paper-figures

March 23, 2016

1 Make the figures for the paper

This notebook generates the figures used in the paper. **No results are calculated here**. We'll only load the results from files produced by other notebooks. All figures will be saved in EPS format to the `manuscript/figures` folder.

1.1 Package imports

```
In [1]: # Insert the plots into the notebook
        %matplotlib inline
```

```
In [2]: from __future__ import division
        import cPickle as pickle
        import zipfile
        import numpy as np
        import matplotlib.pyplot as plt
        from matplotlib import ticker
        from mpl_toolkits.basemap import Basemap
        from mpl_toolkits.axes_grid1 import AxesGrid, make_axes_locatable
        import seaborn  # Makes the default style of the plots nicer
```

```
/home/leo/bin/anaconda/envs/moho/lib/python2.7/site-packages/matplotlib/__init__.py:872: UserWarning: axe
  warnings.warn(self.msg_depr % (key, alt_key))
```

```
In [3]: from datasets import fetch_crust1, load_icgem_gdf, down_sample, fetch_assumpcao_moho_points
        from mohoinv import predict_seismic
```

Set the global plot style parameters.

```
In [4]: seaborn.set_context('paper')
        config = dict(fontsize=6)
        plt.rcParams['font.size'] = config['fontsize']
        plt.rcParams['axes.labelsize'] = config['fontsize']
        plt.rcParams['xtick.labelsize'] = config['fontsize']
        plt.rcParams['ytick.labelsize'] = config['fontsize']
        plt.rcParams['legend.fontsize'] = config['fontsize']
        plt.rcParams['xtick.major.pad'] = 3
        plt.rcParams['ytick.major.pad'] = 3
```

The function below takes the data and sets the colorbar limits so that zero falls in the middle of the color range.

```
In [5]: def data_minmax(data, shift=0):
            ranges = np.abs([data.min(), data.max()]).max()
            return dict(vmin=-ranges + shift, vmax=ranges + shift)
```

1.2 Simple synthetic data test

This section generates figures for the simple synthetic data application.

Load the model, synthetic data, and the results dictionary.

```
In [6]: with open('../model/synthetic-simple.pickle') as f:
            model = pickle.load(f)

In [7]: with open('../data/synthetic-data-simple.txt') as f:
            for i in range(2):
                f.readline()
            line = f.readline()
            shape = map(int, line.split()[1:])
            lat, lon, height, data = np.loadtxt(f, unpack=True, usecols=[0, 1, 2, 4])

In [8]: with zipfile.ZipFile('results/synthetic-simple.zip') as f:
            results = pickle.load(f.open('synthetic-simple.pickle'))

In [9]: results.keys()

Out[9]: ['best_index',
         'solution',
         'solutions',
         'scores',
         'regul_params',
         'config',
         'metadata']

In [10]: print(results['metadata'])

Generated by sinthetic-simple.ipynb on 20 February 2016 22:06:03 UTC
```

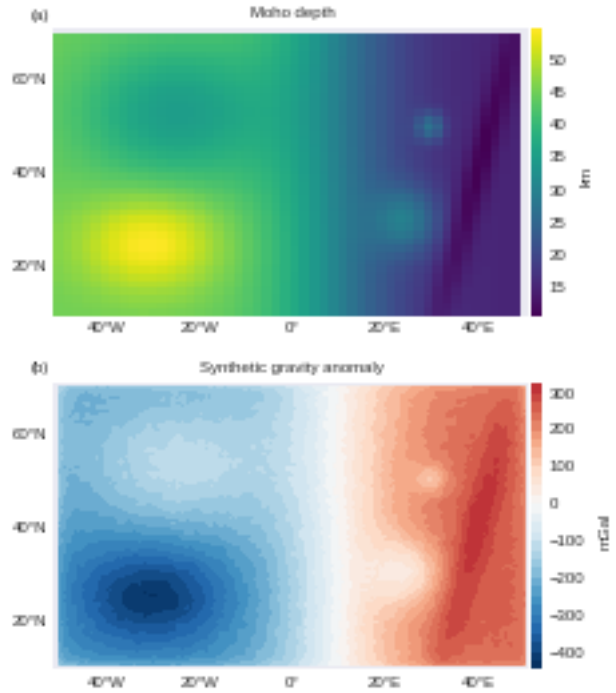
Make the map projection for these plots.

```
In [11]: bm = Basemap(projection='cyl',
                      llcrnrlon=model.area[2], urcrnrlon=model.area[3],
                      llcrnrlat=model.area[0], urcrnrlat=model.area[1],
                      resolution='c')
```

Plot the data and model in a figure.

```
In [12]: fig = plt.figure(figsize=(3.33, 3.7))

         grid = AxesGrid(fig, [0.08, 0.05, 0.8, 0.9],
                         nrows_ncols=(2, 1), axes_pad=0.35,
                         cbar_location="right", cbar_mode="each",
                         cbar_size="2%", cbar_pad=0.01)

         i = 0
         ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
         ax.text(-0.05, 1.04, '(a)', transform=ax.transAxes, **config)
         ax.set_title('Moho depth', **config)
         x, y = bm(model.lon.reshape(model.shape), model.lat.reshape(model.shape))
         tmp = bm.pcolormesh(x, y, -0.001*model.relief.reshape(model.shape), cmap='viridis')
         cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=10))
         cbax.set_ylabel('km')
         bm.drawmeridians([-40, -20, 0, 20, 40], labels=[0, 0, 0, 1], linewidth=0, **config)
```

```
bm.drawparallels([20, 40, 60], labels=[1, 0, 0, 0], linewidth=0, **config)

i = 1
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(-0.05, 1.04, '(b)', transform=ax.transAxes, **config)
ax.set_title('Synthetic gravity anomaly', **config)
x, y = bm(lon.reshape(shape), lat.reshape(shape))
tmp = bm.contourf(x, y, data.reshape(shape), 30, cmap='RdBu_r', **data_minmax(data))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
cbax.set_ylabel('mGal')
bm.drawmeridians([-40, -20, 0, 20, 40], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels([20, 40, 60], labels=[1, 0, 0, 0], linewidth=0, **config)

plt.savefig('../manuscript/figures/synthetic-simple-data.eps')
```



Extract some of the data from the results dictionary.

In [12]:
```
moho = results['solution'].estimate_
solution = results['solution'][0]
residuals = solution.residuals()
regul_params = results['regul_params']
scores = results['scores']
best = results['best_index']
solver = results['solution']
diff = -0.001*(model.relief - moho.relief).reshape(moho.shape)
```

In [13]:
```
diff.max(),  diff.min()
```

Out[13]:
```
(2.1910477689482541, -2.1277272133152509)
```

In [14]:
```
regul_params[best]
```

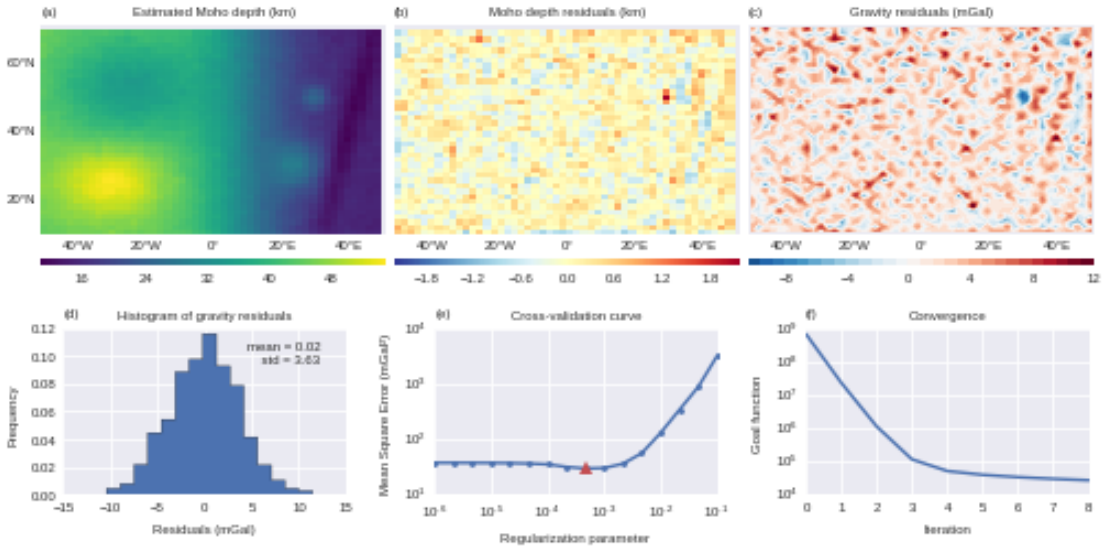
Out[14]:
```
0.00046415888336127773
```

Make a figure of the inversion results.

In [16]:
```
fig = plt.figure(figsize=(7, 3.5))

# The first part will be 3 maps
grid = AxesGrid(fig, [0.04, 0.33, 0.95, 0.8],
                nrows_ncols=(1, 3), axes_pad=0.05,
                cbar_location="bottom", cbar_mode="each",
                cbar_size=0.04, cbar_pad=0.15)

i = 0
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.05, '(a)', transform=ax.transAxes, **config)
ax.set_title('Estimated Moho depth (km)', **config)
x, y = bm(moho.lons, moho.lats)
tmp = bm.pcolormesh(x, y, -0.001*moho.relief.reshape(moho.shape), cmap='viridis')
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-40, -20, 0, 20, 40], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels([20, 40, 60], labels=[1, 0, 0, 0], linewidth=0, **config)

i = 1
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.05, '(b)', transform=ax.transAxes, **config)
ax.set_title('Moho depth residuals (km)', **config)
tmp = bm.pcolormesh(x, y, diff, cmap='RdYlBu_r', **data_minmax(diff))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-40, -20, 0, 20, 40], labels=[0, 0, 0, 1], linewidth=0, **config)

i = 2
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.05, '(c)', transform=ax.transAxes, **config)
ax.set_title('Gravity residuals (mGal)', **config)
x, y = bm(solution.lon, solution.lat)
tmp = bm.contourf(x, y, residuals, 30, tri=True, cmap='RdBu_r', **data_minmax(residuals))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-40, -20, 0, 20, 40], labels=[0, 0, 0, 1], linewidth=0, **config)

# Now make the axes to plot the 3 graphs on the bottom
height, bottom = 0.3, 0.1
left,  width, pad = 0.06, 0.255, 0.08
grid2 = [plt.axes([left, bottom, width, height]),
         plt.axes([left + width + pad, bottom, width, height]),
         plt.axes([left + 2*(width + pad), bottom, width, height])]

ax = grid2[0]
ax.text(0, 1.07, '(d)', transform=ax.transAxes, **config)
ax.set_title('Histogram of gravity residuals', **config)
text = "mean = {:.2f}\n    std = {:.2f}".format(
    residuals.mean(), residuals.std())
ax.text(0.65, 0.8, text, transform=ax.transAxes, **config)
ax.hist(residuals, bins=15, normed=True, histtype='stepfilled')
```

```
        ax.set_xlabel('Residuals (mGal)')
        ax.set_ylabel('Frequency')

        ax = grid2[1]
        ax.text(0, 1.07, '(e)', transform=ax.transAxes, **config)
        ax.set_title('Cross-validation curve', **config)
        ax.plot(regul_params, scores, '.-')
        ax.plot(regul_params[best], scores[best], '^',
                color=seaborn.color_palette()[2],
                label='Minimum')
        ax.set_xscale('log')
        ax.set_yscale('log')
        ax.set_xlabel('Regularization parameter')
        ax.set_ylabel(u'Mean Square Error (mGal$^2$)')

        ax = grid2[2]
        ax.text(0, 1.07, '(f)', transform=ax.transAxes, **config)
        ax.set_title("Convergence", **config)
        ax.plot(range(solver.stats_['iterations'] + 1), solver.stats_['objective'])
        ax.set_yscale('log')
        ax.set_xlabel('Iteration')
        ax.set_ylabel('Goal function')

        plt.savefig('../manuscript/figures/synthetic-simple-results.eps')
```

```
/home/leo/bin/anaconda/envs/moho/lib/python2.7/site-packages/matplotlib/__init__.py:892: UserWarning: axe
  warnings.warn(self.msg_depr % (key, alt_key))
```



1.3 CRUST1.0 synthetic

Makes the figures for the CRUST1.0 based synthetic data test.

Load the model, data, and inversion results.

```
In [17]: with open('../model/synthetic-crust1.pickle') as f:
             model = pickle.load(f)

In [18]: with open('../data/synthetic-data-crust1.txt') as f:
             for i in range(2):
                 f.readline()
             line = f.readline()
             shape = map(int, line.split()[1:])
             lat, lon, height, data = np.loadtxt(f, unpack=True, usecols=[0, 1, 2, 4])

In [19]: latp, lonp, depthp = np.loadtxt('../data/crust1-point-depths.txt', unpack=True)

In [20]: with zipfile.ZipFile('results/synthetic-crust1.zip') as f:
             results = pickle.load(f.open('synthetic-crust1.pickle'))

In [21]: results.keys()

Out[21]: ['models_refdens',
          'densities',
          'reference_levels',
          'solution_regul',
          'scores_regul',
          'models_regul',
          'solution',
          'best_dens',
          'scores_refdens',
          'best_regul',
          'regul_params',
          'config',
          'best_ref',
          'metadata']

In [22]: print(results['metadata'])

Generated by sinthetic-crust1.ipynb on 05 February 2016 21:48:27 UTC
```

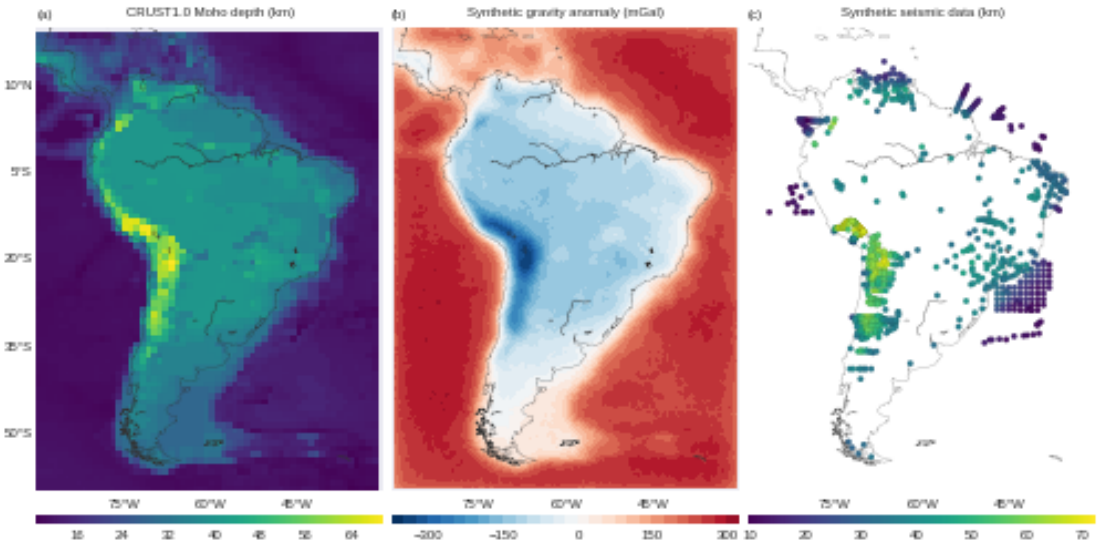
Make the map projection for these plots.

```
In [23]: bm = Basemap(projection='cyl',
                      llcrnrlon=model.area[2], urcrnrlon=model.area[3],
                      llcrnrlat=model.area[0], urcrnrlat=model.area[1],
                      resolution='l')
```

Plot the model and the synthetic gravity and seismological data.

```
In [22]: fig = plt.figure(figsize=(7, 3.5))

         grid = AxesGrid(fig, [0.04, 0.01, 0.95, 0.98],
                         nrows_ncols=(1, 3), axes_pad=0.05,
                         cbar_location="bottom", cbar_mode="each",
                         cbar_size="2%", cbar_pad="5%")

         i = 0
         ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
         ax.set_title('CRUST1.0 Moho depth (km)', **config)
         ax.text(0, 1.02, '(a)', transform=ax.transAxes, **config)
```

```
x, y = bm(model.lon.reshape(model.shape), model.lat.reshape(model.shape))
tmp = bm.pcolormesh(x, y, -0.001*model.relief.reshape(model.shape), cmap='viridis')
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[1, 0, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)

i = 1
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.set_title('Synthetic gravity anomaly (mGal)', **config)
ax.text(0, 1.02, '(b)', transform=ax.transAxes, **config)
x, y = bm(lon.reshape(shape), lat.reshape(shape))
tmp = bm.contourf(x, y, data.reshape(shape), 30, cmap='RdBu_r', **data_minmax(data))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=6))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)

i = 2
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.set_title('Synthetic seismic data (km)', **config)
ax.set_axis_bgcolor('white')
ax.text(0, 1.02, '(c)', transform=ax.transAxes, **config)
xp, yp = bm(lonp, latp)
tmp = bm.scatter(xp, yp, c=depthp*0.001, s=7, cmap='viridis',
                 linewidths=0.05)
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawcoastlines(color="#666666", linewidth=0.2, zorder=0)

plt.savefig('../manuscript/figures/synthetic-crust1-data.eps')
```



Extract some things from the results dictionary.

```
In [24]: moho = results['solution'].estimate_
         solution = results['solution'][0]
```

```
residuals = solution.residuals()
regul_params = results['regul_params']
scores_regul = results['scores_regul']
best_reg = results['best_regul']
reference_levels = results['reference_levels']
densities = results['densities']
scores_refdens = results['scores_refdens']
best_ref = results['best_ref']
best_dens = results['best_dens']
diff_seismic = -0.001*(-depthp - predict_seismic(moho, latp, lonp))
diff_model = -0.001*(model.relief - moho.relief).reshape(moho.shape)
```

In [25]:
```
diff_model.max(),  diff_model.min()
```

Out[25]:
```
(9.8358547811799735, -8.2322778445448286)
```

In [26]:
```
diff_seismic.max(),  diff_seismic.min()
```

Out[26]:
```
(9.4374315564211066, -7.5973400319479261)
```

In [27]:
```
regul_params[best_reg]
```

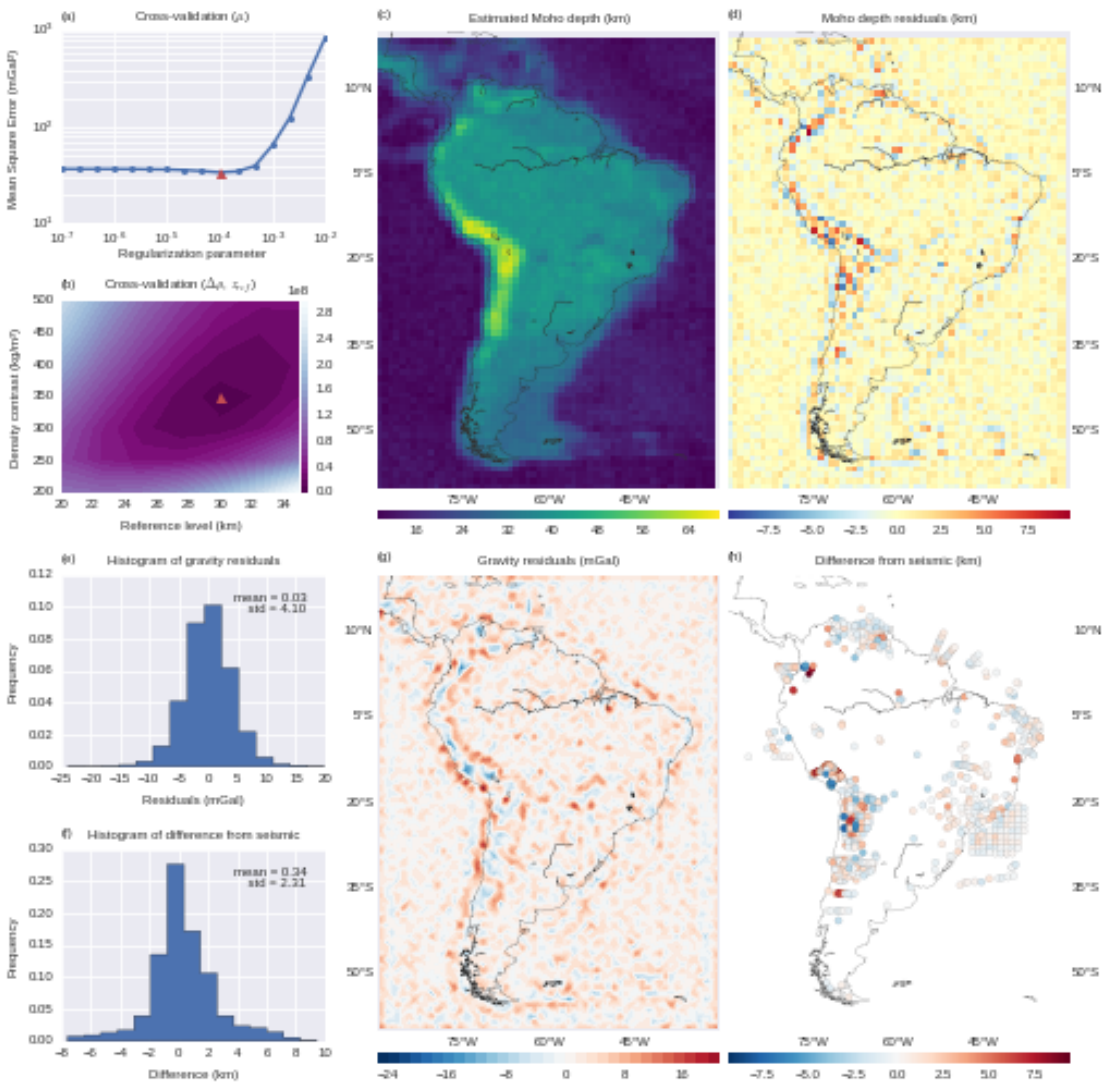
Out[27]:
```
0.0001
```

Make a figure of the inversion results.

In [30]:
```
fig = plt.figure(figsize=(7, 7))

# The four graphs
height, pad = 0.25, 0.075
left, width = 0.052, 0.24
grid2 = [plt.axes([left, 0.545 + height, width, height - pad]),
         plt.axes([left, 0.55, width - 0.015, height - pad]),
         plt.axes([left, 0.05 + height, width, height - pad]),
         plt.axes([left, 0.05, width, height - pad])]


ax = grid2[0]
ax.text(0, 1.06, '(a)', transform=ax.transAxes, **config)
ax.set_title(r'Cross-validation ($\mu$)', **config)
ax.plot(regul_params, scores_regul, marker='o', markersize=3)
ax.plot(regul_params[best_reg], scores_regul[best_reg], '^', markersize=5,
        color=seaborn.color_palette()[2],
        label='Minimum')
ax.set_xscale('log')
ax.set_yscale('log')
ax.set_xlabel('Regularization parameter', labelpad=0.5)
ax.set_ylabel(u'Mean Square Error (mGal$^2$)')
ax.yaxis.grid(True, which='minor')

ax = grid2[1]
ax.text(0, 1.07, '(b)', transform=ax.transAxes, **config)
ax.set_title(r'Cross-validation ($\Delta\rho$, $z_{ref}$)', **config)
tmp = ax.contourf(-0.001*reference_levels, densities, scores_refdens, 30, cmap='BuPu_r')
divider = make_axes_locatable(ax)
cbax = divider.append_axes("right", size=0.05, pad=0.01)
```

```
plt.colorbar(tmp, cax=cbax)
ax.plot(-0.001*reference_levels[best_ref], densities[best_dens], '^', markersize=5,
        color=seaborn.color_palette()[2], label='Minimum')
ax.set_xlabel('Reference level (km)')
ax.set_ylabel(u'Density contrast (kg/m$^3$)')

ax = grid2[2]
ax.text(0, 1.06, '(e)', transform=ax.transAxes, **config)
ax.set_aspect('auto')
ax.set_title('Histogram of gravity residuals', **config)
text = "mean = {:.2f}\n    std = {:.2f}".format(
    residuals.mean(), residuals.std())
ax.text(0.65, 0.8, text, transform=ax.transAxes, **config)
ax.hist(residuals, bins=15, normed=True, histtype='stepfilled')
ax.set_xlabel('Residuals (mGal)')
ax.set_ylabel('Frequency')

ax = grid2[3]
ax.text(0, 1.06, '(f)', transform=ax.transAxes, **config)
ax.set_title('Histogram of difference from seismic', **config)
text = "mean = {:.2f}\n    std = {:.2f}".format(
    diff_seismic.mean(), diff_seismic.std())
ax.text(0.65, 0.8, text, transform=ax.transAxes, **config)
ax.hist(diff_seismic, bins=15, normed=True, histtype='stepfilled')
ax.set_xlabel('Difference (km)')
ax.set_ylabel('Frequency')


# The four maps
grid = AxesGrid(fig, [0.34, 0.01, 0.63, 0.98],
                nrows_ncols=(2, 2), axes_pad=(0.05, 0.35),
                cbar_location="bottom", cbar_mode="each",
                cbar_size="2%", cbar_pad="5%")

i = 0
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(c)', transform=ax.transAxes, **config)
ax.set_title('Estimated Moho depth (km)', **config)
x, y = bm(moho.lons, moho.lats)
vmin, vmax = [func(-0.001*model.relief) for func in [np.min, np.max]]
tmp = bm.pcolormesh(x, y, -0.001*moho.relief.reshape(moho.shape), cmap='viridis',
                    vmin=vmin, vmax=vmax)
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[1, 0, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)

i = 1
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(d)', transform=ax.transAxes, **config)
ax.set_title('Moho depth residuals (km)', **config)
x, y = bm(moho.lons, moho.lats)
tmp = bm.pcolormesh(x, y, diff_model, cmap='RdYlBu_r', **data_minmax(diff_model))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
```

```
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[0, 1, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)

i = 2
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(g)', transform=ax.transAxes, **config)
ax.set_title('Gravity residuals (mGal)', **config)
x, y = bm(solution.lon, solution.lat)
tmp = bm.contourf(x, y, residuals, 30, tri=True, cmap='RdBu_r', **data_minmax(residuals))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[1, 0, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)

i = 3
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(h)', transform=ax.transAxes, **config)
ax.set_axis_bgcolor('white')
ax.set_title('Difference from seismic (km)', **config)
xp, yp = bm(lonp, latp)
tmp = bm.scatter(xp, yp, c=diff_seismic, s=10, cmap='RdBu_r',
                 linewidths=0.05, **data_minmax(diff_seismic))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[0, 1, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#666666", linewidth=0.2, zorder=0)


plt.savefig('../manuscript/figures/synthetic-crust1-results.eps')
```



1.4 Data for the South America application

Load the processed gravity data.

```
In [6]: with open('../data/processed-goco5s-data-sam-h50km.txt') as f:
            for i in range(2):
                f.readline()
            shape = tuple(int(i) for i in f.readline().split()[1:])
            data = np.loadtxt(f, unpack=True)
            lat, lon, height, topo, grav, disturbance, topo_effect, bouguer = data[:8]
            upper_sed, middle_sed, lower_sed, total_sed, sedfree_bouguer = data[8:]
            area = (lat.min(), lat.max(), lon.min(), lon.max())
```

Load the sediment model from CRUST1.0.

```
In [7]: crust1 = fetch_crust1('../data/crust1.0.tar.gz').cut(area)
```

Load the seismic point estimates of Moho depth from Assumpção et al. (2013).

```
In [8]: seismic_data = fetch_assumpcao_moho_points('../data/Moho_Map_SAm2013_data.tar.gz',
                                                   todepth=True, return_height=False)
        latp, lonp, seismic_moho = seismic_data[:-1]
        lonp += 360
```

Setup a basemap to plot the data with an appropriate projection.

```
In [9]: bm = Basemap(projection='cyl',
                     llcrnrlon=area[2], urcrnrlon=area[3],
                     llcrnrlat=area[0], urcrnrlat=area[1],
                     lon_0=0.5*(area[2] + area[3]), lat_0=0.5*(area[1] + area[0]),
                     resolution='l')
```

Convert the data, CRUST1.0, and seismic data coordinates to the projection.

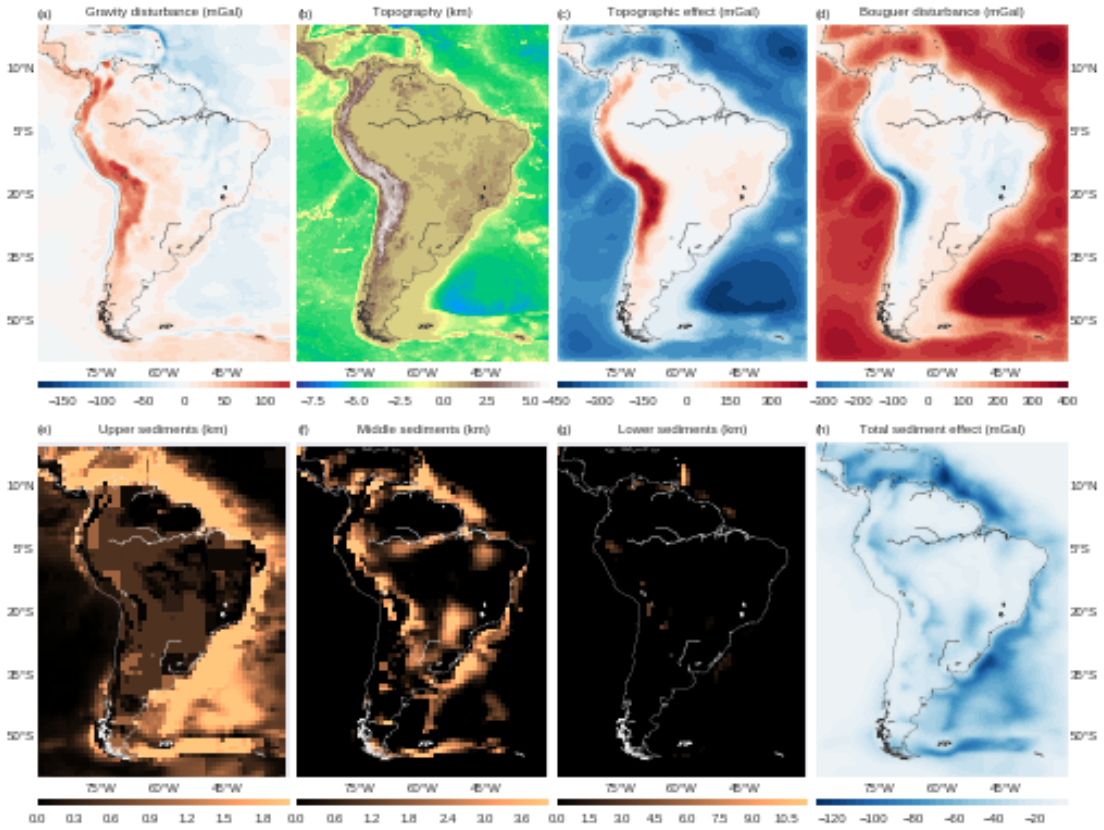
```
In [10]: x, y = bm(lon.reshape(shape), lat.reshape(shape))

In [11]: xc, yc = bm(crust1.lon + 360, crust1.lat)

In [12]: xp, yp = bm(lonp, latp)
```

Plot maps of the stages in the data correction, topography, and the sediment model used.

```
In [14]: fig = plt.figure(figsize=(7, 5.4))

         grid = AxesGrid(fig, [0.03, 0.01, 0.94, 0.98],
                         nrows_ncols=(2, 4), axes_pad=(0.05, 0.35),
                         cbar_location="bottom", cbar_mode="each",
                         cbar_size="2%", cbar_pad="6%")

         i = 0
         ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
         ax.text(0, 1.03, '(a)', transform=ax.transAxes, **config)
         ax.set_title('Gravity disturbance (mGal)', **config)
         tmp = bm.contourf(x, y, disturbance.reshape(shape), 30, cmap='RdBu_r',
                           **data_minmax(disturbance))
         cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
         bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
         bm.drawparallels(np.arange(-50, 30, 15), labels=[1, 0, 0, 0], linewidth=0, **config)
         bm.drawcoastlines(color="#333333", linewidth=0.2)

         i = 1
         ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
         ax.text(0, 1.03, '(b)', transform=ax.transAxes, **config)
         ax.set_title('Topography (km)', **config)
         tmp = bm.contourf(x, y, 0.001*topo.reshape(shape), 40, cmap='terrain')
         cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=7))
         bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
         bm.drawcoastlines(color="#333333", linewidth=0.2)

         i = 2
         ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
         ax.text(0, 1.03, '(c)', transform=ax.transAxes, **config)
         ax.set_title('Topographic effect (mGal)', **config)
```

```
tmp = bm.contourf(x, y, topo_effect.reshape(shape), 30, cmap='RdBu_r',
                  **data_minmax(topo_effect))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=6))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)

i = 3
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(d)', transform=ax.transAxes, **config)
ax.set_title('Bouguer disturbance (mGal)', **config)
tmp = bm.contourf(x, y, bouguer.reshape(shape), 30, cmap='RdBu_r',
                  **data_minmax(bouguer))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[0, 1, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)

i = 4
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(e)', transform=ax.transAxes, **config)
ax.set_title('Upper sediments (km)', **config)
tmp = bm.pcolormesh(xc, yc, 0.001*crust1.upper_sediments.thickness, cmap='copper')
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[1, 0, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#eeeeee", linewidth=0.2)

i = 5
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(f)', transform=ax.transAxes, **config)
ax.set_title('Middle sediments (km)', **config)
tmp = bm.pcolormesh(xc, yc, 0.001*crust1.middle_sediments.thickness, cmap='copper')
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawcoastlines(color="#eeeeee", linewidth=0.2)

i = 6
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(g)', transform=ax.transAxes, **config)
ax.set_title('Lower sediments (km)', **config)
tmp = bm.pcolormesh(xc, yc, 0.001*crust1.lower_sediments.thickness, cmap='copper')
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawcoastlines(color="#eeeeee", linewidth=0.2)

i = 7
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.03, '(h)', transform=ax.transAxes, **config)
ax.set_title('Total sediment effect (mGal)', **config)
tmp = bm.contourf(x, y, total_sed.reshape(shape), 30, cmap='RdBu_r',
                  **data_minmax(total_sed))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=8))
bm.drawmeridians([-75, -60, -45], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[0, 1, 0, 0], linewidth=0, **config)
```

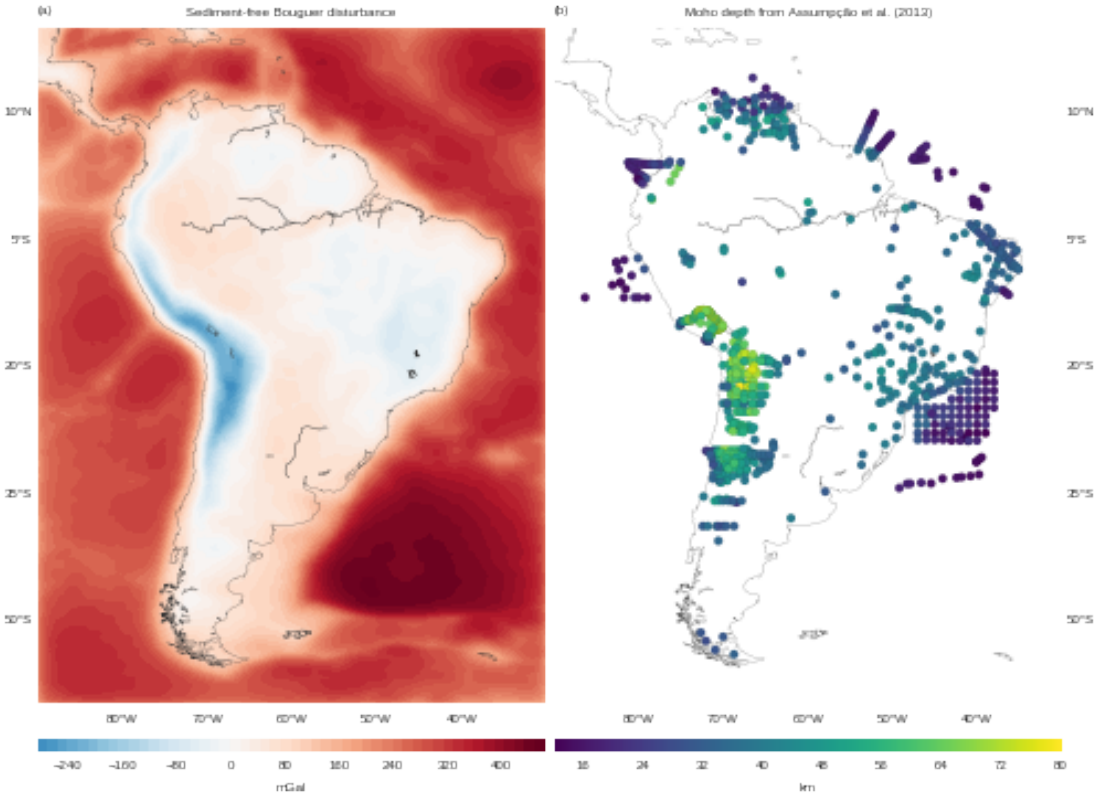
```
bm.drawcoastlines(color="#333333", linewidth=0.2)

plt.savefig('../manuscript/figures/south-america-corrections.eps')
```



Plot the input data for the inversion: the final sediment-free Bouguer disturbance and the seismic data.

In [34]:
```
fig = plt.figure(figsize=(7, 5))

grid = AxesGrid(fig, [0.04, 0.02, 0.92, 0.98],
                nrows_ncols=(1, 2), axes_pad=(0.05),
                cbar_location="bottom", cbar_mode="each",
                cbar_size="2%", cbar_pad="5%")

i = 0
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.02, '(a)', transform=ax.transAxes, **config)
ax.set_title('Sediment-free Bouguer disturbance', **config)
tmp = bm.contourf(x, y, sedfree_bouguer.reshape(shape), 50, cmap='RdBu_r',
                  **data_minmax(sedfree_bouguer))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=10))
cbax.set_xlabel('mGal')
bm.drawmeridians([-80, -70, -60, -50, -40], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[1, 0, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)
```

```
i = 1
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.02, '(b)', transform=ax.transAxes, **config)
ax.set_title(u'Moho depth from Assumpção et al. (2013)', **config)
ax.set_axis_bgcolor('white')
tmp = bm.scatter(xp, yp, c=-seismic_moho*0.001, s=15, cmap='viridis',
                 linewidths=0.05)
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=10))
cbax.set_xlabel('km')
bm.drawmeridians([-80, -70, -60, -50, -40], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 30, 15), labels=[0, 1, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#666666", linewidth=0.2, zorder=0)

plt.savefig('../manuscript/figures/south-america-data.eps')
```



1.5 South American Moho inversion

Plot the inversion results for the South American Moho application.

First, load the inversion results that were saved to a Python pickle file. The file was large so we had to split it into two parts. To load it, we'll join the two halfs of the zipped results into a single file using some bash commands.

```
In [13]: %%bash
         cd results
         cat south-america-moho.zip.part* > south-america-moho.zip
         cd ..
```

Now we can load the pickled results dictionary from the combined zip file.

```
In [14]: with zipfile.ZipFile('results/south-america-moho.zip') as f:
             results = pickle.load(f.open('south-america-moho.pickle'))
```

```
In [15]: solution = results['solution']
         moho = solution.estimate_
```

We'll use the same basemap from the previous figures.

```
In [16]: xm, ym = bm(moho.lon, moho.lat)
```

We'll load the outlines of the main geologic provinces of South America to the basemap object so that we can plot it later in the maps.

The shapefiles were used in Goutorbe et al. (2015) and downloaded from the Github repository bgoutorbe/seismic-noise-tomography.

```
In [17]: bm.readshapefile('../data/south-america-provinces/SouthAmericaTectonicElements',
                          'provinces', drawbounds=False)
```

```
Out[17]: (4,
          5,
          [-81.35639999999998, -53.886390999999925, 0.0, 0.0],
          [-34.79250299999992, 12.463887999999983, 0.0, 0.0])
```

Load the plate boundaries from Bird (2003). The files were downloaded from the website http://peterbird.name/publications/2003_PB2002/2003_PB2002.htm

```
In [18]: with open('../data/south-america-provinces/PB2002_plates.dig.txt') as f:
             plates = {}
             platename = None
             tmpx, tmpy = [], []
             for line in f:
                 if not line:
                     continue
                 if platename is None:
                     platename = line.strip()
                 elif "*** end of line segment ***" in line:
                     plates[platename] = [np.array(tmpx), np.array(tmpy)]
                     tmpx, tmpy = [], []
                     platename = None
                 else:
                     i, j = [float(number) for number in line.split(',')]
                     tmpx.append(i)
                     tmpy.append(j)
```

Calculate the difference with the seismological estimates and the observed gravity data.

```
In [19]: diff_seismic = -0.001*(seismic_moho - predict_seismic(moho, latp, lonp))
         print(diff_seismic.min(), diff_seismic.max())
         print(diff_seismic.mean(), diff_seismic.std())
```

```
(-22.788392791744613, 22.78909884206325)
(1.1758194640786224, 6.8359476475916532)
```

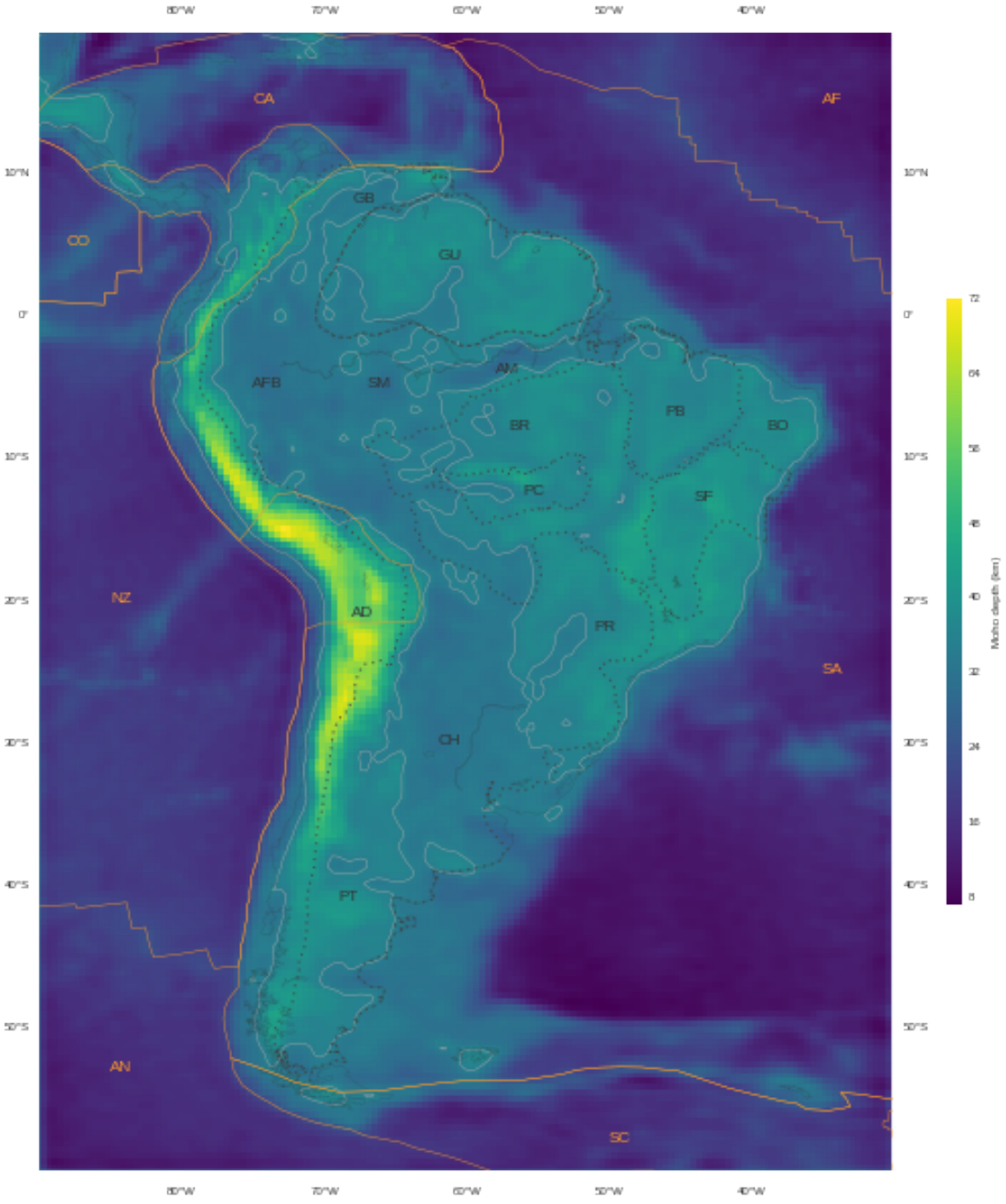
```
In [20]: residuals = solution[0].residuals()
         xr, yr = bm(solution[0].lon, solution[0].lat)
         print(residuals.min(), residuals.max())
```

```
(-28.362343001382925, 22.995475661988333)
```

Plot the estimated Moho depth with the major geologic provinces and plabe boundaries.

```
In [21]: provinces = set([2, 4, 9, 11])
         province_labels = [
             ['SF', -44, -13],
             ['PB', -46, -7],
             ['BO', -39, -8],
             ['BR', -57, -8],
             ['PC', -56, -12.5],
             ['PR', -51, -22],
             ['GU', -62, 4],
             ['GB', -68, 8],
             ['SM', -67, -5],
             ['AM', -58, -4],
             ['AFB', -75, -5],
             ['AD', -68, -21],
             ['CH', -62, -30],
             ['PT', -69, -41],
         ]
         plate_labels = [
             ['SA', -35, -25],
             ['CO', -88, 5],
             ['CA', -75, 15],
             ['SC', -50, -58],
             ['NZ', -85, -20],
             ['AN', -85, -53],
             ['AF', -35, 15],
         ]

In [27]: fig = plt.figure(figsize=(7, 8.3))

         ax = plt.axes([0.0, 0.03, 0.94, 0.94])
         cbax = plt.axes([0.94, 0.25, 0.015, 0.5])
         bm.ax = ax
         tmp = bm.pcolormesh(xm, ym, -0.001*moho.relief.reshape(moho.shape),
                             cmap='viridis')
         cb = plt.colorbar(tmp, cax=cbax)
         cb.set_label('Moho depth (km)')
         cs = bm.contour(xm, ym, -0.001*moho.relief.reshape(moho.shape), [35],
                         colors='#aaaaaa', linewidths=0.4)
         bm.drawmeridians([-80, -70, -60, -50, -40], labels=[0, 0, 1, 1],
                          linewidth=0, **config)
         bm.drawparallels(np.arange(-50, 20, 10), labels=[1, 1, 0, 0],
                          linewidth=0, **config)
         bm.drawcoastlines(color="#333333", linewidth=0.1)
         # Plot the major geologic provinces loaded from the shapefile
         for i, shp in enumerate(bm.provinces):
             if i in provinces:
                 xi, yi = np.transpose(shp)
                 bm.plot(xi + 360, yi, color='#444444', linestyle='dotted', linewidth=1)
         for label, llon, llat in province_labels:
             xi, yi = bm(llon, llat)
             ax.text(360 + xi, yi, label, fontsize=8, color="#333333")
```

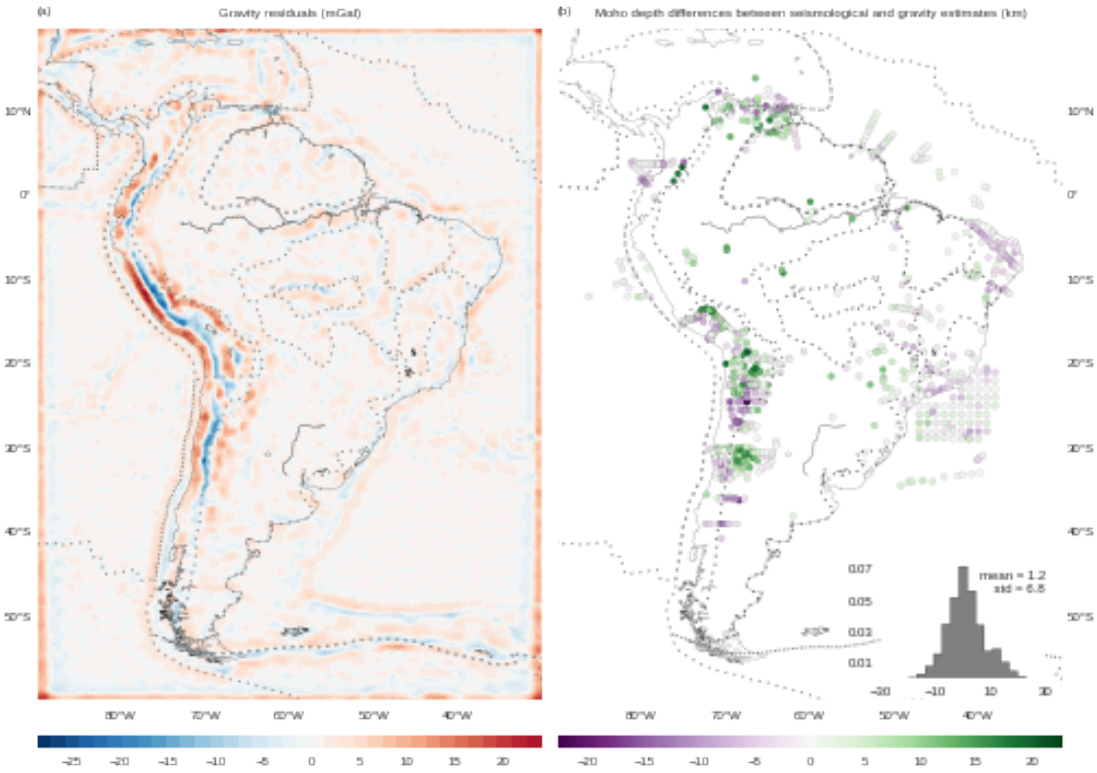
```
# Plot the boundaries of the lithospheric plates
for plate in ['SA', 'CO', 'CA', 'SC', 'NZ']:
    xi, yi = plates[plate]
    bm.plot(xi + 360, yi, color='#ff9c2a', linestyle='solid', linewidth=0.4)
for label, llon, llat in plate_labels:
    xi, yi = bm(llon, llat)
    ax.text(360 + xi, yi, label, fontsize=8, color="#ff9c2a")

plt.savefig('../manuscript/figures/south-america-moho.eps')
```



Plot the gravity residuals and the differences with the seismological estimates.

In [30]:
```
fig = plt.figure(figsize=(7, 5.))

grid = AxesGrid(fig, [0.035, 0.01, 0.93, 0.98],
                nrows_ncols=(1, 2), axes_pad=0.1,
                cbar_location="bottom", cbar_mode="each",
                cbar_size="2%", cbar_pad="5%")

i = 0
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.02, '(a)', transform=ax.transAxes, **config)
ax.set_title('Gravity residuals (mGal)', **config)
tmp = bm.contourf(xr, yr, residuals, 50, tri=True, cmap='RdBu_r', **data_minmax(residuals))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=12))
bm.drawmeridians([-80, -70, -60, -50, -40], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 20, 10), labels=[1, 0, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#333333", linewidth=0.2)
# Plot the major geologic provinces loaded from the shapefile
for i, shp in enumerate(bm.provinces):
    if i in provinces:
        xi, yi = np.transpose(shp)
        bm.plot(xi + 360, yi, ax=ax, color='#888888', linestyle='dotted', linewidth=1)
# Plot the boundaries of the lithospheric plates
for plate in ['SA', 'CO', 'CA', 'SC', 'NZ']:
    xi, yi = plates[plate]
    bm.plot(xi + 360, yi, color='#888888', linestyle='dotted', linewidth=1)

i = 1
ax, bm.ax, cbax = grid[i], grid[i], grid.cbar_axes[i]
ax.text(0, 1.02, '(b)', transform=ax.transAxes, **config)
ax.set_axis_bgcolor('white')
ax.set_title(u'Moho depth differences between seismological and gravity estimates (km)',
             **config)
tmp = bm.scatter(xp, yp, c=diff_seismic, s=9, cmap='PRGn',
                 linewidths=0.05, **data_minmax(diff_seismic))
cb = cbax.colorbar(tmp, locator=ticker.MaxNLocator(nbins=10))
bm.drawmeridians([-80, -70, -60, -50, -40], labels=[0, 0, 0, 1], linewidth=0, **config)
bm.drawparallels(np.arange(-50, 20, 10), labels=[0, 1, 0, 0], linewidth=0, **config)
bm.drawcoastlines(color="#666666", linewidth=0.2, zorder=0)
# Plot the major geologic provinces loaded from the shapefile
args = dict()
for i, shp in enumerate(bm.provinces):
    if i in provinces:
        xi, yi = np.transpose(shp)
        bm.plot(xi + 360, yi, ax=ax, color='#666666', linestyle='dotted', linewidth=1)
# Plot the boundaries of the lithospheric plates
for plate in ['SA', 'CO', 'CA', 'SC', 'NZ']:
    xi, yi = plates[plate]
    bm.plot(xi + 360, yi, color='#888888', linestyle='dotted', linewidth=1)

ax = plt.axes([0.8, 0.13, 0.15, 0.16])
ax.set_axis_bgcolor('white')
ax.grid(False)
```

```
    text = "mean = {:.1f}\n    std = {:.1f}".format(
        diff_seismic.mean(), diff_seismic.std())
    ax.text(0.6, 0.7, text, transform=ax.transAxes,
            fontsize=config['fontsize'])
    ax.hist(diff_seismic, bins=15, normed=True, histtype='stepfilled', color='grey')
    ax.set_yticks(ax.get_yticks()[1:-1:2])
    ax.set_xticks(ax.get_xticks()[::2])

    plt.savefig('../manuscript/figures/south-america-residuals.eps')
```



Plot the cross-validation results.

In [22]:
```
regul_params = results['regul_params']
scores_regul = results['scores_regul']
best_reg = results['best_regul']
reference_levels = results['reference_levels']
densities = results['densities']
scores_refdens = results['scores_refdens']
best_ref = results['best_ref']
best_dens = results['best_dens']
```

In [23]:
```
fig = plt.figure(figsize=(3.33, 3.5))

left, width, height = 0.2, 0.6, 0.36
grid = [plt.axes([left, 0.59, width, height]),
        plt.axes([left, 0.08, width, height])]
```

```
        ax = grid[0]
        ax.text(0, 1.06, '(a)', transform=ax.transAxes, **config)
        ax.set_title(r'Cross-validation ($\mu$)', **config)
        ax.plot(regul_params, scores_regul, marker='o', markersize=3)
        ax.plot(regul_params[best_reg], scores_regul[best_reg], '^', markersize=5,
                color=seaborn.color_palette()[2],
                label='Minimum')
        ax.set_xscale('log')
        ax.set_yscale('log')
        ax.set_xlabel('Regularization parameter')
        ax.set_ylabel(u'Mean Square Error (mGal$^2$)')
        ax.yaxis.grid(True, which='minor')

        ax = grid[1]
        ax.text(0, 1.06, '(b)', transform=ax.transAxes, **config)
        ax.set_title(r'Cross-validation ($\Delta\rho$, $z_{ref}$)', **config)
        tmp = ax.contourf(-0.001*reference_levels, densities, scores_refdens, 30, cmap='BuPu_r')
        divider = make_axes_locatable(ax)
        cbax = divider.append_axes("right", size=0.05, pad=0.03)
        plt.colorbar(tmp, cax=cbax)
        cbax.set_ylabel(u'Mean Square Error (km$^2$)')
        ax.plot(-0.001*reference_levels[best_ref], densities[best_dens], '^', markersize=5,
                color=seaborn.color_palette()[2], label='Minimum')
        ax.set_xlabel('Reference level (km)')
        ax.set_ylabel(u'Density contrast (kg/m$^3$)')

        plt.savefig('../manuscript/figures/south-america-cv.eps')
```

```
/home/leo/bin/anaconda/envs/moho/lib/python2.7/site-packages/matplotlib/__init__.py:892: UserWarning: axe
  warnings.warn(self.msg_depr % (key, alt_key))
```