi. This indicates that provenance is the major control on the variation of TZi within the SFSI barrier.

Table 5.. Zircon percentage in the different SFSI geomorphological units. Q1 = first quartile, Q3 = third quartile.

Zircon	Beach	Foredune	Blowouts	Paleo dunes	Beach Ridges
Number	7	7	6	6	19
Mean	77.8	73.4	75.3	72.0	58.4
St Dev	13.5	10.1	8.3	13.6	22.9
Minimum	57.4	59.2	66.0	56.9	11.1
Q1	71.2	67.5	68.9	62.5	46.7
Median	82.1	72.5	75.6	72.2	61.7
Q3	84.5	78.4	79.0	75.1	76.0
Maximum	93.8	90.1	88.0	95.1	88.0

Fig. 12. (A) Typical zircon grain from sample SFS-12-L (paleodune) with length to width ratio of 257:87 μm (B) Typical reworked zircon grain from sample SFS-13-L (beach ridge) with length to width ratio of 77:63 μm .

Table 6. RZi and TZi. Striking differences in RZi and TZi among the SFSI geomorphological units. Q1 = first quartile, Q3 = third quartile.

Ru/Zi	Beach	Foredune	Blowouts	Paleo dunes	Beach Ridges
Number	7	7	6	6	19
Mean	1.5	1.6	2.1	2.9	18.1
St Dev	1.2	0.8	0.9	1.4	9.9
Minimum	0.5	0.9	1.0	1.0	5.0
Q1	0.6	1.0	1.4	2.0	7.8
Median	1.0	1.4	2.2	2.8	21.1
Q3	2.3	2.0	2.8	4.1	26.2
Maximum	3.3	3.0	3.3	4.7	35.7

Tu/Zi	Beach	Foredune	Blowouts	Paleo dunes	Beach Ridges
Number	7	7	6	6	19
Mean	0.8	1.9	2.1	4.9	15.7
St Dev	0.9	1.6	0.9	4.1	18.1
Minimum	0.0	0.0	1.2	0.0	0.0
Q1	0.0	0.9	1.4	2.6	3.2
Median	0.7	1.9	1.7	4.5	6.4
Q3	1.2	2.4	2.7	6.0	24.9
Maximum	2.4	4.9	3.4	11.8	57.1

Fig.13. Boxplots of RZi and TZi values. Beach ridges show higher and more varied values of RZi and TZi compared to all other units.

2.4.4. OSL ages and sensitivity

The equivalent dose, dose rate and OSL ages are shown on Table 7. Fig. 14 shows the linear fitting of the dose-response data in an aliquot of sample SFS-8-L3. All the equivalent dose values from different aliquots of the same sample follow a narrow frequency distribution. Dose distributions from 2 samples are shown in Fig. 15. Recycling ratios vary from 0.9 to 1.1 in 99% of the measured aliquots with a mean of 0.99 ($n = 252$) connoting that sensitive changes had been corrected adequately (Fig. 16). All other samples display similar results which are expected for

well-bleached samples. All these procedures attest to a reliable OSL age determination. The OSL ages range from 0.087 to 4.54 ka (Table 7) with errors from 8% to 11%, covering the Mid to Late Holocene.

The dates follow expected temporal progression based on their geomorphological positions indicating a prograding coastline and supporting a depositional model of wave-dominated beach ridges that in some locations may have superimposed dunes. Beach ridges without dune cover are older than 3 ka whereas paleodunes show ages younger than 1.9 ka (Figs. 17, 18, 19). Recently reactivated blowouts are located close to foredunes (Figs. 7, 20) or paleodunes less than 200m from the shore. All beach ridge ages are consistent, with ages decreasing from base to top in vertical profiles or seaward in horizontal transects, except for sample SFS-8-L2 compared to sample SFS-8-L1. The two samples were taken from the same unit apparently representing equal facies. OSL ages for SFS-8-L1 (bottom layer) and SFS-8-L2 (top layer) were 3.10 ± 0.305 and 4.54 ± 0.454 ka, respectively. This apparent age inversion possibly indicates incomplete bleaching due to local reworking followed by cycles of stabilization and reactivation or by dose rate error caused by leaching (Madsen and Murray, 2009).

Table 7. OSL dating results in SFSI

Sample	X (UTM)	Y (UTM)	Landform	Aliquots	Dose (mGy)	Sensitivity (mGy)	K (%)	Th (ppm)	U (ppm)	Total dose rate (mGy/year)	Gama dose rate (mGy/year)	Beta dose rate (mGy/year)	Cosmic dose rate (mGy/year)	Age (years)
SF-18-L	748801	7095029	Blowout	24	76 ± 4	24	0.341	4.025	0.328	0.880 ± 0.066	0.301 ± 0.0037	0.378 ± 0.054	0.2015 ± 0.0101	87 ± 8
SF-8-L3	748034	7094844	Paleodune	24	1366 ± 58	48	0.328	3.623	0.156	0.787 ± 0.063	0.257 ± 0.038	0.333 ± 0.049	0.1971 ± 0.0099	1735 ± 158
SF-9-L	748352	7094860	Paleodune	24	1949 ± 83	51	0.233	7.008	0.59	1.030 ± 0.072	0.437 ± 0.049	0.392 ± 0.052	0.2017 ± 0.0101	1891 ± 155
SF-12-L	746217	7090565	Paleodune	24	1214 ± 52	37	0.347	1.45	0.115	0.646 ± 0.056	0.158 ± 0.032	0.294 ± 0.045	0.1934 ± 0.097	1881 ± 182
SF-15-L	747367	7093504	Paleodune	20	1063 ± 46	-34	0.379	3.881	0.388	0.875 ± 0.065	0.304 ± 0.035	0.402 ± 0.055	0.1689 ± 0.0084	1215 ± 105
SF-16-L	747649	7093410	Paleodune	24	1505 ± 68	337	0.287	6.227	0.48	1.001 ± 0.100	0.400 ± 0.078	0.400 ± 0.062	0.2014 ± 0.0101	1503 ± 165
SF-11-L	745770	7090759	Beach Ridge	24	3583 ± 153	110	0.24	6.8	0.858	1.079 ± 0.081	0.453 ± 0.056	0.421 ± 0.058	0.2048 ± 0.0102	3321 ± 287
SF-14-L	744968	7088705	Beach Ridge	24	2024 ± 87	26	0.213	1.976	0.243	0.589 ± 0.055	0.162 ± 0.222	0.222 ± 0.04	0.2046 ± 0.0102	3439 ± 354
SF-13-L	746392	7092520	Beach Ridge	20	7472 ± 337	2237	0.2	12.199	1.476	1.521 ± 0.130	0.743 ± 0.104	0.574 ± 0.078	0.2038 ± 0.0102	4914 ± 475
SF-8-L1	748014	7094824	Beach Ridge	24	2893 ± 124	48	0.656	1.598	0.401	0.932 ± 0.082	0.267 ± 0.037	0.557 ± 0.074	0.1079 ± 0.0054	3104 ± 305
SF-8-L2	748024	7094834	Beach Ridge	20	2140 ± 96	1295	0.271	0.762	0.207	0.471 ± 0.042	0.118 ± 0.018	0.235 ± 0.038	0.118 ± 0.0059	4541 ± 454

Fig.14. Plot of sensitivity corrected OSL signal versus radiation dose for single-aliquot from sample SFS-8-L.3 The horizontal line shows the natural OSL signal. The dose is given in time of irradiation (dose rate of 95.95 ± 4.1 mGy/s).

Fig.15. Equivalent doses estimated for the aliquots of samples SFS-9-L and SFS-12-L. N = number of aliquots.

Fig. 16. Histogram of recycling ratio distribution of 252 dating aliquots.

Fig. 17. Comparison among beach ridges, blowouts and paleodunes ages.

Fig. 18. Mean size distribution in different geomorphological units.

Fig.19. Digitized Google Earth image of SFSI (2009, by GeoEye). Coastal progradation on the central- northernmost part of the SFSI where OSL ages were obtained. Section "A" denotes the period from from 5 to aproximately 3.1 ka (beach ridge progradation period only). The following section "B" denotes deposition that starts at 3.1ka to the present date. Dashed line indicates the boundary with superimposed dunes.

Fig.20. Sample collection site SFS-18-L, a blowout close to the shore with OSL age of 87 ± 8 years. Sands with cross-bedding dipping from 16° to 34° to WNW are common in the blowout facies in SFSI.

2.5. Discussion

2.5.1. Holocene barrier progradation and dune building in São Francisco do Sul Island

Elevation may be useful to separate Holocene from Pleistocene barriers in southern Brazil due to its relatively tectonic stability and significant difference between the Pleistocene and Holocene relative sea-level highstands. In the SFSI, the elevation of terrains westward from the Icaraí Lagoon varies from 5 to 22 m, while eastward terrains varies from 0 (present shoreline) to 17 m. Despite terrain elevation being also dependent on tree canopy heights, this difference in elevation could indicate the separation between Pleistocene and Holocene barriers, with a boundary roughly following the Icaraí lagoon. Its meandering morphology suggests a lost connection with the drainage basin and may be interpreted as a fluvial channel correlated to the last sea level lowstand. The oldest beach ridge age obtained for SFSI was 4.914 ± 0.475 ka, suggesting that barrier progradation began during the Mid Holocene, around the relative sea-level maximum at 5.0 ka in the Brazilian coast.

The progradation of the Holocene barrier in northeastern part of the SFSI occurred under two modes of deposition. The first mode, that comprised the period from 4.914 ± 0.475 ka to at least 3.104 ± 0.305 ka (section “A”, fig. 19), encompasses the beach ridges formation without significant dune building. This period started around the Mid-Holocene relative sea-

level maximum of 2.5 ± 1.0 m at about 5.0 ka (Angulo et al., 2006) and marks the onset of the barrier progradation and coastline regression. Progradation occurred under a sea level fall of 1.5 m since 4.9 ka. The progradation rates vary from 0.1 to 0.6 m/year on the shore-normal direction. Highest progradation rates values were found on the north-central part of SFSI. The range of progradation rates obtained for the SFSI is similar to that obtained for Australian barriers and for the Ilha Comprida barrier (Guedes et al., 2011b).

The oldest OSL-age determined for the paleodunes was 1.891 ± 155 ka (sample SFS-9-L). This sample is located on the northern part of the barrier and is about 400 m from the present beach face. The second oldest OSL-age determined for the paleodunes was 1.881 ± 0.182 ka (sample SFS-12-L). No overriding dunes were observed at either site. The SFS-12-L sample site was located less than 200 m from the present beach face. Following a 500m perpendicular transect from the coast lays beach ridge sample site SFS-11-L (OSL-age 3.3 ka). SFS-12-L is located only 130 m from the beach ridge-dune boundary (Fig. 6) determined through Google Earth and Landsat images. It should then be expected that the age of 1.891 ± 0.155 ka represents the inception of the primary dune emplacement on SFSI. Elongated parabolic dunes in SFSI also attest to higher wind speeds as suggested by Gaylord et. al. (1987) in studies of airflow-terrain interactions. Blowout and parabolic dunes formation may also be linked to periods of increased storminess, high velocity wind erosion and climate change (Hesp, 2002). Thus, dune development in SFSI starts around 1.8-1.9 ka years, represented by parabolic dunes pointing to NNW. Aeolian dunes migrating to NNW are formed by SSE winds, which are active during the northward advance of cold fronts.

Throughout the Holocene evolution of SFSI, sand becomes coarser with decreasing age and tends to become better sorted (Figs. 10, 18). The patterns of decreasing heavy minerals and increasing grain-size across-shore (from W to E) and alongshore (from SW to NE) are also in accordance with the wind transport and present littoral drift on SFSI and the Santa Catarina coast (Giannini, 2002; Angulo and Souza, 2004; Pereira et al., 2009).

Beach ridge sediments (> 3.1 ka) show a conspicuous decoupling from the superimposed parabolic dunes sediments (< 1.9 ka) and the more recently deposited foredunes, blowouts and beach sands. On average beach ridge sands are 0.6 phi finer than the

paleodunes sands (Table 1). This suggests either a lower wind and wave energy/sediment input ratio or a finer and/or more reworked source (beach sands) under different morphodynamic conditions in the past relative to the present. Also, paleodune formation and stabilization between 1.9 to 1.2 ka may imply a relatively wet climate, but under a SSE wind regime able to provide episodes of dune movement. This augmentation of southeasterly wind speed and frequency indicates increasing action of cold fronts since 1.9 ka.

2.5.2. Changes in sediment provenance and reworking

The heavy minerals of the SFSI sands comprise two different assemblages. Beach ridges sands are enriched in minerals from medium to high-grade metamorphic rocks such as kyanite, sillimanite, staurolite and rutile (Table 4) pointing to a primary provenance from precambrian substrate northward the Perimbó shear zone (Fig. 2) . These sands can be transported directly from the primary source rocks to the Holocene barrier or correspond to reworked Pleistocene sediments. All other units exhibit a higher contribution of acid plutonic rocks provenance identified by elevated contents of zircon and hornblende (Table 4). Acid plutonic rocks dominate the source areas southward the Perimbó shear zone. Both assemblages show some degree of intermixing with each other.

Rutile, zircon and tourmaline are among the most stable heavy minerals under earth surface and diagenetic conditions (Hubert, 1962; Morton and Hallsworth, 1999). Although granitic or mafic igneous rocks may be the source rocks of rutile, the high-grade metamorphic rocks are the most important bedrock source for detrital rutile (Force, 1980) concurrently with recycled sediments. Most igneous rocks lack rutile except where they are hydrothermally altered and in granite it is sparse. As a result, rutile still contains information from its primary source area, even in extremely mature sediments and after burial to significant depth (Zack et al., 2004). Whereas zircon generally survives the rock cycle from sedimentary to high grade metamorphic and often even magmatic processes, rutile breakdown occurs at the beginning of the greenschist facies and is newly formed at upper amphibolite facies conditions (Zack et al., 2004).

Zircon and rutile have similar habit (equant or prismatic) and density. Their hydraulic properties behave in similar fashion and the rutile to zircon ratio can be used as an indicator of provenance (Morton and Hallsworth, 1994). Although the TZi is not completely controlled by provenance, zircon and tourmaline have contrasting hydrodynamic behavior and consequently, variations in hydraulic conditions at the time of deposition could also account for the differences in TZi between the different sedimentary units.

Heavy minerals content on beach ridges is substantially lower than the paleodune's (Table 3) and heavy minerals indexes RZi and TZi are contrastingly different and point to unambiguous provenance variation (Table 6). The higher RZi values for the beach ridge sands indicate a greater contribution of sediments derived from metamorphic rocks, which is in agreement with a heavy mineral assemblage with relatively elevated contents of staurolite, sillimanite and kyanite. The TZi trend is similar to that observed for the RZi, suggesting that it is mainly controlled by provenance. The plutonic origin of the sediments from the paleodunes, blowouts, foredunes and present beach sands may be traced to the Florianópolis batholith located less than 170 km south from SFSI. The Florianópolis Batholith (Fig. 2) is a major component of northern portion of the Neoproterozoic Dom Feliciano Belt in Santa Catarina state. It is exposed over an area of about 12,000 km² (about 200 km long and 60 km wide), along the coast, extending continuously from 26° 45' S to 28° 45' S (Silva et al., 2003). According to Silva et al. (2003), zircons from this site are morphologically simple, composed of euhedral long-prismatic grains with typical magmatic length to width ratios of 3:1. Zircons from the paleodunes present a similar length to width ratio (Fig. 12). In addition, in a coastal depositional system, prevalence of moderately well sorted medium sands on the aeolian and beach sands indicates proximity to sediment source and/or high transport energy (Abuodha, 2003).

Differences in OSL sensitivity of quartz may connote distinctive source areas indicating the thermal history of the source rocks and sedimentary reworking during the transport of grains from source to sink (Chen and Murray, 2000; Li et al., 2002; Piestch et al., 2008; Sawakuchi et al., 2011). Elevated OSL-sensitivity values (>1200) associated with the oldest samples (SFS-8-L2 and SFS-13-L) indicate highly reworked sediments, possibly submitted to many cycles of barrier construction and erosion. This suggests that at the Mid-Holocene

highstand, sands were carried by currents from the inner shelf to be subsequently transported onshore. It appears that at this period, there was a higher contribution of sands from the inner shelf than from the south by means of the littoral drift. This may have occurred due to weak/low intensity currents and winds. Sands from the paleodunes deposited from 1.9 to 1.2 ka show much lower OSL-sensitivity values (<110) indicating low sedimentary reworking and proximity to source. Variation in the morphodynamics induced by climate changes may have contributed to a higher input of sediment from southern coastal sectors due to an increase in northward littoral drift. Studies by Lessa et al. (2000) at the Paranaguá barrier system, (~90km north of SFSI) and by Angulo et al. (2009) at the Pontal do Sul barrier (~70km north of SFSI), both with a similar geomorphological setting to SFSI, show progradation evolution in agreement with an increase in strength/intensity of the littoral drift at this period. An increase of progradation rates associated with a northward littoral drift and starting about 2 ka is also found in Ilha Comprida barrier (Guedes et al., 2011b), though the authors interpret it as an effect of changing coastal physiography.

The definition of the source rocks of the SFSI sands allows making some inferences about the pathways of sand transport in the southern Brazilian coast. The terrigenous sediments supplied to the southern Brazilian coast derive from the La Plata River (Dominguez, 2006; Mahiques et al., 2009) and from many other minor rivers. The La Plata River, which is the major river of southern South America, reaches the South Atlantic coast more than 1500 km southward of SFSI. Its sediments are transported northward, feeding the South Atlantic around Brazil with distal sediments. The La Plata river discharge fluctuations are mainly controlled by climatic changes (Cavallotto et al., 2004) and may be correlated with the onset of modern climatic conditions in South America (Mahiques et al., 2009). Though suspension load derived from the La Plata River is transported throughout more than 1000 km northward (Mahiques *et al.*, 2008), its contribution to the coastal sand supply in SFSI would be reduced due to the distance. Thus, minor rivers flowing directly to the coast would be the major sand supplier to the SFSI Holocene coastal systems. Sands from the SFSI would be derived from source rocks outcropping in continental areas located less than 170 km southward.

2.5.3. Coastal morphodynamics shift induced by cold fronts intensification in the Late Holocene

The Holocene progradation of the SFSI barrier had a pronounced morphodynamic shift around 1.9-1.8 ka. This shift is characterized by changes in coastal morphology and sediment provenance and it cannot be correlated with relative sea-level changes. Dune building by SSE winds started around 1.9-1.8 ka combined with significant sand coarsening and increase in sediment supply from southern coastal sectors. Fine sand deposition which dominates the SFSI barrier evolution until 1.9-1.8 ka is usually associated with a dissipative morphodynamic beach system (Short and Hesp, 1982) and giving prevailing on-shore winds has the potential to develop aeolian depositional landforms. No concurrent deposition of beach ridge and dunes systems are found on SFSI prior to 1.9 ka, indicating lack of regular strong winds at the beach ridge progradation stage. Conversely, medium to coarse sand are usually associated with an intermediate or reflective morphodynamic beach system (Short and Hesp, 1982) that still persists in SFSI. Also, the increase in heavy minerals concentrations from the beach ridges to the dune ridges units may indicate periods of increase storminess starting at 1.9 ka. Woolsey et al. (1975) suggested that heavy minerals selective sorting processes were found to be most effective during storm periods and that high velocity aeolian winnowing during low tide periods is an important additional effect.

By the time the first paleodunes stabilized when relative sea-level height was around 1.2 $\pm$ 0.5 m and decreasing to present sea level. At this low rate of relative sea-level change, the influence of sea-level variation in progradation is weakened and the sediment supply to the aeolian system becomes highly sensitive to shifts in the wind and wave climate (Sawakuchi et al., 2008). Thus, the 1.9-1.8 ka period indicates a climatic forcing shift from a fine sand beach ridge barrier to a medium sand parabolic dune, blowout and foredune ridge barrier.

The commencement of the deposition of the coastal dunes in SFSI was probably influenced by both proximity to source and by an increase in wind transport energy triggered by stronger SSE winds and a rapid littoral drift in the area. The increase in SSE winds strength indicates more intense cold fronts starting at 1.9-1.8 ka. The period (1.9-1.2 ka) of dune

development in SFSI corresponds to increasing amplitude of ENSO events and the seasonal shift of the westerly storm tracks, poleward in summer and equatorward in winter (Markgraf et al., 2003; Wanner et al., 2008). Sedimentological evidence from Lago Cardiel, Argentina reveals a higher wind activity associated with the Westerlies between ~1800 and 1200 cal yr BP (Gilli et al., 2005) in accordance with iron-content proxy data from sediments from Chile on the same period (Lamy et al., 2001).

The younger period of parabolic dune migration coincides with the period prior to the Medieval Climate Optimum (MCO, 800 to 1200 A.D.) in the Northern Hemisphere. In southeastern Brazil an increase in moisture is found at this time (Behling, 1995, 1997, 1998; Chiessi et al., 2010). Moisture variations are related to the ITCZ, SACZ and to a large extent by the behavior (strength and latitudinal position) of the storm tracks of the Southern Westerlies (Gilli et al., 2005). Through stable isotopic measurements of biogenic carbonate and bulk organic matter in Lake Guanaco, Chile, Moy et al. (2008) found evidence for increased aridity coupled with lessening amplitude of the Westerlies starting at the MCO and terminating at the onset of the Little Ice Age (LIA). Sawakuchi et al. (2008) attributed the development of blowouts and foredunes in the Ilha Comprida barrier, to an increase in the activity of cold fronts, and consequently of the westerlies, during the LIA. In the SFSI, the generation of blowouts and foredunes can also indicate a returning to conditions of increased cold fronts activity since the LIA.

This period was also construed by a mean southward shift of the ITCZ in the Pacific basin, as well as by dry conditions in northern South America (Haug et al., 2001). According to Cruz et al. (2009) during the Holocene a similar, but zonally oriented, antiphasing of precipitation is identified within the same hemisphere. Northeast Brazil experiences humid conditions during low summer insolation and aridity when summer insolation is high, whereas the rest of southern South America shows opposite characteristics. Thus, dune formation and stabilization from 1.9 ka to 1.2 ka may be a valid proxy of ENSO events and SACZ and Westerlies displacement at this period. Dunefield stabilization was also found at Rio Grande do Sul State coastal stretch from Torres to Mostardas starting from 1570 to 710 cal yr BP (radiocarbon dating; Martinho et al., 2008). These conditions were possibly less pervasive during the MCO

(Moberg et al., 2005; Mann et al., 2008) since no dune stabilization ages were found at this period in southeastern Brazil yet and were reinstated at the onset of the Little Ice Age (Sawakuchi et al., 2008; Guedes et al., 2011b).

2.6. Conclusion

A morphodynamic shift occurred in SFSI at 1.9-1.8 ka indicates conditions of stronger northward littoral drift and SSE winds that brought enough dune-forming sediments decoupled from sediments from the previous beach ridges. The development of parabolic dunes between 1.9 and 1.2 ka superimposed to beach ridges were controlled primarily by enhancement of cold fronts provoked by a northbound shift of the Westerlies, intensification of ENSO events and a displacement of the SACZ. This climate forcing on the coastal system generated changes in the barrier morphology, sediment provenance and supply and timing of deposition. Different facies correlation in barrier systems as shown in a small area of SFSI (approximately 7 km²) may act as a valid proxy for past climate events. OSL dating (SAR protocol) combined with grain-size, heavy minerals and geomorphological analyses are reliable in evaluating impacts of centennial to millennial climate changes on coastal depositional systems. Understanding the link of climate variability and coastal processes in the past may help evaluating the response of coastal zones to future climate change.

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**3. Geomorphological analysis of coastal depositional systems in SE
Brazil aided by Google Earth coupled with the integration of
chronological and sedimentological data by means of a Fusion Table**

Geomorphological analysis of coastal depositional systems in SE Brazil aided by Google Earth coupled with the integration of chronological and sedimentological data by means of a Fusion Table

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ABSTRACT

Although Brazilian coastal depositional systems evolution in the Quaternary has been studied in past decades, it is only in the last couple of years that it has been possible to incorporate the latest remote sensing databases available to help understand their development. In comparison to other imagery freely accessible, high resolution images available on Google Earth are advantageous when undertaking local coastal analysis. In some instances, it is possible to differentiate at the facies scale geomorphologic features such as tidal deltas, beach ridges, and dunes. Also, the monitoring of small scale features allows evaluating the sensitivity of coastal zones to high frequency and low intensity processes. On the regional scale, a quick glance of a coastal setting may help framing the sedimentary characteristics of the depositional system. Thus, the downscaling description of coastal zones is now easily accessible, permitting the analysis of the extensive Brazilian coastal depositional systems.

Coastal areas in the States of Santa Catarina and São Paulo are taken into consideration in this study. A comparison is made in the use of Google Earth and its historic images with aerial photographs and Landsat images. In the past, small scale features of these regions were evaluated in aerial photographs while regional features were studied by low resolution satellite images. Accordingly, integration of these two products was difficult. The availability of Google Earth assisted the analysis as a whole. Furthermore, comparison of Google Earth images with

aerial photographs from 1938 onwards allowed the study of short-term migration and deflation of the dunefields probably accelerated in recent years by human interference. In addition, KML files were saved from Google Earth placemarks to facilitate georeferencing raster images on GIS programs. Finally, information provided by luminescence dating, geomorphology of the costal system, grain size, heavy minerals, pollen and carbon isotope analyses combined with a bibliographic survey assisted us in creating a Fusion Table making data retrieval and parsing easily accessible. This database provides information that can be shared with other researchers and may be used as a commencement to address important questions about the development of Brazil's coastal system in the past, present and future.

3.1.Introduction

Sea level has fluctuated throughout geological time, periodically encroaching or retreating across continental margins (Lambeck et al., 2010). The present physiography of the Earth's coastal zones resulted from the last floodings of the continental shelf by the sea rise (Flandrian Transgression) after the Last Glacial Maximum 20,000 years B.P. and the Mid-Holocene sea-level highstand at around 6,000 years B.P. These events favored the development of transgressive and regressive depositional systems tracts, which include deltas, estuaries, tidal channels, lagoons, barriers and dunefields (Woodroffe, 2002). Also, Late Quaternary climate changes have influenced the development of coastal depositional systems through shifts in their morphology and dynamics. Estuaries and barriers are the most common geomorphologic features in the northern portion of the Brazilian SE Coast while lagoons and dunefields occur frequently in the southern portion. A substantial amount of data from different coastal depositional systems have been collected over the past several decades in these areas (Angulo et al., 1997; Martinho et al., 2006; Giannini et al., 2007; Nascimento et al., 2008; Sawakuchi et al., 2008; Guedes et al., 2011a). These data encompass information provided by grain size, heavy minerals, pollen, carbon isotope analyses and Optically Stimulated Luminescence (OSL) dating supported by stratigraphic and geomorphologic surveys. However, it is only in the last couple of years that it has been possible to couple these data with the latest imagery available to better understand the coastal evolution of SE Brazil in the Late Pleistocene and Holocene.

The advent of publicly available tools such as Google Earth has permitted to visualize high resolution images provided by remote sensing techniques. This has proven to be extremely useful in analyzing coastal depositional systems, where the influence of sea-level changes, tsunamis or storms may affect morphologic patterns at different scales, or in finding distinctive sedimentological features. Recently, hundreds of barrier islands were newly identified in a global survey which included the Gurupi Islands, along the equatorial coast of Brazil (Stutz et al., 2011). This survey was conducted with the aid of the Earthsat Geocover Landsat mosaic data

and Google Earth (Stutz et al., 2011). Livingstone et al. (2010) constructed a map of eolian dune types based on visual interpretation of Google Earth images. Google Earth images were used to survey and map the destruction and flooding caused by Hurricane Katrina (Klemas, 2009).

The aim of this research was to show different uses of Google Earth in association with local coastal landforms and depositional systems studies and to bring forward new methods in displaying and sharing this information by means of a Fusion Table. In the first part of this study we analyzed Google Earth images from Brazil's SE coast (Fig. 1).

Fig. 1. Google Earth images of Brazil's SE coast. A) Ilha Comprida, B) São Francisco do Sul, C) Ibiraquera Beach – Imbituba-Laguna Region, D) Tubarão River Delta, E) Campos Verdes and Ji.

These images were effective in helping us framing the different depositional systems in the local and regional context, acquiring initial area measurements of dunefields or prograding terrains, identifying contrasting dune types, surveying terrain variation along elevation transects and in delineating geomorphologic divisions (Fig.2). Identifying geomorphological divisions provides a ready scheme for analyzing areas with similar coastal dynamics. It also provides a pattern to simplify the range of variation encountered in examining coastal areas in SE Brazil.

Comparison among aerial photographs, Landsat 7 images and satellite images from NOAA, NASA and USGS available on Google Earth were carried out. Placemarks on the Google Earth images saved as KML files were used to georeference rasters in GIS software. Pre-field work and regional and local analyses were undertaken with the aid of Google Earth. In addition, historical images were used in clarifying short-term changes in the depositional systems.

Fig. 2. Google Earth image of a partial view of the oceanic coast of São Francisco do Sul Island. Blowouts are outlined in red and paleodunes boundaries in white.

The second part of this study emphasized the functionality of Google Fusion Tables, a cloud-based georeferenced data management and integration tool coupled with Google Earth. Google Fusion Tables were utilized in compiling and integrating data available from different coastal studies in SE Brazil. This was a pioneer work in a way of establishing new directions to

store and visualize records and build user-friendly interfaces with data from coastal depositional systems in SE Brazil. Google Fusion Tables support for collaboration among multiple users and institutions unlocked new ways of sharing data that appeal to a broader audience of users who are less technically skilled. Finally, Google Fusion Tables provided a way of assisting regional interpretation in the future by compiling data from local studies. This in turn can help scientists better understand past environments of the Brazilian SE coastal areas in terms of past sea-level and climate changes. Grain-size, heavy minerals and OSL ages from Ilha Comprida in the State of São Paulo and São Francisco do Sul in the State of Santa Catarina were analyzed with the aid of Google Fusion Tables.

3.2. Regional Settings

The evolution of SE Brazilian coastal depositional systems produced a large variety of landforms. These systems evolved in coastal regions characterized by a microtidal regime (0.6-1.2 m), wave-dominated and by storm events all over the year, though more intense in the winter season (Stech et al., 1992). As a result, transportation and deposition of sediments are highly affected by the action of waves and currents associated to storm events. NE trade winds act during fair weather periods while the northward advance of polar air masses stimulates the action of S and SE winds (Stech et al., 1992). Middle to Late Holocene barriers are conspicuous landforms in SE Brazilian regions (Giannini et al., 2009; Hesp et al., 2009). The barriers in the coastal zones of northern Santa Catarina, Paraná and São Paulo states are formed mainly by beach ridge alignments and many barriers present foredune and blowout alignments in their seaward portion (Sawakuchi et al., 2008; Angulo et al., 2009; Giannini et al., 2009; Hesp et al., 2009).

3.3. Google Earth

3.3.1. Modeling

Although Landsat, SPOT-2, RADARSAT-1, CBERS-1, and other remote sensing images from satellites have been available in Brazil since 1973, they have been of limited use in detailed coastal research. Multi-purpose regional maps prepared at *scale fractions of* 1:1.000.000, 1:500.000 or 1: 250.000 can highly benefit from these images. However, when finer resolution is required in more detailed studies these scales are usually not appropriate. On the other hand, remote sensing images providing scale fractions of 1:25.000, 20.000 to 45.000 or even 1:10.000 in special surveys, can be advantageous in coastal studies. These scales can be obtained from aerial photography surveys. Coastal aerial photography surveys in coastal SE Brazil have been intermittent. Black and white surveys in the short wave spectrum have been conducted in the years of 1938 (1:20.000), 1957 (1:25.000), 1969 (1:20.000), 1976/1978 (1:25.000; <http://geo.pmf.sc.gov.br/historico.php>). In past decades, these images were the primary resource used by researches to further investigate small range coastal environments despite the fact that most of them required exhaustive and time consuming rectification or even orthorectification to correct distortion from terrain. The process of acquiring high resolution imagery by satellite or aerial photography and turning it into a continuously updated mosaic by Google Earth has given a better and easier option to work with for many coastal studies. A recent research on São Francisco do Sul was carried out entirely on Google Earth.

3.3.2. São Francisco do Sul – Santa Catarina State

The island of São Francisco do Sul is located on the northern coast of Santa Catarina State. It covers an area of about 265 km² with an approximate length of oceanic coastline of 40 km (Fig.3).

Fig. 3. Georeferenced Google Earth image of São Francisco do Sul Island processed with the help of ArcGIS software.

The island was formed by coastal depositional systems active during the relative sea-level changes of the last 120,000 years. These depositional systems result from the trapping of sediment supply in the inner shelf and estuaries during relative sea-level highstands and by means of littoral drift. Holocene barrier deposits are found East of Icaraí lagoon (Fig. 3) and consist primarily of prograded beach ridges under wave-dominated coastal system. According to Angulo et al. (2009), limited coastal progradation occurred in the first 1,000 years after sea level maximum (around 5,000 years B.P.) when the estuaries were flood-dominant and sequestered sand from the coastal system. Sea level fall and net positive sedimentation resulted in the partial infilling of the large and in the complete infill of the smaller estuaries (Angulo et al., 2009). Coastal progradation was accelerated first with the halt of flood dominance in the estuaries (that eventually became ebb-dominant) and then with the infilling of coastal compartments by barrier progradation, that turned a multicellular into a unicellular coastal drift system. Superimposed vegetated dunes formed under the influence of the S-SE winds prevail on the central and northern part of the island. Along the coastline, a narrow belt of 5-10 m high foredune ridges associated with swales occurs. The foredunes are gradually replaced inland by 10-20 m high parabolic or irregular dune forms. Pleistocene deposits are located west of Icaraí lagoon. Beach Ridges, foredunes, blowouts and parabolic dunes are

easily identified in the Google Earth image. The boundary between beach ridges deposits and paleodunes is shown in Fig 4.

Fig. 4. Google Earth image showing the boundary between beach ridges and paleodunes terrains in the São Francisco do Sul Island. Despite the cover of intense vegetation, well-preserved paleodune morphology is conspicuous. NW parabolic dune orientation attests to strong SE winds in the past. Paleodunes overimpose older beach ridges. Recently obtained OSL ages for beach ridges are higher than 3.1 ka and lower than 1.9 ka for paleodunes.

The synoptic views obtained from Google Earth of the Brazilian SE Coast are a powerful tool for many aspects of geospatial analyses. Many coastal geomorphological features are identifiable at a quick glance. Fig. 5 shows foredunes and blowouts from São Francisco do Sul displayed through different remote sensing techniques. Resolution provided by aerial photography (Fig. 5 a, b, c) and Landsat imagery (Fig. 5 d) was not sufficient to identify these coastal depositional systems. Google Earth provided excellent elucidation at a scale fraction of 1:6000 (Fig 5e).

Fig. 5. Comparison between aerial photographs, Landsat 7 image and by SIO, NOAA, US Navy, NGA, and GEBCO images available on Google Earth from São Francisco do Sul. (a,b,c) aerial photographs from 1938, 1957 and 1978 surveys, respectively. (d) Landsat 5 image.

The smallest scale available for most topographic maps in SE Brazil is the 1:50000 fraction. In many instances geological maps are available only at a scale fraction of 1:100000 or larger. In most coastal studies small scale geomorphological investigations are required, making it necessary to produce a map at the appropriate scale fraction. At São Francisco do Sul, this was done with ArcGis software associated with Google Earth images that were used for georeferencing. Google Earth images saved as JPG files at 1:6000 scale fraction with assigned placemarks were utilized. Placemarks were exported as KML files directly to ArcGis software. Images with its associated geographic coordinates provided by placemarks, made georeferencing possible with the aid of ArcGis software (Fig.6). Georeferencing is crucial to making Google Earth useful for mapping as it explains how other data such as GPS controls points relate to the imagery.

Fig. 6. Placemarks on the Google Earth image were used to georeference the image in the ArcGis program. The raster obtained from Google Earth was also helpful in georeferencing photographs from 1938, 1956 and 1978 in São Francisco do Sul.

Blowouts are common in the central and northern oceanic coast of São Francisco do Sul. A blowout is a saucer-, cup- or trough-shaped depression or hollow formed by wind erosion on a preexisting sand deposit (Hesp, 2002). Their formation may be related to natural and/or anthropogenic factors. Landmarks recognizable in past aerial photography surveys and still existing in the Google Earth raster were used in georeferencing aerial photography. Georeferenced Google Earth and aerial photography images (surveys of 1938, 1957 and 1978) of São Francisco do Sul made appraisal of recent blowout evolution possible (Fig 7).

Fig. 7. 2009 Google Earth image. Blowout evolution on the northern part of São Francisco do Sul Island. Solid line depicts blowout boundary obtained from the 1938 aerial photography survey.

3.3.3. Ilha Comprida – São Paulo State

Ilha Comprida is a regressive barrier island located in the State of São Paulo in SE Brazil formed by Holocene sandy sediments deposited in a wave-dominated coastal system (Guedes et al. 2011a, 2011b; Sawakuchi et al., 2008; Giannini et al., 2009). The barrier was divided into

three morphological units by Sawakuchi et al. (2008); inner, middle and outer. The inner unit is formed entirely by beach ridges (Guedes et al., 2011a). The middle unit comprises a narrow belt of blowouts (up to 10 m high) aligned alongshore. Blowout lobes pointing NNW are indicative of their generation by the intensification of southern winds during the Little Ice Age (Sawakuchi et al., 2008). The outer unit is represented by low (≤ 3.5 m high) active or stabilized foredunes and a small transgressive dunefield (approx. 1 km²). Sawakuchi et al. (2008) and Guedes *et.al.* (2011a) obtained thirty six luminescence ages (OSL-SAR protocol) for the beach ridges, foredunes and blowouts of these three units. This allowed the outset of a precise chronology sequencing of these landforms and calculation of rates of coastal progradation. Sedimentary studies in Ilha Comprida Barrier (Guedes et al., 2011b) have provided knowledge about grain-size and heavy minerals distribution contributing to barrier evolution understanding.

Studies by Guedes et al. (2011a) showed variation in coastal progradation rates and sediment retention during the last 6000 years in Ilha Comprida supported by OSL dating. Based on beach ridge alignments, six units of growth are identified with two growth directions, transverse and longitudinal. Rates of progradation with transverse growth vary from 0.13 to 4.6 m/year. Rates of longitudinal growth to NE range from 5.2 to 30 m/year. Alternation between longitudinal and transverse growth still occurs (Fig. 8).

Fig. 8. Google Earth historical images were utilized to elucidate sediment dynamics linking erosion and deposition in Ilha Comprida from 2001 to 2010. The barrier has experienced extensive erosion on its oceanic NE side followed by progradation on its northernmost point in this period. An area of 0.69 km^2 was eroded from 2001 to 2010. Conversely, a progradation of 0.74 km^2 occurred at the same period at the northernmost point of the island.

3.3.4. Campos Verdes and Ji – Santa Catarina State

The Holocene strandplains of Campos Verdes and Ji are characterized by truncated sets of beach ridges alternated with dunefields (Tanaka et al., 2009). Google Earth images were helpful in framing the sedimentary evolution of the area by Tanaka et al. (2009). Photographs from 1956 were primarily used to outline the beach ridges. Updated Google Earth images

allowed a closer inspection of some geomorphological characteristics not discernable in aerial photography and evaluation of recent changes in the area that were useful in field trip planning. Erosion and man-made environmental changes were accountable for the disappearance of northern dunefields and of beach ridges on Fig 9.

Fig. 9. Comparison of 1956 photograph with Google Earth image. Circled areas show previous ridges on the photograph no longer visible on the Google Earth image. They were replaced by shrimp tanks.

3.3.5. Tubarão River Delta – Santa Catarina State

The Tubarão river delta, located on the center-south coast of Santa Catarina State, is a rare example of an active lagoonal delta in Brazil. Its delta plain covers an area of about 250km² (Nascimento, 2011). The Google Earth image shows evidence of migration of fluvial channels in a set of truncations of ancient distributaries, some still in activity (Fig. 10).

Fig. 10. The red arrow on the Google Earth image shows the distance from the paleo channel to its current position at Carniça River.

3.3.6. Ibiraquera Beach – Imbituba-Laguna Region – Santa Catarina State

Fig. 11 shows a Google Earth image of the stabilized (G1/G2=eolian generation 1 or 2 and G3=eolian generation 3) and active dunefields (G4=eolian generation 4) on Ibiraquera Beach. Morphological features of G4 deposits include barchanoid chains (BC) and depositional lobes (DL). According to Giannini et al. (2007) these four generations of deposits have been distinguished in the eolian depositional system, based on sedimentological and geomorphological criteria. The Late Quaternary coastal eolian deposits of the Imbituba–Laguna region comprise two “eolian depositional sequences”, separated by an unconformity. The older eolian sequence, G1, is correlated to the relative sea level rise after the last interglacial period. The eolian sequences G2, G3 and G4 were initiated during the relative sea level rise in the post-glacial period and extend up to the active dunefields. The correspondence between the two eolian depositional episodes represented by these sequences and the relative sea level highstand phases is confirmed by thermoluminescence (TL) and OSL dating. This correspondence is made clear by a conceptual model that links the availability of coastal sediments for eolian transport with relative sea level changes. The link between relative sea

level changes and coastal eolian sedimentation can be used to integrate coastal eolian systems to the sequence stratigraphy model.

Fig. 11. Outlining differentiated generations of eolian depositional system with the aid of Google Earth.

3.4. Google Fusion Tables

The ability to visualize spatial data distribution in maps or images in lieu of tables or graphs made the Geographic Information Systems (GIS) an essential tool for geoscience researchers, educators and professionals alike. However, the high cost of programs, learning difficulties and the lack of friendly interfaces have hindered its general acceptance. The emergence of new platforms such as Google Fusion Tables providing several ways of visualizing and integrating data in a free, easy to use environment, appeals to a broader class of users. Google Tables Fusion is a free georeferenced database tool available online that offers a platform for handling large amounts of information. In addition to providing instant viewing with the aid of Google Earth or Google Maps, it also allows displaying data in tables or graphs. Google Fusion Tables offers tools to invite collaborators to view, edit and merge data with

other tables and handling online interaction between research groups. Overviews of the uses of Fusion Tables have been given by several authors (Gonzalez et al. 2010a, 2010b, 2010c, Lu et al. 2011) and detailed comparisons of GIS software and Google Earth are given by Goodchild (2008). Different examples of actual, ongoing uses of Fusion Tables can be found online at the Google Fusion Tables site <https://sites.google.com/site/fusiontablestalks/>. In the study of Southeastern Brazil depositional systems the use of Google Fusion Tables offered the possibility of regional integration and sharing of geomorphological, sedimentological (grain size and heavy minerals), chronological and bibliographical data in a single, easily accessible platform. Emphasis is given on OSL dating results. The OSL dates provide a coherent chronology for sand deposition and allow direct assessment of depositional dynamism in numerous terrestrial and subaqueous (including marine) sedimentary systems, and have demonstrated particular potential in the elucidation of chronologies of dune environments (Stokes, 1999).

In order to explore the functionality of this tool we utilized information on the sedimentary evolution of Ilha Comprida published by Sawakuchi et al. (2008) and Guedes et al. (2011) and recent data from São Francisco do Sul. Initially, structured data from an Excel spreadsheet was uploaded into the Google Fusion Tables environment. Each record corresponded to a sediment sample. All pertinent data concerning different aspects of analyses and methods were included in the Google Fusion Tables as a single field. In addition to these data, bibliographical references, photographs, overlays and KML links were included in each record. The classification and arrangement of these data are shown in Table 1.

Table 1. List of fields used in the Brazilian Coastal Landforms Fusion Table.

Feature	Field	Remarks and Google Earth popup window contents
Geographic	UTM X, UTM Y, UTM Zone, Latitude, Longitude, Location	Local data
General	Comments	Major comments regarding the local sample or study area
Bibliographic	Articles	URL link to relevant articles published on the study area
Germophologic	Distance from coastline (m), Elevation above RSL (m), Landform, Landform Unit	Data obtained by field trips or image analyses
Chronological and OSL parameters	Dose (mGy), Dose standard error (mGy), Gamma dose-rate (mGy/yr), Gamma dose-rate standard error (mGy/yr), Beta dose-rate (mGy/yr), Beta dose-rate standard error (mGy/yr), Cosmic dose-rate (mGy/yr), Cosmic dose-rate standard error (mGy/yr), Total dose-rate (mGy/yr), Total dose-rate standard error (mGy/yr), Age determination method, Age (years), Age standard error (years)	Age determination method, age and standard error shown on popup window. In the case of OSL method, URL links to data analyses table.
Grain-size analyses (grain-size group)	Very Coarse Sand (%), Medium Sand (%), Fine Sand (%), Very Fine Sand (%), Mean Diameter (phi), Standard deviation (phi), Skewness (phi), Kurtosis (phi), Sorting Class, Comments	Bar chart displayed for the sand size class analyses. Statistical data shown as text
Heavy Minerals (heavy minerals group)	Opacues, Non-Opacues, Zircon, Turmaline, Rutile, Hornblende, Epidote, Sillimanite, Kyanite, Staurolite, Apatite, Clinozoisite, Tremolite, Andalusite, Actinolite, Enstatite, Monazite, Hypersthene, Diopside, Garnet, Topaz, Altered Minerals, % Opacues, % Non-Opacues, Total Non-Opacues, Comments	Total of heavy minerals counted is given in the "Total Non-Opacues" field. All individual numbers are absolute. Heavy minerals and % Opacues content shown in pie charts illustrating proportion.
Heavy Minerals Indexes (heavy minerals group)	Zi-Ru, Tu-Hn, Tu- Zr	Text
Heavy Minerals dedicated count (heavy minerals group)	Zi dedicated count Zi + Ru, Ru dedicated count Zi + Ru, Zi dedicated count Zi + Tu, Tu dedicated count Zi + Tu, Tu dedicated count Tu + Hn, Hn dedicated count Tu + Hn	URL linked to server
Overlays	Overlay 1, Overlay 1 Description, Overlay 2, Overlay 2 Description, Overlay 3, Overlay 3 Description	URL linked to server
Pictures	Image 1, Comments Image 1, Image 2, Comments Image 2, Image 3, Comments Image 3, Image 4, Comments	All pictures and comments displayed
Evidences	Anthropological evidence, Paleontological evidence, Comments	Field or research evidences - Text

Google Fusion Tables may also be exported as KML to be viewed on Google Earth where all sample locations are placed as balloons and once selected, a customized window is shown with the most relevant information, graphs, links and pictures (Fig. 12). Customization was

done with the help of KML language in the Google Fusion Tables environment. The framework of KML has been documented by Werneck (2009). The KML code structure consisted of snippets of fixed text combined with dynamic elements provided by different fields from the Google Fusion Tables. Size class distribution and classification of sands into sorting classes based on standard deviations, heavy minerals content and indexes data were coded (supplementary data).

Fig . 12. From an Excel spreadsheet to placemarks on the Google Earth Image. Customized pop-up window with links, sample site pictures and sedimentological and heavy minerals data displayed as graphs and charts.

The Brazilian Coastal Landforms Fusion Table can be viewed at the site:

<http://www.google.com/fusiontables/DataSource?snapid=S231804gbl6>. No sign-in is required.

3.5. Conclusion

This paper addressed different uses of Google Earth applied to characterize coastal depositional systems and landforms in the SE Brazilian coast. We have illustrated features and methods using some examples that highlighted the role played by Google Earth in our coastal studies. Powerful visualization, interactivity, regional context and ease of use were important aspects of Google Earth utilized in our research. Moreover, as our examples suggest, there is a wide range of uses of Google Earth than can be enhanced when combined with a GIS application.

The integration of Google Earth and Google Fusion Tables brings forward some of the analytic, modeling and inferential functionalities of typical GIS and database software to an easier to use and robust environment that can be shared by different collaborators. The possibility of dealing with large amounts of data from different localities throughout the coast provided collaboratively by different researchers paves the way for larger scale regional interpretation. This in turn can contribute to elucidate paleoclimate reconstructions, sediment provenance and sea-level changes among other studies. Feedback from fellow collaborators has been positive though a full evaluation of the Google Fusion Tables benefits is beyond the scope of this assignment.

There are considerable advantages in using free and user-friendly technology for analysis, visualization, integration and sharing of large amounts of coastal depositional systems data from SE Brazil. All that is required is access to the Web and downloading Google Earth and access to Google Fusion Tables. This alone promotes large potential for easy dissemination of knowledge to fellow colleagues and the interested general public around the world. Knowledge

of past evolution of coastal depositional systems as well as description and monitoring of the present state of coastal regions helps reducing the effects of degradation.

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Supplementary KML code

The KML code developed for displaying the bar chart for sand size class parameters worked as follows:

```

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A pie chart divided into sectors illustrating proportion was chosen to depict heavy minerals concentrations dynamically. The KML code worked as follows:

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=200" />
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